Fifty Shapes of Grain

New archaeobotanical approaches towards charred finds of processed cereal-based foods

Cumulative Habilitation Thesis

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I. *Rahmenschrift* and Original Papers

Andreas G. Heiss
May 2019

"Processed and preserved foods kept well,
were easier to digest, and were delicious:

raised white bread
instead of chewy wheat porridge;
thick, nutritious, heady beer
instead of prickly grains of barley;
unctuous olive oil
instead of a tiny, bitter fruit;
soy milk, sauce, and tofu
instead of dreary, flatulent soy beans;
flexible, fragrant tortillas
instead of dry, tough maize;

not to mention red wine, blue cheese, sauerkraut,
hundred-year-old eggs, Smithfield hams,
smoked salmon, yogurt, sugar, chocolate, and fish sauce."

(Laudan, 2001, p. 38)

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[1] For all abbreviated institutions, please refer to **p. 71**.

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Abstract

Remains of ancient dishes can contribute significantly to the knowledge of past dietary habits, adding cuisine as the "missing link" between crop and consumption. Charred and fragmented archaeological remains of processed cereal preparations, while long having been neglected as a find category, bear large potential for analysis just as entire archaeological "bread loaves" do. The submitted work aims at providing a set of methods suitable for the analysis and interpretation of such finds.

After the introduction to the theoretical framework of the research questions, basic processes in food transformation are laid out with a particular focus on their consequences for the raw material's tissue and cell structures. Likewise, major factors affecting the deposition, preservation, and recovery of cereal-based foodstuffs are discussed, particularly highlighting the destructive potential of flotation. The historical overview of the field of ancient bread research together with its consecutive chapter gives an evaluation of previous analytical approaches and a methodological "state of the art" as suggested by the applicant, pointing out possibilities and limitations encountered in the identification and quantification of ingredients and in the observation of possible traces of food transformation processes.

The thesis concludes with highlighting possible strategies for finding answers to the initial questions by giving suggestions for modelling *chaînes opératoires* of archaeological food remains, and for the construction of comprehensive typologies within this complex find category.

Fifty Shapes of Grain — *Rahmenschrift*

Der Mensch ist, was er isst

Feuerbach's famous quote "man is what he eats" (Schuffenhauer 1990, p. 367) which provides the title for this introduction was originally intended in a much broader sense (Cherno 1963; Lemke 2004), yet it can still be seen as an early and explicit argument for the sociocultural significance of food choices (**Fig. 1**). A century later, in 1965, Lévi-Strauss (2004) suggested that, together with language, cuisine even constituted a "truly universal form of human activity" (*une forme d'activité humaine véritablement universelle*).

This activity, as essential for survival as it is, is so much more than just a means for staying alive. Over the past decades, cultural philosophy as well as social and historical anthropology have increasingly elaborated on the numerous aspects of food – or rather, of meals – and their roles in value-creation, in social stratification, in gender role attribution, and generally speaking in the constitution and delimitation of individual and collective identities (Hastorf 2016, pp. 219–308; Mintz & du Bois 2002; Samuel 1996a; Twiss 2012, 2015a). This seems to be true for societies and environments of scarce (Meyer-Rochow 2009) and of excess (Zeller 2015) availability of food alike. It is therefore not at all surprising that research into food ways has long become a key topic in archaeology with ever increasing importance (Bescherer Metheny & Beaudry 2015a, b; Garnsey 1999; Hastorf 2016; Hodder 1992; Renfrew & Bahn 2016, pp. 273–316).



Fig. 1. Four families around the world presenting their weekly diet. Clockwise from top left: Egypt, Mali, Italy, Mongolia. Images: Menzel & D'Aluisio (2005).

Translating Nature into Culture

Environmental constraints and the spectrum of available crops set the rough outlines of what can possibly be produced (Winiwarter 2006; Worster 1990), yet the choice of what is indeed planted and harvested (Chevalier et al. 2014) is also a matter of cultural identity. Equally, the tools and techniques involved in agricultural practices are constrained by availability, necessity and purpose, but within these constraints it is culture which guides their respective ways of application (Anderson et al. 2013; Anderson et al. 2003; Van Gijn et al. 2014).

The various ways of transforming raw matter into actual food may be outlined in the same way; whatever the desired result, food processing is outlined by a general framework of clear purposes such as improving palatability, nutritiousness, shelf life and taste (see p. **17**). Yet within those limits, there exists a vast space of possibilities for how elements of nature get actually incorporated into the social space of a culture (Dietler 1997; Haaland 2007; Hastorf 2016; Hayden 1997; Palmer & van der Veen 2002; Sherratt 1991). This space of possibilities in food transformation can be aggregated into the term cuisine (**Fig. 3**). Buccini (2016, p. 12) defines it as "the cultural domain which is principally concerned with the knowledge and behaviour of a given cultural community regarding the preparation and consumption of food".

Archaeobotany as one part of modern archaeology's methodological universe has already contributed a great deal to the understanding of nutritional regimes and their impact on past societies. As Twiss (2015b) conceded, however, most of the macrobotanical datasets only give indirect evidence of what was actually consumed, as they are based on find assemblages of inedible by-products from various stages of crop processing (Capparelli et al. 2011), or of unprocessed raw ingredients (Trausmuth & Wallner 2017). Even one of the most direct data sources for human consumption patterns – the analysis of human sewage (Boenke 2005; Brombacher et al. 2000; Greig 1982) or gut content (Fahmy 2008) – can only give information on the species composition of diets, but not the variability of cuisine itself.

Against this background, direct analysis of the outcomes of past cuisines – archaeological food remains – seems crucial for bridging the gap between agricultural crops, and actual consumption patterns. The basic research question of such analyses is just as easily formulated as it may be difficult to answer: What were the components of a certain foodstuff, and how were they processed?

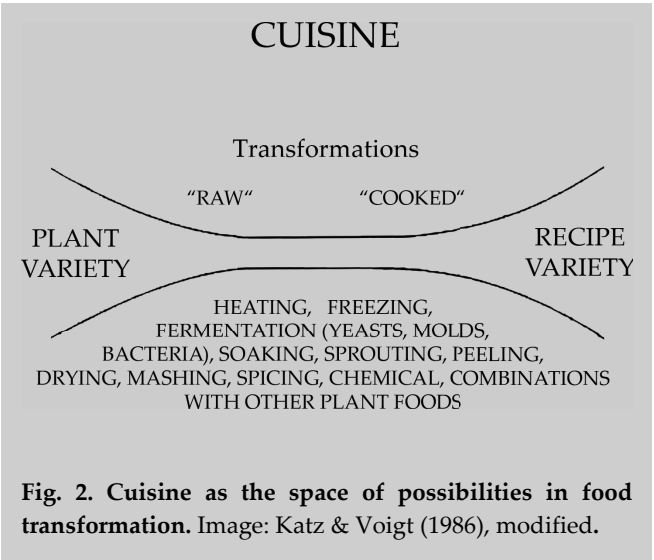


Fig. 2. Cuisine as the space of possibilities in food transformation. Image: Katz & Voigt (1986), modified.

From Ecofact to Artefact

Archaeological finds of plant parts such as cereal grains are commonly regarded as ecofacts, and thus as non-artefactual evidence, by most archaeologists (Jones 2005; Renfrew & Bahn 2008). A summarised definition of ecofacts as "unmodified biological remains, including plants and animals, whose deposition was the result of human activity" is given by Morehart & Morell-Hart (2015). Furthermore, they continue, "ecofacts typically are not considered artefacts unless clear indications exist that they were modified". Even when not considering the authors' subsequent arguments aimed at widening the definition of artefacts towards plant macroremains in general, archaeological finds of processed foodstuffs match the aforementioned as well as any other delimitation of what is an artefact, and of what is not (Balme 2007; Miller 1982; Peacock 1991). Contrary to single opposing opinions (Jones 2005), a meal as the material result of human action and creativity is indeed an artefact.

While in their work on behavioural archaeology Schiffer and Skibo discuss the tight link between cooking vessels and food processing, they hardly ever move their focus away from the pottery towards the food itself as a possible object of interest (Schiffer et al. 2010, pp. 99–100, 162; Skibo & Schiffer 2008, pp. 37–52). Quite differently, food remains do play a role in Hodder's (2011; 2012, pp. 40, 54–58) considerations as something bearing at least potential for analysis. A modified version of his behavioural chain is suggested in **Fig. 3**, incorporating considerations which more specifically deal with human–food interactions (Hastorf 2016, pp. 83–84; Samuel 1996a; Twiss 2012, pp. 361–365).

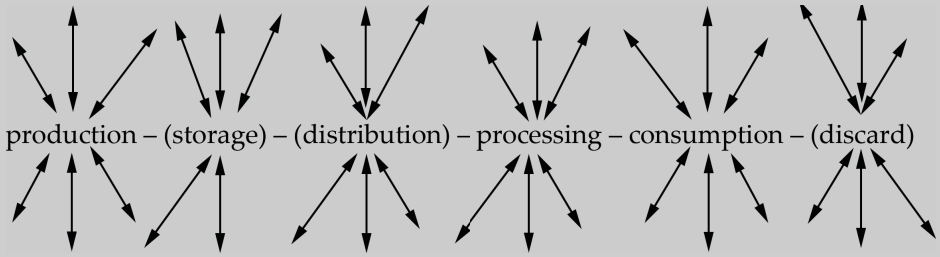


Fig. 3. Human-thing interactions along a behavioural chain for food. Items in brackets are optional activities which can take place in virtually any position of the chain. Image: Hodder (2011, 159), modified according to Twiss (2012, pp. 361–362).

Leroi-Gourhan's (1964, p. 164; 1965, pp. 27–32) initial idea of an entangled syntax of language and action was adapted and redefined for archaeology as the "range of processes by which naturally occurring raw materials are selected, shaped and transformed into usable cultural products" (Schlanger 2005). It has to be stressed that aside from "typical" artefacts, be they lithic, wooden, made of metal, glass or ceramics, the production of a dish can be – and should be – described in a specific *chaîne opératoire* (Twiss 2012, pp. 361–362) just as well. Like any other type of artefact, processed food remains have the prerequisites to be categorised in typologies (Adams & Adams 1991, pp. 76-90; Renfrew & Bahn 2016, p. 128). Such typologies of edible items could be defined as "culinary models repeated throughout history and often encompassing a wide range of different recipes without modification to their significance" (González Turmo 2004, p. 768). The reason for placing so much emphasis on *chaînes opératoires* and typologies of meals will be explained later on (see **p. 44 ff**. "Building Operational Sequences", and **p. 47 ff**. "Culinary Typologies").

If we were to imagine an ultimate goal for the research into food preparations of the past this would certainly be the identification of individual detailed recipes. Given exceptional preserving condi-

tions and thorough analysis of the material, a few attempts have indeed been successful. Maybe the most spectacular example in its outstanding ratio of "fact vs. fiction" (read as: hypothesis) comes from the Early Iron Age salt mines of Hallstatt, Austria: Analysis of human faeces preserved in the salt had already resulted in a spectrum of barley (*Hordeum vulgare*), broomcorn millet (*Panicum miliaceum*) and broad bean (*Vicia faba*) as food plants mainly consumed by miners. It was then the actual food remains still sticking to cutlery which showed that all three ingredients had indeed been prepared and consumed together as a rough porridge-like meal. A still existing dish, the Carinthian *Ritschert*, was then found to be an appropriate modern analogy (Barth 1999; Reschreiter & Kowarik 2008).

Outside the particular preserving conditions of a salt mine, taphonomical and methodological constraints (see on **p. 23 ff.** and on **p. 39 ff.**) make it however more likely that clear recipes stay beyond reach. A general approach may consequently be to 1) aim for the development, the testing and improvement of diagnostic criteria for components and their processing, 2) use the gained knowledge for the construction of a basic classification of certain ancient food types, 3) support this argumentation by experiments, and eventually 4) approximate what may have been the cuisine of a certain place, period, or group.

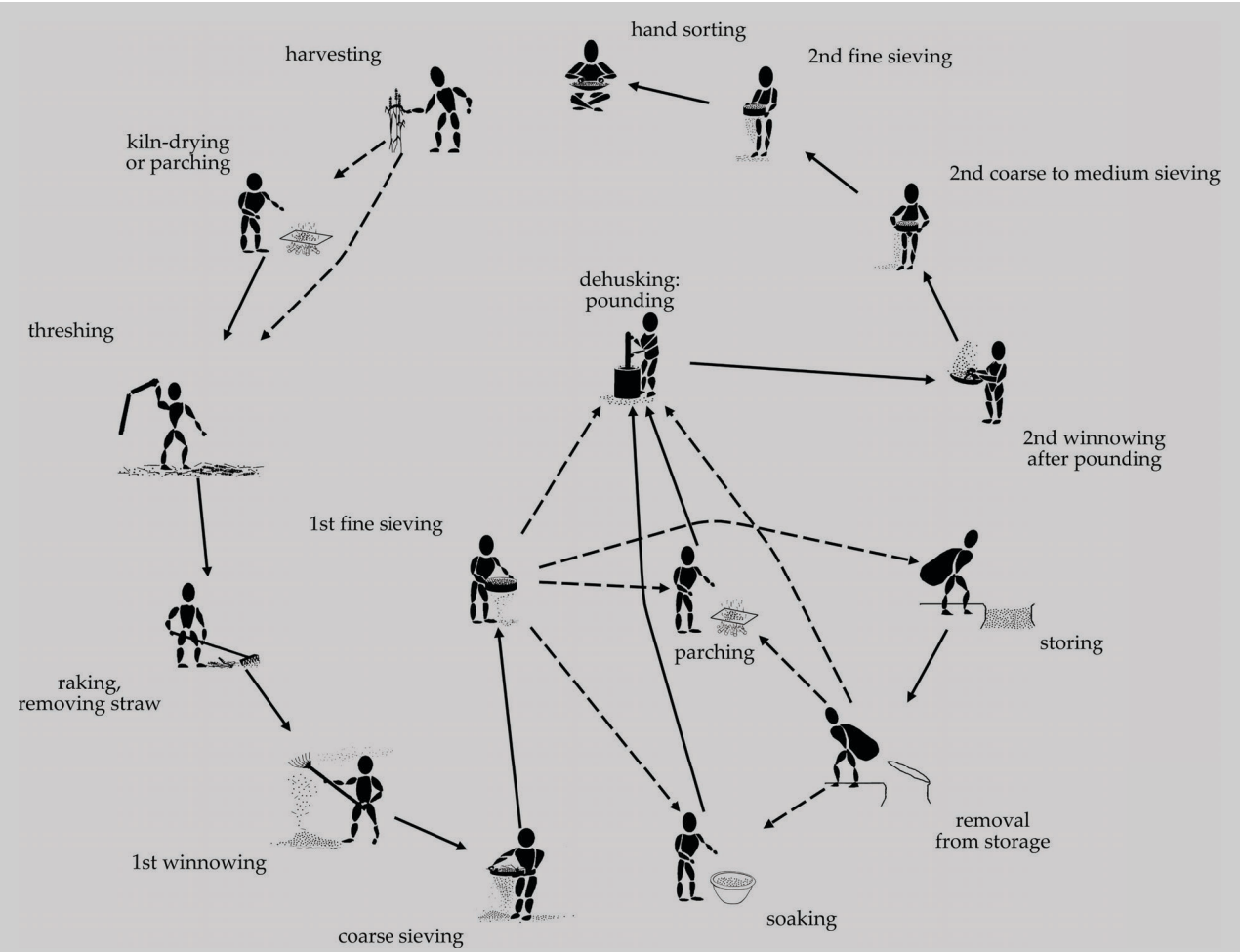


Fig. 4. Illustration of a *chaîne opératoire* for crop processing in hulled wheats, from the cereal plant to "ready-to-cook" grains. The sequence starts on top, proceeding counter-clockwise. Ramifications (optional steps) in dashed lines. Illustration basing on the design by Stevens (2003). Additional steps such as harvesting, kiln-drying, storing, and parching/soaking prior to dehusking were added (Hastorf 2016, p. 94; Peña-Chocarro & Zapata Peña 2003; Samuel 1994b). Image: ÖAW-ÖAI, A. G. Heiss.

Transforming Grains into Food

Beginning with the pioneering works by Gordon Hillman (1984) and Glynis Jones (1990), ethnography and experimental archaeology have allowed for the reconstruction of *chaînes opératoires* of crop processing applicable to archaeological finds of seed assemblages and their composition of grain, chaff, and weed seeds, respectively. These models cover the production stages where the cereal grains are still intact, which might be seen as the "ecofacts stage" of cereal processing (**Fig. 4**).

As soon as the grain loses its outer shape due to grinding, not only is it transformed further into the direction of an artefact, but the resulting archaeological remains become much more difficult to identify, and to interpret. This may be one of the reasons why research into the early prehistory of actual food preparation has only recently resulted in quite impressive insights; human knowledge of grinding, for example, does pre-date agriculture by far, as has been shown by Epipalaeolithic finds from southern Europe (Aranguren et al. 2007), from Israel (Nadel et al. 2012; Piperno et al. 2004), from Australia (Richard et al. 2015), and from New Guinea (Summerhayes et al. 2010).

Natufian preparation of dough-based food predating agriculture by c. 4,000 years has recently been impressively demonstrated (Arranz-Otaegui et al. 2018), while brewing has at least been plausibly hypothesized (Hayden et al. 2013).

Such finds change the view on past cuisines insofar as we must bear in mind that a wide range of individual processes as well as possibly elaborate *chaînes opératoires* for the transformation of plant-based food had already been widely available to people for a long time before even the first domesticates became available (Fuller & González Carretero, 2018).

The following brief overview is not intended as an in-depth study of all variants of processes involved in food transformation but shall instead give a rough characterisation of some of their purposes, and of some of their main effects on a structural level (see also Cappers 2018, pp. 41–73; Delcour & Hoseney 2010).





Fig. 5. Dehusking of einkorn (*Triticum monococcum*) in a wooden mortar. *Linearbandkeramik* (LBK) re-enactment (Landsmann et al. 2013) at the MAMUZ Asparn/Zaya, Lower Austria (Etzlstorfer et al. 2013). Images: univie-VIAS, W. Lobisser.

Dehusking and Grinding

Dehusking (dehulling) is commonly considered as crop processing rather than food processing, but their delimitation is not entirely straightforward (Cappers 2018, p. 56; Cappers et al. 2016, pp. 1311–1335). Removal of the silica-rich glumes which protect the kernels from herbivores (Massey et al. 2006) including humans (Münzing 2004) is an important first step in the preparation of cereal-based meals.



Fig. 6. Traditional Greek barley rusk (*Κριθαρένιο Παξιμάδι*) containing large amounts of glumes. Produced by Astarti–Tzortzopoulos Estate, Karavas, Kythera, Greece. Scale bar units: centimetres. Image: ÖAW-ÖAI, A. G. Heiss.



Fig. 7. Grinding einkorn (*Triticum monococcum*) on a saddle quern. *Linearbandkeramik* (LBK) re-enactment (Landsmann et al. 2013) at the MAMUZ Asparn/Zaya, Lower Austria (Etzlstorfer et al. 2013). Image: univie-VIAS, W. Lobisser.

Even more so, the choice to dehusk a portion of grain is a decisive step away from storage and towards consumption, as it decreases the general storability of the grain (Hillman 1981; Reddy 2003, p. 77; Riesen et al. 1986) and brings with it the risk of damaging the germ. It should be stated, however, that for malting no prior dehusking is required (Nesbitt et al. 1996).

Threshing suffices to remove the glumes of naked cereals, but hulled cereals require additional pounding or squeezing (**Fig. 5**), optionally involving parching or soaking as pre-treatments (Alonso et al. 2013; Hillman 1984; Nesbitt & Samuel 1996; Peña-Chocarro & Zapata Peña 2003; Samuel 1994b; Stevens 2003).

While highly efficient in hulled wheats, the process of dehusking leaves notable percentages of hulled grains in millet (Lundström-Baudais et al. 2002) and especially in hulled barley (Alonso et al. 2013). The remaining glumes are subsequently ground with the rest of the grain to be removed later by sieving. In contrast to wheat chaff, even relatively large quantities of barley glumes (**Fig. 6**) do not render the resulting product inedible (Kremezi 1997; Procopiou 2003; Shetlar & Lyman 1944).

Grinding (**Fig. 7**) and milling break up the endosperm cells and massively enlarge the contact surfaces for the amylases in saliva and pancreatic juice (Heaton et al. 1988; Waldron et al. 2003). On a subcellular level, an increasing amount of starch granules gets damaged and fragmented as a function of the intensity and longevity of the grinding action (Delcour & Hoseney 2010, pp. 108–121).

Soaking and Kneading

It has been mentioned before that soaking and subsequent drying can already play a role in crop processing (**Fig. 4**). In food preparation, it is found at the basis of a wide range of mixtures ranging from broths and beers to porridges or doughs. Besides water, any water-based liquid can be used, dairy products in most cases (Cappers 2018, pp. 49–50), but also less commonly used ingredients such as blood are documented (Hansson 1996; Maurizio 1916, p. 103).

On a microscopic level, soaking leads to the reversible swelling of starch, an effect which is stronger in damaged starch granules (Barrera et al. 2007; Tester & Morrison 1994). If the mixture stays in a wet state for several hours, endogenic amylases from the endosperm's aleurone layer lead to the progressive saccharification of starch (Martínez-Anaya 2003). Again, damaged starch granules are more susceptible to this enzymatic hydrolysis (Barrera et al. 2007).

While the purpose of kneading is primarily mixing a bread's constituents, it also has an impact on numerous other properties of the product, such as the formation of the three-dimensional gluten network (Samuel 1994a, pp. 63–64), gas cell distribution (Chakrabarti-Bell et al. 2014) and even the development of aroma (Zehentbauer & Grosch 1998).



Fig. 8. Kneading, shaping, and baking of einkorn (*Triticum monococcum*) bread. *Linearbandkeramik* (LBK) re-enactment (Landsmann et al. 2013) at the MAMUZ Asparn/Zaya, Lower Austria (Etzlstorfer et al. 2013). Images: univie-VIAS, W. Lobisser.

Heating

Roasting, baking and boiling generally lead to the denaturation of peptidic antinutrients such as lectins and protease (trypsin) inhibitors (Ayyagari et al. 1989; Grela 1996; Liener 1979), and they increase the shelf life of food preparations by killing microorganisms (Stahl 1989; Wandsnider 1997).

If heat is applied onto soaked cereal preparations, the swollen starch granules begin to gelatinize (Lund & Lorenz 1984), which accelerates and facilitates starch digestion upon consumption (Dreher et al. 1984; Stahl 1989). In the production of raised bread, dry heat is crucial for

the formation of a crust, i.e. sealing the product's surface and trapping vapour inside during baking (Altamirano-Fortoul et al. 2012).

It is mainly, but not only, dry heat as applied in baking, kilning, or the production of *frikeh* and *Grünkern* which leads to the formation of melanoidins from reducing sugars and peptides in Maillard reactions, adding characteristic flavours (De Kimpe & Keppens 1996; Fogliano 2016; Maillard 1912). In modern bread, it is these flavours (Zhou et al. 2016) next to the sensory qualities of the crust (Gao et al. 2017) as well as the size distribution and interconnectivity of cavities (Gao et al. 2018) which mainly influence the consumer's perception of the product.

Germinating



Fig. 9. Three days old green barley malt. Product of STAMAG, Vienna. Image: ÖAW-ÖAI, A. G. Heiss

Germination is a process in food preparation with unique characteristics, as it is an entirely endogenic process requiring an intact, living grain. After soaking, it is the release of gibberellic acid (GA) by the embryo leading to the *de novo* synthesis of α-amylase and numerous other hydrolytic enzymes in the scutellum and in the aleurone layer, mobilising the storage materials nourishing the sprouting germ.

Summed up very briefly, the structural consequence is a progressive breakdown of the endosperm's starch content and cell walls (Ashford & Gubler 1984; Briggs 1963; Burton et al. 2010; Gubler et al. 1987; Taiz & Honigman 1976). In beer production's malting process (**Fig. 9**), germination provides the enzymes for the saccharification of the raw material into wort during mashing (Bamforth 2005, pp. 52–56), thereby sustaining the microorganisms involved in the fermentation process.

Fermenting

The many purposes of fermentation in food processing are as diverse as the involved organisms and raw materials (Bamforth 2005, pp. XIV–XVI; Steinkraus 1996, pp. 1–5). Food preservation can certainly be regarded as one of the central aspects of fermentation. The longer shelf life results from the suppression of populations of unwanted germs by the presence of intentionally cultivated microorganisms. Furthermore, the latter produce metabolites actively inhibiting growth of other microorganisms. The organic acids produced by lactic acid and acetic acid bacteria are the most frequently used ones. Ethanol produced by yeasts shall be mentioned as well, just as the innumerable amount of complex antimicrobial metabolites produced by mycelial fungi (Holzapfel et al. 1995). The ethanol, while only a volatile side product in bread-making, is of course the *conditio sine qua non* in brewing beer (Bamforth 2005; Samuel 2000, pp. 29–30).

Improvement of digestibility is another common trait in microbial fermentation, above all the breakdown of starch and proteins in the grain (Benedito de Barber et al. 1989). Depending on the ingredients, some toxins (Tamang 2010a, pp. 68–69) can require biodegradation. In cereals, fermentation degrades antinutrients such as phytic acid (Helou et al. 2016; Lopez et al. 2003), although the relevance of this process for human nutrition has been under debate (Lopez et al. 2002).

Intentionally cultivated microorganisms share the common trait of producing metabolites which are generally non-toxic to humans (Holzapfel et al. 1995) – at least when not taking alcohol into account **Fig. 10**. Beyond this, fermentation also accounts for an increase in a wide range of health-promoting compounds in the substrate, such as vitamins (Steinkraus 1996, pp. 1–5). Fermentation also greatly contributes to a product's taste: the rapid breakdown of proteins and starch into smaller peptidic and saccharidic units (Benedito de Barber et al. 1989) influences both the quantity and the quality of the aforementioned Maillard reactions during baking or roasting (De Kimpe & Keppens 1996; Fogliano 2016).

Some microbial metabolites also have fundamental structural impact on the product. As an example, in bread-making the produced CO_2 is a desired side-effect allowing the rising of the dough. For rye bread (**Fig. 11**), it is also the lactic acid-moderated lowered pH which is required as a precondition for sufficient gas retention and thus rising (Gan et al. 1995). Of the numerous other factors influencing dough rising only the four most important ones shall be mentioned here: water content (MacRitchie 1976), gluten composition (Borghi et al. 1996; Kienmeyer 2010; Sapirstein et al. 2007), the amount of damaged starch (Barrera et al. 2012; Barrera et al. 2007), and the degree of fermentation (Upadhyay et al. 2012).

Aside from macroscopic features such as stabilised airspaces (cavities, see **p. 35**) and

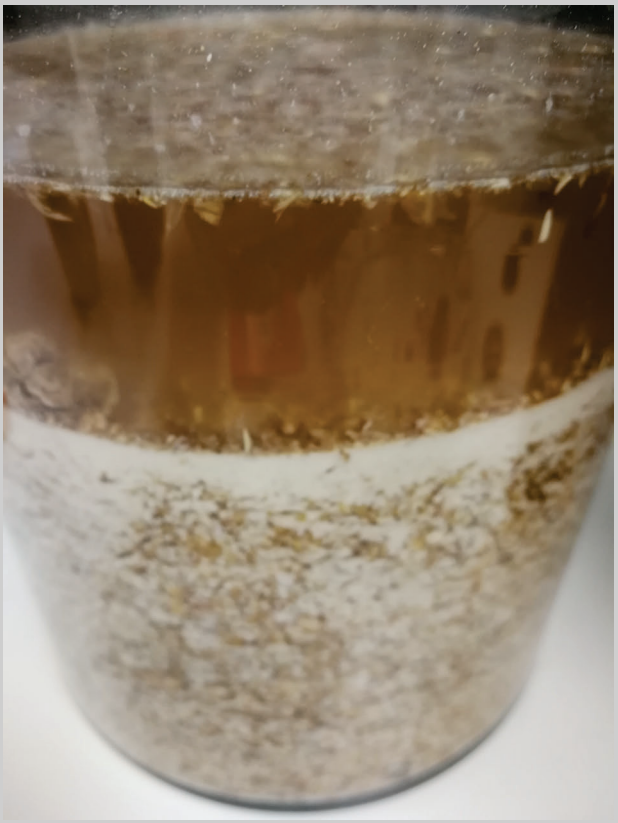


Fig. 10. Experimental beer after 24 hours of spontaneous fermentation (Zarnkow et al. 2006). Image: ÖAW-ÖAI, A. G. Heiss.



Fig. 11. Large cavities in a traditional Alpine "Original Vinschgauer" bread, basing on mixed wheat and rye sourdough. Produced by Bäckerei Preiss, Südtirol – Alto Adige, Italy. Scale bar units: centimetres. Image: ÖAW-ÖAI, A. G. Heiss.

crumb/crust formation in solid cereal products (Scanlon & Zghal 2001; Wang et al. 2011), one of the most notable structural changes caused by fermentation is only observable via Scanning Electron Microscope (SEM): the progressive decomposition of starch granules (Palmer 1972; Samuel 2006; Wang et al. 2017). In cereal products fermented by mycelial fungi, an increasing damage to cell walls is also observable (Tamang 2010a, p. 46).

Taphonomical Considerations

Processing Means Destroying

All the aforementioned cultural techniques allow for the consumption of foodstuffs which would otherwise be difficult or even impossible to digest (Wollstonecroft 2011). Yet it is exactly these processes which are highly detrimental to the preservability of the resulting foodstuffs in archaeological contexts; while the basic product gets more and more refined, plant components which are identifiable under the microscope gradually become rarer and show stronger fragmentation (Kubiak-Martens et al. 2015).

The resulting product's resistance to microbial decay is dramatically lowered, with the consequence that flour-based products decompose within short periods even under waterlogged conditions (Samuel 2002). Outside geographical areas or archaeological contexts with the possibility of desiccated preservation such as in deserts (Chen et al. 2012; Gong et al. 2011; Samuel 1994c) or in salt mines (Hofmann-de Keijzer et al. 2013; Kern et al. 2008), the direct analysis of cereal products is therefore basically limited to charred finds only (Heiss et al. accepted; Heiss et al. 2017a).

Charring

Charring is well-known as a strong filter for plant remains (Popper 1988), and even given optimal charring conditions, the charred preservation of processed food depends on particular events such as "baking accidents", intentional burning (Heiss et al. 2015) or catastrophic fires (Heiss et al. 2017a). The process of charring, however, does not generally affect the determinability of isolated plant tissues, as not only the cell wall structures (Dickson 1987; Hansson & Isaksson 1994) but also subcellular elements such as starch granules can remain recognizable in charred state (Berihuete Azorín et al. forthcoming; Valamoti et al. 2008). Chemically, however, the material is heavily affected by the massive transformations during pyrolysis (Greenwood 1967; Montoya et al. 2016) which sets very tight limits to residual analysis. This may explain why, in comparison to histological approaches, chemical analyses of such material have up to now only yielded rather diffuse results (Hillman et al. 1993; Kubiak-Martens et al. 2015; Lannoy et al. 2002; Martínez Straumann 2004; McLaren & Evans 2002; Oudemans & Boon 1991; Pető et al. 2013). It must be stressed that one consequence of the aforementioned is the difficulty of making specific statements on animal components such as meat, fat or dairy products as well as on soluble ingredients in general when it comes to charred food preparations.

Preservation Biases

Aside from charring, some additional taphonomical factors and also methodological constraints seem to be involved in the preservation of ancient food remains and deserve discussion. In Europe, the majority of charred bread-like objects originate from the waterlogged sediments of lakeshore dwellings around the Alps (Heiss et al. 2017a; Hofmann 1924; Lannoy et al. 2002; Maier et al. 2001; Riehl 2004; Währen 1984). Burnt-down bakeries (**Fig. 13**, **Fig. 12**) are another notorious source for such finds (von Groller-Mildensee 1902; Mayeske 1972; Monteix 2015), as are ritual deposits such as votive offerings and grave goods (Ciaraldi 1997–1998; Hansson 1996; Heiss et al. accepted; Heiss et al. 2015; Herbig 2016; Primavera et al. 2018; Währen 1990). The latter have been particularly emphasised by T. Popova (2016): "[…] bread fragments are among the most common finds in ceremoni-



Fig. 13. The bakery of *Carnuntum*, Lower Austria, excavated in 1900 (von Groller-Mildensee 1902).



Fig. 12. One of the large bread loaves recovered from the *Carnuntum* bakery. Scale bar units: centimetres. Image: ÖAW-ÖAI, A. G. Heiss.

al/ritual fireplaces, burial mounds, and sanctuaries […]". This statement should by no means be understood by the reader as postulating lesser importance of "bread" use in profane contexts, but rather as emphasising the special taphonomy of ritual depositions.

All of the find situations mentioned above share the common trait of reduced mechanical stress affecting the charred finds, either because these fragile objects were a) embedded in soft lakeshore sediments, b) charred and embedded *in situ*, or c) deliberately and carefully deposited. The recovered objects also have in common that they are usually hand-collected, in contrast to flotated material. Albeit modern archaeobotanical research is unimaginable without flotation (Twiss 2015b), the destructive potential of the method on charred plant material (Wagner 1988) has just recently been reconfirmed (Arranz-Otaegui 2016). In order to recognise and preserve such objects, it is therefore strongly recommended to complement standard flotation of bulk soil samples with direct sampling when noticeable concentrations of plant remains are discovered.

Cereal products are indeed a very frequent archaeological find category, yet due to their fragility they are highly prone to fragmentation (Antolín et al. 2018; Fuller & González Carretero 2018), their fragments usually not allowing for any inference to the original artefact such as bread in the broadest sense, porridges, or others (Antolín et al. 2016; Hansson 1994; Heiss 2015b). Even worse, as D. Fuller puts it, they are also "more often than not set aside by archaeobotanists as indeterminate fragments" (Fuller & González Carretero 2018). This find category will be discussed in more detail on **p. 27** ("The Archaeobotanical Side") and **p. 29** ("Initial Classification").

Fragility may also cause a very different kind of bias, as an example, among the many intact bread-like objects recovered from Station "See" at Lake Mondsee, Upper Austria, only a single find of seemingly raised bread has been reported (Hofmann 1924). This may certainly be due to the scarcity of fermented bread in this and other late Neolithic lakeshore dwellings – yet it must also be kept in mind that a charred object full of large cavities is a lot more fragile than a denser one, that it fragments more easily, and is therefore less likely to be found in intact state in an archaeological context. Even within the same object – we might imagine a charred loaf of raised bread – the denser (crust) portions will be more resistant to mechanical stress and therefore will have higher probability of preservation in an archaeological context than the airier (crumb) portions.

Ancient Bread Research: A Brief History

The Early Days

Some of the earliest attempts to identify the components of archaeological "bread" finds (**Fig. 14**) are as old as the roots of archaeobotany in the late nineteenth century, when excavations at the lakeshore dwellings of Wetzikon-Robenhausen at Lake Pfäffikon, Switzerland (Heer 1865; Messikommer 1913, p. 88; plate XXXVII), or at Station "See" at Lake Mondsee, Upper Austria (Hofmann 1924), resulted in numerous finds of supposed bread loaves which sparked interest in archaeologists and botanists. Surprisingly, as Samuel (1994a, pp. 33–35) put it, it was not before the *fin de siècle* that the already long-known desiccated bread loaves from Egypt were also subjected to scientific analysis (Wittmack 1896).

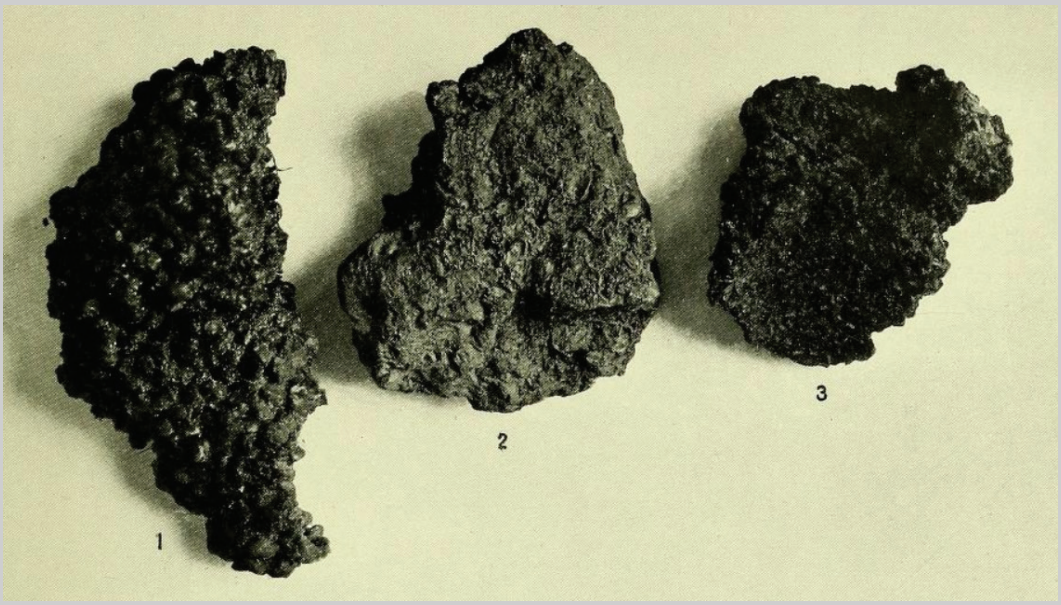


Fig. 14. Archaeological finds of supposed bread from the lakeshore settlements of Robenhausen, Lake Pfäffikon, Switzerland. 1: *Rohbrot* ("*Pumpernickel*") *aus ganzen Weizenkörnern*, 2: *Weizenbrot aus zerquetschten Weizenkörnern*, 3: *Hirsebrot* ("*Ankeweckli*") *aus Hirsekörnern mit Mischung von Weizenkörnern und Leinsamen*. Image: Messikommer (1913, plate XXXVII).

Histological knowledge at the time certainly allowed for the identification of uncharred cereal bran under transmitted light (e.g. Netolitzky 1914; Winton & Winton 1932, 1935; Wittmack 1896). Yet the analysis of charred cereal products requires either a reflected light microscope with magnifications of c. 500-fold and dark field illumination, or an SEM – both of which were not available at the time. Nevertheless, these first analyses were of fundamental importance for the following development of archaeobotany into a discipline (Binder et al. 2018; Jacomet & Kreuz 2013; Schneider 1993).

Notwithstanding their historical importance, the scientific content of these early approaches has to be regarded with caution, and the facts presented therein require thorough re-evaluation. Heer (1865, p. 9), for example, leaves no doubt that several "breads" from Lake Pfäffikon must have been made of millet, without expanding upon the reasons for this conclusion. Maurizio (1916, p. 91) adds up more *unzweifelhafte Hirsekuchen* ("doubtless millet cakes") from Swiss lakeshore settlements.

Hofmann (1924, pp. 387-388), although favouring the same idea for the Lake Mondsee bread objects, at least conceded they might contain virtually any cereal.

Max Währen, Ambiguous Pioneer

From the mid-20th century onwards, the extensive activities of the late Max Währen have brought a lot of public attention to archaeological finds of cereal products. His comprehensive œuvre was mainly focused on material from late Neolithic lakeshore settlements in Switzerland, but also covered numerous other regions and periods (Eiselen 2000). The sheer mass of objects he has been involved with makes his publications something which cannot be ignored.

Although extending up to the recent past, his work must be regarded as a setback in terms of methodology, even in comparison to the very first attempts of analysing archaeological bread remains. The reasons for this seemingly harsh judgement lie mainly in his disregard of established methods in microscopy, and the lack of reproducibility of his own methods and classifications. Examples for earlier critical statements can be found in Stika (1996a, p. 137), Antolín et al. (2016) and Heiss et al. (2017a).

Reference to, and potential rebuttal of, each of his *termini technici* and assigned food categories would clearly miss the scope of this work. Aside from **Fig. 15**, only one further example shall be given in order to outline basic issues: Throughout Währen's work, one of the most frequently used descriptive terms is the *Schrumpfungshügel* ("contraction bump") in the material. While a clear definition of this feature or even the diagnostic purpose of this criterion remains unexplained, further reading shows that the expression seems to refer to his hypothesis of a progressive shrinkage of charred archaeological bread finds through time (Währen 1984, 1989; 1990, p. 199).



Fig. 15. Late Neolithic grain agglomeration of free-threshing wheat (*Triticum aestivum/durum/turgidum*) from Twann, Lake Biel, Switzerland. The object was published as *Energiefladen* (approx. "energizing flat bread") and *Ur- Urbrot* ("palaeo-palaeo-bread") by Währen (1995, reprint 2000b) for unexplained reasons. Property of the Museum der Brotkultur, Ulm (inv. no. O-.2967). Scale bar units: centimetres. Image: ÖAW-ÖAI, N. Gail.

The method deriving from this *Schrumpfungshügel* hypothesis, the *Fotolichtreflex-Schrumpfungshügel-Ausdehnungsmethode*, approximately translating to "photo light reflex contraction bump expansion method", (Währen 1990, p. 196), remains entirely unexplained in its technique, in its outcomes, and even in its purpose. He does seem however to use the hypothesised shrinkages for size reconstructions (Währen 1990, p. 199).

Re-evaluation of M. Währen's œuvre is therefore certainly among the main *desiderata* in the research of central European archaeological bread finds. This seems even more urgent as two of his most famous bread identifications from late Iron Age graves near Wederath (Rhineland-Palatinate, Germany), the *Ringgebäck* ("ring pastry") and the *Blasenkuchen* ("bubble cake") have just recently turned out to

be a beeswax ring and a blotch of birch tar, both uncharred (Heiss & Gail in print; Linke 2019).

All criticism notwithstanding, it is the great achievement of this autodidact (Eiselen 2002) that he massively raised awareness for the find category of bread in the widest sense, keeping it alive for decades by his tireless efforts. Währen's impact on the perception of bread from the past has been of fundamental importance in the German-speaking world and beyond (Fechner & Mesnil 2002), which is why he had been awarded an honorary doctorate by the ETH Zürich in 1979. His anthology (Eiselen 2000) will certainly remain one of the most important catalogues of archaeological bread-like objects in Europe.

The Archaeobotanical Side

In the 1980s, research into archaeological bread remains has seen a strong revival when histological identification criteria for cereals from plant anatomical (Metcalfe 1960; Netolitzky 1914, 1926) and food science literature (Gassner et al. 1989; Hahn & Michaelsen 1996; Winton & Winton 1932, 1935) were adapted for the use in archaeobotany by Udelgard Körber-Grohne (Körber-Grohne & Piening 1980), Helmut Schlichtherle (1983), Camilla Dickson (1987), Sue Colledge (1988), Delwen Samuel (1994a) and Ann-Marie Hansson (Hansson & Isaksson 1994), now allowing for the identification of isolated cereal bran in both uncharred and charred state.

Delwen Samuel's work (exemplarily: 1994a, 1996a, 1999a, b, 2001, 2002) however went much further when she extensively explored the *chaîne opératoire* of Ancient Egyptian bread-making and beer brewing. Likewise, Ann-Marie Hansson's contributions linking the archaeobotanical analysis of Viking Age cereal preparations (Hansson 1994, 1995, 1996, 1997, 2014) to historical and ethnographical accounts must be mentioned as milestones in bread research. A certain overlapping with the analysis of "food crusts" – charred food residues from inside pottery vessels – can be observed concerning general research questions on components and production traits (Capparelli et al. 2011; Hillman et al. 1993), as well as the applied methodologies (Attia et al. 2018; Cleymans et al. 2017; Kubiak-Martens et al. 2015; Martínez Straumann 2004; Popov et al. 2018).

Since the 2000s, "bread research" has again been receiving increased attention, including new impetus in methods development (González Carretero et al. 2017; Heiss 2008, 2014b; Heiss et al. accepted; Heiss et al. 2017a; Heiss et al. 2015; Kubiak-Martens et al. 2015; Martínez Straumann 2004). Small, detached fragments of charred cereal preparations have found their way into archaeobotanical research only very recently. This is not entirely surprising against the background of the previously mentioned fragility of charred cereal dishes and their potential destruction by flotation (see **p. 23**, "Preservation Biases").

Embedded into the larger category of "charred/carbonised organic fragments/remains", possible food remains first show up in Ann-Marie Hansson's work (Hansson & Isaksson 1994). Beginning with the 2000s they have become a more or less constantly documented find category in archaeobotany, published under various denominations and acronyms (see the overviews in Heiss et al. 2017a; Heiss et al. 2015).

Evolving Methodologies

Since his first confrontation with amorphous charred objects and the cereal remains contained therein in 2004, the author has been trying not only to apply existing techniques but also to improve them where possible, and eventually to introduce new methods from other fields. The resulting set of methods is far from being complete, and is still evolving.

The scope of the following subsections is therefore not a complete account of all basics and all available methods. The goal is rather to highlight some of the problems encountered during these 15 years, to point out some potential biases and pitfalls as well as some new insights, and to prepare the ground for future discussions in the ongoing methodological development of the field.

Initial Classification

Even prior to any in-depth analysis it is useful to have basic find categories into which the material of interest can be grouped, notwithstanding any consecutive typological groupings (Adams & Adams 1991, p. 298). When it comes to actual or presumptive remains of cereal-based food, the author currently suggests a very basic approach in order to avoid over-interpretation pitfalls. Terminological suggestions in this and other sections (see **p. 35**, "On Pores and Cavities…") are underlined.

Following previous publications, standardised category names for the above-mentioned "charred/carbonised organic fragments/remains" are recommended, according to the scheme *amorphe Objekte verkohlt* – AOV, *objets amorphes carbonisés* – OAC, and amorphous charred objects – ACO (Bouby et al. 2011; Brombacher & Klee 2011; Heiss 2014b; Jacomet et al. 2006).

Finds from this very general category can, however, derive from a large diversity of sources other than processed foodstuffs (Heiss 2010b, 2014b) such as fruit pulp (Kubiak-Martens 2006), vitrified charcoal (McParland et al. 2010), storage parenchyma (Kubiak-Martens 2002) or even dung (Portillo et al., 2017). A general classification guide for these materials is currently in preparation (Heiss et al. in preparation-b).

For amorphous charred objects (ACO) and any other charred archaeological find bearing evidence of apparently processed cereal grains (**Fig. 16**), the author suggests the very general definitions of cereal preparation, synonymous to cereal product, both basically congruent with the terminology proposed by the Food and Agriculture Organization of the United Nations (FAO 1994). This definition, applied onto archaeological finds, includes ACO containing cereal bran (Heiss 2014b), loose crushed grains

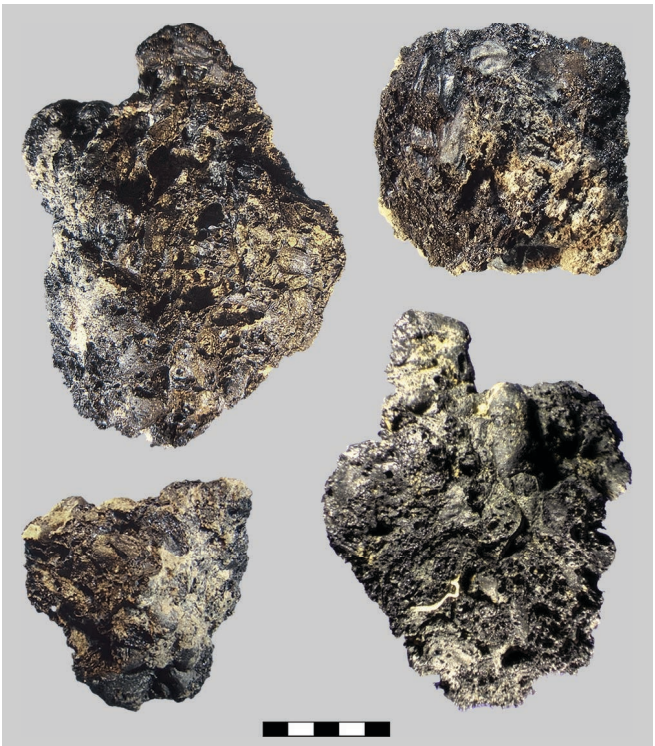


Fig. 16. Fragmented cereal products, i.e. amorphous charred objects (ACO) containing cereal remains. Top: Late Iron Age Roseldorf, Lower Austria (Kohler-Schneider et al. 2015). Scale bar unit: millimetres. Images: ÖAW-ÖAI, A. G. Heiss.

(Valamoti et al. 2019) and objects shaped from dough-like masses alike. Agglomerations of intact grains as they are frequently found fused together during charring (see **Fig. 15** on **p. 26**) do not fall under this category as their outer shape is no apparent result of human action. In the other objects, detailed microscopic analysis may later even shift some presumptive cereal products into the dung category (Wallace & Charles 2013).

The author suggests the term bread-like object as a general category for any cereal product made from some kind of dough and showing traces of supposedly intentional shaping (Heiss et al. accepted; Heiss et al. 2017a). Preference of such a seemingly awkward phrase in contrast to a word as simple as "bread" is due to the *chaîne opératoire* which the latter inevitably implies, and even more so because of the variability of these implications depending on the cultural background of the respective reader (see **p. 47**, "Culinary Typologies"). Loose crushed grains as mentioned above (Valamoti et al. 2019) are not covered by this category.

Sampling and Sample Treatment

The artefactual character of cereal products, and in particular that of bread-like objects, brings with it some challenges which usually do not apply to archaeobotanical material. While, by and large, the composition of seed assemblages can be determined in a non-destructive way, analysis of an archaeological "bread loaf" usually requires subsampling. This destructive act has to counterbalance maintaining the object's shape and composition (Paterakis 1996). It may be evident that, as in any other archaeological find, these subsamples need to be taken with care and in constant dialogue between analyst, conservator and archaeologist.

When dealing with objects from museum collections, knowledge about pre-treatments is crucial not only because of potential health hazards (Balick & Herrera 2014) but also because of potential impact on the analyses. Organic consolidating agents contaminate radiocarbon samples (Brock et al. 2018), render chemical residue analyses impossible (Oudemans & Erhardt 1996), and sometimes make surfaces inaccessible to observation (Heiss et al. accepted). Whereas in many cases basic documentation is available on the applied consolidants or pesticides (Währen 2000a), it is particularly old findings which might require initial chemical analyses and pre-treatments.

Object Descriptions

Detailed descriptions of bread-like objects are crucial for the understanding of their structure, composition and taphonomy, not different from other archaeological artefacts. Size, weight, dimensions, surface structures and shape should be the first features to record, accompanied by drawings or photos.

Some objects, however, are very difficult to describe in a few words while their photographic documentation grasps only some aspects of their shape (**Fig. 17**). In order to overcome such limitations in difficult objects, recent approaches involve the creation of 3D models via photogrammetry (Heiss et al. 2017b; Zech-Matterne et al. 2017) in order to accompany the photos.

This approach has several major advantages as it does not only allow 1) detailed illustration of irregularly shaped objects which are otherwise difficult to describe but also that it 2) makes exact measurements of object volumes possible, 3) simplifies sharing of geometry data among colleagues, 4) extends the possibilities in public science by integrating interactive 3D models into exhibitions

(Heiss 2018b) or even by creating 4) copies of the finds from the 3D printer. Due to the required amount of time – the example displayed in **Fig. 18** required 70 photos from 4 different viewing angles – this procedure will most probably be limited to few prominent finds.



Fig. 17. "Bowl-shaped" bread-like object from the late Neolithic lakeshore settlement of Hornstaad-Hörnle "1A", Lake Constance, Baden-Württemberg, Germany. The object was published as *Brei mit napfförmiger Oberfläche* (Maier et al. 2001, pp. 61, plate 61e). Image: ÖAW-ÖAI, N. Gail.

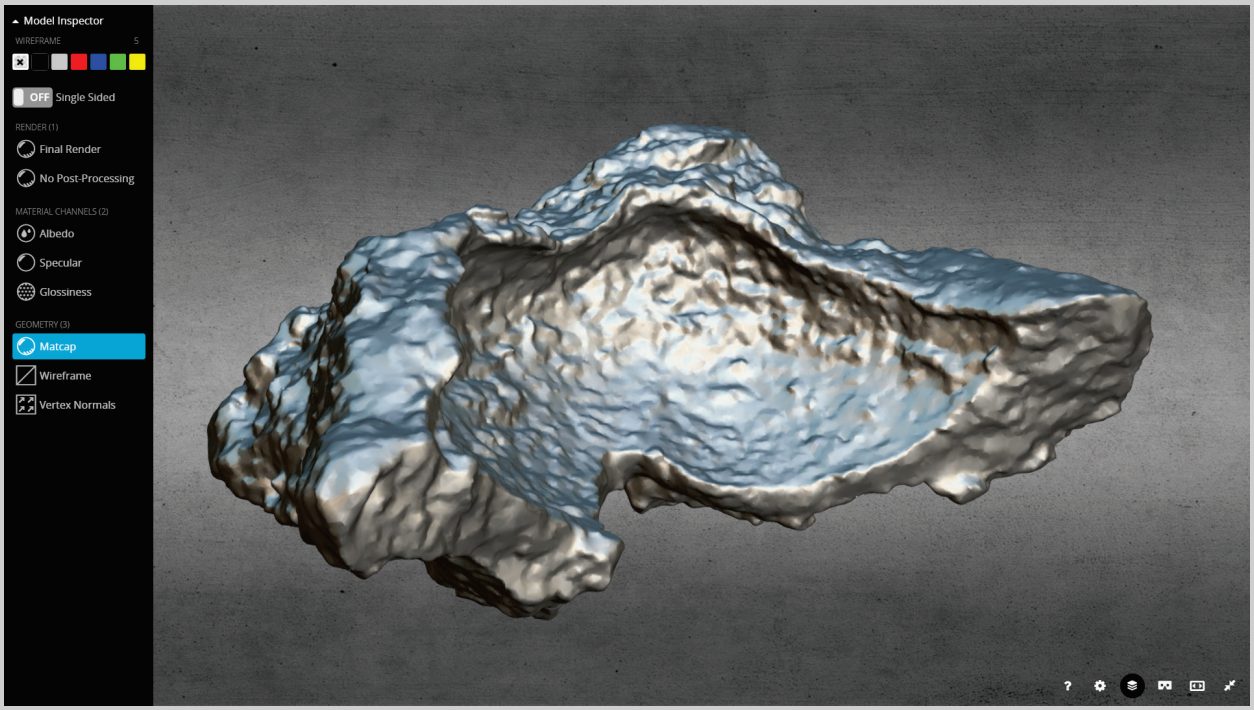


Fig. 18. Photogrammetric 3D representation of the bread-like object from Fig. 17. Image: Heiss et al. (2017b).

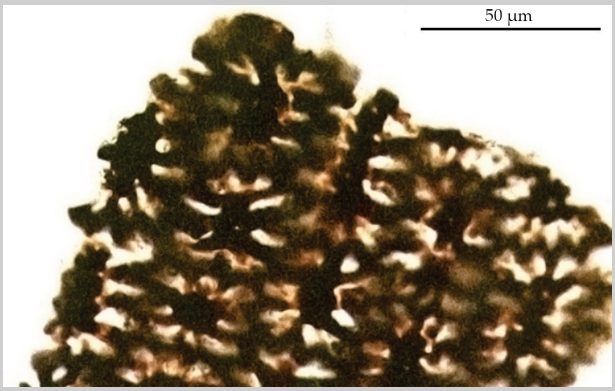


Fig. 19. Glume fragment of foxtail millet (*Setaria italica*) from a dissolved Late Bronze Age ACO from Feldkirch-Altenstadt, Austria (Heiss 2010a). Transmitted light. Image: Heiss (2008).

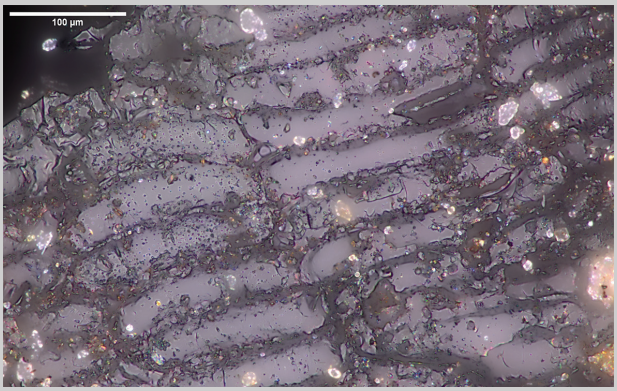


Fig. 20. Wheat (*Triticum* sp.) transverse cells in a Roman Period ACO from Terrace House 2, Ephesus, Turkey. (Heiss & Thanheiser in print). Olympus BX53M metallurgical microscope, reflected light, bright field. Image: ÖAW-ÖAI, A. G. Heiss.

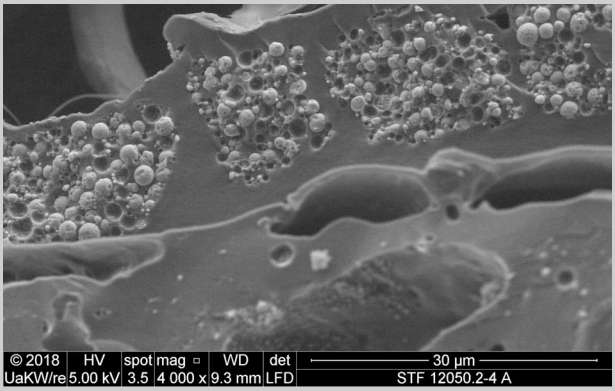


Fig. 21. "Non-barley" single-layered aleurone in a Late Bronze Age bread-like object from Stillfried an der March, Austria. (Heiss et al. accepted). Quanta 250 FEG ESEM. Image: uni-ak, R. Erlach.

Microscopy

Up until now, basically two opposing procedures have been applied for the histological analysis of charred food preparations. One approach is intrinsically highly destructive and involves grinding, dissolving and bleaching subsamples in order to observe tissue fragments in the transmitted light microscope (Hansson & Isaksson 1994; Heiss 2008, pp. 27–28; Martínez Straumann 2004). Although this method does bring results (**Fig. 19**), the disadvantage of a large loss in material outweighs the possible benefit of gaining new information on its components. Furthermore, as grinding is involved, no data on original grain sizes of the components can be recorded in these subsamples.

The more commonly applied, less destructive approach is recommended here and limits itself to the observation of either existing surfaces, or of fresh fractured faces. If only the identification of plant tissues is desired, a metallurgical microscope is often sufficient (**Fig. 20**).

The general recommendation is, however, to use SEM (González Carretero et al. 2017; Heiss 2008, pp. 27-28; 2010b, 2014b; Heiss et al. 2017a; Heiss et al. 2015; Kubiak-Martens et al. 2015), as subcellular structures can also be observed. If an ESEM is available (**Fig. 21**) even subsampling (and sputter coating) can be avoided if the objects are not too large.

Identification Issues

Of all the tissue types present in a cereal grain, only two are specific enough to serve as identification criteria: the transverse cells (cross cells) from the pericarp, and the aleurone layer which is the outermost layer of the endosperm (**Fig. 22**).

Wall thickness and pitting patterns of transverse cells, identification criteria initially developed for food science (Gassner et al. 1989; Hahn & Michaelsen 1996; Winton & Winton 1932, pp. 49–293), have been successfully transferred to archaeological material as a means for clearly

separating the genera *Triticum*, *Secale* and *Hordeum* (Dickson 1987; Hansson & Isaksson 1994), and have been applied in numerous scientific analyses.

As laid out earlier (Heiss et al. 2017a), the archaeobotanist must however bear in mind that these criteria leave some uncertainty in the discrimination of barley and the millets *Setaria italica* and *Panicum miliaceum* (Winton & Winton 1932, pp. 104–108). Furthermore, the transverse cell structure of wild grasses is largely unexplored. Successful histological identification of possible weedy grasses in cereal preparations is therefore not possible up to now, at least not on the basis of patches of transverse cells alone.

It is strongly advised against using measurements of transverse cells for the differentiation between *Hordeum* and *Triticum* (González Carretero et al. 2017), or for further discrimination of wheat species (Körber-Grohne & Piening 1980) when analysing archaeological remains of ground cereals. These criteria can only be reasonably applied to a tissue patch if its original location on the grain is known (Dickson 1987; Körber-Grohne & Piening 1980) – which is clearly not possible in a processed melange of random shredded grain tissue.

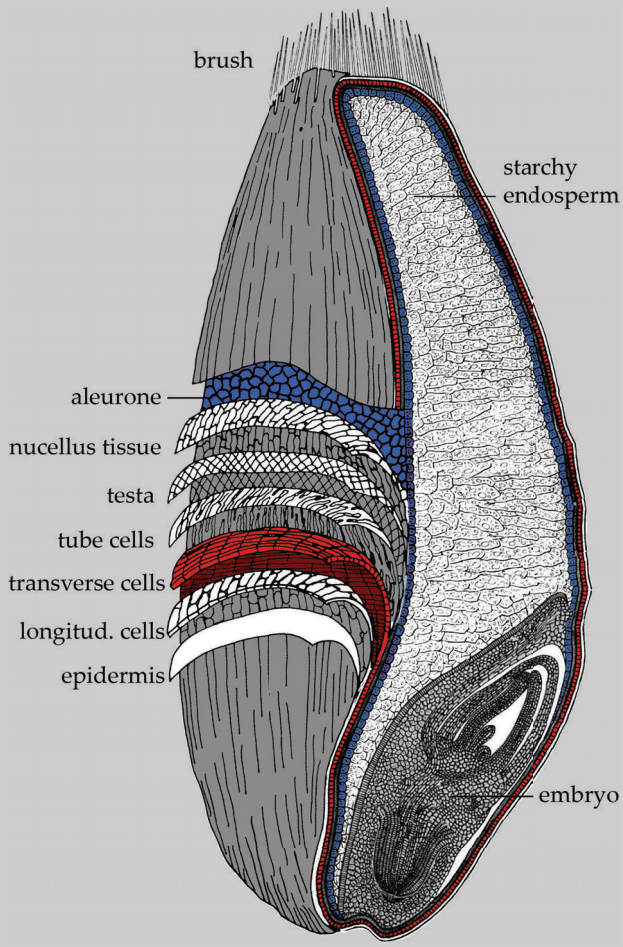


Fig. 22. Tissue types in a grain of bread wheat. Transverse cells (red) and aleurone layer (blue) are highlighted. Image: Wheat Foods Council (2016), modified.

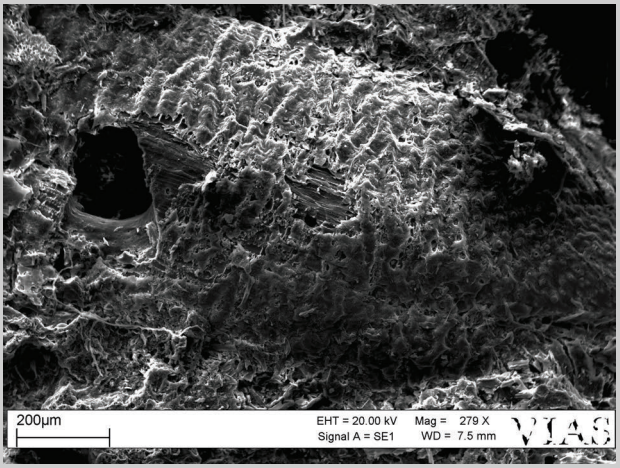


Fig. 23. Glume fragment of foxtail millet (*Setaria italica*) in an Early Iron Age ACO from a high-Alpine votive site (*Brandopferplatz*) at Gögealm, Südtirol – Alto Adige, Italy (Heiss 2015a; Steiner et al. 2012). Image: univie-VIAS, M. Mehofer.

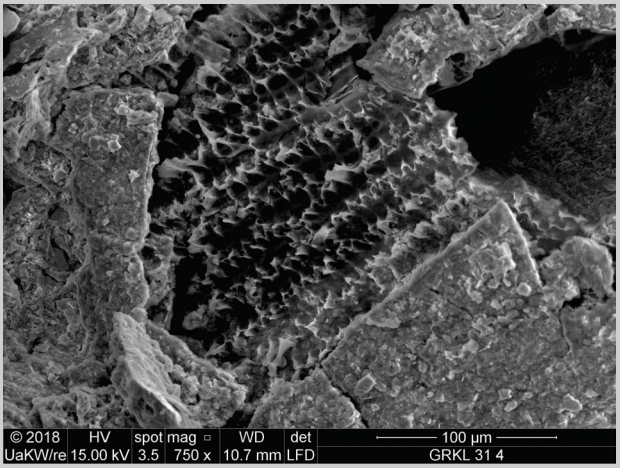


Fig. 24. Glume fragment of broomcorn millet (*Panicum miliaceum*) in an Early Iron Age (Ha C) ACO from a burial mound near Großklein, Styria, Austria (Heiss & Wiesinger 2018b). Image: uni-ak, R. Erlach.

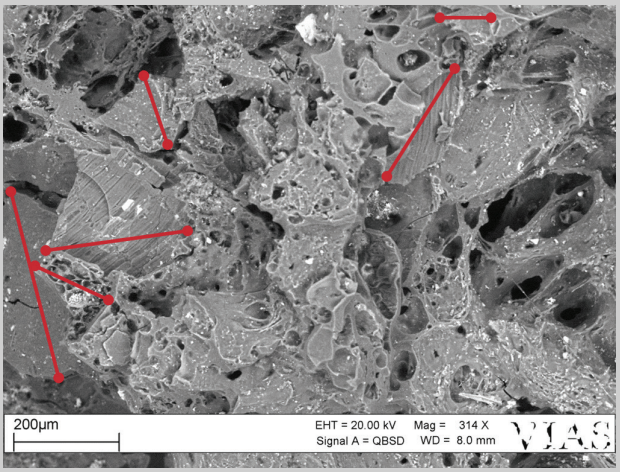


Fig. 25. Illustration of particle measurements in a Late Neolithic bread-like object from the lakeshore settlement of Parkhaus-Opéra, Zürich, Switzerland. Image: Heiss et al. (2017a), modified.

The aleurone's discriminatory power for cereals is very limited as it only enables the separation of barley from all other cereals due to the regular formation of a 2–3 layered aleurone in *Hordeum vulgare* (Hahn & Michaelsen 1996, pp. 7–13). In general, the occurrence of a multilayer vs. single layer aleurone seems to be a highly reliable trait for the separation of cultivated barley from the remaining cereals, and even from quite a few wild grasses including wild barley (Hands et al. 2012). Individual double cells may however occur interspersed in all cereals' single aleurone layers. Furthermore, when interpreting isolated patches tissue in cereal products, it must be made sure that "normal" (peripheral) aleurone is being analysed, because the so-called "modified" aleurone in the grain's ventral furrow shows multiple layers on a regular basis – not only in cereals but also in wild Poaceae (Cochrane & Duffus 1980; Hands et al. 2012).

Chaff as an accidental component in archaeological food remains can be very helpful for the identification of cereal ingredients especially due to the high specificity of epidermal structures (Gassner et al. 1989; Hahn & Michaelsen 1996; Metcalfe 1960; Netolitzky 1914, 1926). This is particularly important for millets (**Fig. 23**, **Fig. 24**), which cannot be satisfactorily differentiated from barley by their cross cells, but are easily identifiable even by small glume fragments (Fuller 2006; Netolitzky 1914). In contrast to barley and millets, remains of wheat chaff may not be expected *a priori* in food preparations (see the argumentation on **p. 18**) but they have been found in some cases (e.g. Heiss et al. 2015).

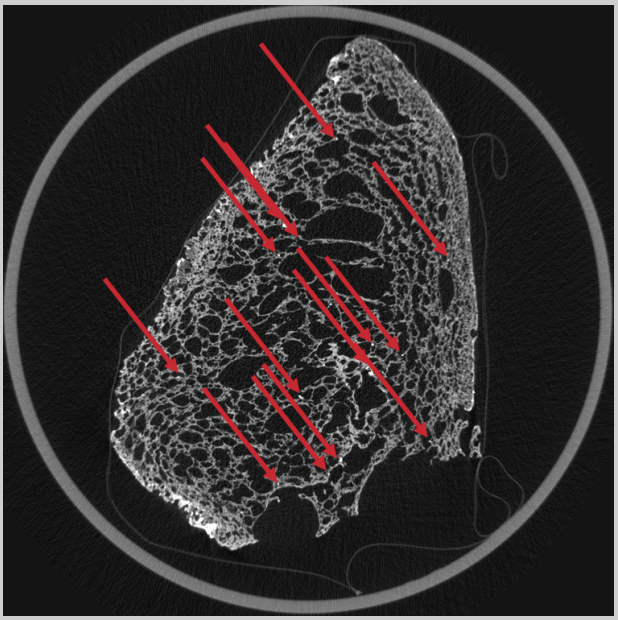


Fig. 26. µCT scan of a bread-like object from Station "See" at Lake Mondsee, Upper Austria (Heiss 2018a). Possible grit (bright spots) indicated by arrows. Zeiss MicroXCT-200. Image: univie-SFB, Y. Städler.

Identification of further plant-based components, either intentional or accidental, largely depends on the sheer coincidence that observable tissues with discriminatory power occur in the material (see also the discussion on **p. 43,** "Add Five Cups of Wheat Flour…").

Successful examples of such identifications involve weeds (Hansson & Isaksson 1994), acorns and tubers (Arranz-Otaegui et al. 2018; Kubiak-Martens et al. 2015), pulses (González Carretero et al. 2017) and possible spices/condiments (Fairbairn et al. 2018; Heiss et al. 2017a).

Particle Sizes

Due to their immediate connection to the combined processes of grinding and sieving (Arnold et al. 2005; Bofill et al. 2018; Kreuz &

Baatz 2003; Portillo et al. 2016), particle sizes of food remain components are a valuable source of information in processed food. For data generation, non-overlapping images of the analysed objects covering an area as large as possible should be acquired in varying magnifications, combining light (10x) and scanning electron microscopy (100–300x). Particle sizes have to be recorded manually in these images (**Fig. 25**) by measuring maximum dimensions of each visible grain/tissue patch with image analysis software such as for example, ImageJ (Rasband 1997–2009).

An alternative approach for data generation has been inspired by M. Währen's idea of using X-ray images for determining grain sizes of millstone grit (Währen 1984): Cereal products were scanned in a µCT at the MNHN Paris (Zech-Matterne et al. 2017) and at the University of Vienna (Heiss 2018a) with the goal of measuring possible contained grit (**Fig. 26**). The results of data evaluation are, however, not available yet.

When interpreting the particle sizes of archaeological charred food remains, the application of extant quality criteria for ground cereal products is recommended. Three size classes of particles are suggested here (Bundesministerium für Gesundheit und Frauen 2010–2017; Seibel 2005): particles smaller than 300 µm (flour/meal together with dunst), those ranging from 300–1000 µm (semolina), and particles larger than 1000 µm (grist). Following previous literature (Heiss et al. 2017a; Kubiak-Martens et al. 2015; Primavera et al. 2018), the differentiation between flour (as in white flour) and meal (as in wholemeal) is not suggested for archaeological finds. This would require determining their bran / endosperm ratio, which is most probably not possible (see **p. 43,** "Add Five Cups of Wheat Flour…").

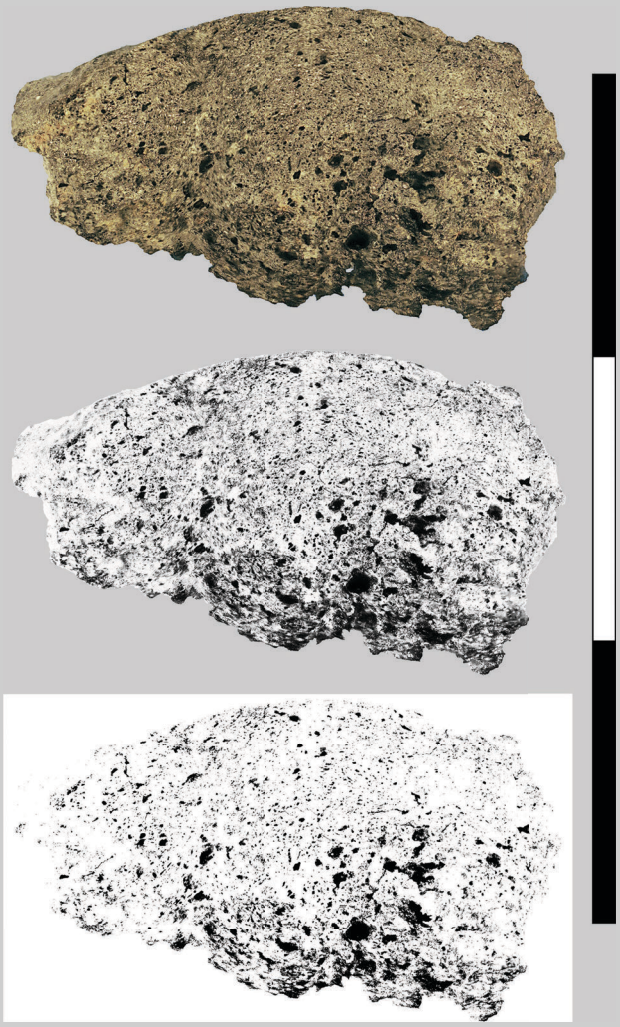


Fig. 27. Image processing of a Late Iron Age bread-like object from a salt mine at Bad Nauheim, Hesse, Germany (Heiss & Kreuz 2007). Top: colour photo, middle: greyscale image after "Auto Contrast", bottom: thresholded image. Scale bar units: centimetres. Images: ÖAW-ÖAI, A. G. Heiss.

On Pores and Cavities…

The description and classification of structures is a main prerequisite for their interpretation, but while regular archaeobotanical work can rely on a clear established terminology from plant anatomy and morphology, descriptive terms for structures in processed food had best be taken from food science, adapting their definitions only where necessary and in a way as precise as possible. This section and the following one feature suggestions (underlined as previously on **p. 29**, "Initial Classification") for a standardised description of microstructures, basically in accordance with Heiss et al.

(accepted) in an attempt to further develop previous approaches.

Following standard terminology in food technology, airspaces within a cereal preparation should be called pores (Heiss et al. 2015; Mondal & Datta 2008) or cavities (Heiss et al. 2017a). Using the term "void" is generally not recommended, mainly because of the recently published composition "close(d) void" (González Carretero et al. 2017) which is insofar misleading as it implies bearing explanatory power on the interconnectivity of pores (i.e. opposed to "open void", see Wang et al. 2011) albeit such statements cannot be made by the observation of surfaces alone (Cafarelli et al. 2014; Falcone et al. 2005; Russ 2004). Following González Carretero et al. (2017), in turn, the term "micropore" is recommended for a pore not exceeding 200 µm in diameter.

Due to their aforementioned impact on the perception of bread quality (Gao et al. 2018), pore size distribution (crumb visual texture, crumb grain) and pore interconnectivity are among the main characteristics of fermented bread which are evaluated in baking industry (Scanlon & Zghal 2001; Wang et al. 2011).

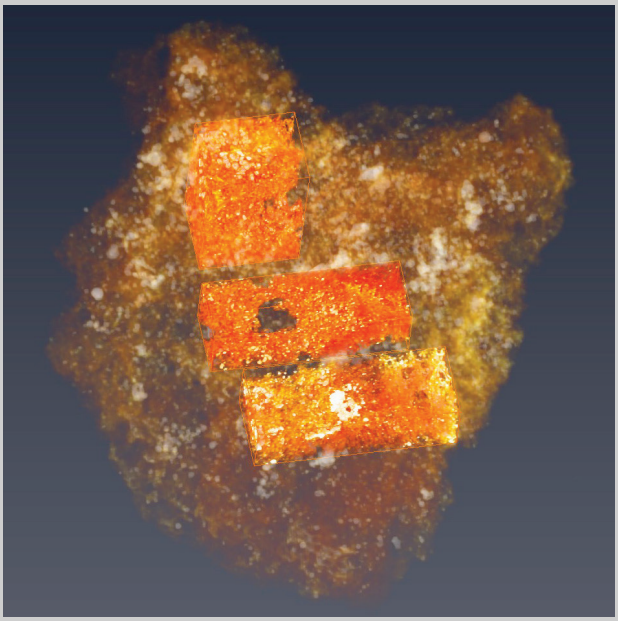


Fig. 28. Volumetric µCT scan rendering of a late Neolithic ACO from the lakeshore settlement of Weyregg II, Upper Austria (Jakobitsch & Heiss 2018). Zeiss MicroXCT-200. Image: univie-SFB, Y. Städler.

Thanks to the high reflectivity of charred material, image data for measuring pore size distribution of charred food remains can easily be acquired using a protocol initially brought forward for ceramics (Hall & Bracchini 1997), later adapted for modern bread (Scanlon & Zghal 2001) and eventually for archaeological bread finds (Heiss et al. 2015): Images are taken in skewed light which results in a highly contrasted image with the solid phase appearing "at the high end of the grey level scale" (Scanlon & Zghal 2001, p. 847).

Subsequent image processing is required in order to obtain a black-and-white image in a "compromise between enhancing contrast and attaining precision" (Scanlon & Zghal 2001, p. 847). The author's recommendation is to use e.g. Photoshop's "Auto Contrast" (Knoll et al. 1990–2010) and then convert the image to black and white by applying a fixed threshold value of 64 (of 255 grayscales) in order to maintain comparability of the resulting measurements (**Fig. 27**).

This threshold, alongside with the "fit ellipse" (Kanatani et al. 2016) function applied in image processing software such as ImageJ (Rasband 1997–2009) does lead to an under-estimation of pore diameters which has to be kept in mind. Only measurements of the respective maximum ellipse diameters are recorded while measurements of cracks and furrows (see below) are suggested to be discarded, as well as objects smaller than 100 µm (more on this on **p. 41**, "Fermented or Unfermented?").

Pore interconnectivity is much more difficult to measure. Acquisition of three-dimensional data is necessary in order to fully describe the foam structure of bread (Mills et al. 2003). This can be achieved by µCT analyses and is already being applied in modern bread (Cafarelli et al. 2014;

Falcone et al. 2005). After promising first attempts on archaeological bread-like objects (Zech-Matterne et al. 2017), standardised protocols are currently being prepared (**Fig. 28**) for archaeological bread-like objects in close cooperation with Y. Städler at the University of Vienna (Heiss 2018a).

… and Cracks and Furrows

As explained in Heiss et al. (accepted), more precise definitions are suggested for different kinds of elongated hollow spaces which can often be observed in the charred mass of a food remain: A crack is defined as a taphonomical feature, either caused by charring (analogous to charcoal, see Marguerie & Hunot 2007, p. 1421) or by mechanical stress after charring. This structure has previously been referred to in a rather imprecise way as "true crack" (Heiss et al. 2015, p. 76). Either way, cracks are most probably not indicative of any production traits of a cereal product with the exception of the superficial *craquelé* pattern typical of charred food crusts (see **Fig. 31** on **p. 38**).

In contrast to a crack, a furrow defines a hollow space which is a feature of the dough/batter itself, recognizable by its irregular margins intergrading with pores (**Fig. 29**), thereby corresponding to the no longer recommended term "fissure" as published in Heiss et al. (2015, p. 76). Neither is it recommended to use the recently published term "channel void" (González Carretero et al. 2017) as up to now it lacks a clear definition.

Mechanical stress during kneading and folding or during subsequent drying processes can easily lead to the rupture of doughs (**Fig. 30**) if the water content is too low, as has been reported e.g. for biscuits (Saleem et al. 2005) and pasta (Marchylo & Dexter 2001). The furrows encountered in archaeological cereal products are consequently interpreted as the consequences of such ruptures, therefore indicating initial low moisture content prior to charring (Heiss et al. accepted; Heiss et al. 2015).



Fig. 29. Distinct furrows (indicated by white arrows) in a Late Bronze Age annular bread-like object from Stillfried an der March, Austria (Heiss et al. accepted). Scale bar units: centimetres. Image: ÖAW-ÖAI, N. Gail.



Fig. 30. Furrows (black arrows) on the lower face of a modern *tarallino* basing on bread wheat flour. Produced in Apulia for BILLA AG, Wr. Neudorf. Scale bar units: centimetres. Image: ÖAW-ÖAI, A. G. Heiss.

General Structure

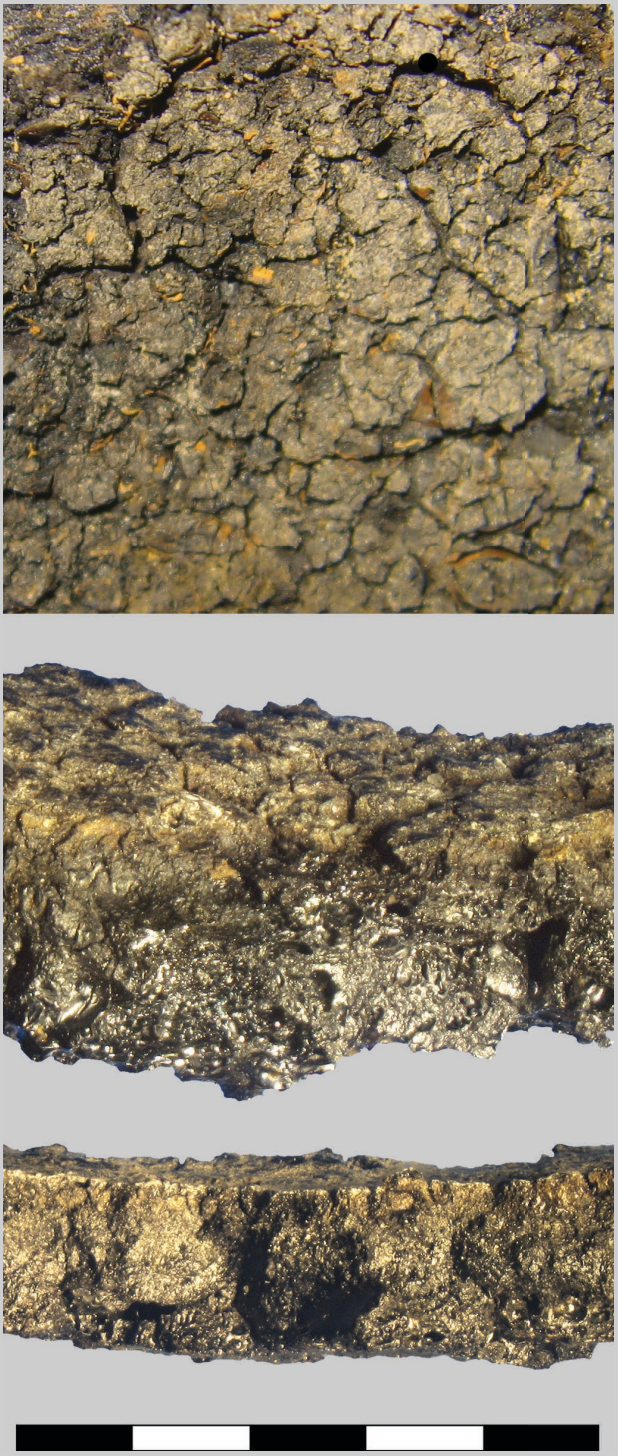


Fig. 31. Food crusts from the late Neolithic lakeshore settlement of Parkhaus-Opéra, Zürich, Switzerland. Plane view (top) and cross sections (middle and bottom) (Heiss 2014a; Heiss et al. 2017a). Scale bar units: millimetres. Image: ÖAW-ÖAI, A. G. Heiss.

Microscopical investigation of the charred cereal products also needs to result in descriptions of the overall structure of outer and inner faces of the material. Characters which should be recorded are e.g. the general homogeneity in the distribution of particles and cavities, or the occurrence of any size sorting. A standardised list of classification criteria for archaeological finds of cereal products is currently in preparation (Heiss et al. in preparation-a).

Raised bread in the modern sense, for example, should display some differentiation between a dense crust and a porous crumb.

Food crusts, as another example, derive from more or less liquid food preparations. They are characterised by the formation of heterogeneous layers, resulting in differing aspects of the "lower" face which was formerly attached to the vessel, and the "upper" (outer) face (**Fig. 31**).

The lower face is usually characterised by a dense, glossy appearance and the absence of macroscopically visible plant remains. Larger plant parts (such as shreds of bran), on the contrary, are usually found on the upper face. Finds preserved in desiccated or waterlogged state may even display partially charred or entirely uncharred bran on this face.

Another typical feature of the former upper face is a more or less conspicuous *craquelé*-like pattern (**Fig. 31**). Formation of these drying cracks is caused by the evaporation of water and shrinkage of the matrix during drying processes preceding charring (Schlichtherle 1983).

Whither Interpretation…? Thoughts on Food as Food for Thought

In order to approximate elements of a past cuisine, the features observed in food remains need to be interpreted against the background of their archaeological contexts. Sheer descriptions of observations are clearly not sufficient and interpretations have to be made, as limited as they may seem. Yet hypothesis-building always needs to rely on sound facts, and it relies equally on the honest discussion where these facts are ambiguous or entirely unknown.

This is of particular importance as the archaeology of bread generates high public interest, and the archaeology of beer does even more so, as may be illustrated by a recent Google search (April 2nd 2019), resulting in c. 13,400 hits for "the oldest bread" and c. 30,400 hits for "the oldest beer". With the impetus the research on food remains has received in the past decades, literature has seen many new lines of interpretation coming up while new research continuously keeps pushing "the earliest evidence of…" further into the past (see **p. 17 f.**, "Transforming Grains into Food").

Communication of such ground-breaking results to a wider scientific audience and to the interested public is certainly a challenge of its own, requiring constant balancing between accuracy and simplification, between fact and fiction. Eventually, it will not be the data but the chosen categories and evoked images which will be received, remembered – and cited. Simply put, questions such as "Is it really bread?" and "What is bread anyway?" deserve some extra thoughts before going public.

Some straightforward aspects of interpretation have already been briefly mentioned such as the specificity of tissue identifications (see **p. 32** "Identification Issues") or the relation between measured particle sizes and the combination of grinding and sieving (see **p. 34** "Particle Sizes"). The following subsections are intended to give the author's view on some of the more difficult or ambiguous issues – a mix of previously formulated ideas, personal experiences, and perspectives for future research.

Liquid or Solid, Raw or Cooked?

Reconstruction of the initial water content of an archaeological charred cereal product – one of the key criteria for the differentiation of beer or broth vs. porridge vs. flat bread – seems to be far from clear-cut. Although the author cannot provide a definite answer, future solutions may lie in the combination of different independent structural features.

Low water content: Intact starch granules in a charred cereal product primarily indicate the lack of conditions favourable for their gelatinisation (see **p. 19** "Soaking" and "Heating"). In products involving a liquid phase at any stage of production (i.e. bread in the widest sense, porridge, broth, beer etc.) this would mean that the product had fallen dry or had been dried intentionally before charring (Heiss et al. accepted). Furrows in bread-like objects (see **p. 37** "… and Cracks and Furrows") originate from ruptures formed during dough preparation, and also indicate low initial water content (Heiss et al. accepted; Heiss et al. 2015).

High water content: Completely gelatinised starch granules point towards either boiling or baking before charring, or towards charring in hydrated state. A clear indicator of a formerly thin liquid cereal preparation is the formation of noticeable layers together with the *craquelé* pattern on the surface as is typical for food crusts (see **p. 38** "General Structure").

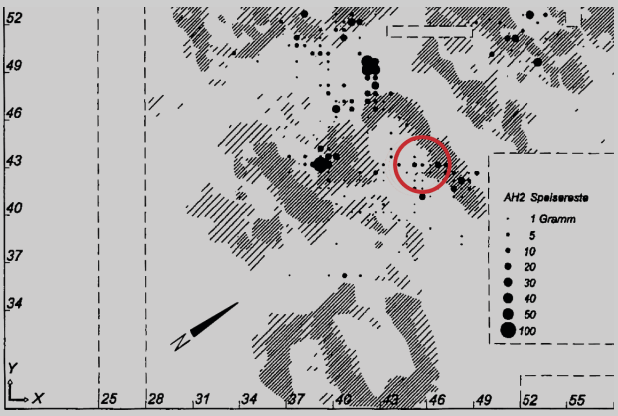


Fig. 33. Southern part of the settlement of Hornstaad Hörnle "1A", burnt layer A2. Hatched areas indicate collapsed walls of rectangular houses, black dots indicate the amount of recovered charred food remains. The circle locates the discussed bread-like object. Drawing from Maier (2001, p. 63), modified.

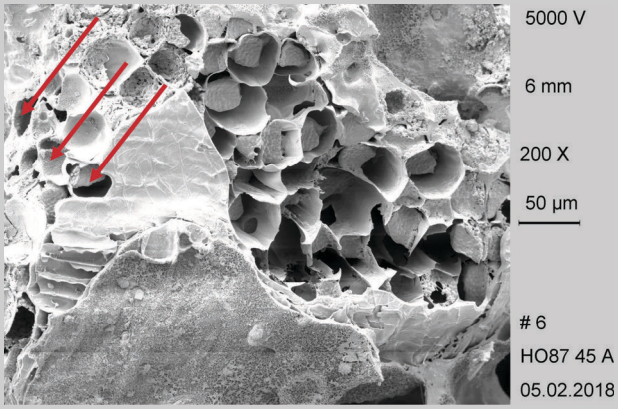


Fig. 32. Cereal bran fragment from the bowl-shaped bread-like object. Zeiss DSM 940 SEM. The triple aleurone layer of barley (*Hordeum vulgare*) is indicated by arrows. Image: ÖAW-ÖAI, A. G. Heiss.

Inclusions of extraneous material can also be interpreted as hints towards a liquid or semi-liquid cereal preparation into which these materials were embedded prior to charring (Heiss 2008, pp. 119, 135, 137; Währen 1990, p. 217). Great care must, however, be taken in order to avoid confusion with dung; herbivore dung is characterised by large amounts of "extraneous" vegetative material, including cereal remains (Kühn et al. 2013), and dung can indeed turn up in charred state (Angelucci et al. 2009; Heiss et al. in preparation-b).

Raw vs. cooked: As implied in the headline, these considerations do not only have consequences for possible conclusions on water content but also on the former raw vs. cooked/baked/roasted condition of an archaeological charred cereal product. However, at the current state of research there are many cases where satisfactory differentiation between the two seems beyond reach as e.g. the state of gelatinisation of starch granules in the charred material depends on water content during charcharring. Still, interdisciplinary discussion on the knowledge on local tools and cooking installations as well as experimental approaches can sometimes help to overcome these difficulties (Popov et al. 2018).

The "bowl-shaped" bread-like object from **Fig. 17** (**p. 31**) and **Fig. 18** (**p. 31**) shall be given as an example how interdisciplinary discussions can lead to new insights on archaeological food preparations. The find was recovered from the burnt layer AH2 deriving from a catastrophic fire (**Fig. 33**) which had burnt down the majority of the settlement. Even without SEM analyses it was possible to identify it as *Brei* ("porridge", Maier et al. 2001, p. 61). The genesis of the object's unusual "bowl shape" remained unclear however, just as for the numerous other objects of similar shape which had been recovered from the burnt layer.

Recent component analysis resulted in barley (*Hordeum vulgare*) as the only identifiable plant component (**Fig. 32**). No intact starch granules could be observed. The structure of the object showed unequivocal features of a food crust such as conspicuous layering and particle size sorting (**Fig. 34**), and even the irregular *craquelé* pattern on its supposed upper face (see **Fig. 17** on **p. 31**).

The supposed lower face, however, seemed far too irregular for a typical food crust and did not suggest moulding by a vessel. Combining 1) the evidence from microscopical analysis indicating an initially liquid state of the mass with 2) the fact that local cooking ware lacks handles and has mostly flat bottoms and 3) prior experimental work (Schlichtherle 1983), a new model could now be brought forward which possibly explains the formation of food remains with the odd "cup-like" shapes (**Fig. 35**; Schlichtherle 2019, pers. comm.).

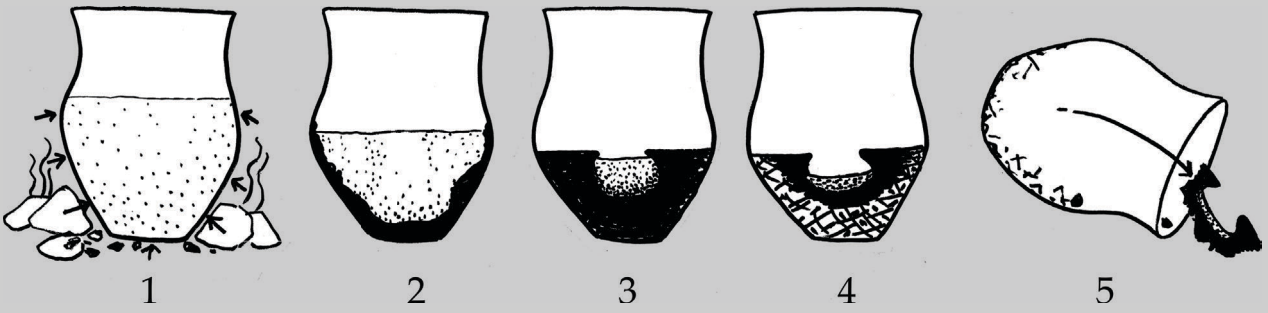


Fig. 35. Model for the formation of the "bowl-shaped" bread-like object from Hornstaad-Hörnle. 1) cooking pot in regular use, surrounded by heated stones. During the catastrophic fire, 2) the massive heat causes the pot's liquid content to boil, dry out and char progressively from the outside inwards until 3) only the final remains of the liquid are left in the centre. 4) All liquid is now dried out, and the outermost parts of the mass begin to burn to ashes (hatched areas). 5) The bowl-shaped innermost part of the charred mass breaks loose as soon as the pot falls over or is destroyed. Image: RPS-BWL, H. Schlichtherle. Interpretation: Schlichtherle (2019, pers. comm.).

Fermented or Unfermented?

The question on dough fermentation has more or less always been a main focus of the research into past production of cereal-based food (Maurizio 1916, pp. 90–109, 149–161). Aside from fermentation's effects on "objective" properties such as nutritiousness, shelf-life and sensory quality (see p. **20**), history and ethnography show that microbial transformation also strongly affects the cultural perception of the resulting product (DaSilva 1996, pp. 239–244; Hastorf 2016, pp. 95–97; Tamang 2010b). In his *triangle culinaire*, Lévi-Strauss opposes the three main states of "raw" (*cru*), "cooked" (*cuit*), and "rotten" (*pourri*) food. The latter encompasses intentionally fermented as well as unintentionally decayed food, pointing out that the perception and differentiation of the two is culturally dependent (Lévi-Strauss 2004, p. 10 f.). It must therefore be stressed that while the leavening of bread and the brewing of beer can certainly be considered under the concept of added value (Van der Veen 2018, p. 66; Gosden & Hather 1999, p. 29), fermentation can also be part of socio-cultural taboo: Leavening is, for example, unthinkable in the *matzah* bread of Jewish Passover rites (Cohn-Sherbok 2005), just as it is for the altar bread of the Catholic Eucharist (Seifert 2004). Using traces of fermentation in the archaeological material itself as a source of information on past operational sequences is

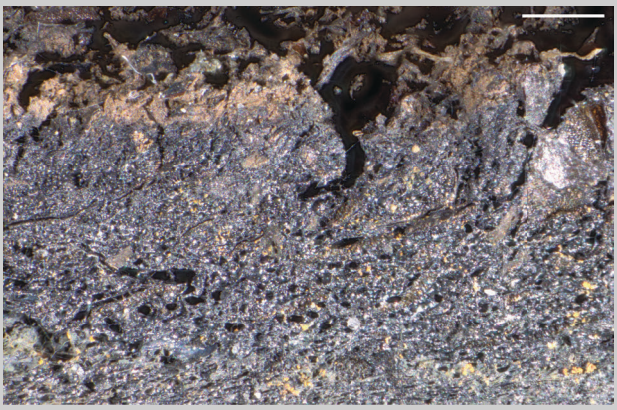


Fig. 34. Cross section through the "bowl" showing the typical layered structure of a food crust. Large bran particles are visible on top. Scale bar length: 1 mm. Image: ÖAW-ÖAI, A. G. Heiss.



Fig. 37. Charred cereal grains with conspicuous cavities. Top: barley (*Hordeum vulgare*) grain from a Late Antique city quarter in Ephesus, prov. İzmir, Turkey (Ladstätter 2018). Bottom: emmer (*Triticum dicoccum*) grain from a Late Bronze Age settlement pit in Neudorf/Unterfladnitz, Styria, Austra (Heiss & Wiesinger 2018a). Scale bar units: millimetres. Images: ÖAW-ÖAI, A. G. Heiss.

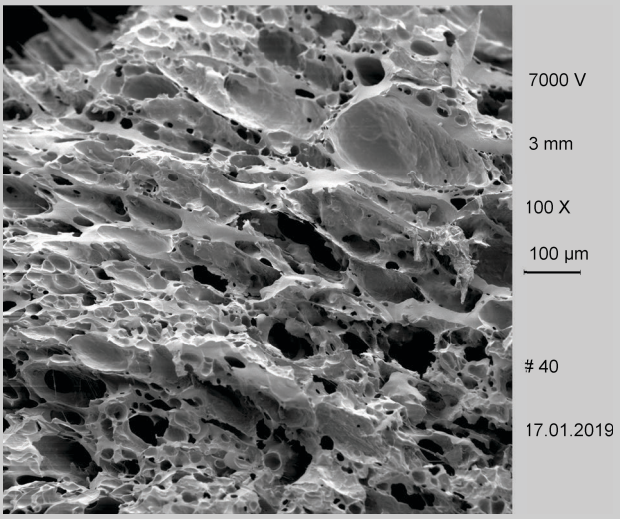


Fig. 36. Experimentally charred grain of *Grünkern* spelt (immature *Triticum spelta* 'Bauländer Spelz'). Charring at 300° C for 6 hours has led to extensive formation of cavities with a broad range of sizes, the largest of these "pores" surpassing the category of micropores (Heiss et al. accepted). Image: UHOH, M. Berihuete Azorín.

at any rate a worthwhile target in ancient food research.

Inferring causality between the cavities or pores observed in a charred cereal product (see **p.35** "On Pores and Cavities…") and fermentation processes is a starting hypothesis as obvious as it can get. It must, however, be stressed that at the current state of research, "well-defined morphological key features" (Pető et al. 2013, p. 67) for fermentation are actually still lacking – or at least they are not as straightforward as they may seem.

While the methodological biases of pore measurements seem to be manageable (Scanlon & Zghal 2001), additional validation of the representativeness of these 2D measurements for a the 3D pore structure of a bread-like object is still suggested. Protocols for the latter are already in operation in food research (Cafarelli et al. 2014; Falcone et al. 2005) and are currently being adapted for charred archaeological material (Heiss 2018a).

However, the data generated by both methods are by no means directly comparable to extant data on modern bread. Charring is well-known for its non-linear effects on the dimensions of various plant seeds (Braadbaart 2004, 2008; Braadbaart et al. 2005; F. Braadbaart et al. 2004; Frederik Braadbaart et al. 2004; Braadbaart & Poole 2008; Charles et al. 2015; Hopf 1955; Kislev & Rosenzweig 1991; Märkle & Rösch 2004, 2008). Observations based on experimentally charred processed food preparations, on the contrary, are generally rare (González Carretero et al. 2017; Hillman et al. 1993; Kubiak-Martens et al. 2015; Valamoti et al. 2008), and the possible dimensional changes of cavities in cereal products during charring are entirely unknown up to now.

Experimental cereal foods are currently being produced within the scope of the project PLANTCULT (Valamoti et al. 2017), spanning not only a wide range of ingredients and *chaînes opératoires* (Bofill et al. 2018) but also various charring regimes. Among other purposes, these

materials will also be subjected to μCT analysis, hopefully allowing for modelling shrinkage/expansion on a cavity-by-cavity approach. For now, and until a database allowing for statistical comparison is available, we have to rely on a comparative approach relating new objects to known finds.

There is, however, a taphonomical aspect which seems to be of fundamental importance in the interpretation of pore sizes. During the charring of organic matter, pyrolysis gas is formed consisting predominantly of carbon dioxide, carbon monoxide and methane (Boateng et al. 2007; Fu et al. 2011). In starch-rich materials, water vapour is additionally released in larger quantities, originating from both residual bound water and from the chemical breakdown of starch (Greenwood 1967). Together, the expanding gases inevitably lead to the formation of cavities in the intermediate liquid phase of biopolymers breaking down (Montoya et al. 2016). It is more than likely that it is these cavities which archaeobotanists know from everyday work – as a feature of badly preserved charred grains (**Fig. 36**). In experiments (**Fig. 37**), such cavity formation has been reproduced at high charring temperatures of 300° C and above (Berihuete Azorín et al. forthcoming; Charles et al. 2015).

A cut-off value of 100 μm in pore measurements has previously been suggested by the applicant, initially motivated by the limitations in camera and image resolution (Heiss et al. 2017a; Heiss et al. 2015). Taking into account the aforementioned considerations on cavities formed during charring, this cut-off value is currently (Heiss et al. accepted) being raised to the size limit of micropores, i.e. 200 μm (see **p. 35** "On Pores and Cavities…").

It may or may not make sense to set an even higher cut-off value in the generation of data. In their interpretation, however, it is clearly advised against taking small pores – and micropores in particular – as single evidence of fermentation and consequently also against using them as a diagnostic character for the presence of leavened bread, as it has already happened (Arranz-Otaegui et al. 2018; González Carretero et al. 2017; Pető et al. 2013). More careful approaches such as in Herbig (2016), using the combined presence of 2–4 mm large pores and of a differentiated crust and crumb structure as diagnostic features for fermented bread, are definitely more reliable.

Fermented beverages – beer in the widest sense – are much more difficult to find in a charred state than solid ones. In general, biogenic evidence has indeed strongly contributed to the research into the past of beer brewing (Rosenstock & Scheibner 2017; Samuel 2000; Stika 2011; Valamoti & Stika 2019) building onto finds of intact sprouted grains (Jacomet 2009; Kroll 1991; Samuel 1994a; Stika 1996b; Valamoti 2017), enzymatically degraded starch granules in desiccated material (Samuel 1996b; Wang et al. 2017), and oxalate crystals formed during brewing process (Michel et al. 1992). Yet until now, although frequent in archaeological contexts (Fuller & González Carretero 2018; Heiss et al. 2017a), charred food remains have not provided tangible criteria for identifying aspects of the brewing process. Recently, charred finds from 4th millennium BCE brewing installations in Egypt and southwestern Germany have however raised attention, and they may yield new insights in the future (Attia et al. 2018; Heiss & Berihuete Azorín 2019).

"Add Five Cups of Wheat Flour…"

As stated on **p. 15 f.**, the ultimate goal for the research into any part of ancient cuisines would of course be a recipe. That this goal is most probably unattainable by using current methods may seem obvious for anyone working in the field. Bearing in mind the necessity of science communication, still this brief paragraph may be dedicated to the impossibility of quantifying the components of an ancient bread or broth by its charred remains – either just for fun or as "defense strategy" for the ar-

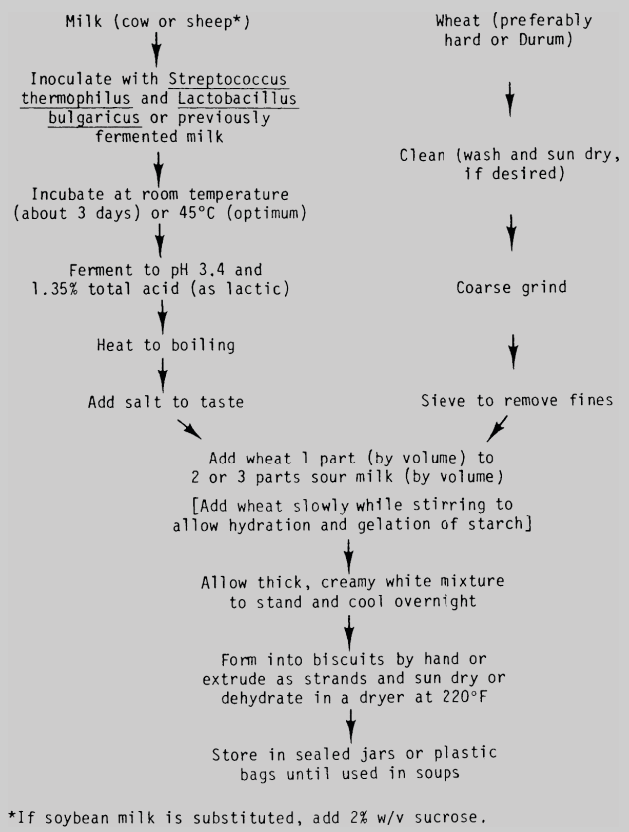


Fig. 39. A *Chaîne opératoire* for Greek *trahanas* / Turkish *tarhana* (Economidou 1975; Steinkraus 1996, p. 302).

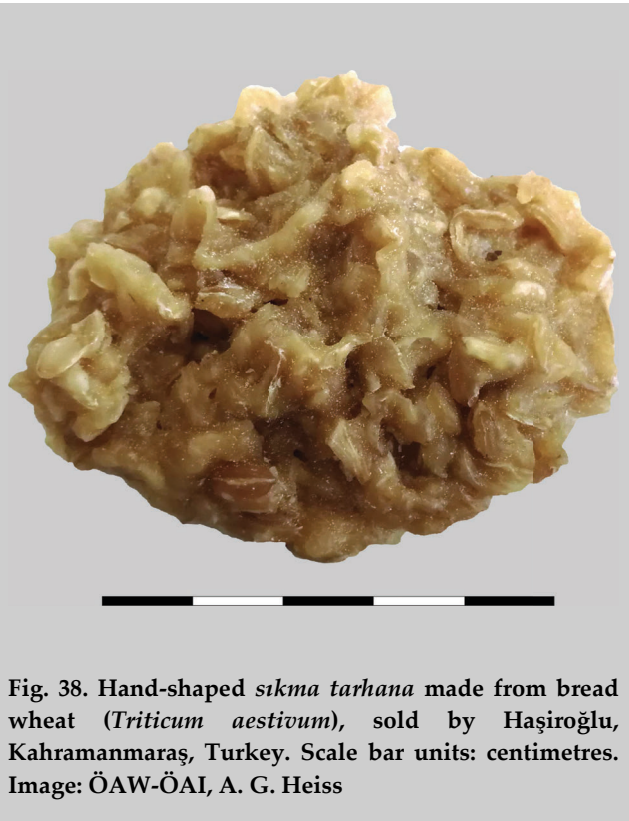


Fig. 38. Hand-shaped *sıkma tarhana* made from bread wheat (*Triticum aestivum*), sold by Haşiroğlu, Kahramanmaraş, Turkey. Scale bar units: centimetres. Image: ÖAW-ÖAI, A. G. Heiss

chaeobotanist who needs to argue why he or she cannot deliver the desired tangible results (see also Heiss et al. 2017a, p. 18 f.):

A cereal grain contains only 7–9% by weight of aleurone, and c. 5% by weight of bran in the stricter sense, that is testa plus pericarp (Rimbach et al. 2015, p. 139). For entirely unsifted wholemeal flour, these percentages sketch the maximum chance of encountering aleurone and transverse cell tissue in the archaeological material – with increasing sieving effort by the ancient baker it would decrease accordingly. Additional considerations have to be taken into account such as: 1) histological identification relies on a certain viewing plane (e.g. cross section in aleurone, plane section in transverse cells) while the tissue patches are expected to be chaotically arranged in a cereal product, 2) only small subsamples of an object can be analysed via SEM, and 3) SEM is limited to the observation of surfaces while all deeper layers remain unexplored. All three will reduce the chance of successfully identifying a cereal even more, as will the low specificity of the tissues themselves.

Accessory components of a cereal product are just as difficult to track, as their proportion in dough preparations may be significantly lower than the cereal main ingredients (see **p. 32 f.**, "Identification Issues").

Building Operational Sequences

As already laid out in the introductory chapters, the ways of processing and producing food are guided by environmental and physiological necessity as well as by social convention. Consequently, the individual processes (**p. 17 ff.**) in their many variations are embedded into the complex social patterns and traditions of the respective community. The results are *chaînes opératoires* which may sometimes be simple and linear, but sometimes turn out as highly complex (**Fig. 39**) even in seemingly simple products (**Fig. 38**).

Furthermore, it has to be highlighted that it is a characteristic of culinary practices that basically every end product of a *chaîne opératoire* can become the initial product of another one, adding up to complexity. Bread, as an example, can be dried and stored and eventually become an ingredient of soup prior to consumption (Staub 1868, p. 9). Bread can be ground and mixed with flour for the production of new bread (Neufeld 1907; Seibel 1987, p. 200 f.). Bread can serve as a starter in beer production (Rosenstock & Scheibner 2017; Samuel 2000; Zarnkow et al. 2006). Spent malt, in turn, can be used as raw matter for bread production (Ktenioudaki et al. 2015; Samuel 1996b).

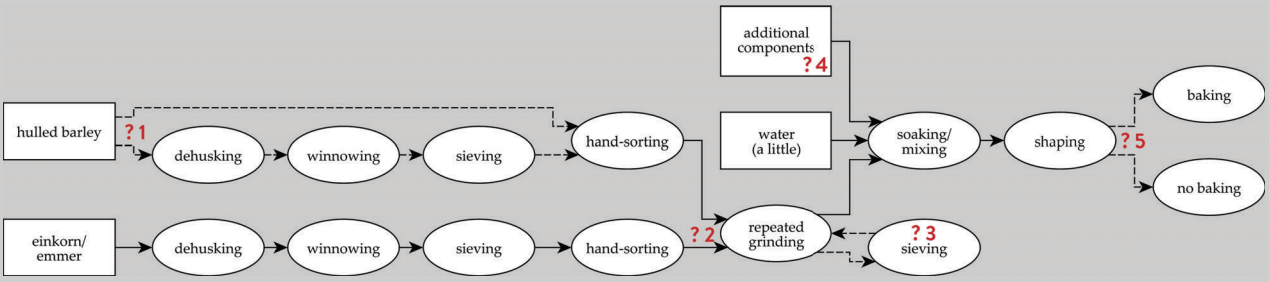


Fig. 40. Hypothetical *chaîne opératoire* for a bread-like object from the Gallo-Roman cemetery of St. Memmie, Champagne-Ardenne, France (Heiss et al. 2015). Rectangles: components, ovals: processes. Dashed lines indicate ramifications, i.e. options in processes. Numbered question marks indicate uncertainties. 1) It is unknown whether it was attempted to dehusk the barley, 2) whether the cereals were ground together, or 3) whether sieving was involved or only repeated thorough grinding. No information is available 4) on additional components (dairy products, condiments, salt etc.), or 5) whether the dough was baked or left raw prior to charring. Image: ÖAW-ÖAI, A. G. Heiss.

Certainly not all of the aforementioned is of relevance for every region and period, but at least the possibility of complex and possibly iterating operational sequences must be kept in mind when investigating past ways of food production. At any rate it is crucial to communicate openly that any *chaîne opératoire* brought forward for archaeological finds must remain incomplete. A possible way of commenting such reconstructed operational sequences is suggested in **Fig. 40**, using the published results from the analysis of an apparent *galette* ("flat bread") from a Gallo-Roman graveyard in the Champagne-Ardenne region, France (Heiss et al. 2015). Processes and components which could not be clearly derived from the data are clearly marked in the diagram as doubtful, and they are explained thereafter.

An example for a somewhat shorter *chaîne opératoire* shall be given, as it was reconstructed for the fragments of a cereal product a Roman cremation grave in Rhineland-Palatinate, Germany (**Fig. 41**). The general study's aim was to re-evaluate previously published results on "bread" remains from the site (Währen 1990;



Fig. 41. Fragment of a cereal product from the Celtic-Roman cemetery of Wederath-*Belginum*, Rhineland-Palatinate, Germany (Heiss & Gail in print). Left: Plane view, right: cross section. Scale bar units: millimetres. Image: ÖAW-ÖAI, A. G. Heiss.

Währen & Rudin 1990). The amorphous charred objects (ACO) retrieved from cremation grave 85/10 date to the mid-1st c. CE and are characterised by large chunks of hulled barley (*Hordeum vulgare*) grains ranging from 1–4 mm in size. Considerably smaller tissue patches of glumes and bran are embedded in the matrix as well (**Fig. 42**). Together, these characters are interpreted as the consequence of very coarse grinding, or crushing (Heiss & Gail in print).

Intact starch granules could not be observed under the SEM which points into the direction of either a cooked product or its charring in hydrated state. While the lack of layering (**Fig. 41**) is taken as a hint against a thin liquid state of the cereal preparation, minor inclusions of charcoal (Währen 1990, p. 217) indicate that the product had come into contact with the fuelwood of the cremation pyre in at least a viscous state.

The conclusion for this material (Heiss & Gail in print) was that the cereal product from the Roman cremation grave may have originally resembled something like a *puls* – a food category which admittedly comprises a wide range of recipes (Hagmann 2017; Währen & Schneider 1995). It is important to note that no information was available on additional ingredients or on the raw vs. cooked state prior to charring (**Fig. 43**).

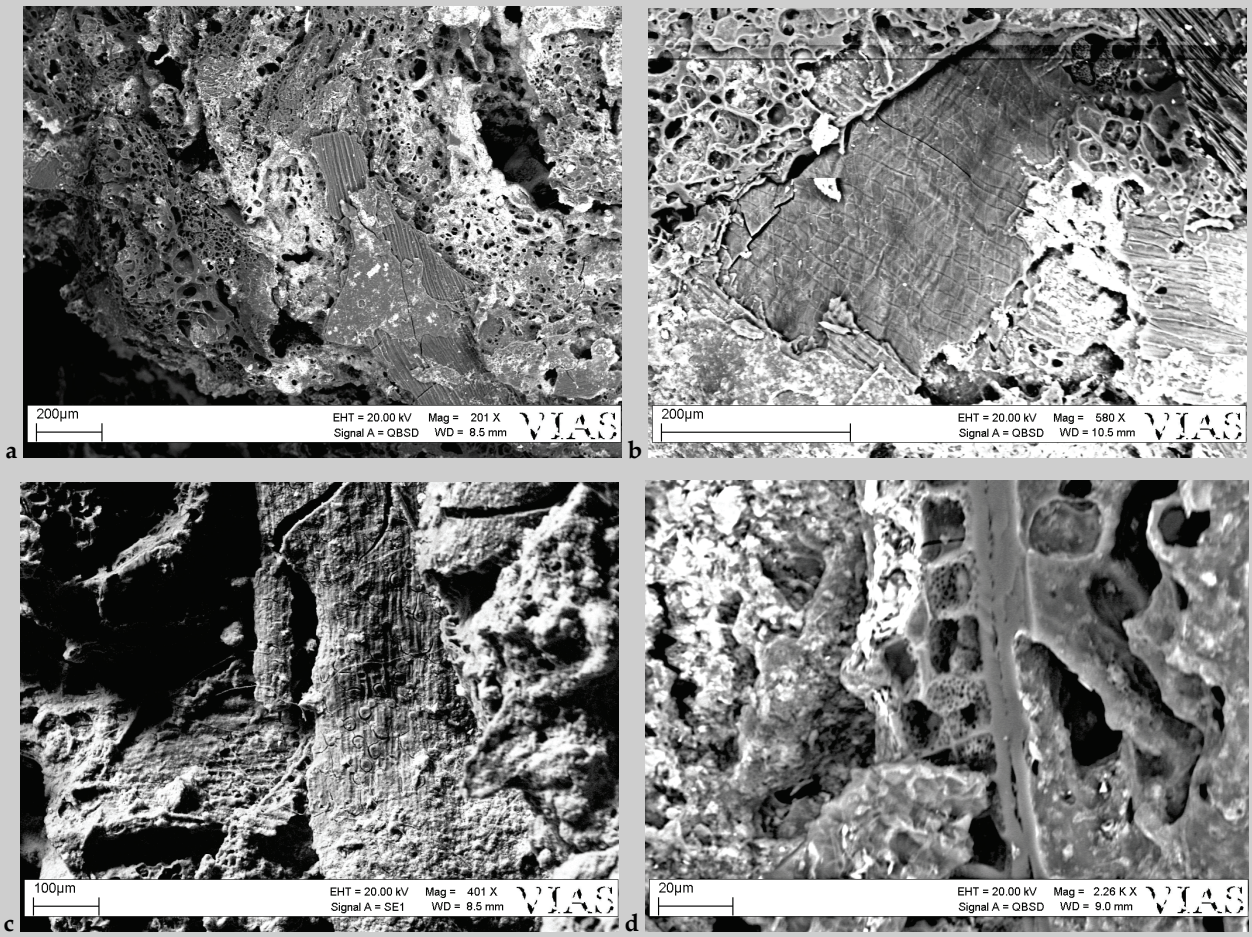


Fig. 42. Small fragments of bran tissue (a–d) and glumes (a, c) in the cereal product from Wederath-*Belginum*: a) unidentified glume fragment, b) transverse cells, possibly from barley (cf. *Hordeum vulgare*), c) barley (*H. vulgare*) glume fragment, d) barley (*H. vulgare*) aleurone tissue. Images: univie-VIAS, M. Mehofer.

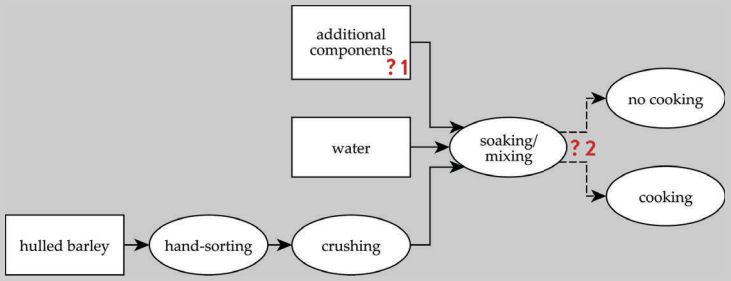


Fig. 43. Suggested *chaîne opératoire* for the cereal product from Wederath-*Belginum* (Heiss & Gail in print). No information is available 1) on additional components (dairy products, condiments, salt etc.) or 2) whether the supposedly viscous mass was cooked or left raw prior to charring. Image: ÖAW-ÖAI, A. G. Heiss.

Culinary Typologies, Analogies, and the Search for The Philosopher's Scone

Compiling large amounts of ingredients and the *chaînes opératoires* of their processing – cooking recipes, that is – allows for the definition of larger categories of processed food. Ingredients can be generalized, and processes can be simplified in the search for common traits and categories. Given enough data and resulting definitions of sufficient precision (Hill & Evans 1972), these schematic approaches set up culinary typologies (González Turmo 2004, p. 768).

Likewise, the creation of typologies for ancient foodstuffs requires sufficient information on the material concerned. As in other archaeological finds, a resulting type should be well-defined covering as many aspects as possible of 1) the find's shape and structure and 2) its composition. Ideally, also 3) the operational sequence of its production should be part of the type's definition. As the current state of research cannot provide descriptions anywhere near the degree of detail as in a cooking recipe, this "naming of names" will certainly have to remain largely incomplete in most cases.

For now, the common use of modern typologies as analogues (**Fig. 44, Fig. 45**) is probably still the most promising approach. Consideration should however be given to the way these classification schemes are applied, and particularly types which only base on a find's shape should give reason for doubt (elongated cereal product ≠ "noodle", see Herbig 2016; Schmidt 1963).

Any comparison of archaeological food remains to a modern food type should involve open discussion where the three aforementioned ideal criteria (shape and structure – composition – *chaîne opératoire*) are met, and where they are not. A find may be approximated using narrowly or rather widely defined modern types as analogies, both of which have their particular pros and cons.

Narrowly defined types usually leave little room for imagination. Their names are sufficiently "exotic" to the outsider as not to evoke any (possibly wrong) preconceptions about the product, and they are sufficiently precise for audiences familiar with them. It may be obvious that it is particularly cereal products with highly complex operational sequences which are very narrowly defined, such as the ring-shaped *bagel* (Balinska 2008) and *koulouria/simit* (Roth 2012) which require boiling before baking, or the likewise annular *kiachl* (Kuhn 2013) which are first fermented and then deep-fried. Also many seemingly simple traditional cereal dishes have very narrow definitions, such as *Ritschert* (Barth 1999; Reschreiter & Kowarik 2008), *trahanas/tarhana* (Economidou 1975; Erbaş et al. 2005; Hill & Bryer 1995), *frikeh* (Cappers et al. 2016, p. 1338) or *couscous* (Cappers 2018, p. 57). The drawback of such narrowly defined types is that their respective *chaînes opératoires* are just as

narrow. As a consequence, the analysis of an archaeological find will not provide sufficient data for reliably applying such a precise categorisation in many cases.

		Sequence of Processes Involved							*References*			
		Germinating	Crushing	Grinding	Soaking	Drying	Fermenting	Cooking, Baking, Roasting	Maurizio 1916	Hansson and Isaksson 1994	Lannoy et al. 2002	Valamoti 2011
Toasted Grains								1	X			
Grain-Paste			1		2				X	X		
Porridge			1		2			3	X	X		
Precooked Dough Products	*bulgur*			4	1	3		2				X
	trahanas			1	2	4	3	5				
Bread	leavened, height exceeding 45 mm			1	2		3	4	X	X	X	
	flat bread, height not exceeding 25 mm			1	2			3	X		X	
Beer		1	3		4		5	2	X		X	

Fig. 44. A tentative typology of some cereal-based foods and the sequences of their production processes (Heiss 2015b, modified), basing on archaeological, historical, and ethnographic data from central and south-eastern Europe (Hansson & Isaksson 1994; Lannoy et al. 2002; Maurizio 1916; Valamoti 2011). The line on *trahanas/tarhana* is modified (Erbaş et al. 2005). Numbers indicate the sequence of operations, Xs mark the sources for this information.

In contrast, **widely defined types** such as "bread" or "beer" have the advantage of easily encompassing a wide range of archaeological foodstuffs. Their low specificity is however also their largest drawback. Some are even so unspecific in themselves that their names may even evoke entirely different preconceptions in audiences of differing origins and socialisations. Following the cliché, "bread" would mean dark rye bread to most Austrians while the French would probably think of crisp white bread in the first place, as the British would possibly think of soft sandwich bread. Also the seemingly more precise category of "beer" contains beverages as different as British porter (Hornsey 2003, pp. 485–508) and traditional South African *kaffir* (Steinkraus 1996, pp. 407–416).

Furthermore, the fuzzy margins of most food categories make them entirely unsuitable for being diagnosed in the archaeological material. Where does "bread" end and where do "cookies" and "cakes" begin in an archaeological find? When does "porridge" become "gruel", and how does one determine this by analysing an archaeological charred crust? It is therefore generally advised to use

the comparison to modern food types in a very cautionary way, as sparsely as possible, and always accompanied by open discussion; every component and every process not corresponding to their modern counterparts should be thoroughly documented, and explanations should leave no room for speculation (see **p. 44 f.**, "Building Operational Sequences").

Cereal product	Hull tightness	Fragmentation			Wetting/drying/heating				Mixing	Germination	Fermentation	Short description
		Threshing	De-graining	Granulation	Pulverization	Cold-drying	Dry-heating	Wet-heating				
galiyya	H	1	2				3					roasted grain
	N	1					2					
frikeh	HN	2		(3)			1					roasted unripe grain (sometimes granulated)
melthuth/tchicha	H	1	2	4			3					roasted granulated grain
	N	1		3			2					
sprouted grain	N	1								2		germinated grain
koliva	H	1	2					3	4			boiled grain mixed with a variety of ingredients
	N	1						2	3			
couscous	H	1	2	3					4			granulated–pulverized grain mixed with water (and salt), made into granules of uniform size
	N	1		2					3			
bulgur	H	1	4	5		3		2				par-boiled granulated grain
	N	1		4		3		2				
polenta	N	1		2				3				boiled granulated grain
mirmiz (barley) frik (wheat)	HN	3		5	5	2	4	1				par-boiled and roasted granulated–pulverized unripe grain
beer	H	1		5		4	3	7	6	2	8	alcoholic beverage from coarsely ground (preferably hulled) grain, water and yeast
pasta	H	1	2	3		5	5	5	4			shaped mixture of finely granulated or pulverized grain, water and salt; eventually par-roasted or par-boiled
	N	1		2		(4)	(4)	(4)	3			
bread	H	1	2		3		6		4		5	shaped dry-heated mixture of pulverized grain, water, salt and yeast
	N	1			2		5		3		4	

Fig. 45. Typology of traditional cereal-based foods as published by Cappers (2018, 57). Numbers indicate the sequence of operations. H = hulled, and N = naked cerals.

In order not to conclude this section with problems, a preliminary solution shall be given. It circumvents some of the aforementioned limitations and hopefully avoids most interpretative pitfalls. Instead of focusing on a single "all-purpose" food type as modern analogue, several individual food types could serve as counterparts for different aspects of the same archaeological find. One type may describe the object's shape, one describes its production techniques and sequence, and possibly a third one its ingredients.

This approach has recently been brought forward (Heiss et al. accepted) for three Late Bronze Age annular bread-like objects found at Stillfried an der March, Lower Austria (see **Fig. 29** on **p. 37**). The fragments of the originally ring-shaped objects were found to be composed of rather finely ground barley and a (perhaps hulled) wheat species. No large pores, being traces of fermentation, were ob-

served while conspicuous furrows in the dough and the only partly gelatinised starch granules were interpreted as a consequence of the low initial water content of a probably air-dried product.

In an attempt to describe the annular objects as thoroughly as possible, two pairs of food types were chosen. Their shapes were related to Russian *sushki* (Anonymous 2009–2013) and Italian *tarallini* (see **Fig. 30** on **p. 37**; Primavera et al. 2018). Their *chaîne opératoire* was, however, partially related to the making of modern pasta and of *trahanas*/*tarhana* (see **Fig. 39** on **p. 44** as well as **Fig. 44** and **Fig. 45**).

Although under the general category of "bread-like objects", the finds from Stillfried may originally have been rather crunchy and dense. As apart from their cereal ingredients we do not have any evidence for other components such as salt, fat, condiments, or others, it is not possible to make qualified statements about their taste or mouth-feel.

The annular objects' find context was an "odd" find assemblage (Garrow 2012) deposited in a secondarily filled former storage pit. Considering their ritual deposition possible – among the other objects, also numerous clay loom weights of the same shape were found (**Fig. 46**) – the dough rings had possibly not even been produced for consumption in the first place (Heiss et al. accepted).



Fig. 46. The annular objects from the find assemblage in the debris layer of pit V5400, Stillfried an der March, Austria (Heiss et al. accepted). Twelve of the 14 rings made of clay (find numbers ST 12044.1–9, 12116.1, 12266.1–2, box 10/60044) are shown, as well as the charred organic rings (find numbers ST 12050.2–4, box 9/60043) probably made of air-dried dough. Scale bar units: centimetres. Image: ÖAW-OREA / B. Biederer.

Outlook

Archaeological food remains are the results of complex actions of complex cuisines. Structural analysis can at least partially unlock the information on ingredients and processes they contain. By integrating own observations with the expertise of researchers previously engaging in this field, the applicant has brought forward a small compendium of analytical and interpretative methodologies helping to approximate the original properties of these foodstuffs.

Thorough analysis, interpretation, and classification cannot only provide sound scientific data on cultural and technological aspects from the daily life of past societies. If applied in a cautionary way, the results can also deliver vivid images and tangible examples for public science.

Aside from the results already presented in this work, a syllabus of typologies for charred archaeological cereal products is currently being developed. It will hopefully provide useful and comprehensive criteria for their characterisation and classification. Comparison of the results from the µCT analyses with the experimental material from the ERC Project PLANTCULT will deliver new insights into the detailed processes involved in the charring of food remains, and allow for improved reconstructions of the original ancient dishes.



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Abbreviated Institutions

AUTH
Aristotle University of Thessaloniki

BOKU-DIB
University of Natural Resources and Life Sciences Vienna, Department of Integrative Biology and Biodiversity Research

DUK
Danube University Krems, Center for Museum Collections Management

EKU
Eberhard-Karls-Universität Tübingen

GRHis
Université de Rouen, Groupe de Recherche d'Histoire

JGU
Mainz University

LFU
Leopold-Franzens-Universität Innsbruck

MBU
Museum der Brotkultur Ulm

MM
Pfahlbau- und Klostermuseum Mondsee

MNHN
Muséum national de l'histoire naturelle

ÖAW-AKG
Austrian Academy of Sciences, Equal Opportunities Working Party

ÖAW-ÖAI
Austrian Academy of Sciences, Austrian Archaeological Institute

ÖAW-OREA
Austrian Academy of Sciences, Institute for Oriental and European Archaeology

OÖM
Federal Museum of Upper Austria, Collection of Prehistory and Early History

RPS-BWL
State Office for Cultural Heritage Baden-Württemberg

UHOH
University of Hohenheim

uni-ak
University of Applied Arts, Vienna

UNIBAS-IPNA/IPAS
University of Basel, Integrative Prehistory and Archaeological Science

univie-IUHA
University of Vienna, Teaching Collection of the Institute of Prehistoric and Historical Archaeology

univie-SFB
University of Vienna, Department of Botany and Biodiversity Research, Division of Structural and Functional Botany

univie-VIAS
University of Vienna, Vienna Institute for Archaeological Science

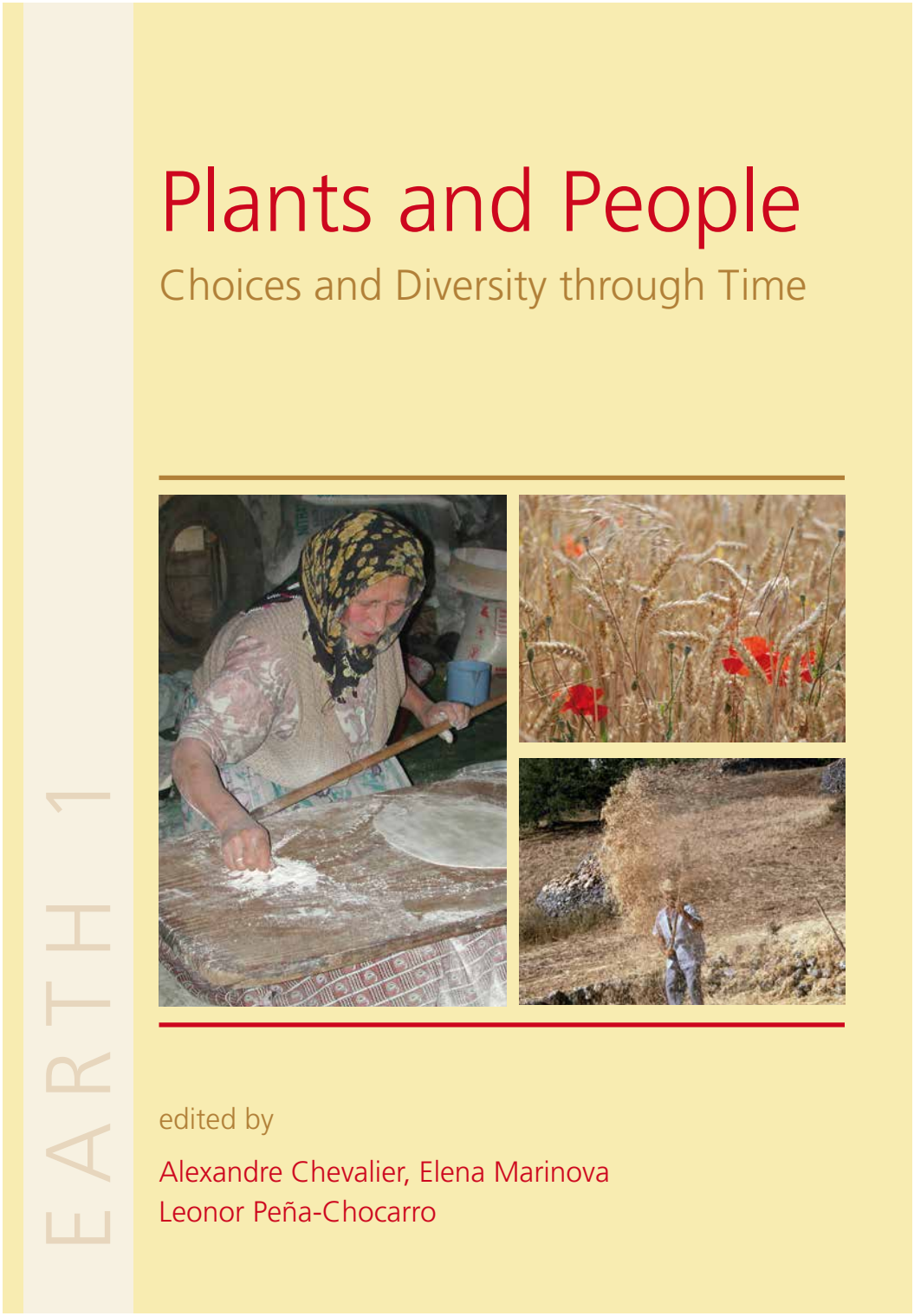
Appendix I
Key References

Short citation	Journal / Book title, Series	Impact	Peer Review	Estimated personal contribution
Heiss 2014	Plants and People, EARTH	-	yes	100%
Heiss 2015	Archaeology of Food	-	yes	100%
Heiss et al. 2015	Journal of Archaeological Science	2,602	yes	90%
Antolín et al., 2016	Jahrbuch Archäologie Schweiz	-	yes	15%
Heiss et al. 2017	PLoS ONE	3,54	yes	90%
Valamoti et al. 2017	Antiquity	1,536	yes	25%
Primavera et al. 2018	Archaeological and Anthropological Sciences	1,844	yes	33%
Valamoti et al. 2019	Journal of Archaeological Science	2,602	yes	15%
Heiss et al. accepted	PLoS ONE	3,54	yes	90%

Table 1. Personal contributions to the publications included in the habilitation thesis.

Heiss 2014

Heiss A. G. (2014) Ceremonial Foodstuffs from Prehistoric Burnt-Offering Places in the Alpine Region. In: A. Chevalier, E. Marinova & L. Peña-Chocarro (eds.) *Plants and People: Choices and Diversity through Time*. Early Agricultural Remnants and Technical Heritage (EARTH): 8,000 Years of Resilience and Innovation. Volume 1. Oxbow Books, Oxford: 343–353. doi: 10.13140/2.1.2776.5767



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7.3. CEREMONIAL FOODSTUFFS FROM PREHISTORIC BURNT-OFFERING PLACES IN THE ALPINE REGION

Andreas G. Heiss

Introduction: Sacrificial Fires in the Alps

Burning is a very common and simple way of transforming an offering into something immaterial and at the same time transporting it into an otherworld by sending the gifts up into the heavens as smoke (Lang 2002; Schwager 2002; see Fig. 7.1). In the following article, one particular group of archaeological sites featuring burnt offerings will be discussed: the *Alpine Brandopferplätze* (Alpine burnt-offering places). The term was coined by the German archaeologist W. Krämer in the 1960s, in a publication suggesting the re-interpretation of some prehistoric sites in the Alpine area, then known as '*Wallburgen*' (hillforts; Krämer 1966). These structures – comprising ramparts, pavings and levellings, or stone circles – had previously been seen as the remains of ancient fortifications, but he demonstrated that the unusual deposits they contained were to be interpreted rather as the remains of burnt sacrifices: soil layers blackened by charcoal, masses of calcinated and highly fragmented animal bones, and artefacts displaying traces of fire and of intentional destruction. The following decades brought intensified research into these offering places, leading to the discovery of more than 200 sites in the Alpine and circum-Alpine area, although some of them are of uncertain classification (Weiss 1997). Their temporal range covers the Middle Bronze Age to the Roman Iron Age. Recent results suggest even older roots, reaching back to the Copper Age (Oberrauch 2005). Spatial extension of this cult phenomenon has recently been expanded to the region of Alpes-de-Haute-Provence, France, in the west (Garcia *et al.* 2006), and to the Sölk valley in Styria, Austria, in the east (Hebert *et al.* 2003). There is wide variety in the complexity of the built structures of burnt-offering places: some consist simply of a stone pavement, or one single stone circle, whereas others have several altars, multiple stone circles (see Fig. 7.40), and often also buildings associated with the offering site.

The gods worshipped in these offering places are still unknown, although for the Early Iron Age there are several hints pointing towards the northern Italian goddess 'Reitia' (as an example in Kossack 2002). As Alpine burnt-offering places share a prominent common feature with the cult of Demeter, *i.e.* sacrificing meat still attached to the bones (see Chapter 7.1), Ardovino (2002) suggested the possibility of – albeit very remote – links between the two types of rituals. It must however be stressed that the hypothesis of direct relations between Alpine burnt-offerings and the Olympian rite, as originally formulated by Krämer (1966), has long been abandoned by archaeologists.

The Question of Plant-Based Food in the Offerings

Plants, while representing the most important part of everyday nutrition, have long been neglected in *Brandopferplatz* research, as is evident in W. Zanier's (1999) review of diagnostic traits for burnt-offering places: these had always remained exclusively focused on archaeological features, artefact finds and animal remains. One reason for this might be the low visibility of individual plant remains in

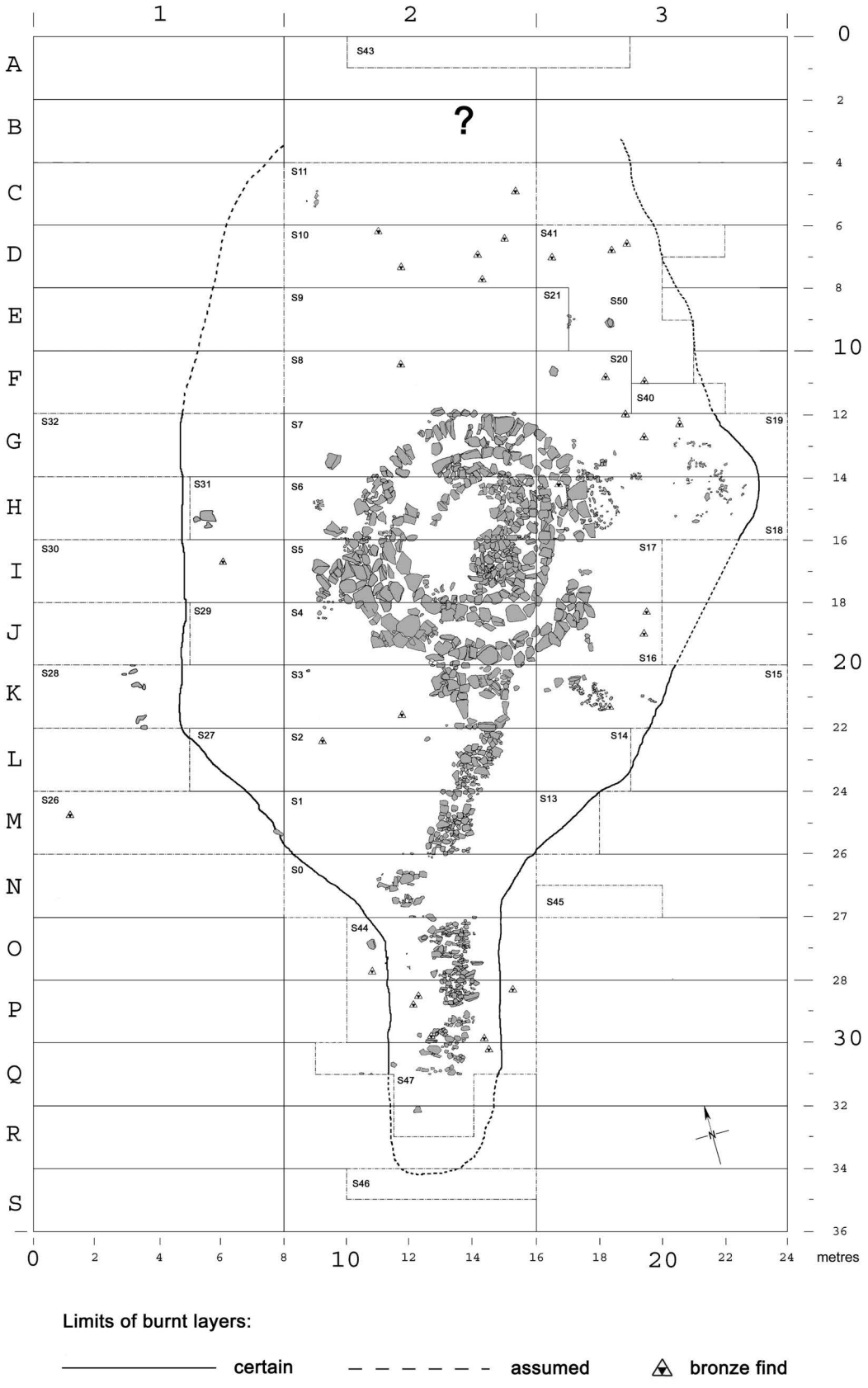


Fig. 7.40. The Late Bronze Age Alpine burnt-offering place of Altenstadt, Grütze, in Feldkirch (Austria, Federal State of Vorarlberg). The plan displays site dimensions, location of built stone structures, and extent of the ashy layers. In the centre lies a double stone circle of ca. eight metres in diameter, with a clay accumulation in its centre, the supposed position of the former altar. Extending to the south lies a row of fireplaces. Drawing from B. Heeb (2009)

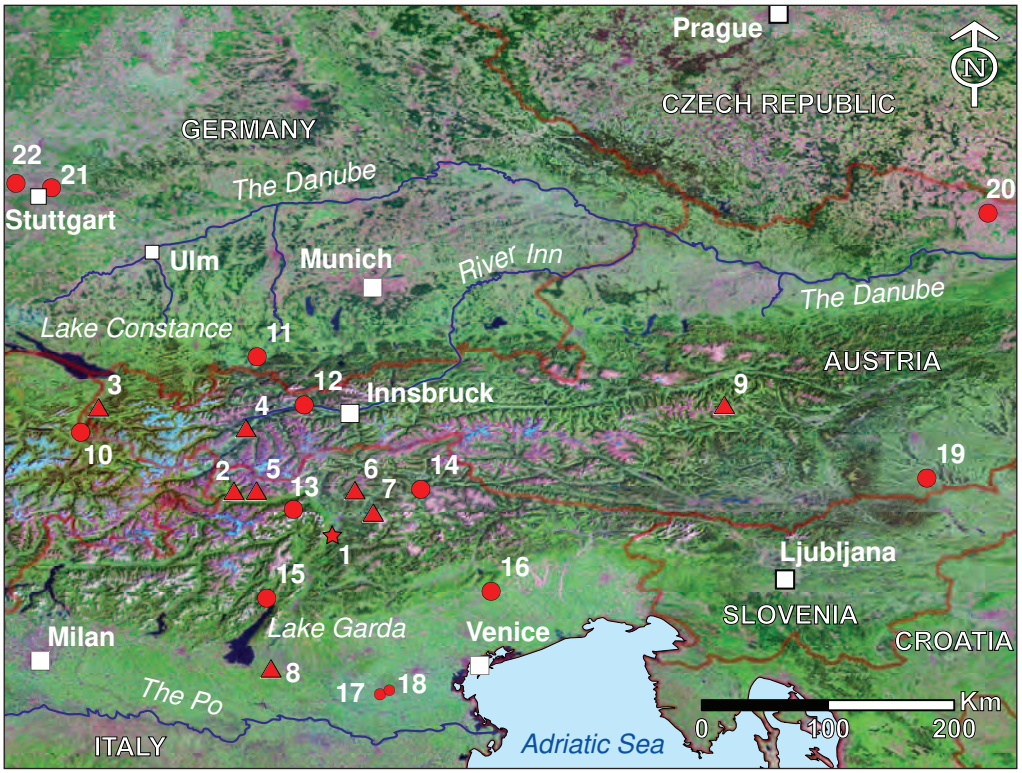


Fig. 7.41. Map of the investigated area. Numbers correspond to the sites in Fig. 7.42. Map: J.-C. Loubier and A. Chevalier.

Site no.	Site name	Period	Municipality	Region/province	Country	Altitude [m a.s.l.]	References
1	Pigloner Kopf	CA	Vadena/Pfatten	Bolzano/Bozen	Italy	550	Gattringer (2006)
2	Ganglegg, Hahnehütterbödele	MBA–LBA	Sluderno/Schluderns	Bolzano/Bozen	Italy	1,100	Heiss (2008)
3	Altenstadt, Grütze	LBA	Feldkirch	Vorarlberg	Austria	444/445	Heiss (2008)
4	Pillerhöhe	LBA–IA; RIA	Fließ im Oberinntal	Tyrol	Austria	1,559	Oeggl (1993), Heiss (2008)
5	Maneidtal, Grubensee	LBA–LIA; LIA–RIA	Silandro/Schlanders	Bolzano/Bozen	Italy	2,435	Heiss (2008)
6	Seeberg, Lago Nero/ Schwarzsee	LBA	Villandro/Villanders	Bolzano/Bozen	Italy	2,035	Castiglioni & Cottini (2000), Oeggl in Niederwanger & Tecchiati (2000)
7	Schlern, Burgstall	LBA; RIA	Siusi/Seis	Bolzano/Bozen	Italy	2,510	Heiss (2008)
8	Sommacampagna	LBA	Custoza	Verona	Italy	124	Nisbet (1996/1997)
9	Sölkpass	LBA	St. Nikolai	Styria	Austria	1,788	Heiss (2008)
10	Ochsenberg	LIA	Wartau	St. Gall	Switzerland	660	Heiss (2008)
11	Forggensee	LIA–RIA	Schwangau	Bavaria	Germany	773	Küster (1999), Tegel (1999)
12	Trappeleacker	LIA	Pfaffenhofen	Tyrol	Austria	700	Heiss (2008)
13	S. Valburga/St. Walburg	LIA	Ultimo/Ulten	Bolzano/Bozen	Italy	1,200	Oeggl (1992), Rösch (2002), Heiss (2008)
14	Prati del Putia	LIA	S. Martino/St. Martin	Bolzano/Bozen	Italy	2,170	Cottini *et al.* (2007)
15	Campi, Monte S. Martino	LIA	Riva del Garda	Veneto	Italy	1,450	Castiglioni (2007)
16	Villa di Villa	LIA-RIA	Cordignano	Treviso	Italy	160	Boaro *et al.* (2005)
17	Fondo Baratella	LIA	Este	Padova	Italy	15	Pasternak (2005)
18	Meggiaro	LIA	Este	Padova	Italy	15	Motella de Carlo (2002)
19	Frauenberg	LIA–RIA	Leibnitz	Styria	Austria	380	Popovtschak (2005)
20	Sandberg, Heiligtum 1	LIA	Roseldorf	Lower Austria	Austria	340	Caneppele *et al.* (2010)

Fig. 7.42. Investigated sites as indicated in Fig. 7.41. Abbreviations: CA: Copper Age, MBA: Middle Bronze Age, LBA: Late Bronze Age, LIA: Late Iron Age, RIA: Roman Iron Age.

archaeological sites: although blackened layers may seem very conspicuous, the charred plant remains they contain usually only become visible after thorough processing of soil samples (by wet-sieving or flotation; see Chapter 7.1).

However, written and iconographic sources on Roman and Greek burnt offerings had already suggested a multitude of plant-based offerings, and consequently these had also to be taken into consideration for the prehistoric Alpine rituals: cereals and their products (porridge, bread, cakes, pastry), fruits, flowers, leaves, roots, wine and beer, oil, and incense are mentioned as sacrifices (Zanier 1999). Just like animal products (meat, wool, fur, honey, and dairy products), they were the results of either hard farm labour or of tedious foraging in the wild, making them precious goods. Thus, there must have been important reasons for sharing them with the gods (see Chapter 7.1). A certain agricultural character of the burnt offerings has been assumed for several years (Weiss 1997) and only recently it was confirmed by the dominance of domesticated animals over game in the archaeozoological record (Rizzi 2000; Leitner 2002; Hebert *et al.* 2003; Schmitzberger 2007; Heeb 2010). Thus, the hypothesis of a linkage between offering rituals and events of agricultural importance, *e.g.* sowing or harvesting (Steiner 2007; 2010), was to be tested for plant-based offerings as well.

Archaeobotanical Analyses: Past Research in a Nutshell and Recent Investigations

The first published data on plant remains from Alpine burnt-offering places date back to the early 1990s, when K. Oeggl (1992) analysed a few samples from the site at St. Valburga/St. Walburg in the Ultimo/Ulten valley, northern Italy. Subsequent occasional analyses were carried out on several other sites. Only recently a comprehensive archaeobotanical study on nine Alpine burnt-offering sites was carried out comprising a synopsis of extant analyses from *Brandopferplätze* and comparable sites in and around the Alps, excluding only sites with a clear connection to funerary rituals (Heiss 2008a; 2010a). The sanctuaries included extend over a large spatial and temporal range, from Switzerland through northern Italy to eastern Austria, and from the Eneolithic (Copper Age) up to Roman times (see Fig. 7.41, 7.42).

The methods applied in the current study mainly followed standard procedures (Jacomet and Kreuz 1999), such as flotation to extract charred plant remains from the surrounding soil, and macrofossil analysis of seeds, fruits, wood charcoal and other plant parts. However, these methods were supplemented by detailed studies of irregularly shaped objects of unknown composition, corresponding to S. Jacomet's 'AOV' category (*Amorphe Objekte Verkohlt*, meaning 'amorphous charred objects'; Jacomet *et al.*

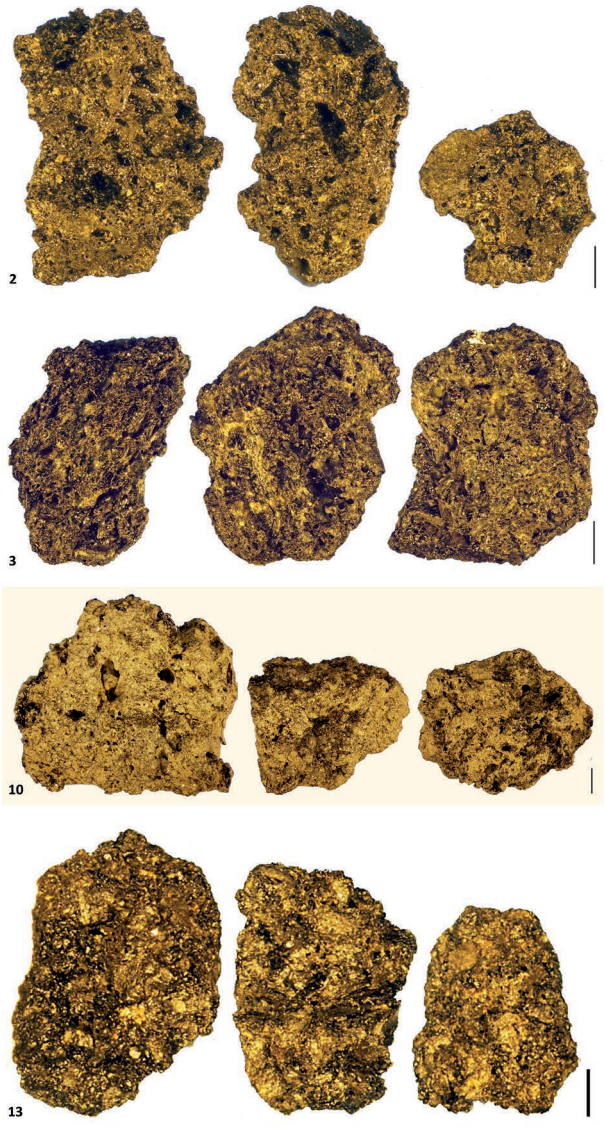


Fig. 7.43. Amorphous charred objects, later identified as cereal products. Scale bar length 1 mm. Site numbers correspond to the sites in Fig. 7.42. 2: Ganglegg, Hahnehütterbödele, 3: Altenstadt, Grütze, 10: Ochsenberg, 13: S. Valburga/St. Walburg. Image: Andreas G. Heiss.

Site no.	2	3	4	5	7	9	10	12	13
Amorphous charred objects (AOV)									
- amount	395	898	418	311	237	2	105	1	4,025
- weight	2,04 g	11,95 g	3,49 g	4,58 g	4,81 g	< 0,01 g	1,01 g	< 0,01 g	42,60 g

Fig. 7.44. Amorphous charred objects (Amorphe Objekte Verkohlt, AOV) as found in the most recent archaeobotanical study of Alpine burnt-offering places. Numbers correspond to the sites in Fig. 7.42. 2: Ganglegg, Hahnehütterbödele, 3: Altenstadt, Grütze, 4: Pillerhöhe, 5: Maneidtal, Grubensee, 7: Schlern, Burgstall, 9: Sölkpass, 10: Ochsenberg, 12: Trappeleacker, 13: S. Valburga/St. Walburg.

2006). Aside from wood charcoal, these amorphous fragments represented the largest proportion of charred finds in the recently investigated Alpine offering sites (Fig. 7.43). Their regular and numerous occurrence (up to several thousand fragments per site, see Fig. 7.44) had suggested a certain importance in the offering rituals and thus required a more thorough investigation. In archaeobotany, charred amorphous remains are usually classified as food remains, and considered as either originating from fruit pulp, or being a cereal product of some kind. So they were searched for potentially identifiable tissue remains with the aim of finding hints about the origin of the material. The methods applied included reflected light microscopy at high magnifications (up to 1000x), Scanning Electron Microscope (SEM) imaging, and chemical digestion of the charred materials following the methodology by Hansson and Isaksson (1994; for details, see Heiss 2008, 26–30, 131–137).

New Insights

The data of the current analyses, together with the synopsis of previous work, resulted in a broad spectrum of plants, of which only food plants shall be discussed here (for the other finds, refer to Heiss 2008a; 2010a). The amorphous objects, for instance, turned out to contain tissue fragments from cereal bran. The term 'bran' describes the sum of all outer layers of a cereal grain, such as the pericarp (the tissues forming the fruit), the testa (the seed coat), and some of the seed's more inward tissue layers. Even in a charred state, the characteristic cell patterns of the transverse cell layer from the pericarp allow the identification of cereals. Also, the structure of the thick-walled aleurone layer which stores the main part of the grain's protein is diagnostic for certain cereal species (Fig. 7.45; see also Chapter 7.2).

For sites 3, 5, 7, 10, and 13 (numbers corresponding to Fig. 7.42), wheat (*Triticum* sp.) could be identified as a component of the charred mass via the transverse cells (Fig. 7.46). The fragments from site No. 3 (Altenstadt, Grütze, western Austria) also contained barley (*Hordeum vulgare*), which was recognised via its multi-layered aleurone layer (Fig. 7.47; Heiss 2010b). Many other tissue remains, mainly fragments of single-layered aleurone layers, were not attributable to particular cereal species.

The tissue remains are clear evidence of cereals in the amorphous objects, but no indication was found for fruit pulp. This suggested the conclusion that the mass was at least predominantly cereal-based. All observed portions of cereal tissue were of minute size, not exceeding 300 µm. Such a high degree of fragmentation indicates grinding of the

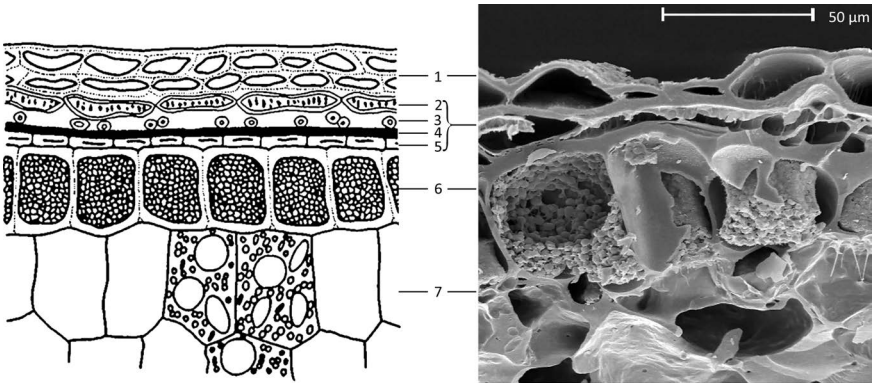


Fig. 7.45. Composition of the seed/fruit layers of a cereal grain, illustrated for bread wheat (*Triticum aestivum* L.). Left: schematic drawing (Hahn and Michaelsen 1996, modified), Right: Scanning Electron Microscope image of an experimentally charred grain. 1: longitudinal cells, 2: transversal cells, 3: tubular cells, 4: testa (seed coat), 5: nucellus remains, 6: aleurone layer, 7: endosperm. Layers 2–6 are collapsed in the experimentally charred specimen. Image: Andreas G. Heiss

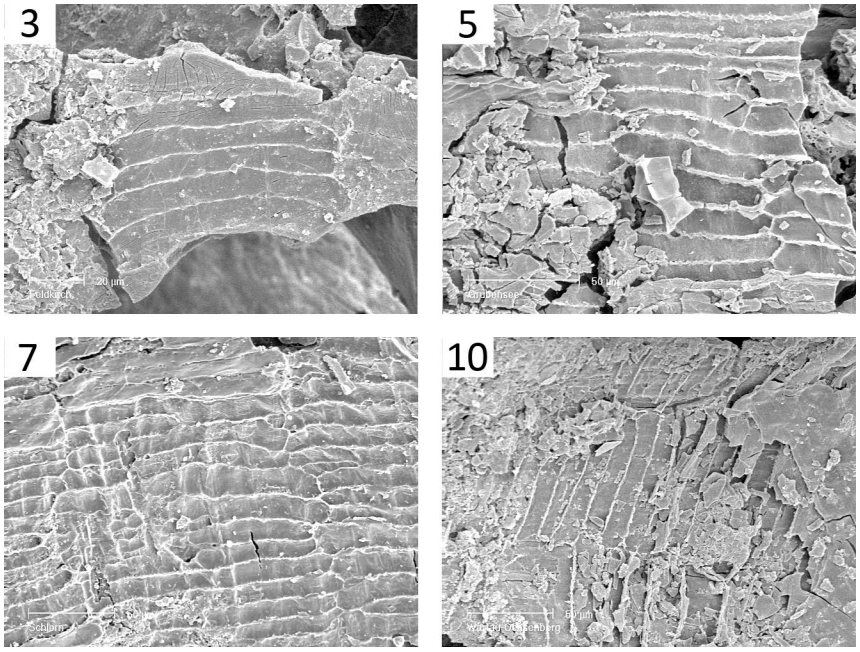


Fig. 7.46. Transverse cell layers from the cereal products. Numbers correspond to the sites in Fig. 7.42: Altenstadt, Grütze (smooth and thin-walled cells indicating barley, *Hordeum vulgare* L.), 5: Maneidtal, Grubensee, 7: Schlern, Burgstall, 10: Ochsenberg (the latter three with regularly thickened and pitted cell walls indicating wheat species, *Triticum* sp.). Image: Andreas G. Heiss.'

cereals, with grain sizes comparable to dunst or fine semolina. This was corroborated by comparative structural studies of the prehistoric material from burnt-offering places with the data and SEM images from ancient charred bread finds (Fig. 7.48), such as the bun from a Celtic salt mine in Bad Nauheim, Germany (Heiss and Kreuz 2007), and bread from grave goods in the Roman cemetery in St. Memmie, France (Heiss 2008b; Heiss *et al.* 2008b), and the Viking Age bread from Birka on Björkö island in Sweden (Hansson and Bergström 2002). Eventually, the amorphous objects were identified as the remains of some prehistoric flour-based food. Due to the high fragmentation, it was however not possible to discern between certain cereal products, such as grain-paste, porridge/gruel, or bread (Hansson 1994; Lannoy *et al.* 2002).

Figure 7.49 shows the total cereal remains covered in the study. It is clear that in addition to the cereal product, cereal grains also played a major role in the offerings, both in terms of diversity and numbers of finds. Still, the amounts of fragments of the cereal product suggest that this material was of much higher importance in the sacrificial rites than the actual grains. Among the cereals identified, hulled barley (*Hordeum vulgare* L.) and broomcorn millet (*Panicum miliaceum* L.) show the highest frequency in the sites, whereas wheat species (*Triticum* spp.) dominate in terms of numbers of finds. Chaff is virtually absent. Comparison of these spectra with archaeobotanical data from settlements in the region shows that barley, although the main cereal crop in the prehistoric Alps, is not at all well represented in the offerings during the Late Bronze Age. One factor causing this seeming discrepancy might be the less dense data for ritual sites of this period. But even at sites rich in botanical finds (such as No. 3 Altenstadt, Grütze), barley is barely represented. In the Late Iron Age sites, the remains from the rituals reflect the actual situation of daily nutrition more closely. The cereal product is however well represented during both periods. The presence of rye (*Secale cereale* L.) is only documented for one Late Iron Age site. This goes very well with the rather late cultivation of rye in central Europe, supposedly dating back to the Early Iron Age. However, utilisation of this cereal did not rise to a position of economic importance until Roman times (Behre 1992; Körber-Grohne 1995).

Seeds of legumes (pulses) are preserved less well in a carbonised state than cereal grains (Willerding 1971; Stika 1996; Jacomet, *pers. comm.*), and are thus found somewhat more rarely in settlements. Faba bean (*Vicia faba*), also called broad bean, or field bean, is the most frequent pulse identified from the ritual sites' burnt layers (see Fig. 7.50). The second most frequent legume seeds in burnt offerings are garden pea (*Pisum sativum*) and lentil (*Lens culinaris*). Judging from the data available, pulses are poorly represented in the older sites, but possibly more

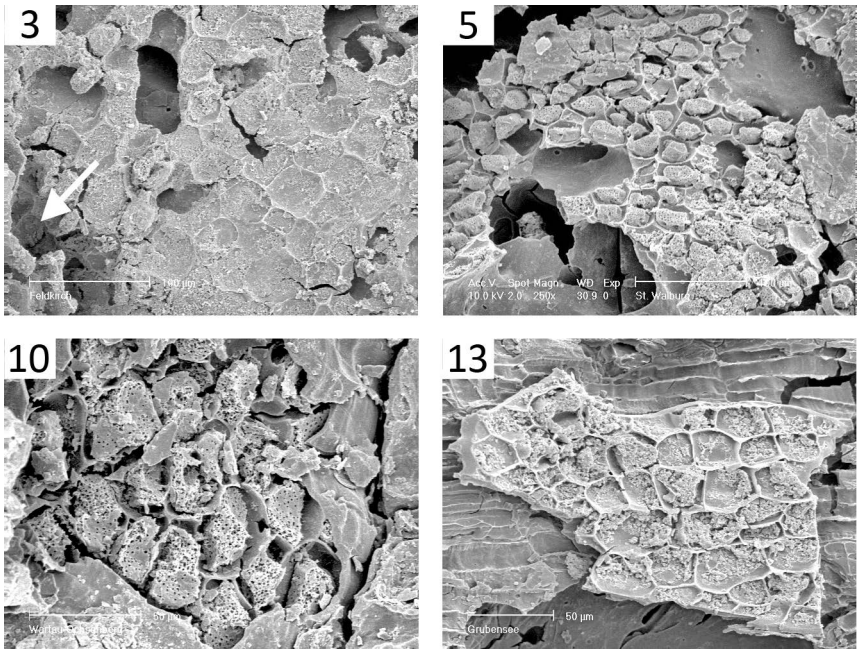


Fig. 7.47. Aleurone cell layers from the cereal products. Numbers correspond to the sites in Fig. 7.42: Altenstadt, Grütze (multi-layered aleurone layer indicating barley, Hordeum vulgare L.), 5: Maneidtal, Grubensee, 10: Ochsenberg, 13: S. Valburga/St. Walburg (the latter three with single-layered aleurone as found in most cereals). Image: Andreas G. Heiss.

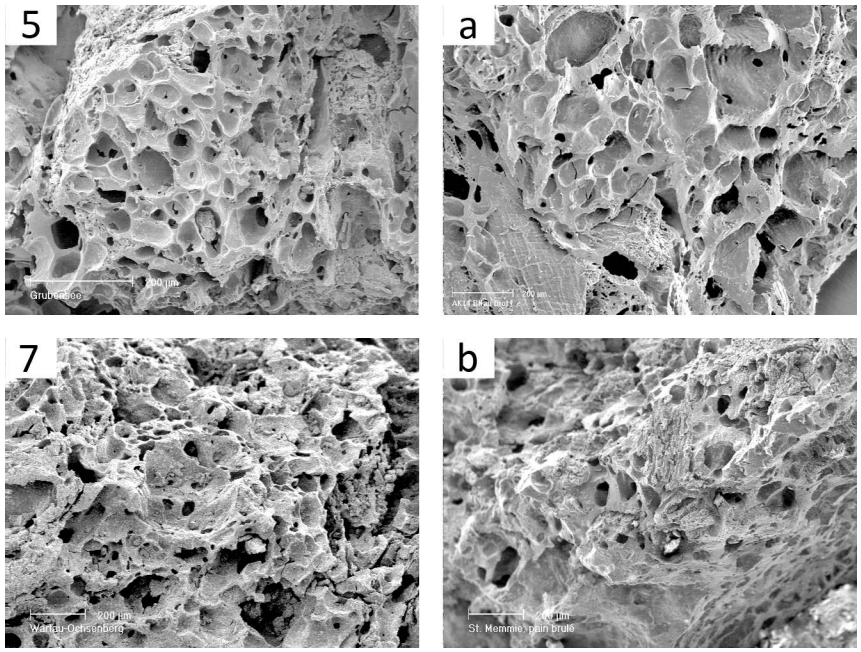


Fig. 7.48. Comparative microstructure of the cereal products from the burnt-offering places and of archaeological bread buns. a: the Late Iron Age saline of Bad Nauheim, Germany (Heiss and Kreuz 2007), and b: the Roman cemetery at St. Memmie, France (Heiss 2008b). Numbers correspond to the sites in Fig. 7.42: 5: Maneidtal, Grubensee, 7: Schlern, Burgstall. Image: Andreas G. Heiss.

related to lower preservability than to rarer use. The spatial distribution of sites with legume finds, however, seems to show a focus in northern Italy: only two sites out of eight from outside this area (No. 11, Forggensee, Bavaria and No. 20, Sandberg, Lower Austria, *cf.* Fig. 7.51) resulted in finds of charred pulse seeds. In contrast, seven out of twelve north Italian sites provided evidence of pulses. This may suggest a local characteristic in the burnt-offering cult practice and is reminiscent of the high symbolic significance of faba bean in the Mediterranean during Antiquity (see Chapter 7.1). Postulating an actual connection would however be purely speculative.

Evidence of oilseeds (such as flax/linseed, *Linum usitatissimum* L., opium poppy, *Papaver somniferum* L., hemp, *Cannabis sativa* L., or gold-of-pleasure, *Camelina sativa* [L.] Crantz) is often difficult to obtain in archaeobotany. Under the influence of

	CA	Middle to Late Bronze Age								Late Iron Age to Roman Age											Ubiquity (percentage of sites)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Cereals																					100%
Hordeum vulgare L. (hulled barley)	+	•	•	•	–	–	–	–	–	•	+	–	+	+	+	–	++	–	+	+++	60%
Triticum monococcum L., T. *dicoccum* Schübl., *T. spelta* L. (species of hulled wheat, total)	++	–	++	–	–	–	–	–	–	–	–	–	++	+	+++	–	++	–	++	++++	40%
Triticum aestivum/durum/turgidum (species of naked wheat)	•	–	–	–	–	–	–	–	–	–	–	–	+	–	++	–	+	•	–	+	30%
Triticum sp. (unidentified wheat species)	•	–	+	•	–	+	–	–	–	•	–	–	+	–	–	–	–	–	+	++	40%
Panicum miliaceum L. (broomcorn millet)	–	+	+	–	•	+	–	+++(+)	–	–	–	–	++	–	++	–	+	–	++	++	50%
Setaria italica (L.) P. Beauv. (foxtail millet)	–	–	•	–	–	–	–	–	–	–	–	–	•	–	–	–	++++	–	++	–	20%
Secale cereale L. (rye)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	++	5%
indet. (unidentified cereals)	++	•	+	•	–	–	–	–	–	+	–	–	++	–	++++	–	–	–	++	++++	45%
porridge/bread fragments	–	+++	++++	+++	+++	–	+++	–	+	+++	–	•	++++	–	–	+(+++)	–	–	–	–	50%

Fig. 7.49. Semi-quantitative list of charred cereal remains from Alpine and circum- Alpine sites with burnt offerings. Uncertain identifications ('cf.') are included in the respective taxa. Site numbers correspond to the sites in Fig. 7.42. CA... Copper Age. Categories of find numbers: • ... single find, + ... 2–9, ++ ... 10–99, +++ ... 100–499, ++++... 500 and more.

	CA	Middle to Late Bronze Age								Late Iron Age to Roman Age											Ubiquity (percentage of sites)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Pulses/legumes																					45%
Lathyrus sativus L. (white pea)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	–	–	5%
Lens culinaris Medik. (lentil)	–	–	–	–	–	–	–	–	–	–	–	–	•	+	–	–	++	–	–	++	20%
Pisum sativum L. (garden pea)	–	–	–	–	–	–	–	–	–	–	+	–	+	++	–	–	•	–	–	+	25%
Vicia ervilia (L.) Willd. (bitter vetch)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	•	–	•	–	–	–	10%
Vicia faba L. (broad bean)	–	–	–	–	•	–	–	•	–	–	+	–	+	+	•	–	–	–	–	–	30%
indet. (unidentified legumes)	–	•	–	–	+	–	–	–	–	–	++	–	++	+	•	–	++	–	–	–	35%
Oilseeds																					20%
Camelina sativa (L.) Crantz (gold-of-pleasure)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	++	–	–	++	10%
Linum usitatissimum L. (linseed)	+	–	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–	–	–	5%
Papaver somniferum L. (opium poppy)	–	–	–	–	–	–	–	–	–	–	–	–	•	–	–	–	+	–	–	+	15%

Fig. 7.50. Semi-quantitative list of charred legume and oilseed remains from Alpine and circum-Alpine sites with burnt offerings. Uncertain identifications ('cf.') are included in the respective taxa. Site numbers correspond to the sites in Fig. 7.42. CA... Copper Age. Categories of find numbers: • ... single find, + ... 2–9, ++ ... 10–99, +++ ... 100–499, ++++... 500 and more.

	CA	Middle to Late Bronze Age								Late Iron Age to Roman Age											Ubiquity (percentage of sites)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Gathered fruits																					65%
Cornus mas L. (Cornelian cherry)	+	–	–	–	–	–	–	•	–	–	–	–	–	–	+	–	–	–	–	–	15%
Cornus sanguinea L. (common dogwood)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+++	–	–	10%
Corylus avellana L. (hazel)	++	–	+	++	–	+	–	–	–	–	–	+	+	++	–	–	++	++	++	•	55%
Crataegus laevigata (Poir.) DC. (hawthorn)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	•	5%
Fragaria spp. (strawberry)	–	–	–	–	–	–	•	–	–	–	–	–	•	–	–	–	–	–	•	–	15%
Quercus sp. (oak)	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	•	+	–	–	15%
Pinus cembra L. (Swiss stone pine)	–	–	–	–	–	–	–	–	–	–	–	–	–	++	–	–	–	–	–	–	5%
Prunus spinosa L. (blackthorn)	+	–	–	•	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	10%
Rosa sp. (rose)	–	–	–	–	–	–	–	–	–	–	–	–	•	–	–	–	–	–	–	–	5%
Rubus spp. (brambles, raspberry etc.)	–	–	•	–	–	–	–	–	–	–	–	–	+	–	–	–	+	+++	–	–	20%
Sambucus spp. (elder)	++	–	++	–	–	–	–	–	–	–	–	–	+	–	–	–	+	++	+	–	30%
Solanum nigrum L. agg. (black nightshade)	•	–	•	–	–	–	–	–	–	–	–	–	–	–	–	–	++	–	–	–	15%
Sorbus aucuparia L. (rowan)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	5%
Vitis vinifera L. ssp. *sylvestris* (C.C.Gmel.) Hegi (wild grapevine)	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	++	+++	–	–	15%
Cultivated/introduced fruits																					20%
Ficus carica L. (fig)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	•	–	–	–	5%
Juglans regia L. (walnut)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	+++	–	10%
Olea europaea L. (olive)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	•	–	10%
Vitis vinifera L. ssp. *vinifera* (cultivated grapevine)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	++	+++	+	•	20%

Fig. 7.51. Semi-quantitative list of charred fruit remains from Alpine and circum-Alpine sites with burnt offerings. Uncertain identifications ('cf.') are included in the respective taxa. Site numbers correspond to the sites in Fig. 7.42. CA... Copper Age. Categories of find numbers: • ... single find, + ... 2–9, ++ ... 10–99, +++ ... 100–499, ++++... 500 and more.

heat, the fat contained in their storage tissues usually starts to boil, developing flammable and expansive gases. Their escape causes ruptures in the tissue as well as favouring complete combustion of the seeds. As a consequence, oilseeds survive charring with difficulty and thus are only rarely preserved in dry soils (see Chapter 7.1). Their chances for preservation in a context of intentional combustion (as can be assumed for burnt offerings) can be imagined to be even lower. In contrast, impressive find numbers sometimes reaching tens of thousands are documented for some waterlogged sediments, as for instance in lakeshore settlements in Germany and Switzerland (Jacomet 2009). Against this background, the very few grains of oilseeds recovered from burnt offerings are more inspiring than disappointing: their presence in four sites (Fig. 7.50) is the proof of their utilisation in the Alpine (sites No. 1, 13) and circum-Alpine (No. 17, 20) offering rituals. Their absence in the other sites however is of no significance.

Edible fruits from trees or shrubs (and rarely from forbs, such as strawberry) are commonly regarded as having been gathered in the wild on purpose. Their seeds constantly occur in areas of human activity throughout the archaeological record. Besides their vital importance for hunter-gatherers, even in agricultural societies they made a good complementary food rich in vitamins (and probably were a welcome relief in regards of taste). Yet, in spite of their common occurrence in human settlements, they are not well represented in the burnt-offerings (Fig. 7.51): after a high diversity of remains of gathered fruits found at the Copper Age site of Pigloner Kopf in South Tyrol/Alto Adige (No. 1), they are only sporadically present in the Late Bronze Age and Late Iron Age sites. The only conspicuous exceptions during these periods are Altenstadt, Grütze (No. 3), and S. Valburga/St. Walburg (No. 13). Later, under Roman influence (sites No. 17–19), the diversity of gathered fruits rises again and is complemented by finds of imported fruits such as fig (*Ficus carica* L.), grapevine (*Vitis vinifera* L.) or walnut (*Juglans regia* L.), some of which might also have been cultivated locally. Hazel (*Corylus avellana* L.) is represented during all periods. Preservability of the respective finds is not a likely reason for these changing patterns, as the seeds/fruits of gathered fruit plants easily 'survive' charring due to their morphology: they either have a hard-shelled pericarp such as nuts (as in hazel, acorn, or sweet chestnut) or nutlets (in strawberry and rosehip), or they are thick-walled fruit stones (as in raspberry, elder, or Cornelian cherry). For the Late Bronze Age and Late Iron Age sites (prior to Roman influence), a low importance of gathered fruits for the offering rituals seems to be a likely explanation for their low presence in the charred layers.

The remaining wild plants discovered in the charred record were usually segetal (crop weeds) and ruderal (wayside and fallow) plants: plants belonging to these groups need nutrient-rich soils and plenty of light, easily tolerate disturbance (such as repeated damage by being trampled on), and their reproductive life cycles are very short. These plants – weeds – thus are perfectly adapted to man-made ecosystems like waysides, fallow land and crop fields. From the archaeological record, however, most of these plants cannot be clearly attributed to either ruderals or segetals: they might have been transported to the sacrificial fires with the crops, or might have been part of the on-site vegetation developing during times the pyres were not in use. Using the flowering times (and consequently, the beginning of the fruiting times) of the weeds found in the nine most recently investigated sites (No. 2, 3, 4, 5, 7, 9, 10, 12, 13), a *terminus post quem* for the offerings may be suggested for August when most of the plants found would already bear fruit (Fig. 7.52). However, this hypothesis can only be maintained if the weeds were indeed growing on-site. If they were brought to the pyres together with the crops (which might have been stored for several months before the sacrifice) or inadvertently transported there in the sacrificial animals' fur (and thus could have been in a stable for months), we must dismiss it.

Conclusions and Perspectives

The spectra of charred food plant remains recovered from Alpine burnt-offering places (*Brandopferplätze*) and from circum-Alpine sacrificial sites with burnt offerings reflect an important part of daily nutrition, although the Late Bronze Age sites show an under-representation of barley. The common and constant representation of cereals (mainly represented by a cereal product) and other cultivated crops in the burnt plant remains goes

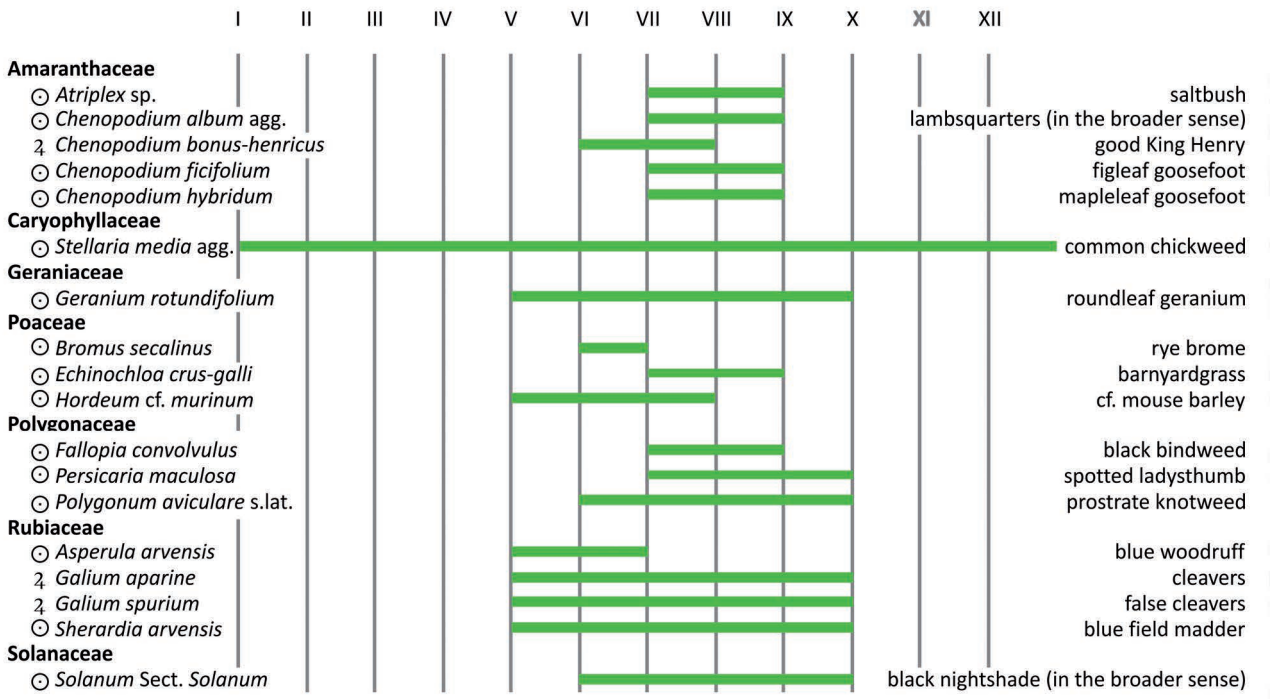


Fig. 7.52. Weeds found in the nine most recently investigated Alpine burnt-offering sites (numbers 2, 3, 4, 5, 7, 9, 10, 12 and 13 according to Fig. 7.42) with their flowering times according to Lauber and Wagner (1996). Roman numerals indicate months, symbols indicate annual (⊙) and perennial (2) plants.

well with the clear dominance of domesticated animals in the archaeozoological record, and with the obvious lack of importance of gathered fruits. All lead to the conclusion of a close link to agricultural practices, in contrast to gathering and hunting. The oldest Alpine far burnt-offering place found thus, the Pigloner Kopf (Fig. 7.41, No. 1), shows the same correlations in an opposite pattern: moderate amounts of cereals are opposed by a more numerous and more varied record of gathered fruits, and the bulk of animal bones originates from wild animals (Riedel and Tecchiati 2005). So this Copper Age site seems to display not only an older, but also a different aspect of burnt offerings.

The initial question of whether the most recently investigated Alpine sites could have been linked to certain agricultural events such as sowing and harvesting must remain unanswered for now: indeed there is no evidence to argue against annual post-harvest sacrifices in autumn, perhaps even at the equinox, whereas the evidence supporting this hypothesis is still markedly weak. Currently, multidisciplinary research on a larger scale is being carried out at one of the sites investigated, the high plateau of Mount Schlern/Sciliar in northern Italy, by the University of Mainz (Haupt 2009), and this promises to provide further insights into a complex matter.

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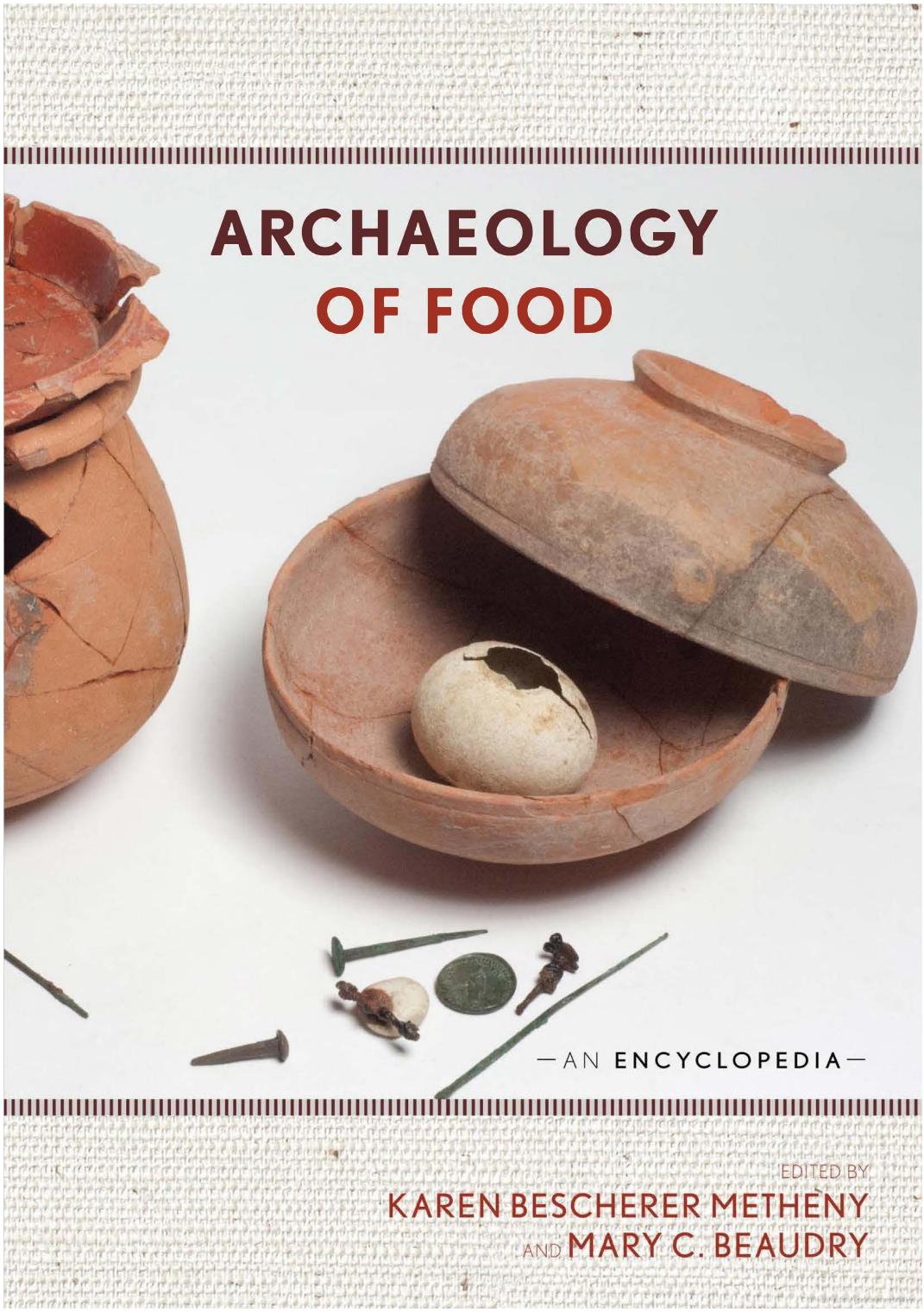
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Archaeology of Food

An Encyclopedia

Volume 1: A–K

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BREAD

Bread is a processed foodstuff made of cereal flour and water, optionally containing ingredients as diverse as salt, dairy products (milk, cream), blood, vegetable oils or oil-bearing seeds (linseed, sesame, opium poppy), fruits (date, fig), legume flour (lentil, pea), aromatic condiments (caraway, black cumin, coriander), and virtually any other substance either liquid or apt for grinding (e.g., acorns or even the inner bark of pines). The dough can be directly baked or dried, resulting in flat bread, or first fermented with yeast, sour dough, or a mixture of both, resulting in leavened bread. Fermentation causes the formation of CO_2 gas bubbles and degradation of phytic acid (inositol hexakisphosphate, an antinutritive

sequestrant binding to metal ions such as zinc, iron, calcium, and magnesium, preventing their absorption by the small intestine), thus improving availability of micronutrients. Baking creates the browned crust and various aromas, and destroys antinutritive components such as protease inhibitors (peptides or proteins inhibiting the digestive action of enzymes such as pepsin or trypsin, thereby restricting protein digestion). As with beer, the processed outcome is both more appealing in terms of taste and easier to digest and more nutritious than the raw grain.

Preparation of leavened bread is not possible with all cereals to the same extent and with the same quality. The crucial component is the elastic protein composite gluten, which traps CO_2 gas in the dough, causing it to rise. High amounts of gluten are found in all wheat species, and to a much lesser extent in oats, barley, and rye. Maize, rice, and millets are gluten-free. In rye, the low gluten content is compensated for by a high amount of pentosan/arabinoxylan (a mucilaginous compound of the sugars arabinose and xylose) serving the same purpose, but only in an acidic environment (i.e., when using sour dough). The divergent baking properties of cereals are the reason why the occurrence of leavened bread has always been more or less limited to the availability of wheat species and rye.

Depending on the operations and sequences of cereal processing, different cereal products result (table 1). Bread is one of the most time-consuming and elaborate cereal products, requiring finely ground flour, time to rise, and in some cases the construction of oven structures. One of its benefits, however, is its usefulness as a food reserve: bread can easily be dried, stored, and reused again when crushed and soaked or boiled (examples range from third-millennium BC Sumerian *bappir* or brewing bread to the rye bread preserves prepared in the Swiss Valais region up to the 20th century AD).

Archaeological and textual sources from Europe and the Near East and experimental and ethnographic approaches indicate the high workload necessary for bread preparation, supporting the hypothesis that risen bread was not an everyday foodstuff in many past cultures (e.g., Egyptian, Greek, Roman, Germanic, Celtic), but rather was restricted to festive/ritual occasions or higher social strata (e.g., the bread finds of Ancient Egyptian elite graves, such as in Qurnet Murai, or in Gallo-Roman and Viking cremation burials). Prehistoric and historic-period populations in Europe and the Near East most probably consumed their everyday cereal food in the form of porridge or as flat bread. Further research is needed, however, to test this hypothesis, in particular for prehistoric periods.

As the archaeological evidence for raised prehistoric bread has long been limited to the desiccated Ancient Egyptian bread finds known since the 18th century, it is a common misapprehension that leavened bread was invented in Ancient Egypt. In fact, European raised bread finds, although rare, are as old as the Chalcolithic (e.g., the site of Twann at Lake Biel, Switzerland, ca. 3900–3500 BC). Bread as a highly processed foodstuff (containing only finely ground plant tissues) does not preserve archaeologically if not desiccated or charred, thus limiting the overall possibility of archaeological finds.

Early bread research is inseparably connected with the Swiss autodidact Max Währen, who, in the mid-20th century, provided morphological descriptions of countless archaeological bread finds. The topic received new impetus in the 1980s with the application of microscopic analyses and scientific methods into Ancient Egyptian and European cereal

Table 1. Operational Sequences and Corresponding Terminology for Some Historical and Archaeological Cereal Products

		Sequence of Processes Involved							*References*			
		Germinating	Crushing	Grinding	Soaking	Drying	Fermenting	Cooking, Baking, Roasting	Maurizio 1916	Hansson and Isaksson 1994	Lannoy et al. 2002	Valamoti 2011
Toasted Grains								1	X			
Grain-Paste			1		2				X	X		
Porridge			1		2			3	X	X		
Precooked Dough Products	*bulgur*			4	1	3		2				X
	trachanas		5	1	2	4		3				
Bread	leavened, height exceeding 45 mm			1	2		3	4	X	X	X	
	flat bread, height not exceeding 25 mm			1	2			3	X		X	
Beer		1	3		4		5	2	X		X	

Sources: Hansson, Ann-Marie, and Sven Isaksson. 1994. Analyses of Charred Organic Remains. *Laborativ Arkeologi* 7:21–29; Lannoy, Sylvie, Philippe Marinval, Alain Buleon, et al. 2002. Études de "pains/galettes" archéologiques français. In *Pain, fours et foyers des temps passés/Bread, Ovens and Hearths of the Past*, edited by Kai Fechner and Marianne Mesnil. *Civilisations* 49:119–60. http://www.jstor.org/stable/41229645; Maurizio, Adam. 1916. *Die Getreide-Nahrung im Wandel der Zeiten*. Zürich: Orell Füssli; Valamoti, Soultana M. 2011. Ground Cereal Food Preparations from Greece: The Prehistory and Modern Survival of Traditional Mediterranean "Fast Foods." *Archaeological and Anthropological Sciences* 3(1):19–39.

and bread research (figure 9). More recently, methods such as starch granule analysis and chemical analyses of residual lipids and carbohydrates in charred material have advanced this area of study. Ethnoarchaeological as well as experimental approaches have complemented these scientific approaches (table 2).

Bread analyses can provide insights into technological and economic aspects of bread making: Which cereals or other ingredients were used, and how were they processed? Which contaminants (weeds, chaff, ergot) does it contain? Are there hints of watered-down or adulterated flour? What was the overall quality of the bread? How long did it take to prepare? Bread use also overlaps with social and cultural factors, such as status, culture, or specific religious practices. Examples can be found in the strongly

Table 2. Some Common Methods Applied in the Analysis of Ancient Bread Finds

Method	*Characters*	*Purpose*	*References (exemplary)*
Macroscopic bread morphology	general bread outline and height, handprints, impressions of baking stones	hints on bread manufacture, and possible cultural implications; evaluation of dough properties and processing (kneading, rising)	Währen (various articles) in Eiselen 2000; Samuel 2000; Lannoy et al. 2002; Heiss and Kreuz 2007; Hansson 2013; Heiss et al. 2015
Microscopic bread morphology	pore size/shape, presence of drying cracks	evaluation of dough properties and processing (water content, kneading, rising)	Samuel 2000; Heiss and Kreuz 2007; Heiss 2013; Heiss et al. 2015
X-ray	counting and measuring of grinding quern grit	implications for flour processing such as grinding/milling or the mesh sizes used in flour sieving	Währen (various articles) in Eiselen 2000; Hansson 2013
	identification of possible foreign objects (e.g., stones, metal pieces) in the bread	hints on bread manufacture (baking stones), or on possible "unusual" (e.g., ritual) purposes for the bread	
Light microscopy and SEM	identification of tissue remains	analysis of plant-based ingredients (cereal species, condiments, additives, adulterants, and contaminants)	Dickson 1987; Körber-Grohne and Piening 1980; Hansson and Isaksson 1994; Samuel 2000; Heiss and Kreuz 2007; Valamoti 2011; Heiss 2013; Heiss et al. 2015
	measuring of tissue remains	implications for flour processing such as grinding/milling or the mesh sizes used in flour sieving	
	starch granule analysis	differentiation between raw and cooked cereal products	

(*continued*)

Table 2. *Continued*

Method	*Characters*	*Purpose*	*References (exemplary)*
MS (mass spectrometry), GC (gas chromatography)	presence of certain lipids, proteins, or carbohydrates	analysis of liquid ingredients (fat, milk, oil)	Lannoy et al. 2002; McLaren and Evans 2002

Sources: Dickson, Camilla. 1987. The Identification of Cereals from Ancient Bran Fragments. *Circaea* 4(2):95–102; Eiselen, Hermann, ed. 2000. *Max Währen: Gesammelte Aufsätze zur Brot- und Gebäckkunde und -geschichte, 1940–1999*. Ulm: Museum der Brotkultur; Hansson, Ann-Marie. 2013. Hidden Stone: A Unique Bread Offering from an Early Medieval Cremation Grave at Lovö, Sweden. In *Plants and People: Choices and Diversity through Time*, edited by Alexandre Chevalier, Elena Marinova, and Leonor Peña-Chocarro, 335–42. Oxford: Oxbow; Hansson, Ann-Marie, and Sven Isaksson. 1994. Analyses of Charred Organic Remains. *Laborativ Arkeologi* 7:21–29; Heiss, Andreas G. 2013. Ceremonial Foodstuffs from Prehistoric Burnt-Offering Places in the Alpine Region. In *Plants and People: Choices and Diversity through Time*, edited by Alexandre Chevalier, Elena Marinova, and Leonor Peña-Chocarro, 343–53. Oxford: Oxbow; Heiss, Andreas G., and Angela Kreuz. 2007. Brot für die Salinenarbeiter—das Keltenbrot von Bad Nauheim aus archäobotanischer Sicht. *hessenArchäologie* 2006:70–73; Heiss, Andreas G., Nathalie Pouget, Julian Wiethold, et al. 2015. Tissue-Based Analysis of a Charred Flat Bread (galette) from a Roman Cemetery at Saint-Memmie (Dép. Marne, Champagne-Ardenne, North-Eastern France). *Journal of Archaeological Science* 55:71–82; Körber-Grohne, Udelgard, and Ulrike Piening. 1980. Microstructures of the Surfaces of Carbonized and Non-Carbonized Grains of Cereals as Observed in Scanning Electron and Light Microscopes as an Additional Aid in Determining Prehistoric Findings. *Flora* 170:189–228; Lannoy, Sylvie, Philippe Marinval, Alain Buleon, et al. 2002. Études de "pains/galettes" archéologiques français. In *Pain, fours et foyers des temps passés/Bread, Ovens and Hearths of the Past*, edited by Kai Fechner and Marianne Mesnil. *Civilisations* 49:119–60. http://www.jstor.org/stable/41229645; McLaren, Frances, and John Evans. 2002. The Chemical Identification of Ancient British Bread Flours: Encountering and Overcoming Some of the Obstacles. In *Pain, fours et foyers des temps passés/Bread, Ovens and Hearths of the Past*, edited by Kai Fechner and Marianne Mesnil. *Civilisations* 49:169–82. doi:10.4000/civilisations.1427; Procopiou, Hara, and René Treuil. 2002. *Moudre et broyer: L'interprétation fonctionnelle de l'outillage de mouture et de broyage dans la Préhistoire et l'Antiquité*. 2 vols. Paris: CTHS; Samuel, Delwen. 2000. Brewing and Baking. In *Ancient Egyptian Materials and Technology*, edited by Paul T. Nicholson and Ian Shaw, 537–76. Cambridge: Cambridge University Press; Samuel, Delwen. 2002. Bread in Archaeology. In *Pain, fours et foyers des temps passés/Bread, Ovens and Hearths of the Past*, edited by Kai Fechner and Marianne Mesnil. *Civilisations* 49:27–36. doi:10.4000/civilisations.1353; Valamoti, Soultana M. 2011. Ground Cereal Food Preparations from Greece: The Prehistory and Modern Survival of Traditional Mediterranean "Fast Foods." *Archaeological and Anthropological Sciences* 3(1):19–39.

diverging values assigned to certain crops and their products, such as barley (Greek vs. Roman culture) or oats (Romans vs. Germanic peoples). Bread and porridge played significant roles in many rites across the Mediterranean in antiquity (e.g., Greek burnt offerings to Persephone/Kore, as well as the *elaphebolia* and *liknophora* ceremonies; Roman offerings of *mola salsa* porridge or *farreum libum* spelt cake) as well as in Bronze and Iron Age burnt offerings in the Alpine region. Bread is a common grave good found in Egyptian as well as Roman and Viking burials. Such finds, and equally those of bread-shaped objects such as the beeswax-based loaf from Ipwege Bog (eighth–seventh century BC) near Oldenburg, Germany, suggest a particular symbolic value to bread throughout history and prehistory.

See also Bakeries; Biomolecular Analysis; Cereals; Ethnoarchaeology; Experimental Archaeology; Fermentation; Offerings and Grave Goods; Representational Models of Food and Food Production; Residue Analysis, Starch; Yeast

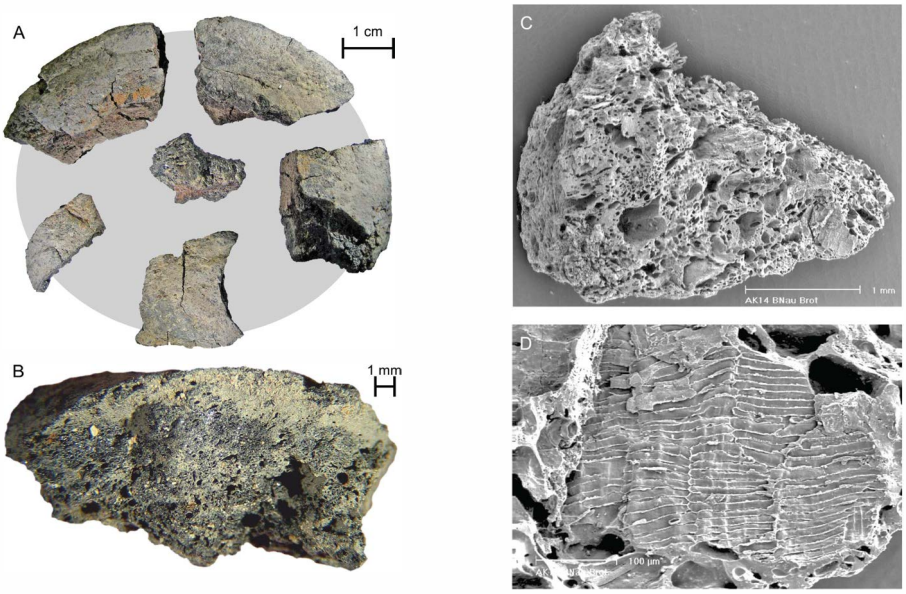


Figure 9. Late Iron Age (mid-third century BC) bread from Bad Nauheim, Hesse, Germany. (A) Total view (reconstructed diameter ~15 centimeters); (B) Detailed view, displaying denser crust (above) and crumb with gas bubbles (below); (C) SEM image showing bran fragments; (D) Bran fragment with thick-walled, regularly pitted transverse cells that are typical for wheat (*Triticum*) species. Photographs by Andreas G. Heiss.

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Tissue-based analysis of a charred flat bread (*galette*) from a Roman cemetery at Saint-Memmie (Dép. Marne, Champagne-Ardenne, north-eastern France)

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ABSTRACT

During a rescue excavation by the Institut de recherches archéologiques préventives (Inrap) at the Gallo-Roman cemetery of Saint-Memmie (Champagne-Ardenne, France) in 2006, a remarkably well-preserved charred flat bread was unearthed from a pit containing a secondary deposit of burnt objects (feature 109/110), dating to a time frame between the middle of the 1st century AD and the beginning of the Flavian period (69 AD). As a part of the archaeobotanical research on the charred plant remains from the site, the bread was analyzed with the aim to reveal the cereals used in the bread's preparation and to investigate the processes involved (grinding, sieving, leavening, baking). The results indicate that the bread is composed of finely ground flour of a mixture of barley (*Hordeum vulgare* L.) and either einkorn (*Triticum monococcum* L.) or emmer (*Triticum dicoccon* Schrank.), and apparently was prepared without leavening.
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RÉSUMÉ

En 2006, pendant la fouille d'une nécropole gallo-romaine à Saint-Memmie (Marne, Champagne-Ardenne, France) par l'Institut de recherches archéologiques préventives (Inrap), une galette carbonisée a été récupérée d'une fosse à dépôt de résidus de combustion (structure 109/110) contenant les résidus d'un bûcher funéraire. Dans le cadre des analyses archéobotaniques, une analyse de la galette a été effectuée, ayant pour but d'obtenir des informations sur sa composition et sur les procédés de sa préparation (mouture, tamisage, levage, cuisson). Les résultats montrent que la galette a été préparée à partir d'un mélange de la farine fine d'orge (*Hordeum vulgare* L.) et d'engrain (*Triticum monococcum* L.) ou d'amidonnier (*Triticum dicoccon* Schrank.), et qu'elle a apparemment été préparée sans levage.
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1. Introduction: purpose of, and state of the art in bread analysis

As nutrition science tells us, the various processes involved in the preparation of bread or porridge facilitate digestion of useful components, and help avoiding noxious substances in the cereal plant: Dehusking of hulled cereals removes the silica-rich glumes

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which are not just indigestible but also abrasive to the mucosa (Münzing, 2004). Milling breaks up the grain's starch-containing endosperm tissue improving access of the digestive juices to the cell contents (Heaton et al., 1988; Waldron et al., 2003). In leavened bread, microorganisms degrade phytic acid, which would otherwise inhibit the intake of important macro and micro elements (van Staveren and Dagnelie, 1988; Sanders, 1999). Drying, cooking or baking destroy protease inhibitors which hamper protein digestion (Liener, 1979). The latter two processes also contribute to the product's taste by Maillard reactions (Maillard, 1912; De Kimpe and Keppens, 1996) and improve starch accessibility by gelatinisation (e.g. Dreher et al., 1984; Lund and Lorenz, 1984). Bread, in addition, can serve as a food preserve storable for weeks and months given it is kept in a dry and protected place, and rehydrated (boiled) before consumption (see e.g. Staub, 1868, 9, on rye bread in the Valais, Switzerland).

These nutritional, culinary, and practical advantages make it highly likely to assume that processed cereals may have been of high importance ever since the Neolithic. The accumulating evidence from archaeological finds contributes to this hypothesis, ever increasing the available knowledge of the presence, composition, and properties of these cereal products. Archaeological evidence of cereal products is usually found in charred state. This is due to two main reasons: firstly, as cooking and baking require fire, "baking accidents" easily happen. Secondly, due to their resistance to chemical and microbial decay, charred remains in general are more likely to preserve in the soil than uncharred material (Jacomet and Kreuz, 1999).

The oldest archaeological remains of bread in Europe date back to the Neolithic Cortaillod and Horgen cultures (roughly covering a range from 4500 until 2800 BC; Währen, 1995). Various finds from later periods are documented, as from Bronze Age until medieval Northern Europe (Hjelmqvist, 1990; Hansson, 1994a,b), from Neolithic to Medieval France (Lannoy et al., 2002), from classical Graecia Magna (Ciaraldi, 1997–1998), or from Late Iron Age and Roman Germany (Währen, 1983; Heiss and Kreuz, 2007), to name just a few. From outside Europe, D. Samuel's extensive work on desiccated Egyptian bread has to be mentioned (as e.g. in Samuel, 1989, 1997). For a comprehensive overview on archaeological bread finds in general, also see Samuel (2002).

Apart from these more or less intact bread finds, a long-known biogenic archaeological material, usually subsumed as amorphous charred objects (AOV – "Amorphe Objekte Verkohlt", see Jacomet et al., 2006; OAC – "objets amorphes carbonisés", see Brombacher and Klee, 2011; Wiethold, 2011; MOC – "matière amorphe carbonisée" see Wiethold, 2013a,b; BGF – "Brot, Gebäck, Fruchtfleisch" = bread, pastry, fruit pulp, see Kreuz and Schäfer, 2006), has been increasingly well analysed during the past years. Many of these amorphous charred remains were recognised as containing cereal components, and representing fragments of either bread or gruel/porridge (e.g. Valamoti, 2002, 2011; Bouby and Marinval, 2004; Valamoti et al., 2008; Heiss, 2008b, 2010, 2012; Kohler-Schneider and Heiss, 2010; Kubiak-Martens et al., 2015; Kohler-Schneider et al., 2014). However, microscopical analysis of the remains is very time-consuming and is only rarely carried out.

The necessity for investigating archaeological food from the Roman period may seem surprising regarding the vast amount of Roman written sources. But notwithstanding the remarkable amount of literature that Roman culture has left behind, written sources on daily life – and on daily nutrition – in the provinces, here in the southern part of the province of *Gallia Belgica*, are in fact very rare, unevenly distributed, and often enough unreliable (*cf.* Kreuz, 2005). Only few sites have already revealed evidence of the complete and varied *chaîne opératoire* of funeral rites (*cf.* Poux, 2009), including the incineration of the body. Thus analysis and interpretation of food remains are still important means for elucidating the living conditions in the Roman provinces.

The analysis of food remains from ritual contexts as the funeral site of "La Trussonnerie" certainly does not allow direct conclusions on daily nutritional habits. But still the results may contribute significantly to the knowledge of locally available food plants, the attitudes towards food, and ways of cereal processing itself. With this goal in mind, the flat bread from feature 109/110, together with the carpological remains (Wiethold, 2010a), was analysed.

1.1. The site

The Gallo-Roman cemetery of Saint-Memmie "La Trussonnerie" (Dép. Marne, Champagne-Ardennes, France) is situated in the centre of the flat and fertile plain of the central Champagne, in a neighbouring community of the town of Châlons-en-Champagne, about 3 km southeast of today's city centre. Châlons-en-Champagne was the Roman *Durocatelaunos*, belonging formerly to the *civitas* of the Celtic tribe *Catalauni*, historically known as clients of the well known *Remi*, who settled further north (Clause and Ravaux, 1983).

After initial prospection trenches on the parcel situated in the corner of Avenue du Maréchal Juin and Rue des Pâtures in Saint-Memmie ("La Trussonnerie", *cf.* Fiabane, 2005; location: 48° 56′ 49″ N 4°23′ 0″ E), in 2006 an extensive excavation campaign by the French National Institute of Preventive Archaeology (Inrap, *Institut national de recherches archéologiques préventives*) under direction of Nathalie Pouget partially unearthed a Gallo-Roman funerary site dating to the second half of the 1st century AD (Fig. 1). Among the excavated structures were 24 wells, 22 postholes, 10 inhumation graves, eight *ustrina* (funerary pyres), 27 incineration graves, and 26 pits inside which mainly burnt pottery linked to the funerary rites had been deposited (Fig. 2a).

Among the latter group is feature 109/110 (Fig. 2a, b), a deposit distributed on a rectangular surface of 1.1 m × 0.65 m. The concentration of burnt remains therein, reaching a maximum thickness of 0.14 m, contained six nails possibly deriving from boarding constructions or wooden caskets, charred organic remains (see below), and five almost complete ceramic vessels (two jugs, two cooking or food storage pots, and a small Gallo-Belgian sauce dish), all deposited at the same depth, and all with traces of burning. Belonging most probably to a primary deposit of a funerary pyre, the uncovered ceramics seemed to be only part of the initial deposit, as most of the pottery assemblages that were found on intact funerary pyres at the site also included plates and dishes. No particular arrangement of the pottery in the pit was observed, and the vessels (which were archaeologically complete) are thought to have been thrown in without much care – except for the small dish they were already fragmented when deposited. The pottery assemblage does not give any hints on a possibly elevated social status of the deceased but, in comparison to other local domestic contexts, allowed dating to the middle of the 1st century AD and to the beginning of the Flavian period. No human or animal bone remains were found in feature 109/110. However, as overall bone quantities were very low in comparable pits containing secondary deposits, their lack cannot be regarded as a unique trait and may simply be due to decomposition. At any rate, the find situation implies that only selected objects were taken from the funerary pyre and then discarded in the pit. This secondary deposit could correspond to the final cleaning of a funerary pyre, but its real meaning still remains uncertain (refuse or ritual pit?).

From a regional point of view the graves of *Gallia Belgica* are already well known. However, this is not yet true for the funerary pyres (*bûcher funéraire*) and for the other features containing incinerated remains of the burial, which up to now have only rarely



Fig. 1. Location of the excavation site. Drawing: P. Huart (Inrap).

been documented *in situ*. Therefore, after the initial evaluation of the site (Delor-Ahü et al., 2008; Pouget et al., 2010), detailed studies on the *chaîne opératoire* of the funerary practices in the region are essential. The analysis of organic remains, such as charcoal and charred fruits/seeds or food preparations, contributes to this understanding of Roman and Gallo-Roman funerary practices and burial rites (Preiss, 2003; Preiss et al. 2005; Wiethold, 1996, 2000, 2009, 2010a, 2010b, 2011, 2013a, 2013b; Wiethold, Preiss, 2009; see also Bouby, Marinval, 2004).

1.2. Preliminary archaeobotanical analyses

The overall archaeobotanical analyses of the Gallo-Roman cemetery at "La Trussonnerie" resulted in rather few finds of charred cereal grains (120 caryopses), indicating the presence of naked wheat (*Triticum aestivum/durum/turgidum*), hulled barley (*Hordeum vulgare* ssp. *vulgare*) and emmer wheat (*Triticum dicoccon*), while the material from the features investigated so far (Features 59, 91, 108, 109/110, 138, 208, 272, 273, 287, 292, 298, and 303) revealed numerous fragments of AOV/OAC/MOC/BGF, i. e. pastry or bread fragments (Heiss, 2008a; Wiethold, 2010a; Wiethold and Pouget, forthcoming). Together with the flat bread from St.109/110, it seems that it was those remains of processed cereals which dominated the plant-based grave goods in this cemetery, followed by large amounts of lentil seeds (*Lens culinaris*), some seeds of pea (*Pisum sativum*) and broad bean (*Vicia faba*) and few other cultivated plants like plums (*Prunus domestica* ssp. *domestica*) and probably fennel (cf. *Foeniculum vulgare*). The only two imported cultivated plants are olive (*Olea europaea* cf. ssp. *europaea*), documented by fragments of about four kernels, and two fragments of stone pine (*Pinus pinea*) kernels. These remains point to the fact that the local population had at least some access to luxurious food and imports of the Mediterranean (Wiethold, 2010a).

2. Material and methods

During excavation, the large chunks of charred organic material from Feature 109/110 were originally identified as charcoal remains. Only during post-excavation work on charcoal and archaeobotanical remains (Wiethold, 2010a,b) these objects were identified as AOV/OAC/MOC/BGF (see introduction), as were numerous other fragments recovered across the whole cemetery, 1250 of them in total (Table 1).

Among the 27 fragments from feature 109/110, one particularly large semi-circular object measuring ca. 10 cm in length was identified as bread, or flat bread, and given to the first author for detailed analysis. The fragments found together with the loaf may originally have been part of it, but from the fracture faces alone only three of them could be associated to it. Due to time restrictions, only the main part of the (flat) bread was subjected to detailed analysis, while the remaining fragments from the "La Trussonnerie" find assemblage were briefly evaluated and verified as AOV/OAC/MOC/BGF under the light microscope.

The loaf had most probably been charred intentionally on the pyre by burning it together with the deceased, and later deposited in the pit, a practice well known from several other archaeobotanical studies in the *Gallia Belgica* (Heiss et al., 2008a,b; Pouget et al. 2008; Wiethold and Preiss, 2009; Wiethold, 2000, 2010b, 2013a,b).

Several methodological approaches can be followed in the analysis of archaeological cereal products, ranging from morphological and microanatomical tissue analysis to the application of chemical methods (cf. Tableau 2 in Lannoy et al., 2002). We chose to follow two of these approaches, which seemed most promising to us due to the greater amount of information yielded by previous studies (e.g. Heiss, 2008b, 2010, 2012): a basic morphological description of the object and an extensive SEM study of tissue remains in the dough.

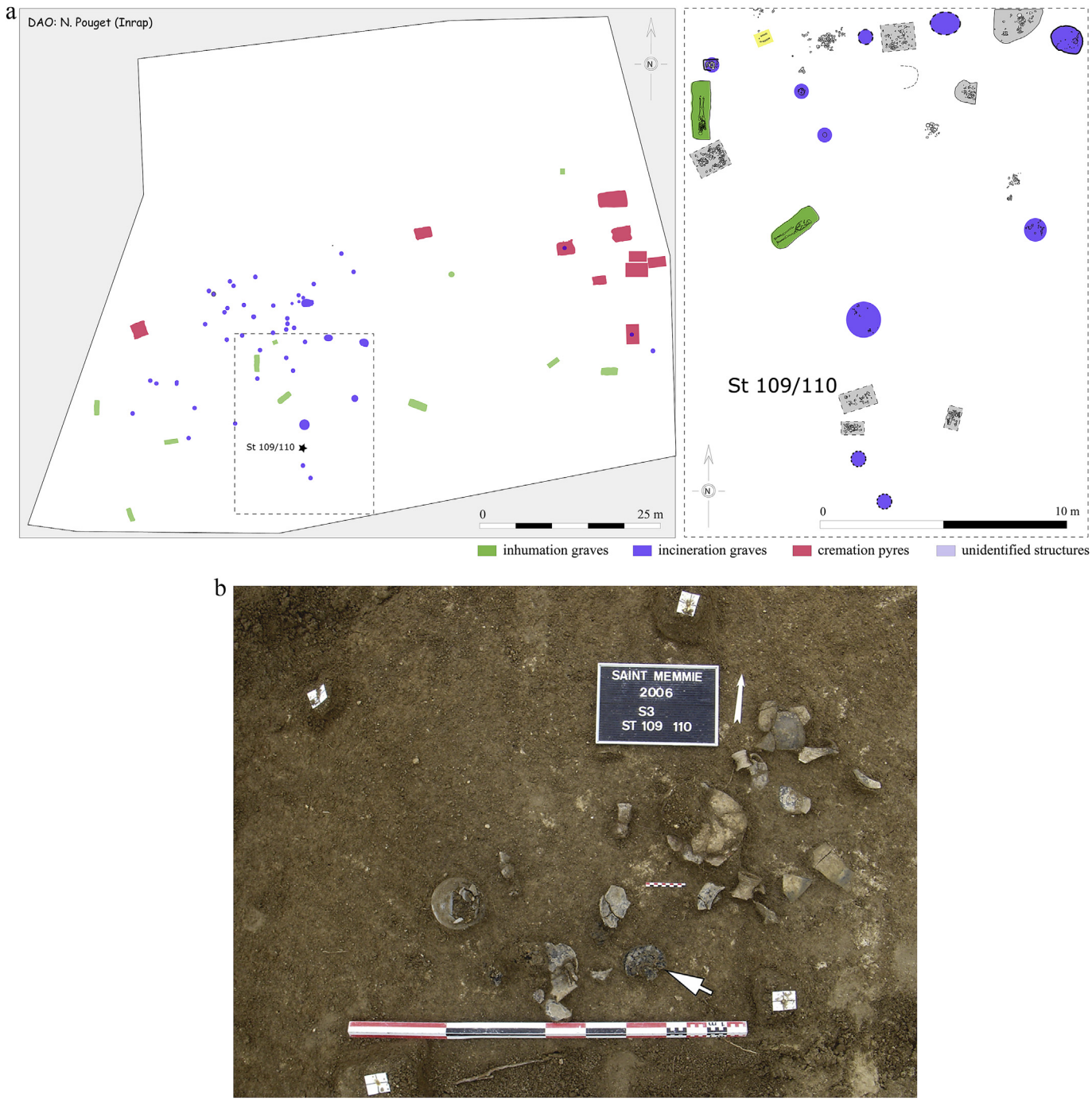


Fig. 2. a) Excavation overview and position of the investigated pit 109/110. b) Position of the charred flat bread within feature 109/110 (white arrow). Drawing and image: N. Pouget.

Morphological analysis of the material was carried out using a Reichert stereo binocular microscope at magnifications of 7× to 45×. Images were created using a Canon Powershot A540 camera and an ocular adapter hand-tailored by R. Mehnert (Weil der Stadt, Germany).

Detailed analysis of tissue remains was carried out on a loose part of the loaf, measuring 4.2 × 2.7 × 1.3 cm, weighing 5.07 g (approximately 9% of the object), with an observable surface of ca. 11 cm^2. Adhering soil sediments were first mechanically removed with fine-pointed tweezers and a brush, and the remaining (mainly calcareous) material dissolved by immersing the fragment in a 5% aqueous solution of lactic acid for 12 h. After leaching in distilled water for another 12 h, the fragment was then gently dried in a drying oven at 40 °C for 72 h. One smaller piece weighing ca. 0.16 g (surface: ca. 4 cm^2) was then separated from this fragment and prepared for SEM-based analysis of tissue remains. After application of a ca. 1 μm gold–palladium sputter coating, analysis was carried out at a Philips XL20 scanning electron microscope. Combining prior methodologies and identification characters developed in archaeobotany (Körber-Grohne and Piening, 1980; Dickson, 1987) and food analysis (Gassner et al., 1989; Hahn and Michaelsen, 1996), and also using comparative cereal material

Table 1
Total amount of amorphous charred objects (AOV/OAC/MOC/BGF), most likely representing cereal products, recovered from the cemetery of "La Trussonnerie".

Feature/structure	59	91	108	109/110	138	208	272	273	287	292	298	303	Total
Number of fragments	363	696	4	27	34	6	52	8	1	3	48	8	1250
Total weight[a] [g]	–	76.50	–	71.40	–	5.00	–	–	5.20	–	19.20	12.40	189.70
Mean fragment weight[a] [g]	–	0.11	–	2.64	–	0.83	–	–	5.20	–	0.40	1.55	0.15
Smallest fragment, max. diameter[b] [mm]	2	2	2	7	2	12	2	2	39	2	4	9	2
Largest fragment, max. diameter [mm]	20	43	20	99	17	35	17	17	39	16	36	45	99

[a] Where recorded.
[b] AOV/OAC/MOC/BGF were only retrieved from sieve fractions measuring 2 mm and larger.

experimentally charred by the first author as well as by A. Schmidl (unpubl.), the following grain tissues were investigated (as tested in e.g. Heiss, 2008b, 2010, 2012):

- **Bran** (pericarp and seed coat, Fig. 3): fragments of pericarp tissues are very often observed in cereal preparations. The **transverse cells** are specific for several cereal genera, while longitudinal and tube cells are only of limited diagnostic value (Körber-Grohne and Piening, 1980; Dickson, 1987; Gassner et al. 1989; Hahn and Michaelsen, 1996). The thick-walled **aleurone cells**, bearing the grain's main protein content, usually preserve well. A multi-cellular aleurone cell layer separates *Hordeum* (barley) from the other cereal taxa abundant in prehistoric and Roman Europe, which are all single-layered (Hahn and Michaelsen, 1996).
- **Chaff**: the crop cleaning and preparation steps preceding baking usually make it very unlikely to find naked cereals' paleas/lemma or awns in bread dough. Their overall presence is thus a strong indicator of hulled cereals (hulled barley *Hordeum vulgare*, einkorn *Triticum monococcum*, emmer *T. dicoccon*, or spelt *T. spelta*). The epidermis structures of paleas and lemmas are genus specific (Hahn and Michaelsen, 1996), while awn morphology allows species identification.
- **Starch granules** do not easily preserve in charred material, and their diagnostic value for separating cereal taxa is limited. But if present, they can at any rate give important hints on the processes involved in cereal preparation (Samuel, 1996; Babot, 2006; Valamoti et al., 2008). Due to the destructive nature of some of the methods suggested for microscopic analysis (bleaching in sodium hypochlorite as in Lannoy et al., 2002; or in hydrogen peroxide as in Hansson and Isaksson, 1994), none of these specific procedures were applied to the current material in order to conserve possibly preserved starch granules.

Taking into account the current state of archaeobotanical research in the Roman provinces of northeastern Gaul (e.g. Jacomet and Vandorpe, 2011; Lepetz and Matterne, 2003, 2001; Wiethold, 2000), the following cereals had to be regarded as possible ingredients of the bread material from "La Trussonnerie": naked and hulled barley (*Hordeum vulgare* var. *nudum* and var. *vulgare*), hulled wheats (*T. monococcum*, *T. dicoccon*, *Triticum spelta*), naked wheats (*T. aestivum* s. l., *Triticum durum*), rye (*Secale cereale*), oats (*Avena sativa*), and millets (*Panicum miliaceum* and *Setaria italica*). Furthermore, also various pulses/legumes and condiments had to be considered as possible further ingredients (Hansson, 1994a,b; Thüry and Walter, 2001).

Measurements were carried out using the software ImageJ (Rasband, 1997–2007) on calibrated high-resolution images. In contrast to tissue fragments observed in SEM micrographs, each manually measured, bubble diameters in light micrographs were established with ImageJ's "Analyze Particles" function on a thresholded version of the image, only retaining the "Major" (i.e. larger) measurement of each bubble. Measurement range (100 μm–5000 μm) was chosen in order to exclude the cracks, at the same time avoiding pseudo accuracy due to pixel resolution limitations.

3. Results

3.1. Morphology

The maximum dimensions (length × width × height) of the charred object from feature 109/110 were measured as 9.9 × 5.8 × 2.3 cm, the total weight recorded as 56.5 g. The find represents ca. 40% of an originally roughly circular bread loaf with an estimated former diameter of ca. 13 cm (Fig. 4), which is quite comparable to other bread finds from Gallo-Roman times (Währen, 1983; Lannoy et al. 2002; Heiss and Kreuz, 2007). Its surfaces were smooth, undecorated and only slightly irregular, the upper face with noticeably elevated margins. Several fissures were observed on both faces, but no indentations of fingers.

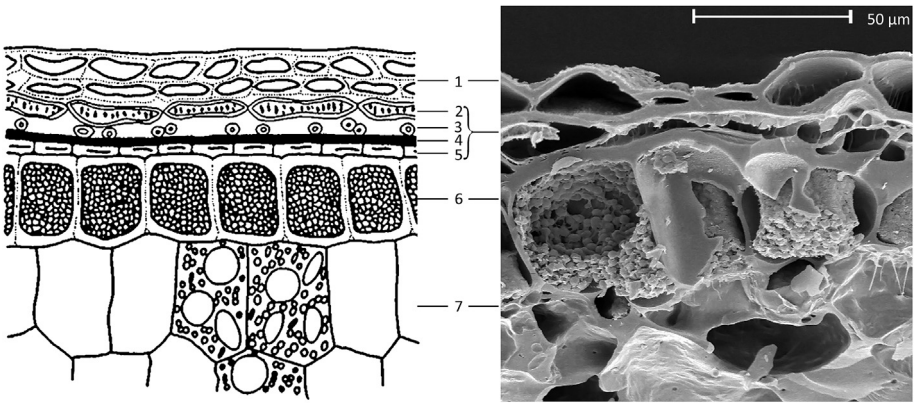


Fig. 3. Composition of the seed/fruit layers of a cereal grain, illustrated for bread wheat (*Triticum aestivum* L.). Left: schematic drawing (Hahn and Michaelsen, 1996; modified), Right: Scanning Electron Microscope image of an experimentally charred grain (image: A. G. Heiss). 1 … longitudinal cells, 2 … transversal cells, 3 … tubular cells, 4 … testa (seed coat), 5 … nucellus remains, 6 … aleurone layer, 7 … endosperm. Layers 2–6 are collapsed in the experimentally charred specimen.

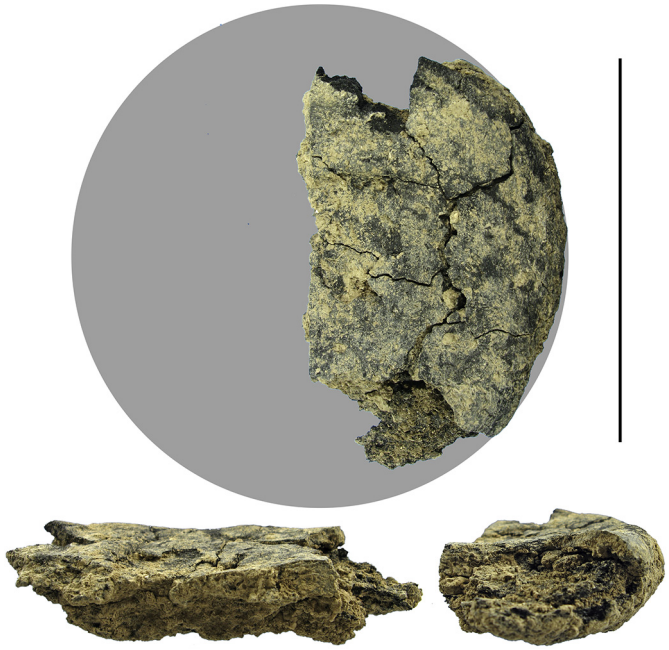


Fig. 4. The charred flat bread from feature 109/110 in three views. The grey disk indicates the putative former shape of the bread. Scale bar = 10 cm. Image: A. G. Heiss.



Fig. 5. Profile of the flat bread. The fissures and the very small gas bubbles are visible, as well as the lack of a clear crust/crumb differentiation. Scale bar = 1 cm. Image: A. G. Heiss.

Under low magnification, mainly two types of fissures were differentiated (Figs. 4 and 5): superficially visible ones, with sharp and linear margins and intersecting the gas bubbles, and making the impression of "true" cracks. Appearance of internal fissures (Fig. 5) seemed quite different, as their margins looked highly irregularly shaped, and often intergraded with larger gas bubbles in the bread, pervading the whole loaf fragment. A clear differentiation of a dense crust towards a less dense crumb could not be made: in fact, the observed gas bubbles were roughly evenly distributed (Fig. 5). Automatic measurement of all bubbles visible in a flat fractured surface (measure: 20.27 × 17.568 mm) resulted in a wide pore diameter range of 124–2648 μm. Nevertheless, the vast majority of bubbles was limited to very low diameters (median: 238 μm, midspread 152 μm; see also the histogram in Fig. 6).

3.2. Components

Already under the binocular, minute plant remains had been visible as small shiny areas in the charred bread material. However, identification of tissue types and – in some cases – species was only possible via the SEM micrographs: Two awn fragments were found in the sample prepared for SEM: their epidermis was completely missing. Identification was however still possible to a certain extent, as their cross-section was characteristic of einkorn (*T. monococcum*) or emmer (*T. dicoccon*), which both develop ovate-triangular awns. Other hulled cereals could clearly be ruled out due to their strongly different awn morphologies. Aside from these few finds of einkorn/emmer awn fragments, bran fragments were much more abundant, the most frequent finds being patches of aleurone tissue. Fragments of both single-layered (as in wheat, oats, millets, and rye: Fig. 8) and multi-layered (only in barley: Fig. 9) aleurone tissue fragments were found. In addition, numerous fragments of transverse cell layers were discovered. Their regular alignment together with the total lack of thickened cell walls or conspicuous pitting characterised their origin from barley (*Hordeum vulgare*) bran. In addition, all observed glume fragments could be assigned to *Hordeum* as well: the typical feature in the glume epidermis, the "twin" arrangement of two short cells with a larger crescent-shaped cell encircling a smaller circular one, was found throughout the material. All observed tissue fragments were measured, resulting in a total of 55 values ranging from 100 to ca. 660 μm, with mean values around 200–300 μm (Table 2) (Figs. 8–10).

Starch granules were not observed in the material, endosperm cells seem to have completely lost their structure, and molten into an amorphous mass (see the "vitreous" structures in Figs. 7–9), rendering morphological analyses of starchy components impossible.

4. Discussion

4.1. Components of the Saint-Memmie bread

Barley (*Hordeum vulgare*) and either einkorn (*T. monococcum*) or emmer wheat (*T. dicoccon*) were identified as ingredients of the flat bread, a combination not uncommon in archaeological cereal preparations as found in the Aegean (see Sarpaki, 2001; Valamoti, 2002). The proportions of these cereals can of course not be quantified due to the small surface observed in the analyses, but the dominance of barley remains at least suggests that it may have been a major component of the *galette*. Additional cereals are possible as ingredients, but could not be found. The same is true for legume/pulse flour (cf. Sarpaki, 2001; Valamoti et al., 2011) or condiments, the evidence of which is altogether missing. Barley (*Hordeum vulgare*) and emmer (*Triticum* cf. *dicoccon*), albeit only as singular grains, were also found during archaeobotanical analysis of other structures in the cemetery of Saint-Memmie "La Trussonnerie" (Wiethold and Pouget, forthcoming) and in the adjacent Roman cemetery near the rue du Pont Alips (Matterne, 2007).

A large-scale study of 60 Gallo-Roman sites in northern France revealed dominance of naked wheats throughout the Roman period (1st – 5th c. CE), while hulled wheat (*T. monococcum*, *T. dicoccon*, and *T. spelta*) cultivation seemed more prevalent in the coastal areas of today's Picardie (Lepetz and Matterne, 2003). However, as even the site closest to Saint-Memmie, the site of Cerny-en-Laonnois, Dép. Aisne, investigated in the study is about 70 km away, conclusions need to be taken very cautiously. And indeed, the analysis of grave goods at the Roman cemetery at Faulquemont-Créhange-Pontpierre, Dép. Moselle, resulted in a

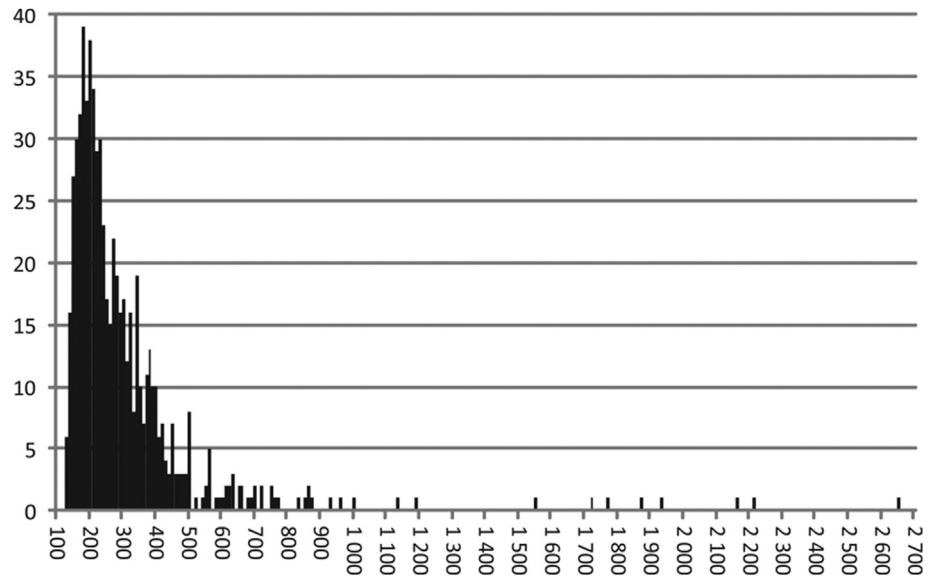


Fig. 6. Histogram of measured bubble/pore sizes in a flat fractured surface measuring 20.27 × 17.568 mm. Vertical axis: number of counts (N = 657), horizontal axis: maximum diameter [μm] per bubble.

cereal spectrum nearly exclusively dominated by barley and hulled wheats (Preiss et al., 2005). Besides, also from this site, numerous fragments of bread/pastry were recovered from there.

4.2. Production processes of the bread

Whereas flat bread ("*galette*" *sensu* Lannoy et al., 2002; see also Table 3) can be rather massive in its structure and need not have been subject to rising/fermentation, bread in the narrower sense ("pain" *sensu* Lannoy et al., 2002) is characterised by its increased volume and a clear differentiation of crust and crumb. The latter two structures derive from the process of rising, when microorganisms – yeast fungi, lactic acid and acetic acid bacteria, in varying combinations – digest the sugars contained in the dough producing carbon dioxide. Depending both on elasticity and stickiness of the dough, the CO_2 either oozes out or is retained as gas bubbles. These bubbles cause the bread to rise and to form a more or less fluffy crumb (Gan et al., 1995). During baking, the outer dough layers dry out and harden (forming the crust), trapping the remaining gas and also most of the moisture inside. In archaeological material, crumb and crust are usually still discernible.

The mentioned elasticity and stickiness of the dough strongly depend on its ingredients. Besides starch itself, mainly the gluten content of the used cereals plays a major role in gas retention. Wheat species contain the highest amounts of gluten proteins among cultivated cereals, and they are considered the best choice for producing raised bread. Although often differently stated (cf. Moritz, 1979a; Lannoy et al., 2002), bread wheat (*T. aestivum*) and spelt (*T. spelta*) are not the only wheat taxa suitable for baking. In fact, also the hulled wheats einkorn (*T. monococcum*) and emmer (*T. dicoccon*) basically contain sufficient amounts of gluten proteins to produce raised bread. Indeed, the baking properties within the genus *Triticum* seem to be more cultivar-specific than species specific (Borghi et al., 1996; Abdel-Aal et al., 1997; Kreuz and Baatz, 2003). Of the Old World cereals, rye is also suitable for baking, even though it usually results in denser bread. Its baking properties are commonly attributed to the high pentosan contents of rye, although their gas retaining properties are regarded as questionable (Gan et al., 1995). Barley and oats are generally regarded as cereals unsuitable for baking, due to their low gluten contents. However, if they are admixed to rye or wheat, raised bread can still be produced. Also, adding pulse flour e.g. to barley bread is documented as a leavening agent by historical and ethnographical sources (see Valamoti et al., 2011).

The measured fragment sizes of bran and chaff tissues indicate that the flour of the St. Memmie bread must have been sieved after

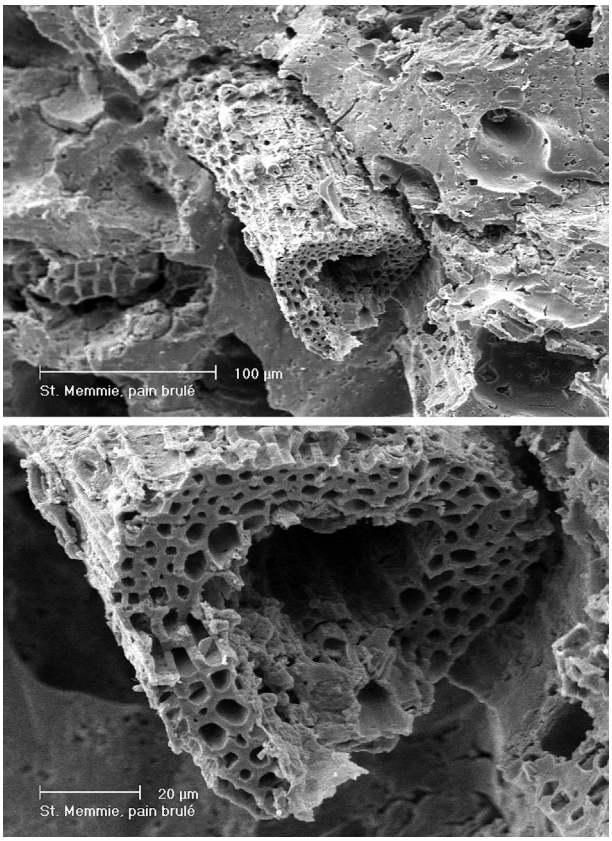


Fig. 7. Awn fragment of *Triticum monococcum*/*T. dicoccon* from the flat bread. Image: A. G. Heiss.

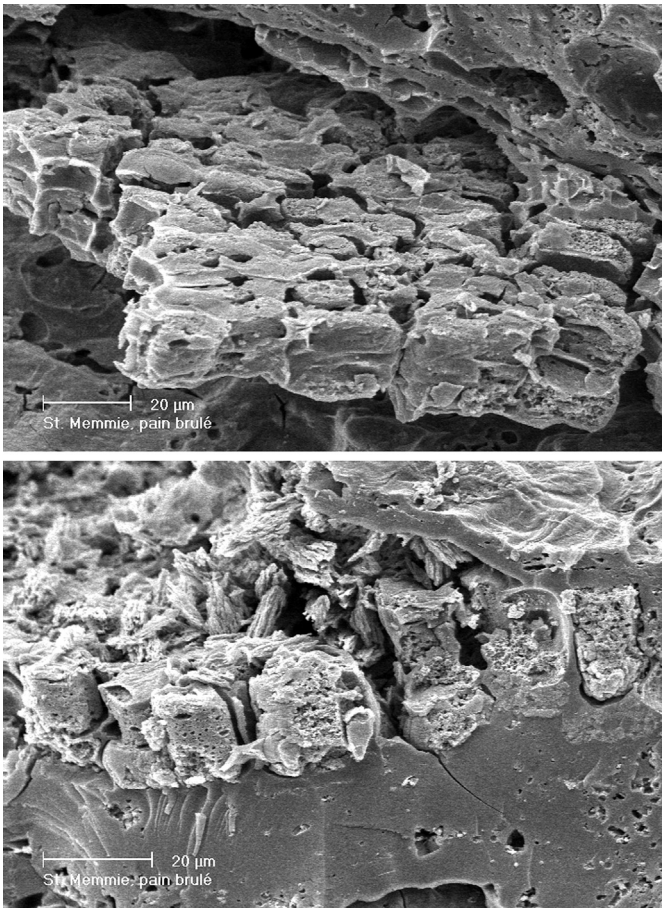


Fig. 8. Unicellular aleurone layer fragments from the flat bread, as found in all Old World cereal taxa apart from *Hordeum*. Image: A. G. Heiss.

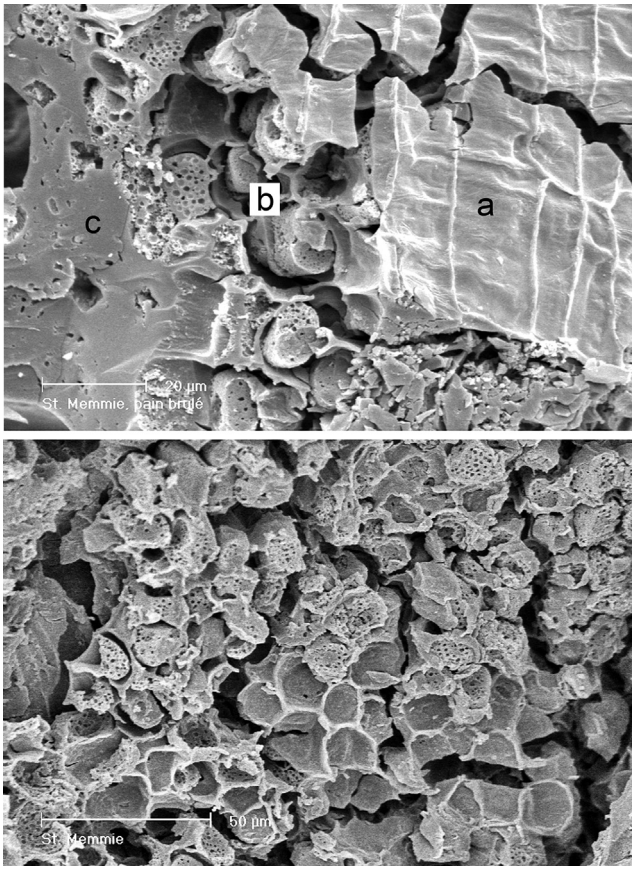


Fig. 9. Remains of barley (*Hordeum vulgare*) grains from the flat bread. Top: section through pericarp. a) longitudinal cells, b) multicellular aleurone layer, c) remains of starchy endosperm. Bottom: multicellular aleurone layer. Image: A. G. Heiss.

milling, or at least been subjected to repeated milling: no tissue parts were visible to the naked eye, and only four of the measured fragments (7% of total measurements) exceeded a maximum length of 500 µm while the major part of fragments ranged between 200 and 300 µm. According to Dickson (1990), without sieving, large bran fragments of 5 mm length and above would have to be expected in the respective cereal product.

The two different types of fissures observed in the bread from Saint-Memmie seem to derive from two separate processes: The rather linear cracks strongly resemble the structures frequently found in charred plant material of various origins (seeds, wood), and are commonly caused by rapid vapour expansion and irregular material shrinkage during charring (e.g. Slocum et al., 1978; Jacomet and Kreuz, 1999; Braadbaart, 2008). Also, post-depositional factors (such as mechanical force or freezing–thawing cycles in the soil) cannot be excluded as causes for these cracks. The second fissure type, however, with irregular shape and showing gradual transitions with gas bubbles, seem to form an integral part of the bread structure. In modern bread, such ruptures in the dough are usually connected with too low moisture content or a too short soaking/rising period (MacRitchie, 1976). The observed overall very low pore (bubble) sizes point to lacking or insufficient rising, or the production of semi-raised bread (Procopiou, 2003). Also low moisture content of the dough – as pointed out above – can be the reason for reduced gas retention and weakly raised bread (MacRitchie, 1976; Gan et al., 1995).

According to the criteria applied by Lannoy et al. (2002; see also Table 3), the low maximum bread height, the overall small pore size and the lacking differentiation between crust and crumb clearly classify the object as an unleavened *galette* (flat bread). The lack of leavening traces may derive either from very quick production (i.e. without giving it time to rise), a very high proportion of barley flour, originally low water content, or a combination of the three.

Also, the question must be addressed whether the dough was baked/cooked at all prior to charring, or whether the *galette* rather represents an offering of raw dough. According to the experiments carried out by Valamoti et al. (2008), the observed fusion of endosperm tissues and the starch granules contained therein into a vitreous mass can be caused either by gelatinisation of the starch prior to charring (and therefore soaking and baking), or by charring at high temperatures of at least 350 °C. As temperature distribution patterns are highly variable in funerary pyres (from 250 °C in the pyre's periphery to roughly 1000 °C in its center; see Mäder, 2002, 123–146; Becker et al., 2005), the *galette* may have been exposed to

Table 2
Measurements of the cereal components observed in the charred bread under SEM, in a sample surface area of ca. 4 cm^2.

Tissue type	N	Max. Dimensions [µm]		
		Min.	Max.	Mean
Transverse cell layer	9	138	368	234
Aleurone layer	18	100	663	235
Tube cell layer	1	198	198	198
Palea/lemma fragments	25	106	615	300
Awn fragments	2	174	236	206
Total	55	100	663	262

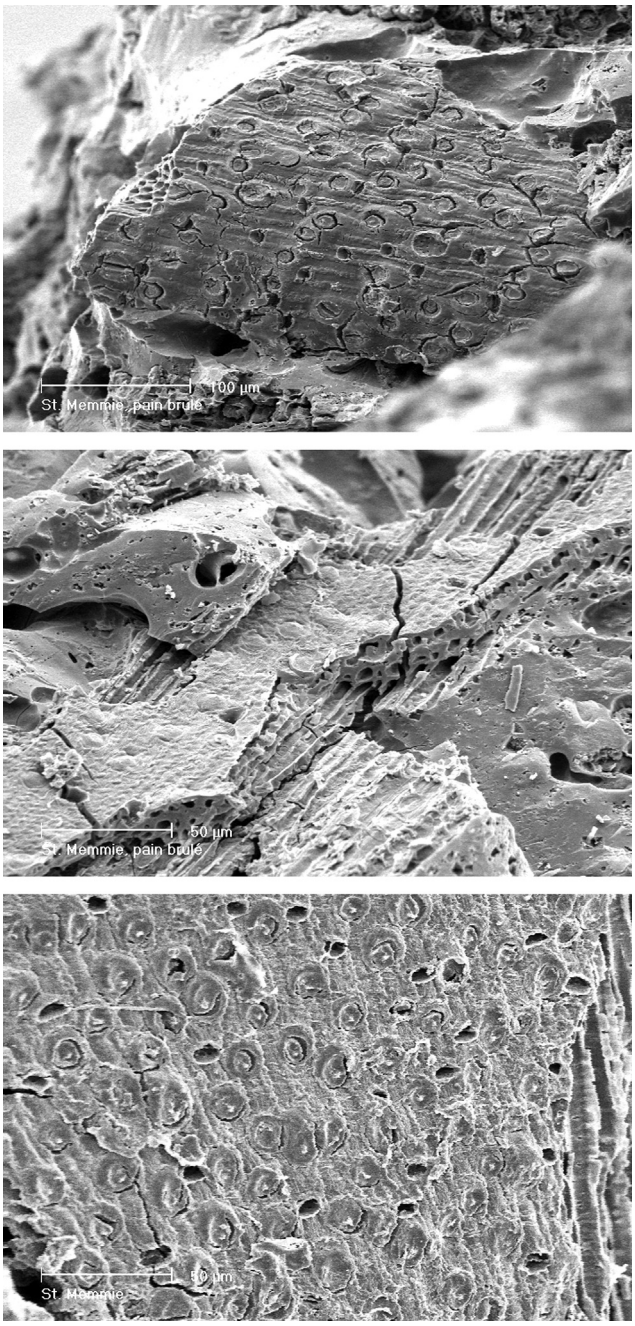


Fig. 10. Barley (*Hordeum vulgare*) glume fragments from the flat bread.

either low or high charring temperatures, leaving the question on prior baking/cooking unanswered.

4.3. Comparison to other Roman bread finds

Food is a very common part of grave goods during Roman times, and various foodstuffs are now well-documented for many Gallo-Roman funerary sites in France, Germany and Switzerland (e.g. Petrucci-Bavaud and Jacomet, 1997; Kreuz, 2000; Lannoy et al., 2002; Bouby and Marinval, 2004; Preiss et al., 2005; Wiethold and Preiss, 2009). As the object analysed in the current study is charred and was found together with other objects displaying traces of fire, it is safe to assume that it must have been placed on a funerary pyre prior to deposition in the pit (Kreuz, 2000; Bouby and Marinval, 2004), and can thus be regarded as a grave good or offering placed on the pyre during the funerary rites. The detailed nature of these rites such as specific deposition procedures cannot, however, be assessed yet for the cemetery of St. Memmie, but feature 109/110 is at least very well comparable to other structures of this kind found in the cemetery. They are currently described as "pits containing deposits of remains of burnt grave goods and offerings" (*fosses à depot de reliquats de mobilier brûlé*).

But albeit the above-mentioned general good state of knowledge on food as grave goods, finds of more or less intact bread loaves are rather rare, and data on bread composition even more so. Hence, only four comparable objects from the Roman period (more or less intact loaves from funerary contexts in western central Europe) could be found in the literature (Table 4).

However, comparison is only possible on a very rough basis, as species identification was not possible in three of the compared finds, and seems highly unreliable in the fourth one, the loaf from Saffig (Kr. Mayen-Koblenz, Rhineland-Pfalz, Germany): the author observed barley glume fragments, but deduced from the shape of the bread's pores alone that also wheat must have been an ingredient (Währen, 1983). Then, obviously mistaking charring for carbonisation, he then concluded that the Saffig bread, although charred, had been placed in the grave "unharmed by the cremation fire". But leaving these issues aside (for an overview on Währen's work and methodologies, see the compilation in Eiselen, 2000), the five listed objects are more or less similar in size, overall shape, their funerary context, their (supposed) flour quality, and (where available) supposed ingredients. All loaves are quite simple products, mostly lacking decorations, and are either unleavened or only slightly risen. Still, quite some work must have been invested in sieving the flour in at least three of them: the loaves either produced no cereal tissue remains at all or only a few ones (Vaissyère, Valladas), or they were of minute fragment sizes (Saint-Memmie).

Comparison to other bread or pastry fragments (the AOV/OAC/MOC/BGF mentioned above) from the Roman period currently is not possible, although they have been discovered in numerous graveyards (Blänkle et al., 1995; Petrucci-Bavaud and Jacomet, 1997; Kreuz, 2000; Bouby and Marinval, 2004; Preiss et al., 2005), as none of these remains have been analysed by SEM up to now, leaving them as a promising perspective for future research, as is true for the bread finds discovered in the Auvergne (Cabanis and Marinval, 2014). Also, the only recently discovered Roman bread loaves from the urban site of St. Symphorien, Reims (Marne, Champagne-Ardenne, France), will be a valuable source of comparative data as soon as their analysis is accomplished (Zech-Matterne, pers. comm.).

4.4. Comparison to written evidence

The Roman civilisation having been a literate one, linking archaeological finds with written documents seems like an evident way to go. But as concrete recipes are hardly ever given, or are often ambiguous, the task is rather difficult. At least it is easy to assume what the St Memmie *galette* was certainly not: it does most probably not correspond to the idealistic recipes passed down for rised bread made from white flour, such as *libum* cakes, *mustaceus*, or *panis candidus* (e.g. Cato the Elder, *De agri cultura*, 74–85, 121; see Goetz, 1922). And although "lesser" bread qualities are often mentioned in Roman literature, such as the *panis acerosus*/*panis sordidus* (Seneca, Ep. Mor. 18.7, Gummere, 1979; Ep. Mor. 90.12, 99.3, Gummere, 1925; Plautus, Asinaria, 1.2, Leo, 1912), we cannot judge whether their denomination derived from a possible lack of rising, the admixture of lesser cereals such as barley (such as in Pliny, Nat. Hist. 18.14, Bostock, 1855), a higher bran content, or from bad overall quality. Direct comparison of the analysed bread from

Table 3
Analysis of archaeological finds of cereal preparations has resulted in various attempts to establish terminologies and criteria for the different products. These are summarised here basing on the processes involved.

		Sequence of processes involved							References			
		Germinating	Crushing	Grinding	Soaking	Drying	Fermenting	Cooking, baking, Roasting	Maurizio (1916)	Hansson (1994a)	Lannoy et al. (2002)	Valamoti (2011)
Toasted grains								1	X			
Grain-paste			1		2				X	X		
Porridge			1		2			3	X	X		
Pre-cooked dough products	***bulgur***			4	1	3		2				X
	trachanas		5	1	2	4		3				
Bread	**Leavened bread** height exceeding 45 mm			1	2		3	4	X	X	X	
	Flat bread height not exceeding 25 mm			1	2			3	X		X	
Beer		1	3		4		5	2	X		X	

Table 4
Comparative overview of the analysis results of five more or less intact bread loaves recovered from Roman funerary contexts. Measures are given for the whole objects, if incompletely preserved.

Site	Period (centuries CE)	Length × width × height [mm]	Classification	Ingredients	Reference
St. Memmie, "La Trussonnerie" (Champagne-Ardenne)	2nd half of 1st c.	ca. 130 × ca. 130 × 23	Flat bread	Barley, einkorn/emmer	Current study
Vayssière, L' Hospitalet-du-Larzac (Aveyron)	1st–2nd c.	ca. 90 × ca. 90 × 10–15	Flat bread	Unknown (no observable vegetable tissues)	Lannoy et al. (2002).
Valladas, Saint-Paul-Trois-Châteaux (Drôme)	1st–2nd c.	91 × 83 × 45	Bread	Unknown (vegetable tissues unidentifiable)	Bel (1986), cited in Lannoy et al. (2002).
Calade à Cabasse (Var)	1st–2nd c.	130 × 110 x ?	Bread	Unknown	Bérard (1961), cited in Lannoy et al. (2002).
Saffig, Mayen (Rheinland-Pfalz)	2nd c.	105 × 80–95 × 14.2–17.5	Flat bread	Barley, wheat (?)	Währen (1983).

the votive pit in St. Memmie to written sources is therefore not possible at the current time.

Pertaining to barley, in contrast to Greek antiquity (e.g. Brumfield, 1997; Hansson and Heiss, 2014), Roman authors attribute quite low esteem to this cereal (summarised e.g. in Moritz, 1979b; in Junkelmann, 2006; also see e.g. Aulus Gellius, *Noctes Atticae*, Lib. IV, 1: Rolfe, 1927). Therefore, a "barley mixed bread" as the one from Saint-Memmie might easily be interpreted as a sign of simple rural life, or even of poverty. However, numerous archaeological finds do document that barley seems to have been a very regular meal in many parts of the Roman provinces (Knörzer, 1970; Preiss et al., 2005; Kreuz, 2005, 2006; Jacomet et al., 2006; Wiethold et al. 2008; Britton and Huntley, 2010). Furthermore, the presence of barley does not at all imply an absence of luxury goods such as olives, dates, and grapes in the same archaeological contexts (Petrucci-Bavaud and Jacomet, 1997; Bouby and Marinval, 2004; Preiss et al., 2005; Wiethold and Preiss, 2009, Wiethold, 2000). It may thus very well be that the above-mentioned Roman authors writing of barley as a lesser or unacceptable food, or of barley bread as mere animal fodder (such as Varro, Lib. 2 – Keil and Goetz, 1929), were not writing about the daily rural life in the provinces, but rather of their idealised ideas on it.

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Grütze, Bulgur, Mehl und Griess*

Bericht zum internationalen Arbeitstreffen «Archäobotanische Identifikation von Getreidespeisen» (Basel, 2. und 3. Juli 2015) mit einem praktischen Leitfaden zu ihrer integrativen Untersuchung

Keywords: Archäobotanik, Mahlen, Gebrauchsspuren-Analyse, Schweiz, Methodik. – Archéobotanique, mouture, tracéologie, Suisse, méthodes. – Archeobotanica, macinatura, analisi delle tracce d'uso, Svizzera, metodologia. – Archaeobotany, grinding, use-wear analysis, Switzerland, methodology.

Zusammenfassung

Getreide gehören weltweit zu den wichtigsten Grundnahrungsmitteln. Trotzdem ist wenig darüber bekannt, in welcher Form sie in vorgeschichtlicher Zeit konsumiert wurden. Das am IPNA durchgeführte Arbeitstreffen brachte deshalb internationale Experten und Expertinnen von botanischen Makroresten (Samen, Früchte usw.), Mikroresten (Stärkekörner und Phytolithen) sowie Gebrauchsspuren und Morphotechnologie von Mahlwerkzeugen zusammen. Der vorliegende Artikel präsentiert eine Zusammenfassung der gehaltenen Vorträge und gibt einen Überblick über den Forschungsstand sowie über die grosse Vielfalt an Getreidespeisen, welche aus ethnografischen Quellen bekannt ist. Er will vermitteln, wie solche Reste sachgerecht geborgen werden und wo die Forschungslücken am grössten sind. In Zukunft sollten einheitliche Kriterien für die Untersuchung von Getreideprodukten erarbeitet und eine Datenbank der Inhalte und der strukturellen Eigenschaften solcher Reste aufgebaut werden.

Résumé

Partout dans le monde, les céréales sont essentielles parmi les aliments de base. Malgré cette suprématie, on ne sait pratiquement rien de la forme sous laquelle elles étaient consommées aux époques pré- et protohistoriques. La réunion de travail organisée à l'IPNA a rassemblé des experts internationaux spécialisés dans le domaine des macrorestes botaniques (graines, fruits, etc.), des microrestes (particules d'amidon et phytolithes), de même que dans celui de la tracéologie et de la morphotechnologie des outils utilisés pour la mouture. Le présent article propose un résumé des communications et fournit une vue d'ensemble de l'état de la recherche, de même que de la grande diversité des aliments à base de céréales connus de sources ethnographiques. Les auteurs ont pour objectifs d'informer sur le maniement correct de ces vestiges et de déceler les principales lacunes dont souffre la recherche. Il est prévu de mettre sur pied des critères homogènes applicables à l'étude des produits à base de céréale, et de créer une banque de données rassemblant les contenus et les propriétés structurales de tels vestiges.

Riassunto

A livello mondiale i cereali sono tra gli alimenti di base di maggiore importanza. Ciononostante poco è risaputo sui modi di consumazione nella preistoria. L'incontro di lavoro tenutosi all'IPNA ha riunito esperti ed esperte internazionali di macroresti botanici (semi, frutti, ecc.), di microresti (granuli di amidi, fitoliti), dell'analisi di tracce d'uso e di tecno-morfologia degli attrezzi per la macinatura. L'articolo riassume le presentazioni tenute, fornisce un quadro dello stato della ricerca e sintetizza la grande varietà di alimenti a base di ereali conosciuti da fonti etnografiche. Inoltre, vuole informare su come recuperare questi resti in modo appropriato e sulle attuali lacune della ricerca. Per il futuro si auspica l'elaborazione di criteri unanimi per l'analisi dei resti cereali e la creazione di una banca dati per i contenuti e le caratteristiche strutturali di questi resti.

Summary

Although cereals are among the most important staple foods worldwide, we know little about how they were prepared for consumption in prehistoric times. That is why international experts on macrobotanical remains (seeds, fruits etc.), microfossils (starch granules and phytoliths), and on use-wear analysis and morphotechnology of grinding devices were invited to attend a workshop at the IPAS. The article published here summarises the lectures held at the workshop and provides an overview on the state of research and on the great variety of cereal-based foods known from ethnographical sources. It aims to show how such remains should be recovered and what the biggest gaps in the research are. Standard criteria must be established for the study of cereal products and a database must be created which records the contents and structural characteristics of such remains.

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1. Einleitung

Getreide sind auf der ganzen Welt die wichtigsten Grundnahrungsmittel. Sie tragen sehr viel zum täglichen Wohlergehen von Menschen unter ganz unterschiedlichen sozialen, wirtschaftlichen und ökologischen Bedingungen bei. Heutzutage traditionelle Getreide sind in Europa und Nordamerika Weizen, in Teilen Amerikas und Afrikas Mais, in Afrika und Indien verschiedene Hirsen, in Ost- und Südasien sowie Afrika Reis. Getreide waren weltweit unter den ältesten domestizierten Pflanzen. Ihre Kultivierung begann im ausgehenden Paläolithikum, im Neolithikum waren sie domestiziert. Die Entwicklung erfolgte unabhängig voneinander in verschiedenen Gebieten der Erde, so z.B. im ostmediterranen Raum (Weizen und Gerste) und in Ostasien (China; Reis und Hirse) vor mehr als 10 000 Jahren (Zohary et al. 2012). Da Getreide immer zu den Grundnahrungsmitteln gehörte, war die frühere Landwirtschaft – und insbesondere der Getreideanbau – in den letzten 50 Jahren Gegenstand zahlreicher archäobotanischer Untersuchungen und Publikationen. Dank umfangreicher archäobotanischer, experimenteller und ethnografischer Forschung an nicht mechanisiertem Ackerbau (besonders der Ernte- und Getreideverarbeitungsverfahren) beginnen wir prähistorische landwirtschaftliche Systeme zu verstehen (van Gijn et al. 2014). Wir können uns ein Bild davon machen, wie der Umgang mit Getreidenahrung z.B. neolithische Sozialsysteme (Arbeitsorganisation, Geschlechterrollen, soziale Verbindungen und Tauschsysteme) beeinflusste. Dennoch ist unser Wissen über prähistorische Agrargesellschaften lückenhaft, da wir nur wenig darüber wissen, wie die angebauten Getreidearten zubereitet und konsumiert wurden. Die Erforschung der Zubereitung und der Zusammensetzung prähistorischer Getreidespeisen ist deshalb entscheidend für das Verständnis von prähistorischen Ackerbau treibenden Gesellschaften. Es ist bisher nämlich kaum bekannt, welche Verbindungen zwischen einerseits Nahrungsmitteln und Gruppenidentität, andererseits der Zubereitung von Speisen und der Sozialstruktur bestanden; auch über den Nährstoffgehalt der prähistorischen Ernährungsweise wissen wir wenig resp. wir können nur Mutmassungen anstellen (Fuller/Rowlands 2009; Haaland 2007; Lyons/D'Andrea 2003; Kreuz 2012).

Nachweise zu Zubereitungsarten von Getreidespeisen in prähistorischer Zeit sind aus verschiedenen Gründen spärlich: die Überlieferung von Pflanzenresten hängt stark von den Erhaltungsbedingungen – subfossile (unverkohlte) Reste erhalten sich nur unter anoxischen Bedingungen – oder vom Verkohlungsgrad ab (nur unter gewissen Hitzebedingungen und Sauerstoffarmut zerfallen die Reste nicht zu Asche). Ausserdem waren viele Geräte, welche für die Nahrungszubereitung benutzt wurden, aus Holz oder anderen vergänglichen Materialien hergestellt und unterlagen denselben Problemen der Erhaltung. Hingegen wurde die Zerkleinerung bis hin zum Mahlen von Getreide oft mit dauerhaften Geräten wie Mahlsteinen und steinernen Mörsern durchgeführt (für einen Überblick der ethnografischen Nachweise s. Alonso 2014). An ihnen können verschiedenartige Studien durchgeführt werden: Bestimmung des Artefakttyps, Beschreibung seiner Charateristika, Gebrauchsspuren-Analyse (welche dazu dient, die Art der Benutzung der betreffenden Steinartefakte zu ermitteln) sowie die Untersuchung botanischer Mikroreste, welche in den Poren der Steingeräte erhalten geblieben sind. Durch letzteres erhält man Informationen zu den verarbeiteten Pflanzen und der Art des Vorgangs (Entspelzung oder Vermahlung zu Produkten unterschiedlicher Qualität und Korngrösse). Die Identifizierung verschiedener, durch Vermahlung gewonnener Produkte (wie zerbrochene Körner, Bulgur, etc.; s. Kap. 2) ist nur durch die Beobachtung solcher transformierter Reste selbst möglich. Diese wurden allerdings nach den beschriebenen Verarbeitungsschritten nur versehentlich verkohlt, entweder beim Kochen oder – selten – während ihrer Lagerung.

Die Erforschung der Zubereitung von Getreidespeisen ist indessen nicht systematisiert. Die Kriterien, welche von unterschiedlichen Forschern dafür benutzt werden, sind uneinheitlich. Auch ist es nicht üblich, bei der Untersuchung ur- und frühgeschichtlicher Getreidespeisen verschiedene Disziplinen zu integrieren. Um die Situation zu verbessern, wurde deshalb ein durch den SNF und die AVUBA (Assistierendenvereinigung der Universität Basel) gefördertes internationales Arbeitstreffen (International Exploratory Workshop, IZ32Z0_161668) am IPNA (Integrative prähistorische und naturwissenschaftliche Archäologie, Dept. Umweltwissenschaften, Universität Basel) durchgeführt. Ziel war es, Spezialisten und Spezialistinnen unterschiedlicher Disziplinen zusammenzubringen und Möglichkeiten für eine in Zukunft systematische Vorgehensweise zu diskutieren. Im Folgenden geben wir zuerst einen Überblick über die unterschiedlichen Getreidespeisen, welche ethnografisch nachweisbar und im archäologischen Befund möglicherweise identifizierbar sind (Kap. 2). Es folgt sodann ein Überblick über den Forschungsstand – was Getreidespeisen betrifft – in der Schweiz (Kap. 3). Die wichtigsten Ergebnisse des Workshops sind in Kap. 4 vorgestellt. Schliesslich (Kap. 5) präsentieren wir Beprobungsrichtlinien für die Feldarbeit, welche eine integrative Studie von Getreidespeisen ermöglichen sollen.

2. Nicht nur Mehl ...

Beim Stichwort «Nahrungsmittel aus Getreide» fallen einem meist nur eine relativ begrenzte Anzahl Gerichte ein, vor allem dann, wenn man an prähistorische Epochen wie Neolithikum und Bronzezeit denkt. Dasselbe Bild gewinnt man beim Blättern in Kochbüchern, welche «prähistorische» Rezepte enthalten (z.B. Bauer et al. 2003; Werner 2004; Werner/Dummer 2010) – eigentlich erstaunlich, da allein schon die Vielzahl an Produkten, welche mit Hilfe eines Mahlsteines gewonnen werden können (Mehl, Griess, Grütze), gross ist und andeutet, welch grosses Potenzial Getreide als kulinarisches Grundelement besitzt. Jedes Getreide

hat seinen eigenen Geschmack und jeweils spezielle Eigenschaften. Wir zählen im Folgenden einige von ihnen auf und erläutern ihre Zubereitung (Taf. 1; eine Liste aller Produkte, die aus der Ethnografie bekannt sind, wäre zu ausführlich).

- *Grüne, d.h. unreife Körner (Grünkern oder Dinkel, arab. frikke):* die Pflanze, normalerweise Saatweizen, wird tief am Halm, also bodennah abgeschnitten, solange sie noch grün ist. Sie wird über dem Feuer geröstet, und die angerösteten Körner werden als Snack gegessen (Al Azm 2009; Hillman 1984; Miedaner/Longin 2012).
- *Geröstete Körner:* entspelzte Körner von Nacktweizen oder Gerste werden in einer Pfanne mit unterschiedlichen Gewürzen (*Pistacia terebinthus, Pistacia atlantica*, etc.) sowie mit anderen Samen (z.B. Kichererbsen, Linsen, Hanfsamen, Fenchel) geröstet. Verkohlte Körner werden entsorgt (Hillman 1985). Aus den gerösteten (Saatweizen-)Körnern stellt man ein Mehl her, welches mit Joghurt oder Wasser vermischt ein gut haltbares Brot ergibt (Hillman 1985).
- *Körner-Bruch:* erhält man als Nebenerzeugnis beim Mahlen; wird roh mit Olivenöl als Häppchen gegessen (Alonso et al. 2014).
- *Bulgur:* Körner von Emmer, Einkorn oder Hartweizen werden zuerst kurz gekocht, dann in der Sonne getrocknet. Die Kleie wird durch Stampfen entfernt, das Korn wird zerbrochen und mit mehreren Siebgrössen in unterschiedliche Bulgur-Typen getrennt (Hillman 1984; Valamoti 2011).
- *Kornpaste/Brei/Grütze:* Körner oder Graupen oder Bulgur (Emmer, Saat-Weizen) werden gekocht und mit Milch oder Eiern vermischt (Hillman, 1984, 1985). Dies war in der Vergangenheit eine traditionelle Mahlzeit vieler Bauern. Grütze lässt sich auch für die Zubereitung von Suppe verwenden (Alonso et al. 2014).
- *Trachanas:* entspelzte Körner werden in saurer Milch gekocht oder darin eingelegt, danach zu Klumpen geformt und in der Sonne getrocknet. Die Klumpen können später auch zu kleineren Partikeln gerieben werden.
- *Mehl:* Körner werden vermahlen und mehrmals gesiebt, bis ein feinkörniges Produkt vorliegt. Saatweizen ergibt eine gute Qualität Mehl (elastisch), welches zur Herstellung von gesäuertem Brot verwendet wird; Mehl von anderen Getreiden ist zum selben Zweck geeignet, aber auch für anderes, z.B. für Getränke (Alonso et al. 2014).
- *Griess:* kantige, gereinigte Teilstückchen (Mehl von mittlerer Feinheit) aus Körnern von Hartweizen dienen zur Herstellung von ungesäuertem Brot oder Couscous. Gerste lässt sich auf ähnliche Weise verarbeiten (Alonso et al. 2014).
- *Brot:* aus Mehl, wird normalerweise mit Hilfe von Triebmitteln (Hefe oder Sauerteig, gesäuertes Brot) oder ohne (ungesäuertes Brot, z.B. Fladenbrot) bei 200°–300°C gebacken.
- *Knödel:* gedämpfter Teig aus jeder Getreideart.

	Mahlen	Einweichen	Trocknen	Mörsern/Zerkleinern	Sieben	Kochen, Backen, Rösten	Saatweizen	Hartweizen	Gerste	Emmer	Einkorn	Dinkel	Roggen	Hirse	Mais	Mohrenhirse	Reis
Grünkern (frikke)	•		•	•		1											
Geröstete Körner	•					1											
Zerkleinerte Körner	•			•	•	•											
Teig/Brei/Grütze		2		1		3											
Bulgur	4		2	3	5	1											
Trachanas	1	2	4	5		3											
Mehl	2	•		1	3	•											
Griess	2			1	3	•											
Brot	2	4		1	3	5											
Knödel	2	3		1		4											

Taf. 1. Wichtige Getreidespeisen, in ihre Herstellung einbezogene Aktivitäten und deren potentielle Reihenfolge sowie die wichtigsten Getreide, aus denen Getreidespeisen hergestellt wurden. Leicht verändert nach Heiss 2015.

Um Einblick in die Essgewohnheiten und den Gesundheitszustand einer prähistorischen Bevölkerung zu erhalten, ist es unerlässlich, die Art und Zusammensetzung der Speisen, vor allem der Getreide enthaltenden Gerichte, zu untersuchen (Ellis et al. 2004; Wollstonecroft et al. 2008). Die Aufnahme von Nährstoffen wird durch die Essgewohnheiten einer Gruppe gesteuert, also wie oft und wie viel gegessen wurde und wie die Nahrung zusammengesetzt war. Die Form, in der ein Produkt gegessen wurde, hat einen wichtigen Einfluss auf die Menge und die Qualität der aufgenommenen Nährstoffe (Wills et al. 1998). Dies liegt daran, dass Art und Grad der Verarbeitung einen grossen Einfluss darauf hat, welche Mengen Nährstoffe der menschliche Körper durch die Verdauung aufzunehmen und zu verstoffwechseln vermag (Ellis et al. 2004). Getreide ist reich an Stärke; deren Verdaulichkeit hängt von der Zubereitung ab, insbesondere vom Erhitzungsgrad und von der zugegebenen Wassermenge sowie von der Partikelgrösse der Nahrungsmittelmatrix und schliesslich dem Grad der Gelatinisierung der Stärke (Vincent/Lillford 1991). Lebensmittelverarbeitung kann negative sowie positive Auswirkungen auf die menschliche Gesundheit haben. Nahrungsmittel aus Getreide haben einen unterschiedlichen Glykämischen Index (GI). Der GI ist ein Mass für die Wirkung von Nahrungsmitteln auf den Körper gemäss der von ihnen ausgelösten Erhöhung des Blutzuckerspiegels (Ellis et al., 1996). Verschiedene Studien haben gezeigt, dass eine Ernährungsweise, in welcher Nahrungsmittel mit hohen GI-Werten eine grosse Rolle spielen, Diabetes, Fettleibigkeit und Herzerkrankungen auslösen können. Zwar beeinflussen viele Faktoren der Ernährung den Blutzuckerspiegel, doch ist die Lebensmittelverarbeitung (z.B. das Vermahlen von Getreide) ein Hauptfaktor. Brot aus Weizen hat z.B. einen hohen, ganze gekochte Körner einen tiefen GI-Wert (FAB 2004).

3. Forschungsstand

Von den verschiedenen Disziplinen, welche zur Erforschung von Getreidespeisen etwas beitragen können, sind vor allem die Untersuchung botanischer Makro- und Mikroreste, die Morphotechnologie und die Gebrauchsspurenanalyse grosser steinerner Artefakte wichtig. Der Stand der Forschung auf diesen Gebieten ist in der Schweiz sehr unterschiedlich; wir fassen im Folgenden die Ergebnisse einiger wichtiger bisher veröffentlichter Arbeiten zusammen.

Die Untersuchung der prähistorischen Landwirtschaft hat eine lange Tradition in der Schweiz. Sie gehört diesbezüglich zu den weltweit am besten untersuchten Regionen. Grund dafür ist vor allem die Tatsache, dass die Existenz von Seeufersiedlungen mit ausserordentlich gut erhaltenen pflanzlichen Makroresten unsere Gegend zu einer privilegierten Umgebung für die Studie von Getreideanbau und -verzehr vom Neolithikum bis zur Bronzezeit macht (z. B. Brombacher/Jacomet 1997; Jacomet 2014; Jacomet et al. 1989). Auch Produkte aus Getreide, insbesondere Brot, kennt man aus archäologischen Fundstellen in der Schweiz. Berühmt ist insbesondere die Seeufersiedlung Twann BE, wo das älteste bekannte Brot gefunden wurde (dendrodatiert um 3550 v.Chr.; Währen 1989). Nur selten haben sich Forscher und Forscherinnen hingegen mit weniger offensichtlichen Speiseresten befasst: Mithilfe licht- und rasterelektronenmikroskopischer Methoden hat man versucht, den prähistorischen Getreidespeisen auf die Spur zu kommen. Basierend auf den Arbeiten zur Bestimmung von Getreidekleie (Dickson 1987; Körber-Grohne/Piening 1980) seien die Analysen von schwedischem Brot und Brei aus der Wikingerzeit (z.B. Hansson 2002) sowie Bemühungen für eine generelle Klassifizierung und Systematisierung von Brotresten aus Frankreich (Lannoy et al. 2002) erwähnt. Aus Mitteleuropa sind reichlich Reste von brot- oder breiähnlichen Produkten bekannt, etwa aus Hornstaad-Hörnle I am Bodensee (Maier 2001, 59–62) und aus mehreren alpinen Fundstellen mit vermutetem kultischem Hintergrund (Heiss 2014).

Experimentelle Untersuchungen zur Identifizierung anderer Getreidespeisen wie z.B. Bulgur, welche nicht aus Mehl bestanden, wurden von Valamoti (2002) initiiert. Die Autorin etablierte eine Methode zur Erkennung schon vor der Verkohlung zerkleinerter Getreidekörner. Dies ermöglichte eine Bestimmung solcher Fragmente in Mitteleuropa, etwa aus der Seeufersiedlung Torwiesen II am Federsee (Herbig 2006). Eine solche Fragmentierung kann allerdings auch durch andere Aktivitäten als die Produktion von Bulgur entstehen (s. z.B. Alonso et al. 2013; Antolín 2012; 2013), weshalb Herbig für die in Torwiesen II gefundenen Reste die Möglichkeit ausschloss, dass sie Bestandteile einer Speise mit Getreideschrot waren.

Was botanische Mikroreste wie Phytolithen (Abb. 1) und Stärkekörner betrifft, ist der Forschungsstand in Mitteleuropa bisher sehr tief, besonders im Zusammenhang mit Mahlwerkzeugen. Pionierarbeit, bei der Krusten in Kochtöpfen (Abb. 1) untersucht wurden, haben Duplaix-Rata (1995; 1997) und Martínez Straumann (2004) geleistet. Vergleichsweise mehr Studien wurden in anderen Regionen durchgeführt, speziell in Australien und Amerika (z.B. Piperno et al. 2009), vor allem da in diesen Gebieten Makroreste oft schlecht oder nicht erhalten sind. Ausserdem gibt es recht zahlreiche chemische Analysen von Rückständen aus dem Inneren von Gefässen, die wir hier aber nicht näher behandeln (z.B. Michel/McGovern 1992). Solche und ähnliche Analysen sollten vermehrt Teil der alltäglichen archäologischen Arbeit und der experimentellen Projekte werden.

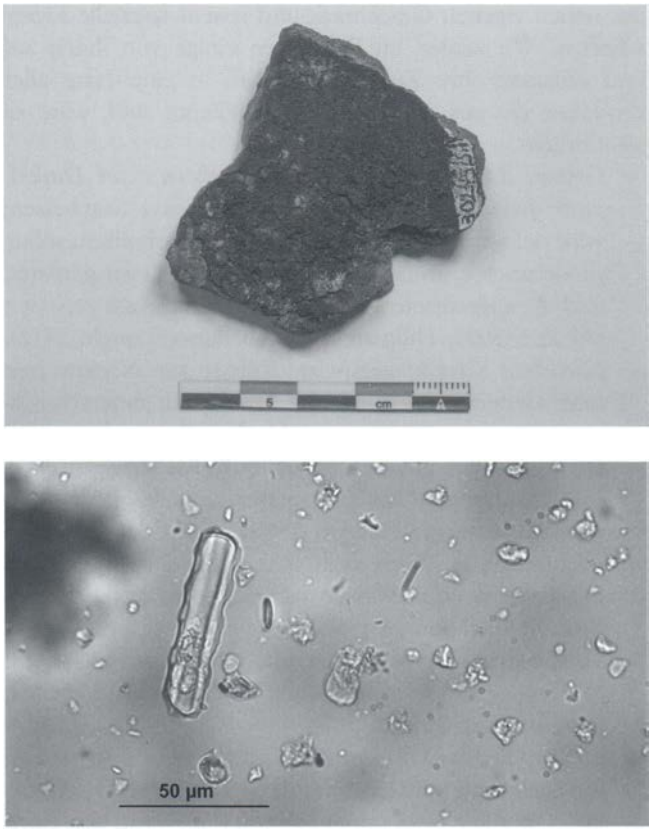


Abb. 1. Oben Krusten in Kochtöpfen, U. 30245, Jungsteinzeit, Çatalhöyük (Türkei); unten trapezförmiger, ausgebuchteter Phytolith eines Grases der Gruppe Rispengräser (Pooidae) aus neolithischen Schichten der Höhle Cova de Can Sadurní (Katalonien, Spanien). Foto L. González-Carretero (oben); J.J. García-Granero (unten).

Auch Studien von Mahlwerkzeugen haben in der Schweiz eine lange Tradition. Stellvertretend erwähnt seien Untersuchungen an neolithischen Steinartefakten aus Concise VD genannt (Burri 2010) sowie Pionier-Studien an solchen Geräten aus den bronzezeitlichen Siedlungen Hauterive-Champréveyres NE und Cortaillod-Est NE (Leuvrey 1999; Ribaux 1986) bis hin zur Untersuchung römischer Steinbrüche (Anderson et al. 2002; 2003). In einigen Regionen Europas – aber nicht in der Schweiz – hat die Analyse von Gebrauchsspuren an Mahlwerkzeugen eine relativ lange Tradition, vor allem in Frankreich, Spanien und Griechenland. Ziel dieser Forschung ist eine Bestimmung der Funktion der jeweiligen Geräte. Damit ist es möglich, prähistorische Aufgabenteilung, Rohstoffverwendung und örtliche Verteilung von Aktivitätszonen in archäologischen Fundstellen zu rekonstruieren, idealerweise in enger Zusammenarbeit mit archäobotanischen Untersuchungen.

4. Beiträge am Basler Arbeitstreffen

Die Beiträge waren vielfältig. Einige Präsentationen konzentrierten sich auf die Geräte, welche benutzt wurden, um Getreidekörner in andere Produkte umzuwandeln (z.B. Mahlsteine), während andere sich mit den Rückständen des in Speisen umgewandelten Getreides befassten oder mit den sozialen Auswirkungen der Arbeiten im Zusammenhang mit der Vor- und Zubereitung von Getreideprodukten. So wurde der gesamte Prozess der Getreideverarbeitung vom Rohprodukt bis zur fertigen Speise abgedeckt.

Um den Mahlprozess zu rekonstruieren, ist es notwendig, einerseits die Art und Morphologie der Geräte zu bestimmen und letztere zu klassifizieren, andererseits Gebrauchsspuren-Analysen an ihrer aktiven Oberfläche durchzuführen. Ethnografische Untersuchungen in Mali (C. Hamon, CNRS) belegten, dass in einer Kulturgruppe Grösse und Form der Mahlgeräte dem Stadium der Verarbeitung und dem erwünschten Produkt entsprechen (Hamon/Le Gall 2013). Experimentelle Arbeit, kombiniert mit Gebrauchsspurenanalyse, bildete die Basis für die Bestimmung einer Verwendung von Mikrokonglomerat-Mahlsteinen aus der grossen neolithischen Siedlung Kleistos im Nordwesten Griechenlands für das Mahlen von Einkorn (D. Chondrou, Aristoteles-Universität Thessaloniki). Die integrierte Erforschung von Steinbrüchen und Siedlungen auf den Kanarischen Inseln (Y. Naranjo, Universität Las Palmas de Gran Canaria) erlaubte eine Bewertung der Investition an Arbeit für die Produktion von Mahlsteinen vor der spanischen Eroberung.

Einen Überblick über die ethnografische Erforschung der Getreidemahlverfahren stellte Natàlia Alonso vor (Universität Lleida). Der Mahlprozess unterschiedlicher Getreide wiederspiegelt sich in einer sehr komplexen *chaine opératoire*, aus der eine unerwartet grosse Anzahl von Produkten und Nebenprodukten resultiert.

Andere Vorträge widmeten sich vor allem den verarbeiteten Getreideprodukten. Archäologische Funde von Getreidekörnern, welche vor ihrer Verkohlung zerkleinert worden waren, dürfen als Nachweis einer Entspelzung oder einer Produktion von Bulgur-ähnlichen Speisen gelten (F. Antolín, Universität Basel). Ethnografische Studien aus Griechenland zu diesem Thema wurden ebenfalls präsentiert (S. Valamoti, Aristoteles-Universität Thessaloniki), zusammen mit den frühesten Nachweisen der Bulgur-Produktion in der Region und Hinweisen zur Diversität der Getreidespeisen, welche aus zerkleinerten Körnern hergestellt worden waren. Andere Nahrungsmittel aus Getreide, basierend auf der Verwendung von Mehl (also u.a. Brote), wurden ebenfalls diskutiert. Neue methodische Ansätze erlauben heute eine verlässlichere Identifikation solcher Esswaren, darunter vor allem die direkten Nachweise von pflanzlichen Geweben von Getreiden, die in vielen Fällen eine Identifikation der Zutaten erlauben. Auch mikromorphologische Merkmale wie die Fragmentgrössen der enthaltenen Gewebe und die Vermessung der Porengrössen scheinen erfolgversprechend (Abb. 2). Vorgestellt wurden Reste von Speisen aus der

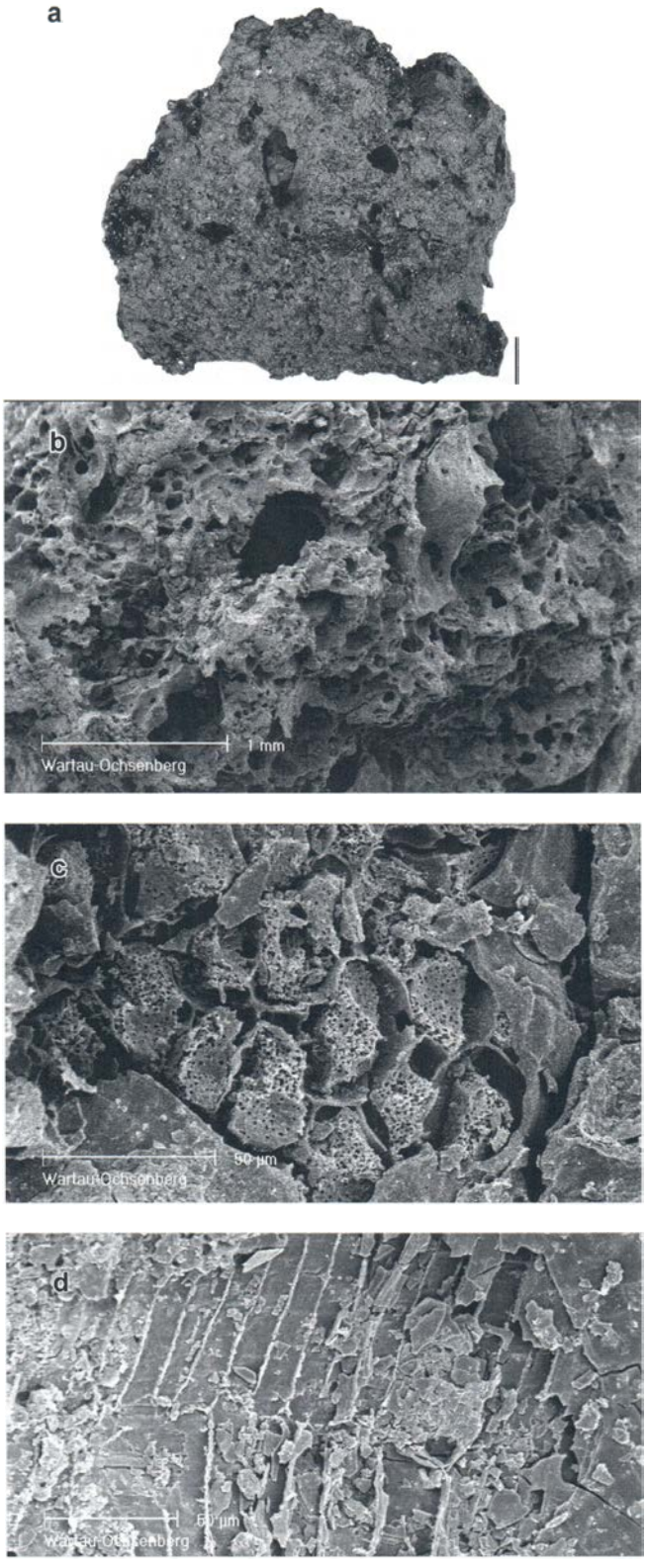


Abb. 2. Speiserest vom jüngereisenzeitlichen Brandopferplatz auf dem Ochsenberg bei Wartau SG. A Ansicht im Lichtmikroskop, Massstabslänge 1 mm; B–D Ansicht im Rasterelektronenmikroskop: B Übersicht mit einzelnen sichtbaren Geweberesten; C Aleuronzellen aus der Schale («Kleie») eines nicht näher bestimmbaren Getreides; D Querzellen vom Weizen-Typ mit der typischen rundherum starken Wandverdickung und deutlichen Tüpfeln (perlschnurartige Strukturen im Bild). Fotos A.G. Heiss.

neolithischen Siedlung Çatalhöyük (Türkei), welche zu den ältesten Getreidespeisen weltweit gehören dürften (L. González-Carretero und M. Wollstonecroft, University College London).

Die Methoden der Brotfragment-Identifizierung wurden kritisch bewertet. Die Pionierarbeiten Währens (1989; 2002) sind wahrscheinlich wissenschaftlich nicht verlässlich, da darin zwar grosse Sorgfalt auf morphologische Beschreibungen der Brote gelegt wurde, jedoch keine naturwissenschaftlichen Daten zu den eigentlichen Zutaten (d.h. direkte Nachweise der enthaltenen Getreide oder anderer Zutaten) erhoben wurden. Die Interpretationen fussen somit vor allem auf dem Augenschein. So wurde das Brot von Twann rein aufgrund seines Aussehens als Gerstenbrot bestimmt, ohne dass ein Nachweis der Getreideart erbracht worden wäre (Währen 1989; 2002). In anderen Fällen wurden Körnergemenge, die wohl erst durch das Verkohlen miteinander verbacken wurden, als Gebäck (oder gar «Knusper-Energie-Fladenbrot», Währen 1989; 2002) interpretiert, oder glänzende Flächen des verkohlten Materials als Hinweis auf Fett als Backzutat gewertet (Währen 1990; 2002). Nach heutigem Wissensstand sind solche Diagnosen wohl nicht haltbar, und die ältesten Brotfunde der Schweiz sollten deshalb mit aktuellen Methoden neu bewertet werden. Durch die Anwendung moderner Methoden gelang etwa die Identifizierung von Fladenbrot aus den kürzlich ergrabenen spätneolithischen Seeufersiedlungen von Zürich-Parkhaus Opéra (A.G. Heiss, Universität Wien). Schliesslich gab J.J. García-Granero (Institució Milà i Fontanals, Barcelona) eine Übersicht über das Potenzial, aber auch die Einschränkungen der Untersuchungen von Mikroresten wie Stärkekörner und Phytolithen für die Identifizierung von Mahlen und Entspelzen von Getreide. Er betonte dabei die Wichtigkeit einer genauen methodischen Anleitung für die Gewinnung solcher Mikroreste bei der Feldarbeit.

Doch nicht nur feste Nahrungsmittel wurden aus Getreide gewonnen, es wurden auch Getränke hergestellt. Eine Präsentation über die Vielfalt von Hirse-Produkten in der Türkei (F. Ertug, İznik, Türkei, wissenschaftliche Mitarbeiterin der Washington Universität in St. Louis) zeigte auf, wie wenig wir über die Produktion und Verarbeitung von so genannt untergeordneten Getreiden wissen, sogar aus ethnografischer Sicht.

Abschliessend behandelte H. Procopiu (Université de Paris 1) die sozialen Implikationen von Mahlprozessen, speziell betreffend Geschlechterrollen. Sie präsentierte ethnografische Forschung aus Nordafrika, welche aufzeigte, wie das entsprechende Wissen von Müttern an ihre Kinder (normalerweise Töchter) weitergegeben wird, normalerweise über die Herstellung von Spielzeug, durch welches sich das Mahlen nachahmen liess. Die Getreideverarbeitung im Haushalt ist klar mit der Arbeit von Frauen verbunden, während Werkstätten für handwerkliche Produkte vorwiegend von Männern benutzt werden.

Die rege Diskussion am Ende des Arbeitstreffens ergab, dass in Zukunft vermehrt eine integrative Vorgehensweise bei der Erforschung von Getreidespeisen in der Archäologie verfolgt werden muss. Zudem wurde das Fehlen von einheitlichen, standardisierten Methoden bemängelt. Ausserdem wurde gefordert, eine Datenbank mit experimentellen und ethnographischen Informationen zur Produktion von Getreidespeisen aufzubauen. Auch war man sich einig, dass die Kommunikation mit Archäologen und Archäologinnen, die im Feld arbeiten oder in «tradtioneller» Weise z.B. von Keramik auswerten, stark verbesserungsbedürftig ist. Zum einen muss vermittelt werden, welch grosse Vielfalt von Getreidespeisen es in traditionellen landwirtschaftlichen Gesellschaften gibt. Ebenso gross ist die Vielfalt der Prozesse, die für deren Vor- und Zubereitung benötigt werden. Zum anderen ist es unabdingbar genau zu beschreiben, welche Massnahmen im Feld bei der Bergung von Gerätschaften, die im Zusammenhang mit Getreideverarbeitung stehen, getroffen werden sollen, damit sie adäquat untersucht werden können (s. Kap. 5).

5. Praktischer Leitfaden für eine integrative Untersuchung von Getreidespeisen in der Archäologie

Ein wichtiges Ergebnis des Treffens war, dass für eine Identifizierung von Getreidespeisen die Integration mehrerer Disziplinen und die Studie verschiedener Materialkategorien unerlässlich ist. Solche Arbeiten sollten als erstes eine Analyse der Gerätschaften umfassen, welche für die Verarbeitung des Getreides benutzt wurden. Dies sind nicht nur steinerne Geräte, sondern auch hölzerne, falls solche erhalten sind. Dabei sollten die Artefakte typologisiert und auf Gebrauchsspuren untersucht werden. Wichtig ist zudem eine Analyse der botanischen Mikroreste, welche in den Poren eines Steingerätes enthalten sind. Als zweites müssen botanische Makroreste identifiziert werden, inklusive der «amorphen verkohlten organischen Objekte», welche meist Speisereste darstellen.

Hauptziel unseres Beitrages ist es, Hinweise auf die Art der Bergung von Steingeräten und deren weitere Untersuchung zu vermitteln. Detaillierte Publikationen zur Typologie von Steingeräten sind für andere Regionen wie Frankreich verfügbar (Jaccottey et al. 2014). Im Folgenden werden einige Fakten, die bei deren Bearbeitung zu beachten sind, kurz vorgestellt. Zunächst muss klar sein, dass jeder Mahlstein und Mörser das Potenzial hat, eine bestimmte Aktivität zu dokumentieren, wie durch die oben erwähnten ethnografischen Studien belegt wurde (Hamon/Le Gall 2013). Ein integrativer Ansatz, welcher Morphotechnologie, Gebrauchsspuren- und Rückstandanalyse (Stärkekörner und Phytolithen) dieser Werkzeuge verbindet, ist deshalb grundlegend für die Charakterisierung ihrer Funktionalität. Wie bei anderen Typen von Artefakten ist zunächst der archäologische Fundzusammenhang ausschlaggebend für deren Interpretation. Deshalb ist es von besonderer Wichtigkeit, bestimmte Abläufe einzuhalten, vor allem, wenn bei optimalen Rahmenbedingungen ein (Stein)artefakt in situ gefunden wird, also am Ort seines Gebrauches oder am Ort, an welchem es hinterlassen wurde. Nur so besteht die Chance,

seine Lage in Zusammenhang mit der Zubereitung von Nahrungsmitteln zu bringen.

Bei der korrekten Bergung und Untersuchung von Mahlwerkzeugen ist folgendes zu beachten:

- Das Mahlgerät mit desinfizierten Händen und ohne Berührung der aktiven Oberfläche bergen. Möglichst keine Handschuhe verwenden, da auch vermeintlich pulverfreie Handschuhe mitunter Stärkekörner enthalten, welche das Gerät kontaminieren können (Crowther et al. 2014).
- Vom umgebenden Sediment mit einem sauberen Löffel über, neben und unter dem Fund Kontrollproben entnehmen und separat in sauberen Röhrchen oder in einem Minigrip-Beutel aufbewahren.
- Das freigelegte Gerät sollte dann (ohne vorherige Reinigung!) direkt im Feld für eine Phytolithen- und Stärkekörner-Analyse beprobt oder – falls dies nicht möglich ist – in dicht schliessenden Plastikbeuteln (evtl. doppelte Schicht vorsehen) aufbewahrt werden.
- Damit eine morphotechnologische Bearbeitung sowie eine Gebrauchsspurenanalyse erfolgversprechend ist, muss darauf geachtet werden, dass die ehemalige Arbeitsfläche des Geräts nicht beschädigt wird und dass sich bei der Aufbewahrung die Artefakte nicht berühren.

Beprobungsstrategien für archäobotanische Untersuchungen wurden mehrfach beschrieben und publiziert (z.B. Jacomet/Kreuz 1999; aktuell s. Website IPNA https://ipna.unibas.ch/archbot/index.htm#probent), weshalb hier nicht näher darauf eingegangen wird. Samen, Früchte, Druschreste und ähnliche Makroreste wurden in grosser Zahl untersucht. Hingegen steckt die Untersuchung von «amorphen verkohlten organischen Objekten» und von Krusten in Keramikgefässen in den Kinderschuhen; bei diesen handelt es sich um Reste von Fruchtfleisch oder Speiserückstände. Es ist dringend notwendig, solche Untersuchungen voranzutreiben, denn nur so kann man der Nahrungszusammensetzung auf die Spur kommen. Kürzlich erschienene Publikationen zeigen das grosse Potenzial solcher Studien (Heiss et al. 2015; Kubiak-Martens et al. 2015).

6. Wertung

Das hier vorgestellte Arbeitstreffen hatte das Ziel, Experten verschiedener Forschungsrichtungen zusammenzubringen, welche sich mit der Untersuchung von Getreidespeisen in der Archäologie befassen. Die Diskussionen waren überaus hilfreich für die Entwicklung einer zukünftigen Forschungsstrategie, welche vor allem integrative Analysen beinhalten muss. Dies ist nur durch eine Zusammenarbeit aller bei der Bergung und Erforschung beteiligter Personen möglich.

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RESEARCH ARTICLE

State of the (t)art. Analytical approaches in the investigation of components and production traits of archaeological bread-like objects, applied to two finds from the Neolithic lakeshore settlement Parkhaus Opéra (Zürich, Switzerland)

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Abstract

The site of Parkhaus Opéra is located on the north-eastern shore of Lake Zürich (Switzerland) and was documented during a rescue excavation in 2010 and 2011 by the Office for Urbanism, City of Zürich. Two charred bread-like objects were found in late Neolithic Layer 13 of the pile-dwelling, and are investigated using a novel set of analyses for cereal-based foodstuffs. Tissue remains of barley and wheat were identified, as well as a schizocarp of celery (cf. *Apium graveolens*), providing the first evidence for the use of bread condiments in the Neolithic. Cereal particle sizes were recorded and used to draw conclusions regarding milling and sieving of the raw material. Gas bubbles in the charred objects were measured in order to evaluate possible leavening of the dough. The outcomes of this research significantly advance the understanding of the production traits of cereal-based food during the Neolithic. The analytical techniques proposed by this study open up new possibilities for systematic and consistent investigations of cereal-based archaeological foodstuffs.

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PLOS ONE | Analysis of archaeological bread-like objects

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Introduction

Is bread as old as cereal cultivation, or was it the outcome of a progressive development that culminated with the flourishing of the major civilisations of Classical Antiquity? Was prehistoric bread always the same culinary product that we know today, or that we can deduct from historical records? What was the role of bread in everyday alimentation? Has it always been as essential as it is regarded today in the western World? How should bread be defined after all, and where do we draw the line between bread and other cereal products created in the past?

As we know today, the scientific investigation of actual archaeological finds must always play a key role in the process of answering such questions [1–3]. It is such research which demonstrated the Upper Palaeolithic beginnings of (wild cereal) food processing as in Ohalo II [4–6], and the processing of cereals at Catalhöyük from the earliest Neolithic onwards [7]. The first "bread" finds from the Swiss Cortaillod culture [8] resulted in the scientific consensus that bread-making has been a part of central European food culture since the Neolithic. Most details in the history and development of bread-making are however still unclear in many aspects.

Regardless, no typology or standardised terminology exists for archaeological finds of cereal preparations. The habit of equalling archaeological finds to their presumptive modern counterparts has a long tradition. Widely used terminology such as Pumpernickel [9], cakes [10, 11], dumplings [11], or noodles [11–13] usually only consider the objects' shapes and not the *chaînes opératoires* of their production. When referring to supposed "bread" finds in archaeology, very general definitions seem to be more appropriate. One definition may be that bread is a processed (and usually, but not always, cereal-based) foodstuff made of a variety of solid and liquid ingredients, optionally fermented, but eventually dried or cooked/baked [14, 15]. Such a broad definition of bread, if applied to present time, would encompass nearly all bakery and pastry products imaginable. There are also narrower definitions, some implying fermentation when using the term "bread", opposing it to unfermented flat bread [16].

In light of this background, the aim of this study is to propose a standardised approach to record the parameters for archaeological "bread" finds. Morphological descriptions of prehistoric bread-like objects will be integrated with the microscopic analysis of their plant content. Moreover, procedures from material analysis will be applied to gain additional qualitative data on the components, as well as quantitative data on grinding and baking traits. The ultimate goal of this approach is the identification of (1) ingredients of the cereal products in order to link archaeobotanical crop spectra with actual food consumption, and also of (2) technological aspects of cereal processing in order to gain insight into the qualities of the products, the time invested in their production, and consequently their value and significance for a society [17–19].

As a case study illustrating this approach we selected two Late Neolithic finds of possible bread buns from the site of Parkhaus Opéra, Zürich, Switzerland, which are extraordinary due to their excellent preservation and precisely recorded find context. By using them as a link between archaeobotanical plant macroremains of cereals and actual culinary practices, we seek to expand the knowledge of local food culture in the lakeshore dwelling.

Additionally, we suggest that the development of an up-to-date classification scheme for archaeological finds of cereal products is a desirable goal for future research–in particular against the background of the artefactual character of bread [3]. For the time being, we suggest the use of more general terms for archaeological finds containing processed cereals. The current research combined with approaches followed within the scope of the ongoing EU Horizon 2020 project PLANTCULT (ERC-2015-CoG 682529) [20], will be used as the basis for a typology of bread remains.

Taphonomy of cereal products

Most cereal products are the results of intentional removal or breaking down of the various types of plant tissues in the grains to varying degrees. The applied techniques include one or several processes in various sequences such as crushing/grinding/milling, sieving, soaking, boiling, fermenting, or baking/roasting, leading to improved palatability and digestibility (see short overviews in [14, 21, 22, 23]). However, these processes also greatly lower the resistance of these products to microbial decay as well as reducing their stability in water, which is why even under otherwise favourable waterlogged conditions, these objects will quickly disintegrate [3]. This explains why the preservation of waterlogged bread and other processed cereal objects is unknown until today. The only documented suspected waterlogged bread find from Ipwege, Lower Saxony [24], later turned out to be a bread-like idol consisting of mostly beeswax [25, 26].

Desiccated bread finds have indeed been recorded since the 19th century [3], but are limited to extremely dry conditions in arid climates as documented by finds in Egypt [27] and Xinjiang, China [11, 28]. Cases of bread-like objects preserved by permafrost are unknown from the literature so far. Given the altogether unstable nature of cereal products in wet environments as mentioned above, for the time being we presume that archaeological cereal preparations (including breads) outside arid climates only preserve in a charred state.

Charred bread-like objects are not commonly found in prehistoric settlements. Among these, only lakeshore dwellings have resulted in relatively high numbers of intact finds of larger objects of cereal origin, including other equally rare and fragile remains such as complete cereal ears. As charred plant material is highly susceptible to mechanical stress [29], it is suggested that the deposition in water and gentle processes of sedimentation may play a major role as a selective force in the preservation of bread-like objects, not only by reducing pre-depositional fragmentation but also by minimizing post-excavational fragmentation by recovery techniques such as flotation [30].

There is also a seemingly high incidence of bread finds from ritual depositions in funerary contexts [16, 21, 31–35]. This may indeed emphasize a particular role that these bread-like objects may have played in burial rites [36], but may also just be the consequence of intentional (and careful) deposition, which therefore reduced the chance of shattering these fragile charred objects. Well-known *in situ* finds of intact breads in burned down Roman bakeries such as in Pompeii [37] or Carnuntum [38]–contexts where the objects did not undergo mechanical stress after charring–could also favour this hypothesis.

Research history of archaeological bread-like objects

Some of the earliest attempts to identify the components of archaeological bread date back to the late nineteenth/early twentieth centuries, when the first lakeshore dwellings were excavated, as documented for sites such as Wetzikon-Robenhausen at Lake Pfäffikon [9, 39], or Station See at Lake Mondsee [40]. Despite the fact that histological knowledge at the time allowed for the identification of cereal bran under transmitted light (e.g. [41–43]), analysis of charred cereal products requires either a reflected light microscope with magnifications of 200-fold or more, or sometimes an SEM–both of which were not available at the time. Heer [9] leaves no doubt that several "breads" from Lake Pfäffikon must have been made of millet, without expanding upon the reasons for this conclusion. Hofmann [40], although favouring the same idea for the Lake Mondsee bread objects, at least concedes they might contain virtually any cereal given they had been thoroughly dehusked and finely ground. Although re-examination of such finds is still clearly needed, the "millet breads of Robenhausen" are still being cited uncritically (e. g. [36]).

Thanks to the pioneering work of Max Währen since the 1940s, archaeological finds of cereal products across Europe have attracted much attention, once again with a main focus on late Neolithic lakeshore settlements [44]. However, no analytical methods or criteria for Währen's identifications and classifications are ever discussed in his oeuvre. Instead, a plethora of undefined terminologies renders the confirmation of Währen's diagnoses difficult, if not impossible [45]. Re-evaluation of these finds with modern scientific methods is therefore among the main goals of bioarchaeological bread research, together with the establishment of a standardised typology of archaeological bread remains [14, 20].

Since the 1980s, research into archaeological bread remains has seen a revival beginning with the first archaeobotanical applications of cereal bran identification in archaeobotany [46–48]. Delwen Samuel's work [3, 27, 49–52] must of course be mentioned in which she extensively explored the *chaîne opératoire* of Ancient Egyptian bread-making. Likewise, Ann-Marie Hansson's contributions linking the archaeobotanical analysis of Viking Age cereal preparations [22, 31, 32, 34, 53] to historical and ethnographical accounts must be mentioned as a milestone in bread research. Since this period, a certain overlapping with the analysis of "food crusts"–charred food residues from inside pottery vessels–can be observed concerning general research questions on components and production traits [23, 54], as well as the applied methodologies [55, 56].

Contemporary analyses of the microstructure of charred food preparations include the application of two opposing procedures: (1) dissolution of the food remains: chemically dissolving incompletely charred parts of the amorphous aggregations, thus separating the entirely charred components and making them observable under the transmitted light microscope [55, 57, 58], or (2) observing intact microstructures *in situ*: leaving the amorphous matrix intact, identifying the components on preferably fresh fractured surfaces using a reflected light microscope or SEM [7, 21, 56, 58–60]. The latter approach can also serve as a source of information for the *chaîne opératoire* of bread-making e.g. by inferring flour grain sizes from measurements of cereal fragments [7, 21]. Identification of possibly fermented dough has usually been made either by qualitative descriptions of the gas bubbles found in broken faces [44] or by applying a threshold height on charred archaeological bread finds, separating them into raised bread (*pain*, higher than 25 mm) or unleavened flat bread (*galette*, lower than 25 mm) [16]. Quite recently, methods delivering quantitative data on pore sizes have been proposed and are currently under evaluation [21].

Chemical analyses have already delivered a few indications of some constituents in food preparations [16, 54], although often not in an unequivocally conclusive way. Furthermore, many archaeological "bread" finds which were unearthed prior to the 1980s and which require re-evaluation, are often not apt for chemical analysis due to sometimes excessive treatment with consolidating agents [61].

The site of Parkhaus Opéra

The site is situated in central Zürich close to the current shoreline of Lake Zürich (Fig 1). A large-scale rescue excavation in 2010 revealed six settlement layers and piles from eight settlement phases (Fig 2). The layers were in very different preservation states. While the oldest deposit contained nearly no organically preserved items, the two following layers showed extraordinary waterlogged preservation (Fig 3) with some leaf fragments still green. The younger three layers had experienced less favourable conditions and exhibited greater variability of conservation states and fewer organically preserved objects. Dendrochronological dating showed that the oldest deposit dates to the years between 3234 and 3226 BCE, while the youngest settlement phase dates between 2735 and 2727 BCE [62].

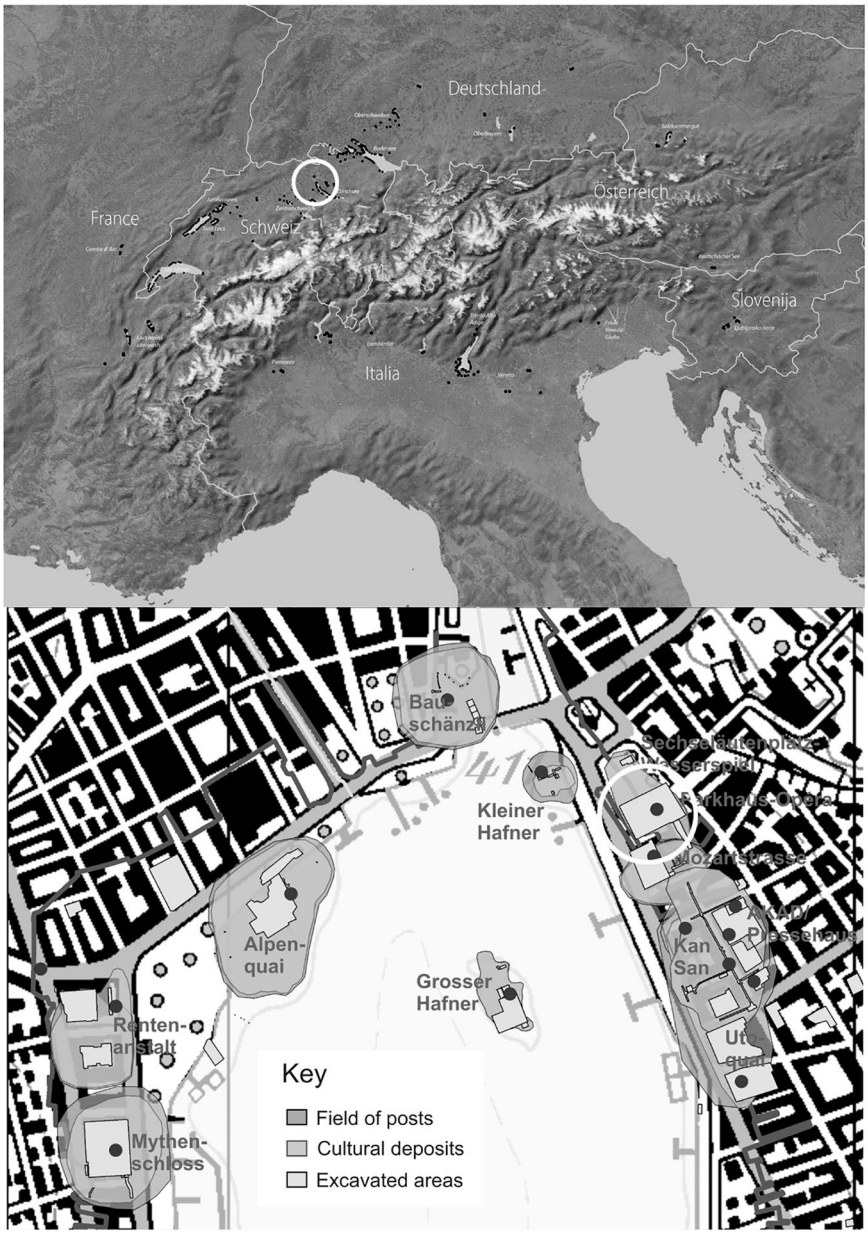


Fig 1. The site of Parkhaus Opéra. Location of Lake Zürich within the Alpine region (above) and plan of Parkhaus Opéra and other prehistoric pile dwellings around Lake Zürich (below). Image: Office for Urbanism Zürich / N. Bleicher.

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Layer 13, which was the best-preserved deposit, was documented over an area of more than 3000 m^2 and spans a period of ca. 20–25 years between 3176 BCE and 3153 BCE. A total of 27 buildings as well as a fence/footbridge were identified and used for dendrochronological analyses [62].

State of research on local plant-based subsistence and on cereal processing

Archaeobotanical analyses at the site allowed for the identification of more than 200,000 plant macroremains (mostly seeds and fruits) in about 250 systematically taken surface samples of



Fig 2. Find location. Section of the excavation at Parkhaus Opéra. Positions of find no. 2010.012.2285.3 = 2285 and find no. 2010.012.2907.5 = 2907 in Layer 13 are indicated in relation to buildings and the charcoal layer of a catastrophic fire event. Image: Office for Urbanism Zürich / N. Bleicher.

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3–10 litres each, with a particular focus on large-seeded remains which are traditionally under-represented in the small investigated volumes of sediment samples from sites with similar conditions of preservation [63], adding up to ca. 1000 litres of gently-sieved sediment using the "wash-over" technique [64]. Domesticates were well represented in the record, particularly cereals and oil plants. Among the cereals, emmer (*Triticum dicoccum*), and naked wheat (*Triticum aestivum/durum/turgidum*, mostly belonging to the *durum/turgidum* group) are better represented in the uncharred record, while barley (*Hordeum vulgare*, multi-rowed and mainly of the naked type) is one of the most important cereals when considering the remains preserved by charring. Oil plants including flax (*Linum usitatissimum*) and opium poppy (*Papaver somniferum*) were found in very large amounts, as is typical for other lakeshore sites [65–69].

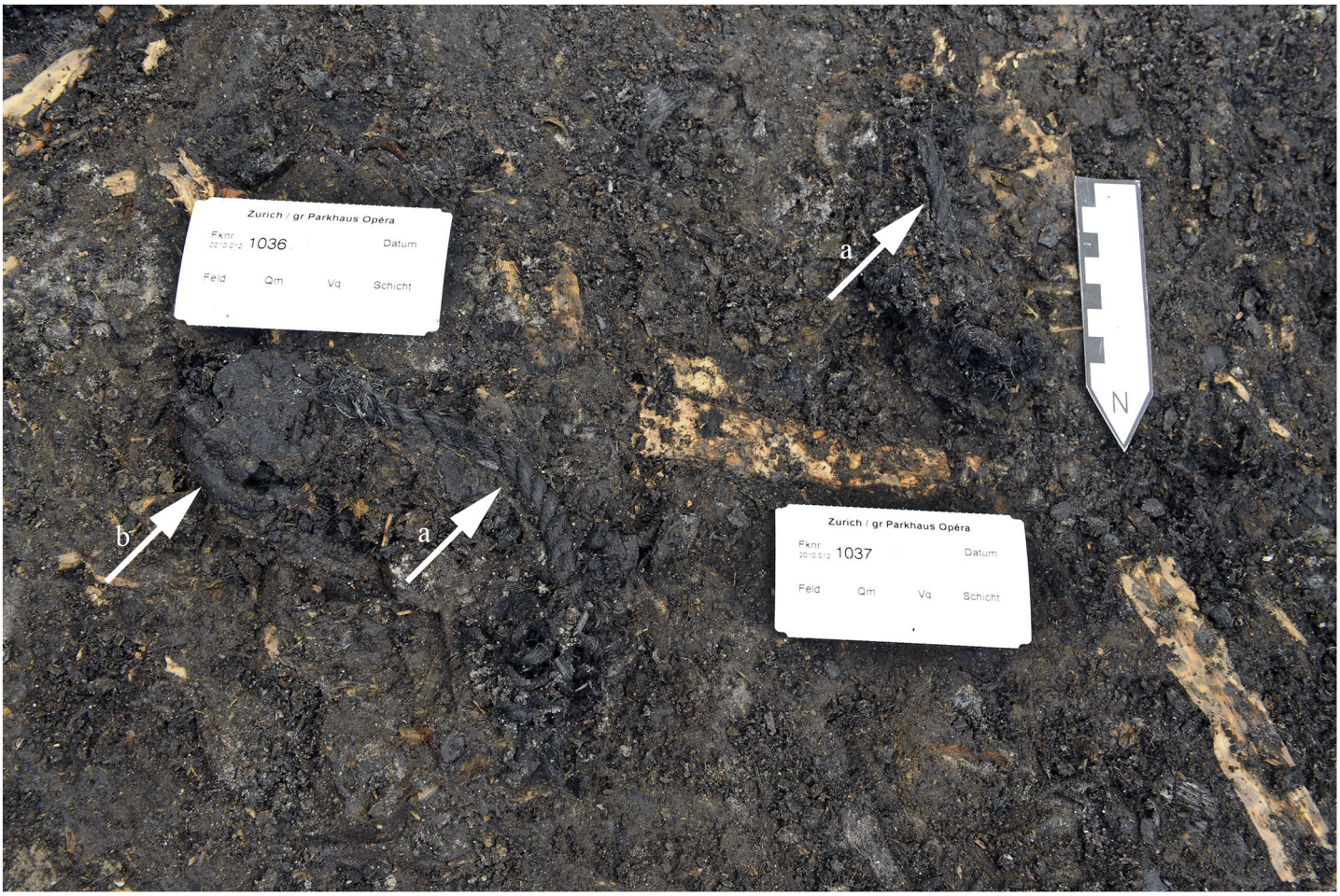


Fig 3. Layer 13 during excavation. Illustration of the state of preservation of organic matter in the cultural layer, in direct vicinity of find no. 2907. Wooden remains are visible as light-brown objects. Arrows indicate a) Rope fragments and a b) Bracket fungus fragment. Image: Office for Urbanism Zürich / N. Bleicher.

https://doi.org/10.1371/journal.pone.0182401.g003

Pulses were underrepresented in the samples due to difficulties during the identification process, currently resulting in the identification of only one find of pea (*Pisum sativum*). Large-seeded wild fruits such as hazelnuts (*Corylus avellana*), acorns (*Quercus* sp.) and wild apples/pears (*Malus sylvestris*/*Pyrus pyraster*) were also observed to play a significant role in the economy of the settlement [70, 71].

Besides the systematic bulk samples presented above, visible concentrations of well-preserved charred and uncharred materials were also collected. Among these finds were the charred objects discussed in this study which turned out to be cereal-based.

Plant food resources were obviously very important for the subsistence of the inhabitants of the site. The form in which they were consumed is not always clear, as the type of remains (mostly chaff) that end up embedded in the cultural layers are usually the refuse obtained from their culinary processing, and not the final products themselves.

Through the analysis of the spatial distribution of the largest concentrations of chaff remains of the different cereal taxa it was possible to determine that cereal processing took place in different forms for different cereals. Chaff of naked wheat and barley was found in accumulations both inside the limits of constructed features as well as in intervening spaces

and along the central palisade. Quite differently, emmer chaff was mostly found in rubbish heaps that accumulated under the floors of those buildings. These cereals were therefore most likely grown, stored, and potentially also consumed separately.

Was there any evidence of further culinary processing of these grains? Besides chaff remains, fragments of bran can also preserve in waterlogged contexts [48, 72–75]. These were not identified at the species level due to the expenditure of time required, while their identification as cereals is straightforward. Fragments of bran were indeed found all over the excavated area, but in some larger concentrations in buildings located to the south of the settlement.

Given the spatial relation of grinding stones and cereal bran fragments in the southern half of the village, it was suggested that these fragments could have originated during cereal grinding (although other routes of entry such as faeces cannot be excluded). The current interpretation is that cereal grinding may have been frequent at least in this southern part of the site and that cereals were consumed in a transformed state, in smaller particles [76]. This is precisely the area where the charred objects presented in this paper were found.

Material and methods

Terminology

As stated in the introduction, finds like the ones analysed in the current study have often been classified using descriptive terms lacking clear delimitations. The authors therefore propose to avoid the use of any direct analogies to modern cereal products ("doughnut", "porridge", "cake", "biscuit", etc. . .) until a standardised and stringent typology for archaeological bread finds is established. Instead, we propose the general terms "cereal preparation" or "cereal product" for any amorphous charred object (AOV–amorphe Objekte verkohlt; OAC–objets amorphes carbonisés; MOC–matière amorphe carbonisée, BGF–Brot, Gebäck, Fruchtfleisch) [21, 77–80] with positive evidence for cereal content. For cereal preparations with a recognizable outer shape, we propose the general term "bread-like object" as used throughout this paper.

Study permissions and sample repositories

The institutions eligible to issue study permits–the Office for Urbanism Zürich and the Cantonal Archaeology of Zürich–were the contracting entities of the current study, and both are represented by co-authors. Therefore, no additional permits were required for the described analyses.

Specimens are accessible to scientists on demand in the permanent repository of the Cantonal Archaeology of Zürich / Kantonsarchäologie Zürich, Stettbachstrasse 7, 8600 Dübendorf, Switzerland. Contact: are.archaeologie@bd.zh.ch / +41 (43) 259 69 00. The SEM subsamples are accessible to scientists on demand in the permanent repository of the Austrian Archaeological Institute, Head Office Vienna, Franz Klein-Gasse 1, 1190 Wien, Austria. Contact: mailbox@oeai.at / +43 (1) 42 77–271 01

The bread-like objects

Two finds were examined in this study. For further ease of use, their find numbers will be shortened, and referred to in abbreviated form (find no. 2010.012.2285.3 = 2285, and find no. 2010.012.2907.5 = 2907). In Layer 13, the two finds lay within the plant detritus, forming the matrix of the deposit (Fig 3). Find no. 2907 was found near a layer of charcoal, find no. 2285

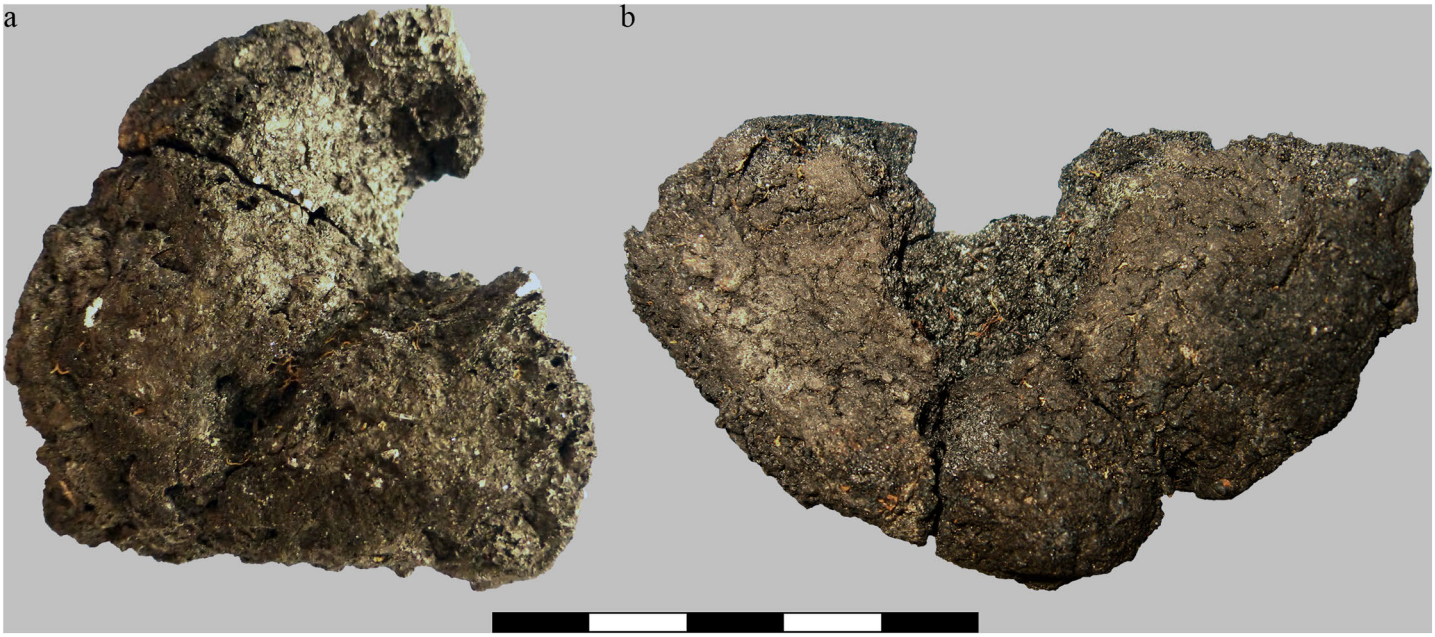


Fig 4. Overview of the two analysed bread-like objects. Possible upper surface of a) Find no. 2285 and b) Find no. 2907. Centimetre scale. Image: ÖAI-ÖAW, VIAS / A. G. Heiss.

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several metres away (Fig 2). There is no indication that the items were charred during the catastrophic fire which was documented for a sector of Layer 13 [81].

Upon excavation, find no. 2285 was recovered broken into two fragments (Fig 4). When fitted together, the resulting shape is that of approximately one half of an irregularly disc-shaped object, with a total diameter of ca. 6 centimetres. We suggest that this was probably also the original diameter of the entire charred object. The low ratio of its maximum diameter vs. maximum height (2.8: 1, see Table 1) gives the find a rather bulky appearance. The inner walls of the find's eccentric hole resemble the outer surfaces of the rest of the object, which is why it seems likely that the hole is indeed an original feature of this bread-like object.

Find no. 2907 was also recovered in fragmented state (Fig 4). Only two larger fragments could be unequivocally associated to each other (i. e. fitted together), while the third and smallest one could not be fitted, and was not considered in the current analyses. Similar to find no. 2285, find no. 2907 also represents roughly one half of a disc-shaped object. While its diameter measures 10.1 centimetres and therefore nearly twice as much as of the aforementioned find,

Table 1. Basic description of the two bread-like objects from the excavation at Parkhaus Opéra.

	Find no. 2285	Find no. 2907
Total weight [g]	10,0	12,1
Total max. diameter [mm]	59	101
Total max. height [mm]	21	19
Radio max. diameter: max. height	1.3: 1	5.3: 1
Number of fragments	2	3
Max. fragment dimensions [mm]	59 x 35 x 21	65 x 38 x 19
L x W x H	37 x 27 x 16	47 x 36 x 16
		15 x 15 x 9

https://doi.org/10.1371/journal.pone.0182401.t001

its maximum height is indeed lower (Table 1). Just like find no. 2285, find no. 2907 also bears a more or less eccentric hole. However, its jagged outline in combination with the appearance of the surface within the hole, which differs greatly from the surface of the undamaged area of the object, strongly suggest that this hole is not an original feature of the find, and must have originated from mechanical stress after charring.

Sample preparation

The supposedly post-depositional fractured faces of both bread-like objects were examined without pretreatment under a light microscope (Olympus SZH10 binocular) with magnification up to 70x. Images were acquired using a Canon Powershot A540 camera and an ocular adapter hand-tailored by R. Mehnert (Weil der Stadt, Germany). The limitations in depth of field were compensated for by stacking multiple images with the software Helicon Focus [82].

No fresh fractures were produced in the objects to prevent any further damage, with the exception of the SEM samples. These, each measuring ca. 2 cm, were taken from the existing fractured faces. Both subsamples were sputter-coated with gold/palladium, and analysed using a Zeiss EVO 60 XVP [83, 84].

Component analysis

Histological identification of cereal tissues was carried out following Heiss et al. [21], using as identification criteria the anatomical structure of the cross cells' (= transverse cells) walls (Fig 5), the arrangement of aleurone cell layers (Fig 6) and glume epidermal features [41, 85–88]. Identification based on the features of cross cells was limited to genus level, as e. g. differentiation of *Triticum* species is only possible if the original tissue location on the grain is known [47]. We did not follow the approach of using cross cell length as a means of distinguishing the genera *Triticum* and *Hordeum* [7] for a similar reason: cross cell length is too variable within the surface of a single grain to bear significance in identification [47, 48]. The millets *Panicum miliaceum* and *Setaria italica*, which can easily be identified by their glumes if present [43, 89], cannot be satisfactorily differentiated from barley by their cross cells alone [41]. As the significance of millets as food crops in Neolithic Europe can certainly be ruled out due to their absence in the period considered [90, 91], cross cells meeting the diagnostic criteria in Fig 5 are considered as originating from barley in the current paper.

Identification of seed admixtures was carried out using the ÖAI/ÖAW Bioarchaeology Department's reference collection, as well as standard identification literature [92–96]. Experimental charring of *Apium graveolens* was carried out in a Nabertherm muffle furnace, simplifying an existing charring protocol under low oxygen / anoxic conditions [97]: temperature was set to 270˚C for 6 hours, and the material (origin: University of Hohenheim [UHOH], IS 1990, Nr. 1413) was embedded in purified sea sand in order to establish a low-oxygen atmosphere.

Measurements

For the evaluation of overall cereal fragment sizes, maximum dimensions of each fragment visible in the fractured faces of the objects were manually recorded using the software ImageJ [98]. These measurements were carried out on (supposedly post-depositional) fractured faces of both bread-like objects, recording all fragments visible with 10-fold magnification under a light microscope, as well as those visible with 100-fold magnification under the SEM. The results, presented in histograms (100 μm steps), are grouped according to modern equivalents of ground cereals [99, 100]: flour and dunst (particles smaller than 300 μm) vs. semolina (300–1000 μm) vs. grist (larger than 1000 μm).

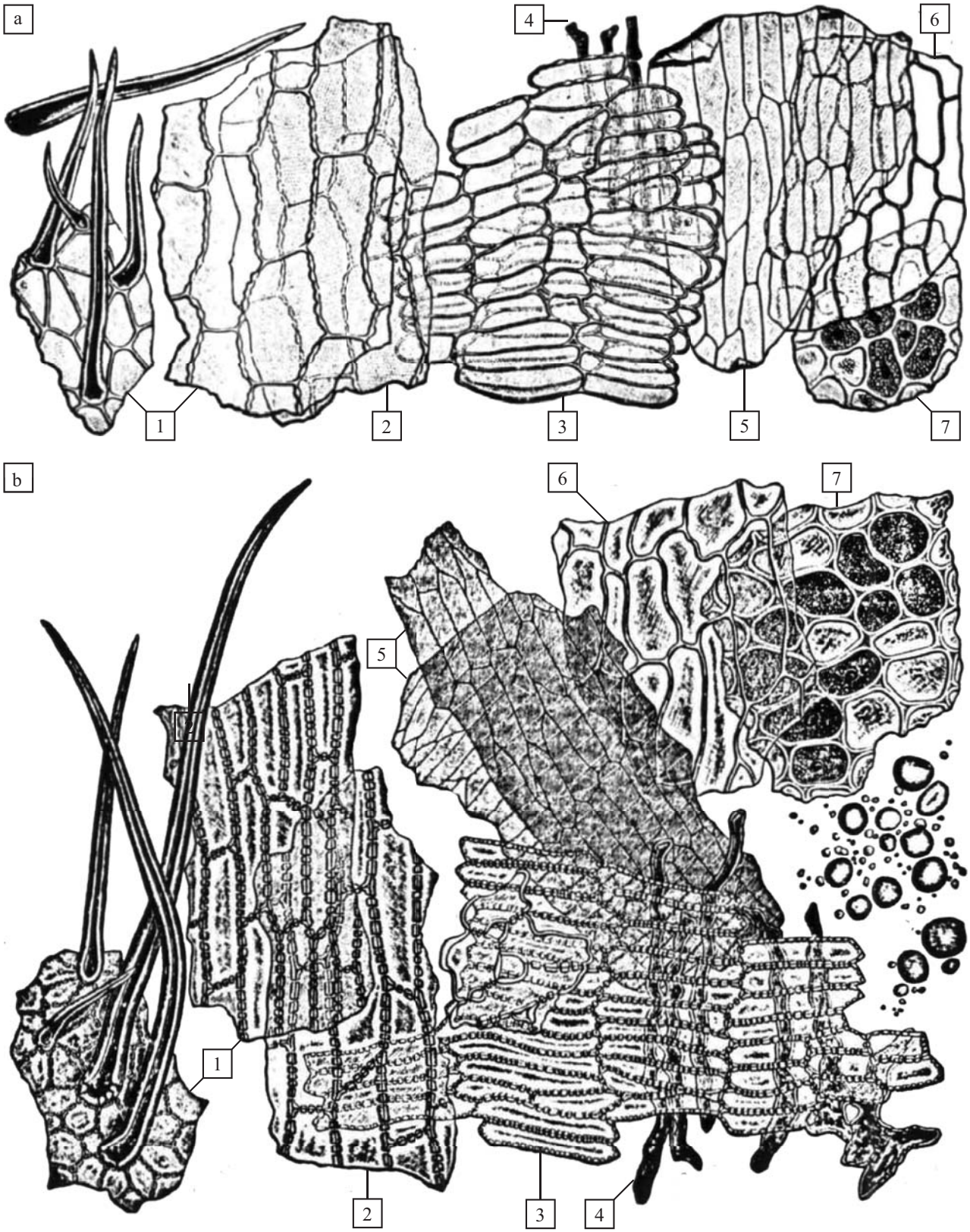


Fig 5. Diagnostic cereal tissue types as visible in plane sections. Species: a) Barley (*Hordeum vulgare*), and b) Bread wheat (*Triticum aestivum*). Tissue types: 1) epidermis at the apex (left) and in the middle of the grain (right), 2) Hypodermis, 3) Cross cells, 4) Tubular cells, 5) Testa, 6) Perisperm, 7) Aleurone. Applied diagnostic features: 3a) Thin-walled cross cell walls in barley, often in a double layer (the latter not visible under SEM), and 3b) Thick-walled, regularly and conspicuously pitted cross cells in wheat species ([41], modified).

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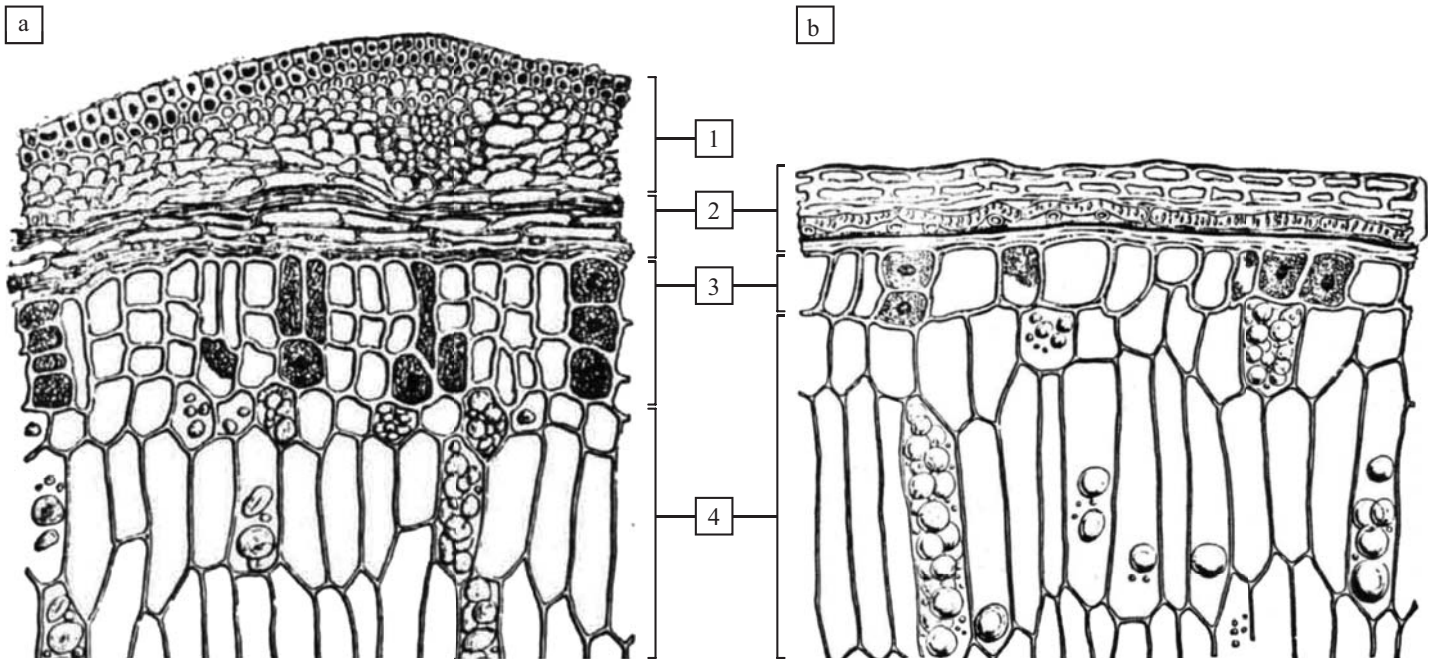


Fig 6. Diagnostic cereal tissue types as visible in cross sections. Species: a) Barley (*Hordeum vulgare*), and b) Bread wheat (*Triticum aestivum*). Grain parts and tissue types: 1) glume, 2) Pericarp and seed layers (corresponding to Fig 5, numbers 1 to 6), 3) aleurone tissue, 4) endosperm. Applied diagnostic features: 3a) Double to triple layer of aleurone in *Hordeum*, in contrast to 3b) Typically single layers as in *Triticum* and all other Old World cereal crops ([41], modified).

https://doi.org/10.1371/journal.pone.0182401.g006

The modern baking industry has applied a broad range of analytical methods in routine quality control for decades. While many of them can only be applied to unbaked (and uncharred) dough, such as the observation of rheological parameters, gas retention, or gluten composition [101–103], some others seem worth exploring for archaeobotanical charred material. The structure of baked bread, a matter technically being a stable foam, can be described by parameters such as pore shape, pore density and connectivity. In the modern bread industry, these factors are measured to assess baking conditions [104, 105].

For the charred bread-like objects presented in the current study, we use a simplified protocol for measuring pore sizes initially developed for pottery [106], which was later adapted for modern bread [104] and eventually for archaeological bread finds [21]. We then compare the results to the older dichotomous classification of archaeological bread finds into raised bread (*pain*, higher than 25 mm) and unleavened flat bread (*galette*, lower than 25 mm) [16].

For the current material, the broken faces of both objects were photographed under skewed light, resulting in a highly contrasted image. After generating a black and white threshold image (Fig 7), ImageJ's [98] "fit ellipse" function was used to automatically count all black areas (cavities) in the observed areas. Measurements below 100 μm were ignored in order to avoid artefacts caused by single pixels. Only the resulting maximum diameters of cavities were evaluated.

Results

Components

Find no. 2285. Of the larger grain fragments visible in the fractured faces, two could be identified as barley (*Hordeum vulgare*) due to their grain outline (see Fig 8). Under the SEM, no cross sections of aleurone tissue allowing for verification of barley as a component (vs.

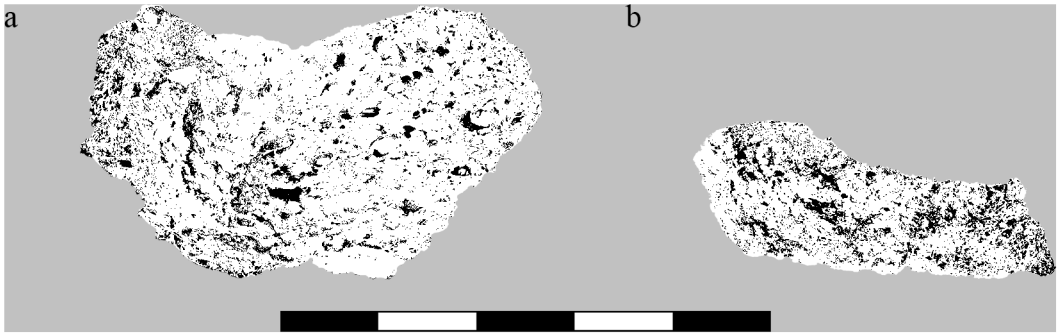


Fig 7. Cavity measurement. B/W images used as raw data for image analysis in a) Find no. 2285, and b) Find no. 2907. Centimetre scale. Image: ÖAW-ÖAI, VIAS / A. G. Heiss.

https://doi.org/10.1371/journal.pone.0182401.g007

identification of other cereals) were visible, however numerous patches of cross cell tissue were found (Fig 9). No evidence of additional cereal taxa or of other admixtures could be recognised in the SEM sample. Starch grains were not observed.

Find no. 2907. Under low magnification (10x), one of the larger grain fragments was found to most likely derive from barley, although a definite identification was not possible (cf. *Hordeum vulgare*, Fig 10). Under the SEM, only hints of *Triticum* sp. (cross cells with thick, pitted walls) and of cereals other than barley (single-layered aleurone tissue) were observed (Fig 11). Starch grains were not observed in the sample.

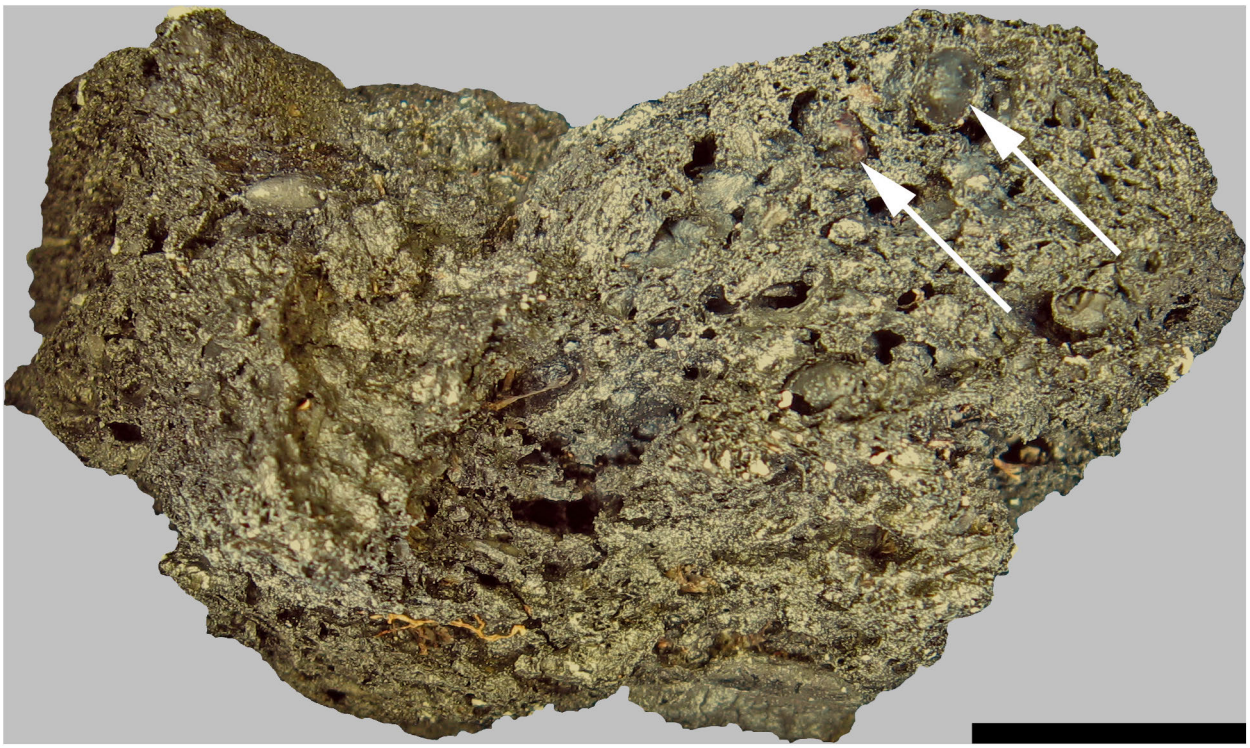


Fig 8. Overview of a fractured face of find no. 2285. Arrows indicate grains identifiable as barley (*Hordeum vulgare*). Scale bar length: 1 cm. Image: ÖAW-ÖAI, VIAS / A. G. Heiss.

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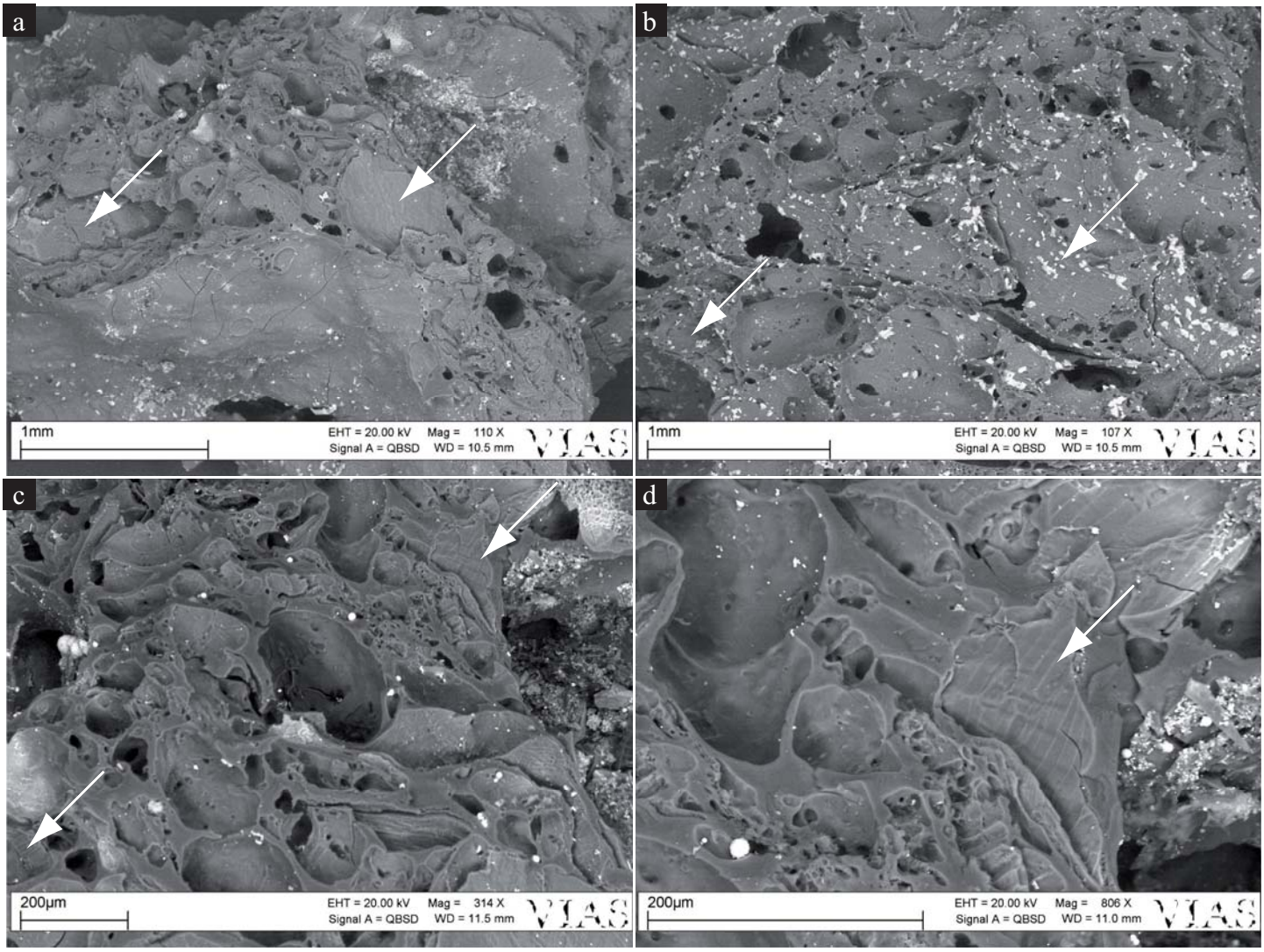


Fig 9. SEM images from find no. 2285. Arrows indicate cross cell patches. a-c) Overview images, d) Detailed view of c, showing thin-walled cross cells as found in barley (*Hordeum vulgare*).

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One sector of the SEM sample of find no. 2907 revealed a relatively isodiametric (ca. 0.5 mm) structure bearing three clearly visible dorsal ridges and two smaller lateral/ventral ones (Fig 12). A distinct differentiation between an outer hull and an inner portion is visible, both lacking clear cellular features, most likely due to charring. In spite of the limited available morphological features, the structure can clearly be identified as an Apiaceae schizocarp. Comparison of size and shape with European Apiaceae reference material as well as with experimentally charred material (Fig 13) resulted in the identification as very probably celery (cf. *Apium graveolens*).

Structure

Find no. 2285. The overall macroscopic and microscopic structure of the object was very heterogeneous, with irregular distribution of larger cereal grain fragments and larger cavities. No clear differentiation of an inner crumb and an outer crust was observed.

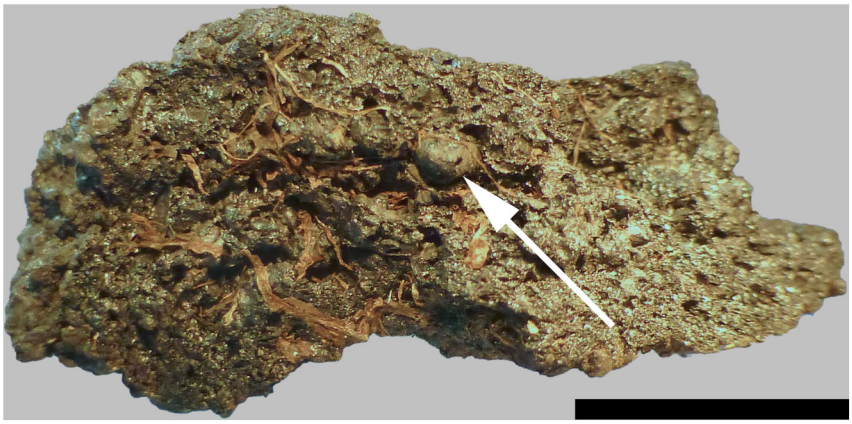


Fig 10. Overview of a fractured face of find no. 2907. The arrow indicates a grain identifiable as most likely barley (cf. *Hordeum vulgare*). Scale bar length: 1 cm. Image: ÖAW-ÖAI, VIAS / A. G. Heiss.

https://doi.org/10.1371/journal.pone.0182401.g010

Fragment sizes of cereal grains were recorded for 61 grain fragments visible under the binocular, and for 162 grain/bran fragments via SEM imagery. The overall data (Fig 14) show a heterogeneous mixture, with fragment sizes ranging from roughly 0.1 to 5.6 millimetres. The entirety of measurements divides roughly equally into three groups: measurement ranges of modern dunst and flour (29% of measurements), semolina (300–1000 μm: 35% of measurements), and grist (36% of measurements).

Image analysis of cavities resulted in a total of 2,368 values ranging from 121 to 7013 μm, 95% of them are below 1 mm (Fig 15).

Find no. 2907. As in find no. 2285, the overall structure of the object could be described as very heterogeneous, but in general denser than the aforementioned find, large cavities were lacking. No clear differentiation between crumb and crust was observed.

80 cereal fragments could be measured under the stereomicroscope, while the dimensions of 207 fragments were recorded using SEM. In spite of the minimum and maximum measures spanning roughly the same range as in find no. 2285 (0.1 to 5.7 millimetres), grain size distribution is strongly shifted towards smaller values (Fig 16): 43% of the measurements correspond to modern equivalents of dunst and flour, while 24% correspond to semolina and 15% to grist.

639 cavities were measured by image analysis, spanning from 126 to 3894 μm. 97% of the values were smaller than 1 mm (Fig 17).

Discussion

Plant-based components

Cereals. In find no. 2285, all evidence indicatres *Hordeum vulgare* as main cereal ingredient, and no traces of other cereals were observed.

In find no. 2907, evidence for barley is uncertain (cf. *Hordeum vulgare*), while a wheat species (*Triticum* sp.) was also identified, therefore indicating a product made from mixed cereal meal. As inferred from the archaeobotanical find assemblage, one or several of *Triticum monococcum*, *T. dicoccum*, *T. aestivum/durum/turgidum*, or also *T. timopheevi* (*Triticum* sp. "new type") are possible sources of the wheat material [76]. It should be noted that based on these results, past generalised implications such as "flat bread = barley bread" [107] should be regarded with even more caution.

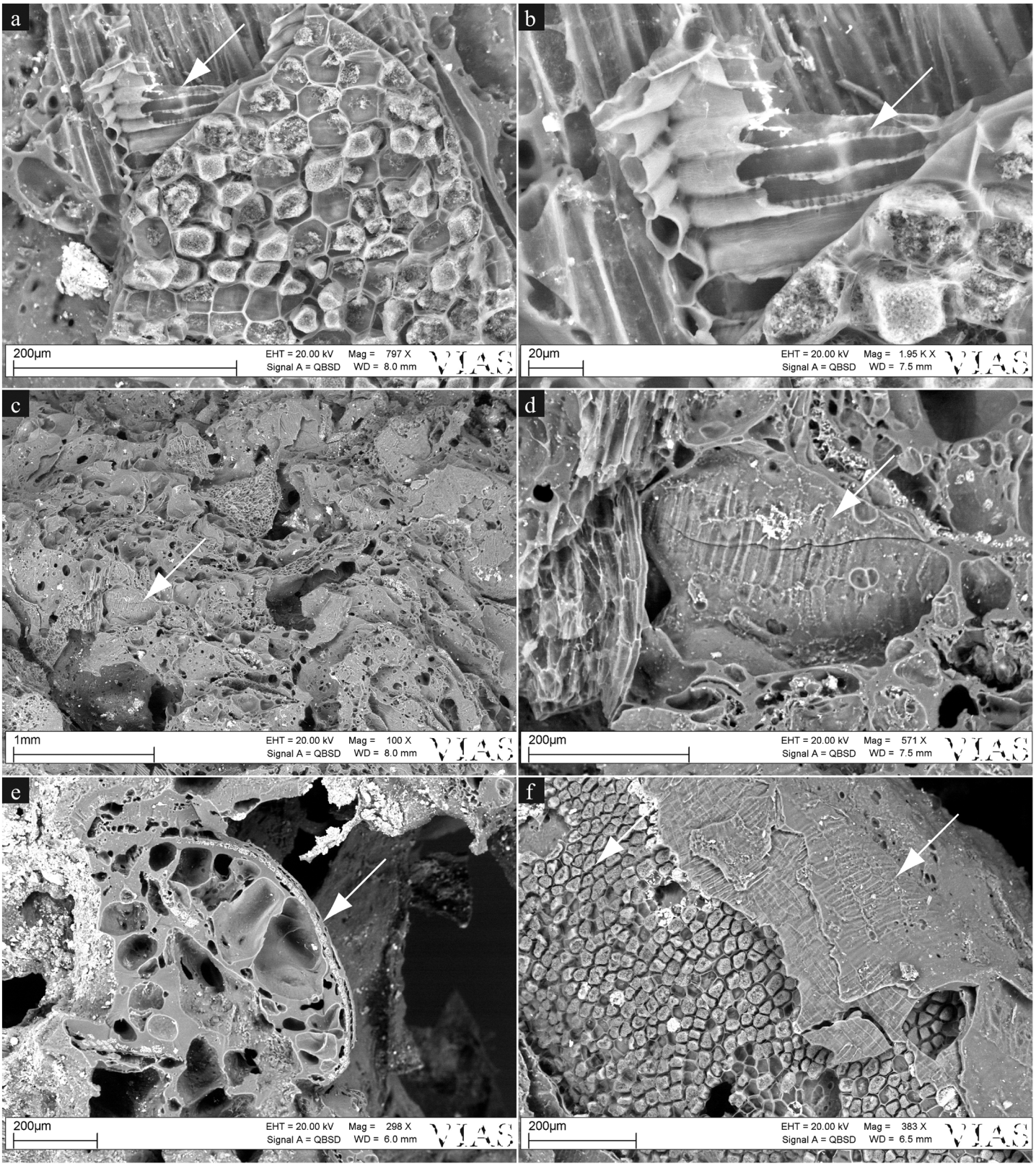


Fig 11. SEM images from find no. 2907. Arrows indicate regions of interest. a) Cross cells patch, covered by a patch of aleurone cells. b) Magnification of a, showing thick-walled and pitted cross cells as found in wheat (*Triticum* sp.). c) Cross cells embedded in the matrix. d) Magnification of c, showing the thick-walled and pitted cross cells of the *Triticum* sp. type. e) Portion of a cereal grain showing single-layered aleurone. f) Cereal grain showing several pericarp layers, from aleurone cells on the left to cross cells on the right hand side. Image: ÖAW-ÖAI, VIAS / A. G. Heiss.

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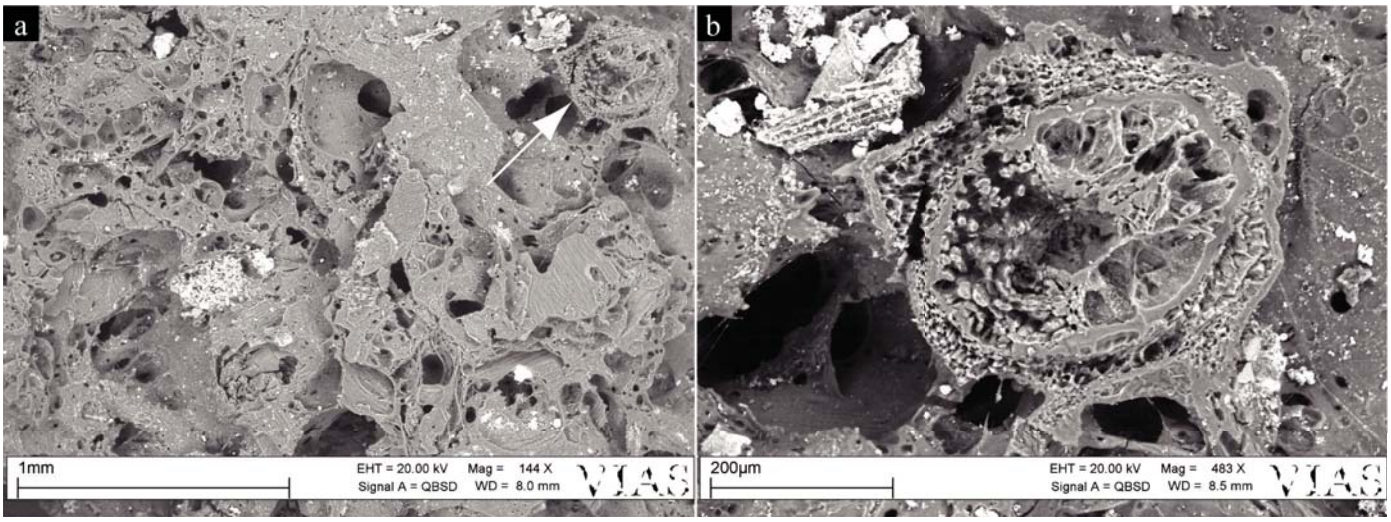


Fig 12. SEM image of the celery (cf. *Apium graveolens*) fruit. a) Embedded in the matrix of find no. 2907, b) In magnified view. Image: ÖAW-ÖAI, VIAS / A. G. Heiss.

https://doi.org/10.1371/journal.pone.0182401.g012

Condiments. For the extraordinary find of a celery (cf. *Apium graveolens*) schizocarp in the matrix of find no. 2907, currently no comparable data are available from previous studies.



Fig 13. Experimentally charred schizocarp of celery (*Apium graveolens*). Scale bar length: 100 µm. Image: ÖAW-ÖAI / A. G. Heiss.

https://doi.org/10.1371/journal.pone.0182401.g013

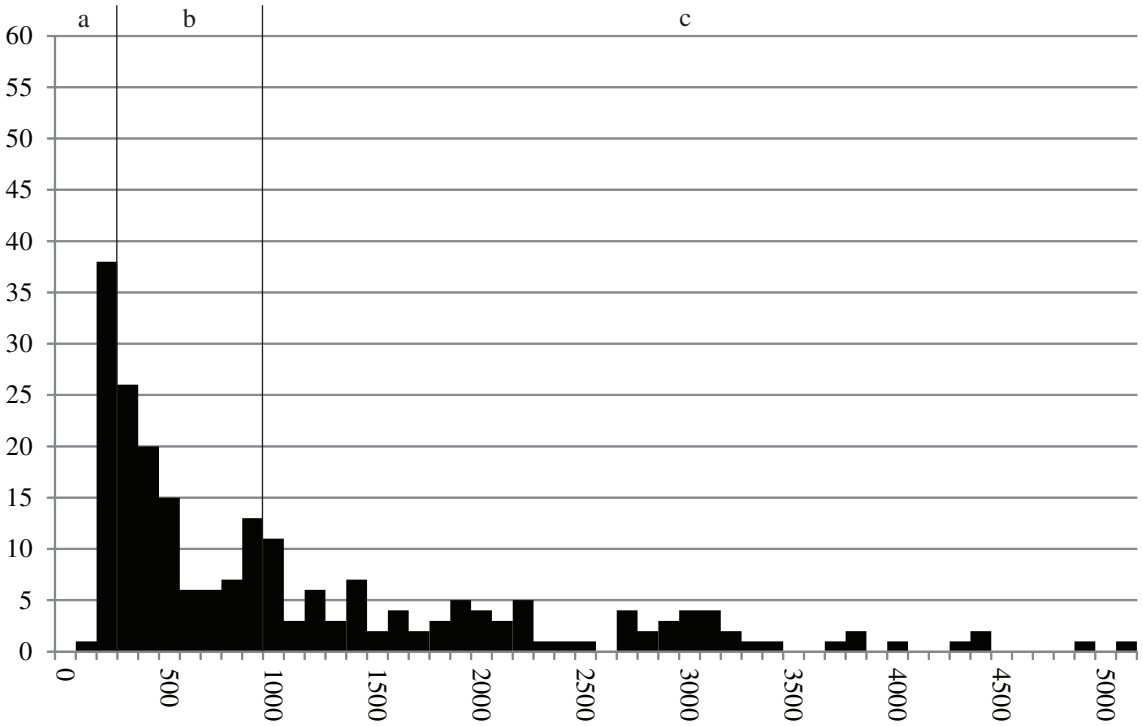


Fig 14. Histogram of the recorded maximum dimensions of components (N = 223) in find no. 2285. Y axis: number of occurrences, Y axis: size class in micrometres (in 100 μm steps). Grouping is according to grain sizes of modern grain products: a) Flour and dunst (smaller than 300 μm), b) Semolina (300–1000 μm), and c) Grist (larger than 1000 μm). Raw data is given in S1 Table.

https://doi.org/10.1371/journal.pone.0182401.g014

This plant occurs in the archaeobotanical find assemblages of several pre-Alpine lakeshore dwellings despite not being native to central Europe [108, 109]. For Parkhaus Opéra it has not yet been documented [76], but is present nearby in more or less contemporary sites along Lake Zürich, such as at Zürich Kanalisationssanierung Seefeld phase 4, and at Zürich Mozartstrasse phase 3 [65, 110]. Previous works have suggested a link of imported Mediterranean condiments *Apium graveolens* and *Anethum graveolens*–the latter also directly documented for Parkhaus Opéra–and salt trade with northern Italy [111]. Whether this may also indicate the possibility of salt as an ingredient of find no. 2907 or not, it would stand to reason to interpret this find of celery as the first evidence for a bread condiment of the central European Neolithic.

Quantification. A question of both archaeological and public interest concerns the quantification of ingredients, as it often occurs that the public eventually expect "recipes" for certain ancient foodstuffs after scientific analyses.

Considering this, one must keep in mind that the acquired quantity of taxon-specific data for both analysed objects is very limited with the applied methods. Very few surfaces can be analysed under SEM and used as a data source for taxon recognition, while the majority of the object remains unobservable. Therefore it must be emphasised–even more so than for the interpretation of "normal" archaeobotanical assemblages–that the lack of evidence for a certain taxon in a ground cereal product can by no means be interpreted as a proof of its absence. The same limited explanatory power applies for quantities, clearly not allowing for an interpretation of relative quantities between cereals in compound preparations such as in find no. 2907.

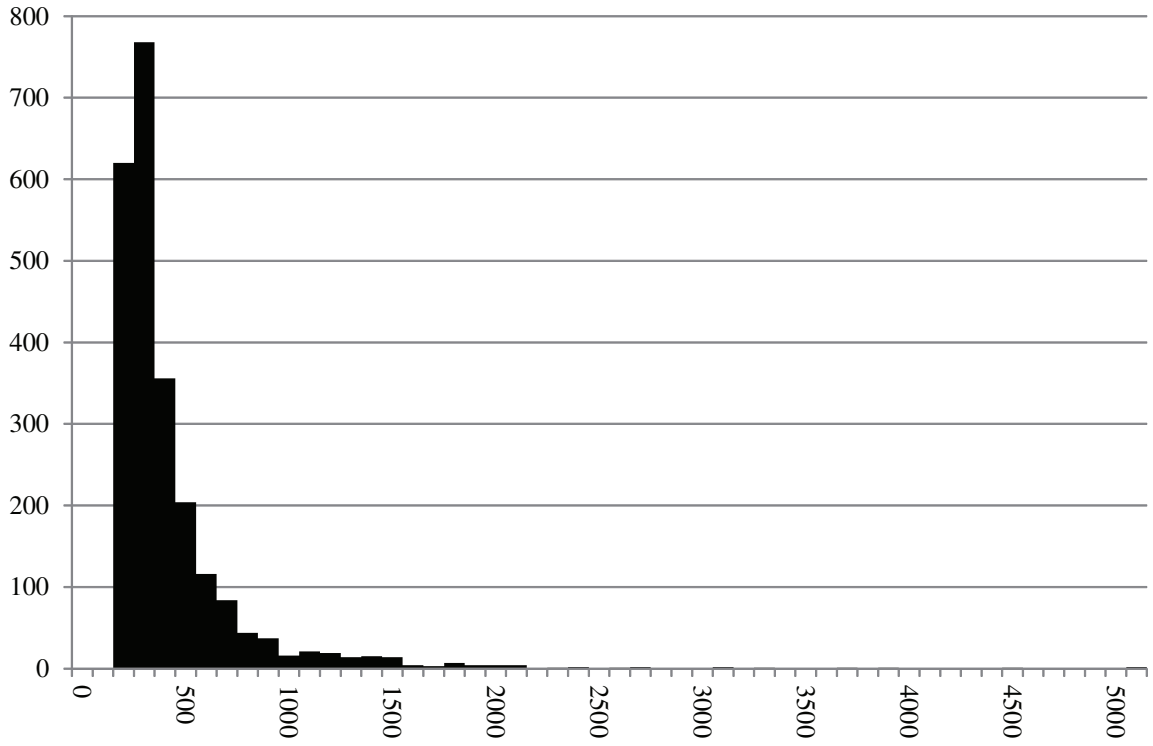


Fig 15. Histogram of the measured cavities (N = 2,368) in find no. 2907. Y axis: number of occurrences, Y axis: size class in micrometres (in 100 μm steps). Raw data is given in S2 Table.

https://doi.org/10.1371/journal.pone.0182401.g015

Quantitative assessments of admixtures, be they intentional (condiments) or accidental (weeds, chaff), seems to be even less sensible due to their expectedly low proportions in cereal products in comparison to the main ingredients i.e. the cereal grains/flour due to the fact that: (1) accidental admixtures can be expected to be strongly reduced by the known *chaînes opératoires* of cereal processing and bread-making [14, 22, 45, 112–116], and (2) intentional admixtures such as condiments can only be expected in minor amounts, or at least this is what historical recipes from the Roman period [117, 118] suggest.

As a summary, the general probability of discovering any condiments in the few observable surfaces of a charred cereal preparation is minute, rendering the celery (cf. *Apium graveolens*) schizocarp in find no. 2907 an exception, and one that will give no hints to the quantities used in the dough preparation.

Structure and production traits

Grinding. Grain size measurements of the two analysed finds results in two very different grain size distributions: While both objects definitely contain finely ground cereal meal mostly comparable to modern dunst and semolina, find no. 2285 displays an overall high degree of heterogeneity with a strong tendency towards larger fragments. This can be interpreted as either an intentional mixture of flour/dunst with semolina and grist, or as the result of quickly and incompletely grinding the grains.

Find no. 2907, in contrast, shows a more homogeneous composition with a large proportion of flour/dunst grain sizes, therefore representing a more refined product (Fig 18). It must

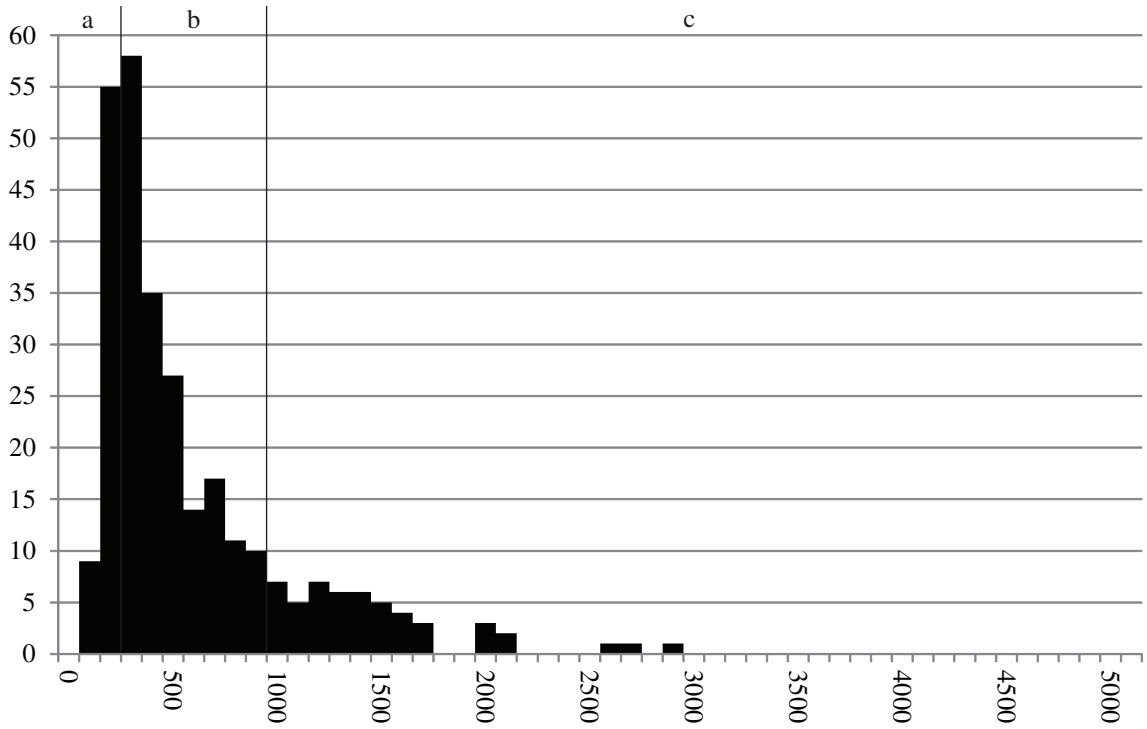


Fig 16. Histogram of the recorded maximum dimensions of components (N = 287) in find no. 2907. Y axis: number of occurrences, Y axis: size class in micrometres (in 100 μm steps). Grouping according to grain sizes of modern grain products: a) Flour and dunst (smaller than 300 μm), b) Semolina (300–1000 μm), and c) Grist (larger than 1000 μm). For raw data see S3 Table.

https://doi.org/10.1371/journal.pone.0182401.g016

be emphasised that such interpretations will greatly profit from the availability of similar data for additional objects, and also from future experimental approaches [20].

Fermenting. Using only the very basic classification system according to Lannoy et al. [16], which only takes into account the overall height of a bread find, both bread-like objects from Zürich Parkhaus Opéra have to be classified as clearly unleavened, and therefore as flat breads (*galette*).

Current results from cavity/pore measurements provide additional quantitative evidence that can be used in confirming the validity of this classification: despite the differences in outlying values, general population parameters are nearly identical in both finds (Fig 19). In total, less than 5% of the cavities exceeded 1 mm in diameter. Although direct comparison to modern raised bread must be regarded with caution (also, but not only, because of the effects of charring), differences in magnitude are evident: image analysis values display percentages of larger (> 1mm) pores typically as high as 40% to 70% [119].

Taking into account the overall density of the finds with the naked eye and the lack of differentiated crust and crumb structure, the low height of the two finds and the aforementioned data, it can safely be assumed that neither of the two bread-like objects seem to have undergone any sufficient fermentation (and resulting gas development).

Shaping. The ring shape of find no. 2285 may be regarded as an indication of this bread-like object's solid state prior to charring. However, this solid state may have been caused either by cooking/baking, or just by drying (see below). The function and purpose of the hole in this

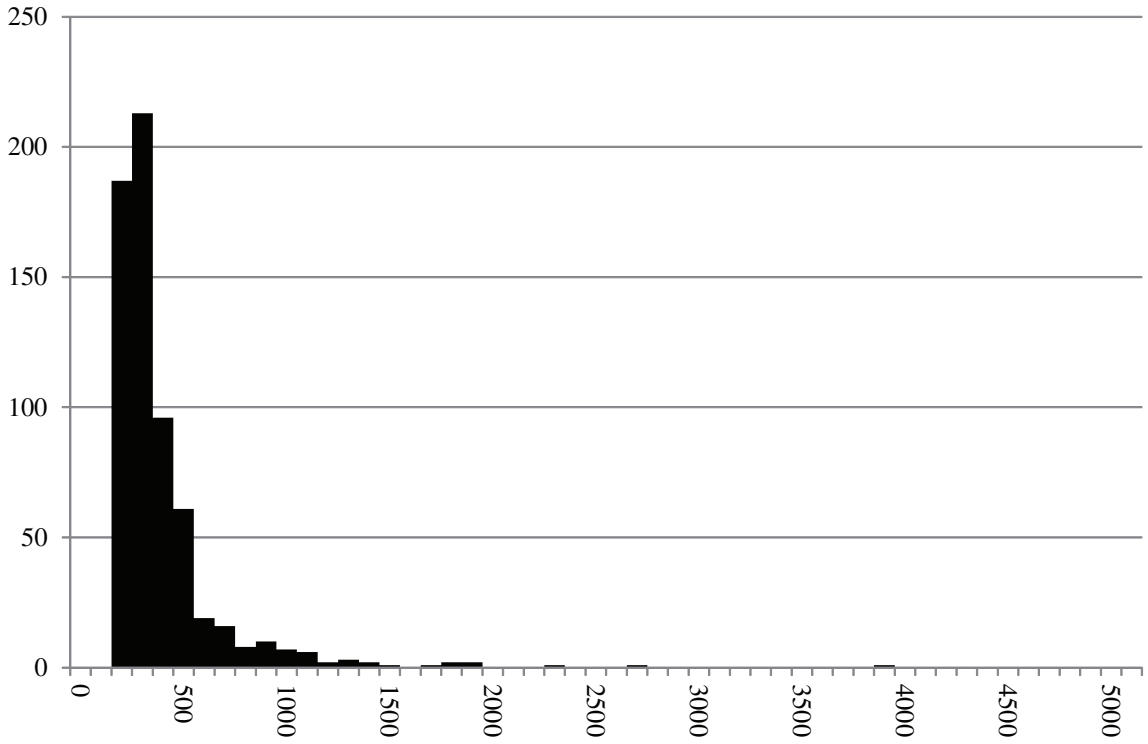


Fig 17. Histogram of the measured cavities (N = 639) in find no. 2907. Y axis: number of occurrences, Y axis: size class in micrometres (in 100 μm steps). Raw data is given in S4 Table.

https://doi.org/10.1371/journal.pone.0182401.g017

find remain uncertain for now. Although the phenomenon of punched bakery products is not new to archaeology or ethnography [32, 120–122], material that can be directly compared to find no. 2285 is not available.

Baking. Neither of the finds showed intact starch granules under the SEM. The absence of starch granules in processed cereal products is usually a consequence of full gelatinisation of the starch: In contrast to the reversible swelling of starch grains by soaking in water, gelatinisation requires elevated temperatures (the lower gelatinisation range of most starches lies between 55 and 75˚C) [27, 123]. The presence of intact starch granules in charred material indicates that no soaking and subsequent cooking/baking processes occurred prior to charring [124]. In contrast, intact starch granules would be expected in any uncooked/unbaked dough, or in soaked flour/grain-paste [22]. The fully gelatinised starch in the analysed finds therefore indeed indicates dough preparation (soaking) and baking prior to charring.

The possible causes of charring also require elaboration, taking into account the two scenarios of "baking accident" vs. "catastrophic fire". A fire event destroying certain houses located in the central part of the dwelling is indeed documented by a charcoal accumulation across more than 65 m in Layer 13 (see Fig 2). Both finds, however, were discovered outside the area in question [81, 125], rendering the scenario of baking accidents for both objects more plausible.

Conclusions

The two bread-like objects from the Neolithic site of Zürich Parkhaus Opéra are unleavened and baked cereal products with heterogeneous composition (grain chunks and ground flour).

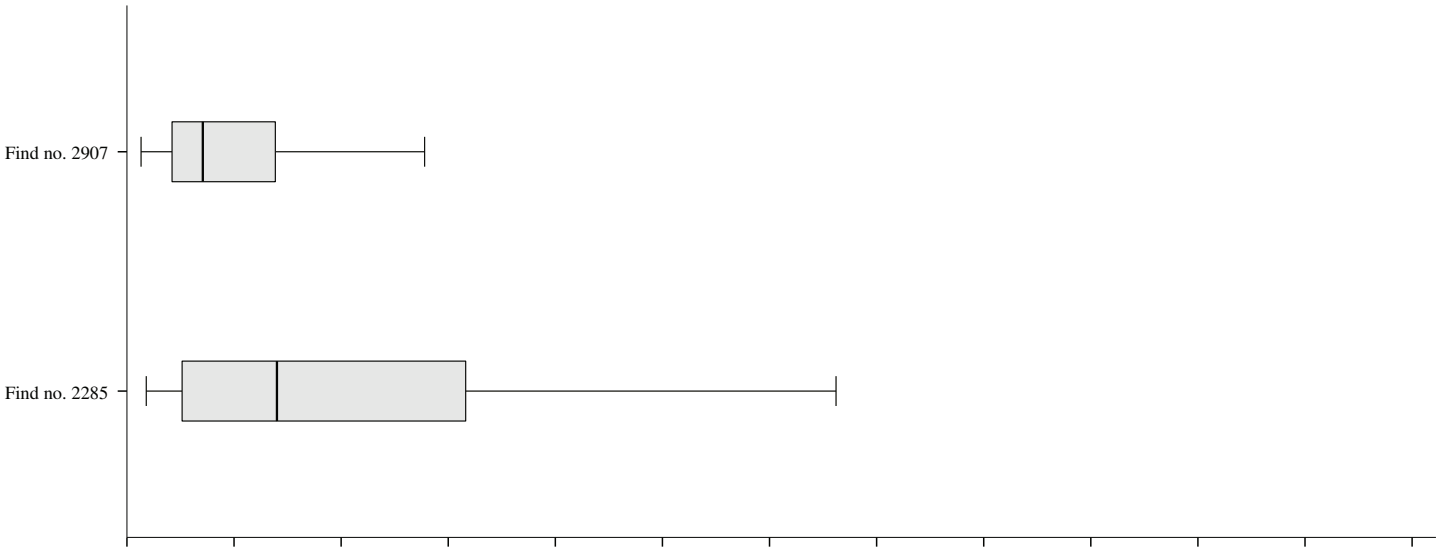


Fig 18. Grain size measurements of both finds. Symbols: °: extremal values, *: outliers. For raw data, see S1 and S3 Tables.

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The ring-shaped find no. 2285 has a basis of a less refined, rougher milling product. In the tradition of other such bread finds, the two bread-like objects would be classified as flat breads [16, 21]. Find no. 2285 bears evidence of barley, and find no. 2907 of a mixture of wheat and barley as raw materials, documenting that flat breads can indeed be composed of other cereals than barley, and of mixtures of more than one cereal. The celery fruit in find no. 2907 seems to be the first evidence for the use of bread condiments in the European Neolithic. Given the concentration of grinding stones and bran fragments in the southern part of the settlement, the area where both bread-like objects were excavated, their place of discovery may very well be their place of production.

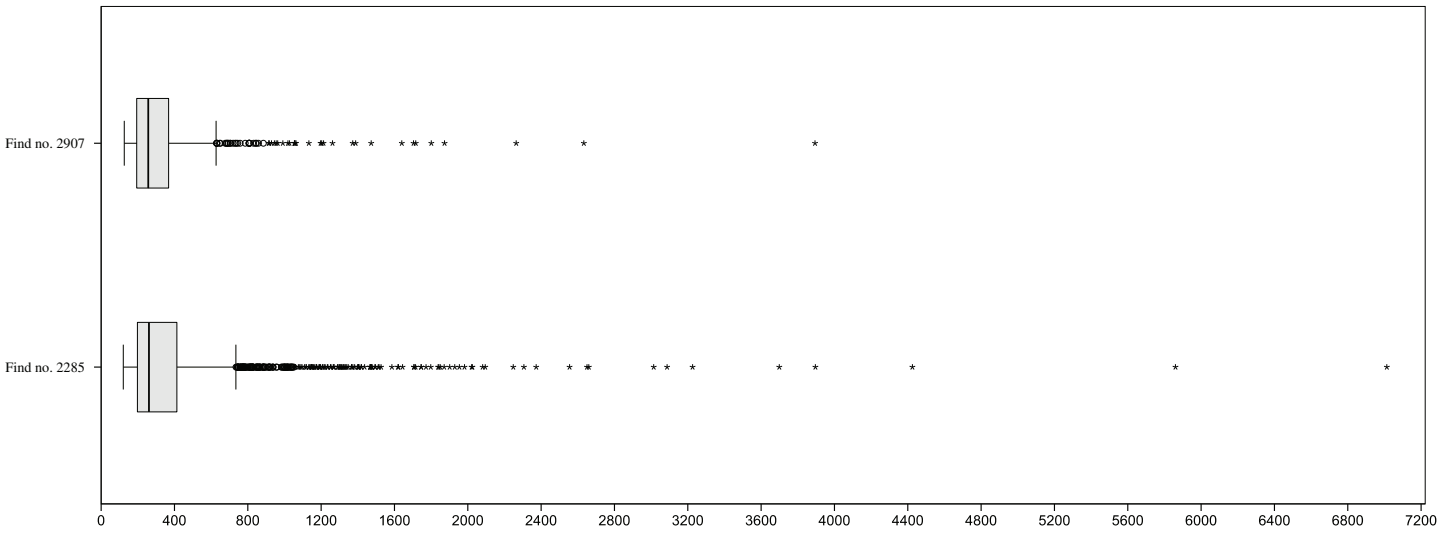


Fig 19. Cavity measurements of both finds. Symbols: °: extremal values, *: outliers. For raw data, see S2 and S4 Tables.

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We suggest establishing a standardised and structured laboratory protocol for analysing archaeological "bread" remains in order to allow for a general comparability of data from such finds [14, 20, 45]. The current paper proposes a general framework for such an approach. Ann-Marie Hansson emphasised very fittingly, "(. . .) the necessity of looking upon our study material with an open mind and of not clouding our understanding of these old loaves by present-day bread concepts" [2].

Supporting information

S1 Table. Particle measurements of find no. 2285. Raw data of the histogram in Figs 13 and 17.
(XLSX)

S2 Table. Cavity measurements of find no. 2285. Raw data of the histogram in Figs 14 and 18.
(XLSX)

S3 Table. Particle measurements of find no. 2907. Raw data of the histogram in Figs 15 and 17.
(XLSX)

S4 Table. Cavity measurements of find no. 2907. Raw data of the histogram in Figs 16 and 18.
(XLSX)

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Valamoti S. M., Jacomet S., Stika H.-P. & Heiss A. G. (2017) The PLANTCULT Project: identifying the plant food cultures of ancient Europe. *Antiquity* **91** (358) e9. doi: 10.15184/aqy.2017.130

The PLANTCULT Project: identifying the plant food cultures of ancient Europe

Soultana-Maria Valamoti[1,*], Stefanie Jacomet[2], Hans-Peter Stika[3] & Andreas G. Heiss[4]

Project Gallery

Plant foods are closely connected to cultural, social and economic aspects of human societies, both past and present. Food-preparation techniques and the etiquette of consumption involve complex interactions of natural resources and human cultures. During European prehistory, these changes included the shift to sedentism, the cultivation and domestication of plants, food storage, the production and exchange of alcoholic beverages and luxury foodstuffs, and the continuous adaptation of established culinary practices to newcomers in fields and gardens.

The ERC-funded PLANTCULT Project explores the role of the culinary transformation of plant ingredients in the shaping of social and cultural identities during prehistory, and the contribution of plant foods to social cohesion and differentiation, including the emergence of elites, in daily, communal or special consumption contexts. Our aim is to identify culinary cultures and their transformation over time across a large region, stretching from the Aegean to Central Europe, and focusing on several key sites rich in the remains of plant foods such as bread, beer, oil and wine (Figure 1). Each part of this region presents a different trajectory of social development under influences from the Eastern Mediterranean and Central Asia. We wish to understand the role of culinary practice and innovation in shaping these trajectories; the chosen study area allows us to explore an east-west dynamic at a wide geographic scale.

An integrated methodology

The project adopts an integrated approach that combines plant food remains, processing equipment, ancient written sources, experimental archaeology and ethnography (Figure 2). The remains of food plants, however, form the focus of our investigation. Ancient samples from key sites are being studied in detail and will involve the development of new

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Figure 1. Study area with key sites. 1) P.O.T.A. Romanou; 2) Limnochori; 3) Angelochorio; 4) Archontiko; 5) Agios Athanasios; 6) Karaburnaki; 7) Mesimeriani Toumba; 8) Dikili Tash; 9) Provadia; 10) Kapitan Andreevo; 11) Vaskovo; 12) Kush Kaya; 13) Sokol; 14) Karanovo; 15) Ada Tepe; 16) Yabalkovo; 17) Kapitan Dimitrievo; 18) Bresto; 19) Mursalevo; 20) Prigglitz-Gasteil; 21) Haselbach 'Im äußeren Urban'; 22) Stillfried an der March 'In der Gans'; 23) Roseldorf Sandberg; 24) Seewalchen Sprungturmgrube; 25) Weyregg II; 26) Lenzing; 27) Mondsee Station See; 28) Arbon Bleiche 3; 29) Hornstaad-Hörnle IA; 30) Zurich-Parkhaus Opéra; 31) Delemont/En la Pran; 32) Allel/Les Aiges; 33) Twann; 34) Thunstetten.

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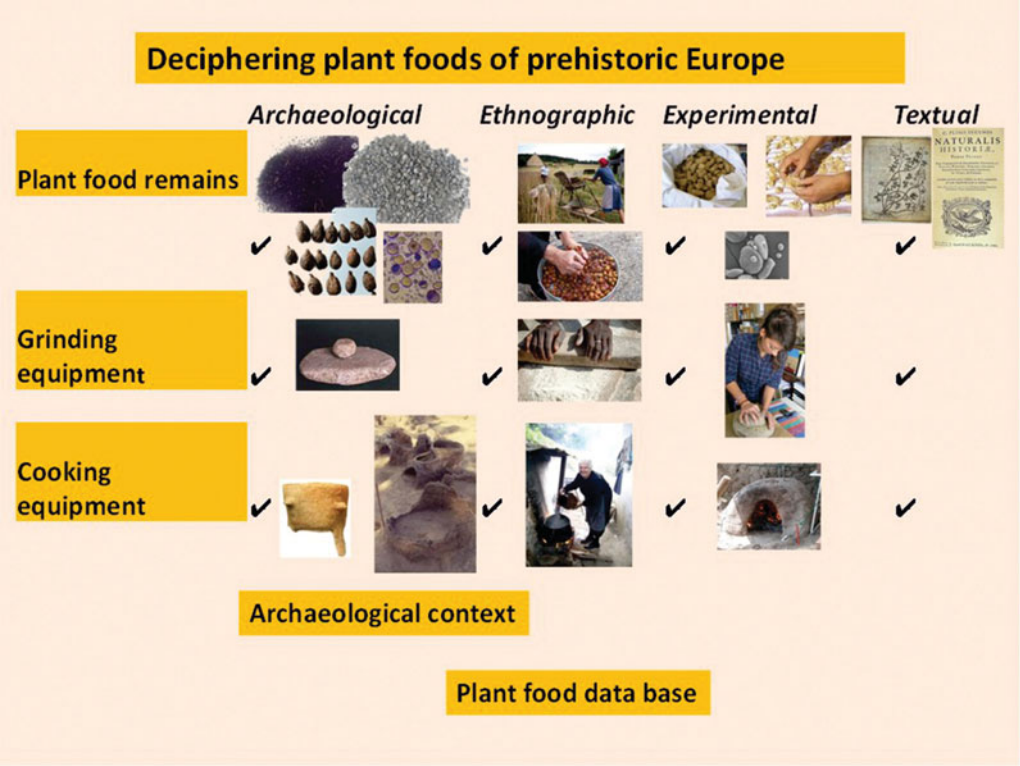


Figure 2. The PLANTCULT Project: an integrated research model.

methodological tools. To this end, a significant body of material (Figure 3) will be examined by stereomicroscopy and scanning electron microscopy (SEM), and will be interpreted by comparison with experimentally generated samples. The latter will be created using observations based on archaeological materials, ethnographic records and ancient texts. For example, pilot investigations have explored the effects of food processing, such as grinding and boiling, on grain morphology (fracture surfaces and endosperm structure, e.g. Valamoti 2002, 2011; Valamoti *et al.* 2007, 2011). Analyses of the components and production traits of ancient finds of bread (Heiss *et al.* 2015), grape juice extraction and fermentation (Valamoti *et al.* 2007; Garnier & Valamoti 2016) and beer-making (Stika 2011) demonstrate the need to develop new methodological tools for the effective analysis of archaeobotanical samples. The project will explore microscopic structures (Figure 3e–f) both in the ancient and the modern experimental samples, which will allow for the proper identification of different plant foods in the archaeobotanical record. We will record which plants were used as foods and the ways that they were transformed into meals, and we will explore why specific food choices, both staples and special food substances, such as alcohol and oil, changed over time and what their links were to emerging social hierarchy.

As the type and scale of food-preparation equipment are closely linked to culinary practice and socio-economic identities, we will address variability and change in

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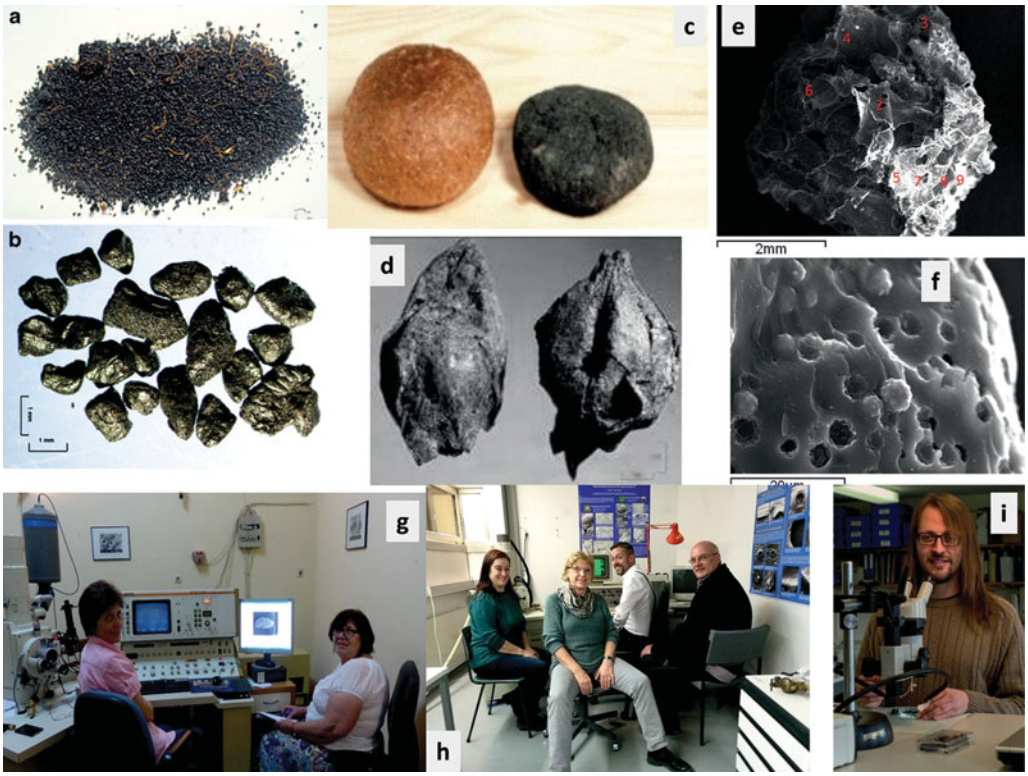


Figure 3. Examples of ancient plant foods that will be studied by SEM. Greece: a) ground wheat 'bulgur' (Mesimeriani Toumba); b) detail of ***a****; Switzerland: c) bread (Twann, 329_1981_82_400_2.jpg, © Archäologischer Dienst Bern); d) grape pressings (Dikili Tash); e–f) Bulgaria: 'food' fragments from Kush Kaya (Popov* et al. *in press); g) SEM work at Aristotle University of Thessaloniki (L. Papadopoulou, Tz. Popova); h) University of Hohenheim (S.M.V., A.G.H., H.-P. S.); i) University of Basel (F. Antolin).*

food-preparation technologies by assembling information on stone grinding tools, cooking facilities and pottery, and the plant macro- and micro-remains trapped within them. Associations between cooking, food sharing and alleged household individualisation processes (cf. Halstead 1999) will thus be explored. A database of plant food ingredients (Kreuz & Schäfer 2002), plant foods (ancient and experimental), equipment and archaeological contexts will form the basis for mapping culinary signatures across the study area.

Samples of ongoing work

Archaeobotany and grinding technology (Figure 4)

We will use experimental and ethnographic information to explore the association between plant ingredients, the raw materials used for tools and grinding productivity. The resulting use-wear traces and plant micro-remains will be employed as a middle-range device to explore archaeological finds. They will also form a reference database.

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Figure 4. Procurement (T. Dimoudis, N. Kardakos) and manufacture (A. Palomo) of grinding tools for experiments (P. Lathiras, E. Almasidou). Studying use-wear of experimental grinding stones at PLANTCULT headquarters, KEDEK (Centre for Interdisciplinary Research and Innovation, AUTH) (M. Bofill & D. Chondrou).

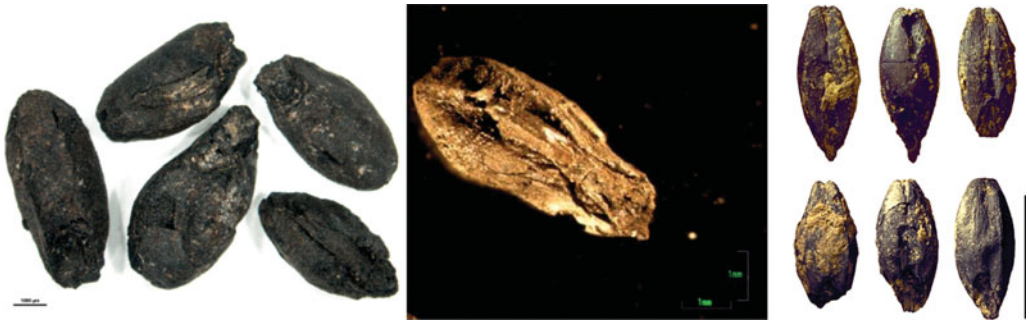


Figure 5. Sprouted barley grains from Bronze Age Argissa Magoula (2100–1700 BC, photographs Lower Saxony Institute for Historical Coastal Research, Wilhelmshaven), Archondiko Giannitson (2100–1700 BC) in Greece, and Hochdorf in Germany, fourth century BC (Stika 2011).

The interface between beer and wine cultures (Figure 5)

By using archaeobotanical and textual evidence, together with residue analyses, we are exploring beer- and wine-making. The interface between wine and beer cultures will be explored on a wide regional scale; for example, the Mediterranean *vs* Central Europe. But we will also explore this interface at a regional scale. Taking Greece as a case study, our initial research reveals that assumptions about wine-making and -consumption over the

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Figure 6. Collecting modern ethnographic data (clockwise from top left): acorn harvesting at Grevena; winnowing grass-pea on Corfu; making grape syrup at Grevena; making Grünkern *(green-harvested and roasted/smoked spelt), recorded by Marian Berihuete Azorín; S.M. Valamoti roasting acorns for experimental foods.*

longue durée may be wrong, as archaeobotanical finds indicate Bronze Age beer-making in Greece.

Plant foods from prehistory to the present (Figure 6)

The project is also undertaking ethnographic work on specific plant foods that were probably used in the past; for example, split pulses, *Grünkern* (green-harvested and roasted/smoked spelt) and wine and grape syrup. This will not only inform our archaeological inquiries, but also open the way towards connecting our research with contemporary society and small companies in the food sector.

The PLANTCULT Project started in April 2016 and is hosted by Aristotle University with three partner institutions: the University of Basel, the University of Hohenheim and the Austrian Academy of Sciences. Our research will allow us to explore how the powerful sensory experience of food preparation and consumption transformed nature into culture, shaped collective memory and identity, and contributed to the emergence of hierarchical societies across large parts of Europe. In this way, we aim to contribute towards the growing awareness of Europe's culinary heritage.

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The PLANTCULT team

The project consists of 47 members (including the principal investigator, S.M.V. and partners S.J., H.-P.S. and A.G.H.). The project postdoctoral researchers are: F. Antolin (University of Basel), M. Bofill, A. Bourliva, M. Berihuete-Azorín (University of Hohenheim), A. Dimoula, I. Hristova, E. Kalogiropoulou, S. Laparidou, M. Ntinou, C. Pagnoux and A. Palomo. The project PhD students are: A. Anagnostoudis, T. Bekiaris, D. Chondrou, S. Michou, D. Nenova, I. Ninou, C. Petridou, G. Prats, Th. Roustanis, K. Symponis, N. Vouronikou, P. Tokmakides and A. Tzelepidou, all based at Aristotle University of Thessaloniki unless otherwise indicated. Project team members contributing specialist advice and material are: N. Alonso, A. Bakalaki, L. Bouby, O. Craig, G. Fiorentino, V. Fyntikoglou, M. Ivanova, A. Kreuz, E. Marinova, C. McNamee, P. Nigdelis, V. Zech-Matterne, L. Papadopoulou, K. Pavlidis, Tz. Popova, S. Prevost-Dermarkar, E. Papadopoulou, M. Primavera, H. Procopiou, J.F. Terral, K. Tokmakides, G. Tsartsidou, Z. Tsirtsoni and S. Vergopoulos.

Further details on the project are available at http://plantcult.web.auth.gr/index.php/en/

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ORIGINAL PAPER

Inside sacrificial cakes: plant components and production processes of food offerings at the Demeter and Persephone sanctuary of Monte Papalucio (Oria, southern Italy)

Milena Primavera[1] · Andreas G. Heiss[2] · Maria S. Valamoti[3] · Gianni Quarta[4] · Maurizio Masieri[4] · Girolamo Fiorentino[1]

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Abstract
Well-preserved finds of sacrificial cakes from the Sanctuary of Demeter at Monte Papalucio (Oria, southern Italy, VI-III cent. B.C.) are among the most famous bread-like remains from the ancient Mediterranean region. These unusual finds represent direct and rare evidence of the food products offered as part of religious practice by the indigenous (*Messapian* people) inside a particular 'place of encounter', a place of worship closely related to the south Italian colonial Greek world (*Magna Graecia*). This paper offers for the first time a detailed analysis of the internal structure of these bread-like remains using *Environmental Scanning Electron Microscope* and Image Analysis in order to detect plant-based ingredients and the techniques employed in the production and cooking processes. Moreover, considering the cultural context, the sacrificial cakes from Oria Sanctuary offer a rare opportunity to directly compare the 'cake' finds and ancient written Greek sources, allowing for a deeper understanding of the *chaînes opératoires* of cereal processing in the past as well as the perception and role of these products among the ancient societies of the region. The contribution presents and discusses the results of these analyses and offers valuable, integrated information hidden inside the ancient cakes. A better understanding of the reciprocal influences and possible divergences between native and Greek culture is achieved by taking into consideration ancient Greek tradition on bread and cakes in sacred contexts and the interplay.

Keywords Archaeological bread-like object · Tissue analyses · Ritual offering · Southern Italy · Messapia · Archaic-Hellenistic period

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Introduction

Bread and cake offerings in written sources

Bread held a very important role in the ancient Mediterranean world as is clearly evident for a wealth of written sources, especially as regards ancient Greece. In a recent paper presented by Valamoti et al. (2016), cereal species, as well as the forms in which they were consumed in antiquity, were examined on the basis of ancient texts. The texts were thoroughly researched using *Thesaurus Linguae Grecae* (TLG) and querying specific key-words corresponding to species identified in the archaeobotanical record of Greece. This is ongoing research in the context of project PLANTCULT with the aim to make this information widely available through an online database currently under construction (http://plantcult.web.auth.gr/index.php/en/). The research into ancient Greek texts

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is very revealing of the many species used in bread making, the different grades of flour and the types of preparing theme (e.g. poppy seed bread, ash-baked bread, barley rusks). In addition to daily bread, a large variety of ritual bread types were offered to deities, Demeter in particular. The texts mention different types of cereal-based preparations corresponding to different names and rituals; those breads specifically dedicated to the agricultural cycle and Demeter were *axaini*, *thargilos*, *myllos* and *hygieia* (Table 1).

A*xaini* was a large bread prepared for the Thesmophoria celebration, a women's festival widespread in the Greek world, celebrated at the end of the summer, its mysteries forbidden to men; it was a celebration not only of Demeter and the gifts of earth but also of the female condition and fertility (Lowe 1998). *Thargilos* (or *thalysios*) was the first bread baked immediately after the cereal harvest in a celebration honouring Apollo and Artemis; *myllos*, a kind of bread prepared for the Thesmophoria in Sicily. Barley flour mixed with wine and olive oil is mentioned as a component of 'hygieia', a sacrificial 'bread'.

Yet, although the amount of Greek written sources describing daily as well as special ritual breads is noteworthy, direct archaeological evidence of these products (bread, cakes, biscuits, pastry, etc.) is rare and/or difficult to recognise. Microscopical analyses of these remains are still rare and often focus on prehistoric cereal preparations (such as in Lannoy et al. 2002; Heiss 2014; González Carretero et al. 2017; Heiss et al. 2017). In contrast to these, finds of cereal preparations from antiquity bear the enormous potential to directly compare scientific data with numerous epigraphic and written sources, as e.g. seen for Pharaonic Egypt (Samuel 2002), the Roman period (Lannoy et al. 2002; Heiss et al. 2015), or the Middle Ages (Hansson 1997; Lannoy et al. 2002), allowing for a deeper understanding of the *chaînes opératoires* of cereal processing in the past, as well as the perception and role of these products in a past society. One of the most famous example of well-preserved finds in ancient Mediterranean region is represented by the charred sacrificial cakes from the Demeter and Persephone Sanctuary of Monte Papalucio, Oria, southern Italy (Ciaraldi 1997, 1998; Fiorentino 2008), an indigenous place of worship closely related to the Greek world.

Archaeological context and cultural/ritual background

The cult area of Monte Papalucio lies on the western slope of a natural hill surrounding the Messapian centre of Oria (Brindisi, Italy). The settlement was situated in a strategic position, in the middle of axes that connect the city of Taranto, and Magna Graecia world, with the Salento area and its indigenous population, the Messapians (Fig. 1). The emergence of the Sanctuary during the Archaic period (VI-V century B.C.) seems to coincide in several aspects to the intensification of the contacts between Messapian settlements and south Italian Greek colonies, the general re-organisation of the settlement and a more extensive exploitation of the countryside (D'Andria 1991; Mastronuzzi 2013). At first, the Sanctuary was placed between the urban space, the necropolis and the farmlands; later, during the construction of the second city walls (IV-III century B.C.), it was included in the settlement area.

As suggested by epigraphic evidence (a retrograde writing reported on a *hydria* fragment; see Pagliara 1979, 1983) and archaeological findings (many Terracotta figurines sit on throne; see Mastronuzzi 2013), the Messapian Sanctuary was dedicated to the cult of Demeter and Persephone (also called Kore), two Greek deities associated to the agricultural cycle and fertility rituals.

Consequently, this place of worship may be defined as a 'place of encounter' between the native and the Greek form of the cult of Demeter (Hinz 1998; Mastronuzzi 2008); it probably was a place where reciprocal influences in ritual, including the cultural and symbolic values of plant and food offerings, were performed (Lombardo 1995; Hansson and Heiss 2014).

According to written sources in the ancient Greek culture, cereals were typically associated with Demeter and Kore, her daughter who, in fact, symbolises the power of growth within the cereal kernel. A number of Festivals in honour of Demeter took place in ancient Greece according to the agricultural calendar and in relation to those processes important to the crops such as sowing, harvesting, threshing, pounding and baking (Brumfield 1976).

The religious festivals held in honour of the goddess were associated with specific ritual breads and the symbolic association of Demeter, and bread is clearly visible in ancient texts (Table 1). In the Homeric Hymn to Demeter (Foley 1994), the goddess myth symbolises the origin of agriculture and of bread; one of the epithet used for Demeter is «Μεγάλαρτος», probably with reference to the existence, at Skolos in Boiotia—as reported by Athenaeus (Athen. III 109b)—of the statues of Megalartos, "Great Wheat-loaf", and Megalomazos, "Great Barley-cake" (Braun 1995). There are also epithets such as «σιτὼ» (Sito) and «σιμαλὶς» (Simalis), used for the goddess in the city of Syracuse (Polemo, in Athenaeus, *Deipnosophistae* 3.73). There also seems to be a Messapian king mentioned by Athenaeus, called Artos, the Greek word for bread, showing a close relationship of Messapians with bread.[1] In addition, Pausanias (I.38.6) described sacred fields where the cereal harvest was used for ritual purposes; these fields were placed in the Rarian plain, overseen by priests of the Eleusinian

[1] Αθήναιος, Δειπνοσοφισταὶ (Epitomae 2.1.23): Ὅτι Ἄρτος βασιλεὺς ἦν Μεσσαπίων ἐν Ἰαπυγίᾳ. ὅτι παρὰ Συρακουσίοις τιμᾶται Δημήτηρ Σιτὼ καὶ Σιμαλία.

Table 1 Ritual bread types in Greek written sources

Name of bread	Source	Ritual context	Ingredients	Original ancient text	English translation
Ἀχαίνη *Achaini*	Αθήναιος, *Δειπνοσοφισταὶ* 3.74	Θεσμοφόρια Thesmophoria	Coarsely ground, possibly wheat. Bread rich in fat.	*τούτου τοῦ ἄρτου* μνημονεύει *Σῆμος ἐν η΄ Δηλιάδος λέγων ταῖς θεσμοφόροις γίνεσθαι. εἰσὶ δὲ ἄρτοι* μεγάλοι, *καὶ ἑορτὴ καλεῖται* Μεγαλάρτια *ἐπιλεγόντων τῶν φερόντων·ἀχαΐνην στέατος ἔμπλεων τράγου.*	There is also a loaf called the achaeinas. And, this loaf is mentioned by Semus, in the eighth book of his Delias; and he says that is made by the women who celebrate the Thesmophoria. They are loaves of a large size. And, the festival is called Megalartia, which is a name given to it by those who carry these loaves, who cry—'Eat a large achaeinas, full of fat'. (Transl.: C. D. Yonge).
Θάργηλος ἡ *θαλύσιος* *Thargilos or thalissios*	Αθήναιος, *Δειπνοσοφισταὶ* 3.80	First fruits harvest (*ἀπαρχαὶ*)	Not indicated	*ὥσπερ καὶ τὸν θάργηλον, ὅντινες καλοῦσι θαλύσιον – Κράτης δ' ἐν β΄ Ἀττικῆς διαλέκτου θάργηλον καλεῖσθαι τὸν ἐκ τῆς συγκομιδῆς πρῶτον γινόμενον ἄρτον.*	...as also he did the thargelus, which some call the thalysius. But Crates, in the second book of his treatise on the Attic Dialect, says that the thargelus is the first loaf made after the carrying home of the harvest. (Transl.: C. D. Yonge).
Μυλλὸς *Myllos*	Αθήναιος, *Δειπνοσοφισταὶ* 14.56	Thesmophoria	Sesame, honey	*Ἡρακλείδης ὁ Συρακόσιος ἐν τῷ περὶ Θεσμῶν ἐν Συρακούσαις φησὶ τοῖς Παντελείοις τῶν Θεσμοφορίων ἐκ σησάμου καὶ μέλιτος κατασκευάζεσθαι ἐφήβαια γυναικεῖα ἃ καλεῖσθαι κατὰ πᾶσαν Σικελίαν μυλλοὺς καὶ περιφέρεσθαι ταῖς θεαῖς.*	Heraclides the Seracusan, in his treatise on Laws, says that in Seracuse, on the principal day of the Thesmophorian festival, cakes of a peculiar shape are made of sesame and honey, which are called μύλλοι throughout all Sicily, and are carried about as offerings to the goddesses. (Transl.: C. D. Yonge).
Ὑγίεια *Hygeia*	-Αθήναιος, *Δειπνοσοφισταὶ* 3.82 -Ηρώ(ν)δας, *Μιμίαμβοι* 4.93–94 -Ιούλιος Πολυδεύκης, *Ὀνομαστικὸν* 6.76)	Athenaeus does not mention a special ritual context. In Ηρώ(ν)δα's *ὑγίεια* is mentioned in the context of a celebration possibly to Apollo. In Πολυδεύκης it is mentioned as an offering to Trofonius, god or heroe of Boeotia.	No ingredients specified. Athenaeus characterises it as maza, indicating the use of barley.	Αθήναιος: *ὑγίεια δὲ καλεῖται ἡ διδομένη ἐν ταῖς θυσίαις μᾶζα ἵνα ἀπογεύσωνται.* Ηρώ(ν)δας: *...καὶ ἐπὶ μὴ λάθηι φέρειν, αὐτῆ, τῆς ὑγιίης †λωι† πρόσδος* Πολυδεύκης: *μελιτοῦττα μὲν Τροφωνίῳ ὡς ἀρεστήρ, καὶ ὑγίεια ὁμοίως.*	But, the barley cake, which is given in sacrifices to be tasted by the sacrificers, is called hygea. (Transl.: C. D. Yonge)
Πέμματα *Pemmata made of barley*	Παυσανίας, *Ἑλλάδος περιήγησις* 1.38.6	Not specified	Barley	*τὸ δὲ πεδίον τὸ Ῥάριον σπαρῆναι πρῶτον λέγουσι καὶ πρῶτον αὐξῆσαι καρπούς, καὶ διὰ τοῦτο οὐλαῖς ἐξ αὐτοῦ χρῆσθαί σφισι καὶ ποιεῖσθαι πέμματα ἐς τὰς θυσίας καθέστηκεν.*	They say that the plain called Rharium was the first to be sown and the first to grow crops, and for this reason, it is the custom to use sacrificial barley and to make cakes for the sacrifices from its produce. (Transl.: W. H. S. Jones)

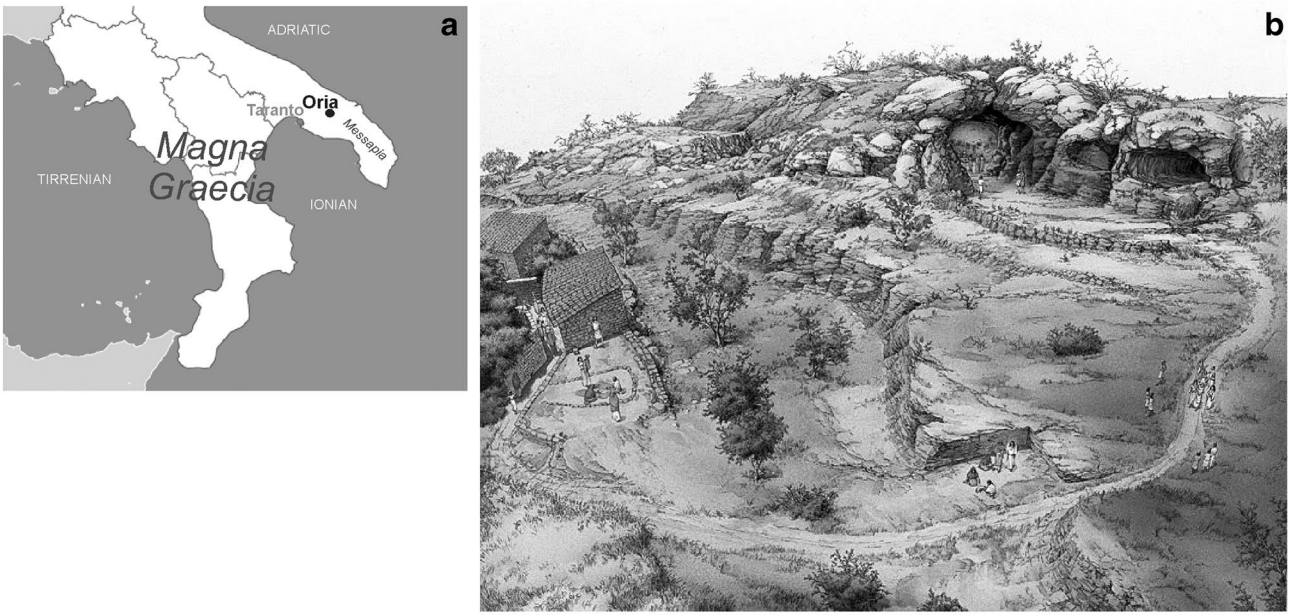


Fig. 1 **a** Geographical map of southern Italy reporting the *Messapian* territory, with the location of Oria archaeological site, and the *Magna Graecia* world. **b** The cult area of Monte Papalucio at Oria (Brindisi-Italy): drawing of the surrounding landscape during the IV-III century B.C. (drawing by InkLink-Firenze, in Mastronuzzi 2013, p. 223)

temple, and were considered to be the first lands to have been cultivated and the first to have been harvested. Here, according to Pausanias, barley in particular was cultivated with the purpose of being used in the manufacture of 'sacrificial cakes' (Brumfield 1976, p. 59, 152, 172).

A likely reproduction of such sacrificial cakes is archaeologically represented by the terracotta likna (λίκνα), the winnowing baskets, recovered as votive offerings from the Sanctuary of Demeter and Kore on Acrocorinth (Greece, VII-II century B.C.). The likna filled with cakes, carefully described by Brumfield (1997), were associated with the sacrifices and sacred meals held in the Sanctuary, and probably, they symbolised the real cakes that were offered to the goddess.

In their different shapes and decorations (Fig. 2), these cakes show incredible resemblance with the burnt cakes recovered in the Sanctuary of Demeter at Oria, Monte Papalucio (Ciaraldi 1997). Therefore, these unusual finds represent direct and rare evidence for the food products offered by indigenous people inside this particular place of encounter. Considering that most of the information given by written sources come from the Greek world, the detailed analysis of 'local' cakes seems crucial for understanding further aspects of the cultural dimension of the foodstuff (in terms of identity, reciprocity, diversity and so on) expressed through ingredients and processes of production.

Given recent considerations addressing incongruences between the terminologies of archaeological bread remains versus hypothetical *chaînes opératoires* of their production (Heiss et al. 2017), it has to be stated that the terms used in the current paper ('cakes', 'bread', 'biscuits', *tarallini*) do not base on the archaeological finds themselves, but rather on their historical or modern counterparts.

General Archaebotanical analysis

Previous archaeobotanical analysis performed by Ciaraldi (1997, 1998) on charred plant remains recovered during the excavations of the Sanctuary of Monte Papalucio has highlighted the presence of cereals, pulses and tree-fruit offerings. Among the cereals, very abundant were barley (above all *Hordeum vulgare* six-row form) and naked wheat (*Triticum aestivum/durum*), during both the Archaic and the Hellenistic period. Generally, the most common species on the site was faba bean (*Vicia faba* var. *minor*). Moreover, together with fruits (grape, olive, pomegranate, crab apple and fig[2]), a large amount of cakes and fragments of dough were recovered and interpreted as burnt food offerings.

On the basis of macroscopic analysis, three different kinds of dough were previously identified: some bearing resemblance to modern filo-pastry (a dough layered, shapeless, probably containing fats); some others quite compact, with recognisable shapes, decorated or containing seeds, and for which the use of yeast was proposed; and a third type of dough, very compact and without cavities (Fig. 3) for which

[2] Some fig syconia are decorated with barley grains all around the rim (Ciaraldi 1997–1998, p.87, Fig. 7a)

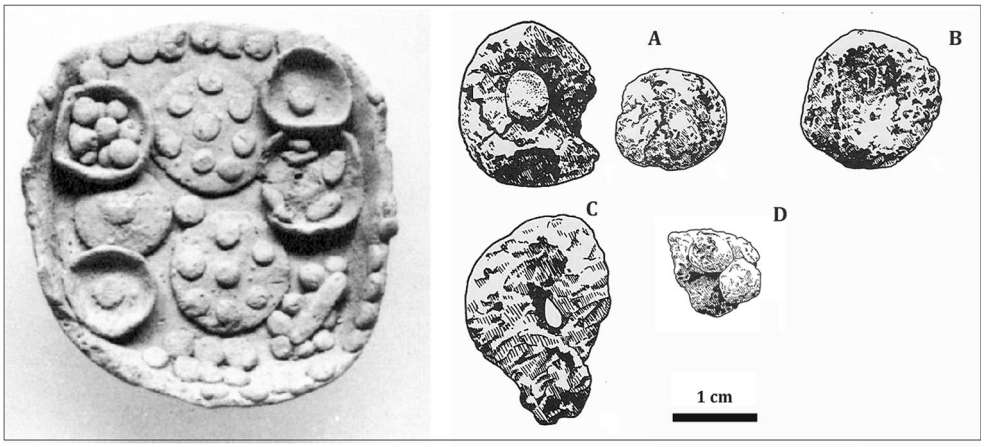


Fig. 2 Some of the *sacrificial cakes* represented in miniature clay *likna* recovered from the Sanctuary of Demeter and Kore on Acrocorinthin Greece (Brumfield 1997, pl. 47 n. 29) compared with the burnt cakes collected in the Sanctuary of Demeter at Oria, Monte Papalucio (drawings by Nigel Dobbs, in Ciaraldi 1997, 1998, p. 86)

the use of faba bean flour has been suggested on the base of ethnographic observations (Forti and Stazio 1983) and its high proportion in the archaeobotanical assemblage.

A first revision of the whole finds, including wood charcoals analysis, was carried out by Fiorentino (2008) who observed that some charcoal remains were classified as layered dough and that fragments of fig syconia were considered as round cakes containing fig seeds. As a result, a revision in the classification of the dough was necessary which led to the detailed microscopic analyses of these cakes presented in this contribution.

Materials and methods

The material examined consists of 21 cakes and 5 types of dough fragments reclassified according to their shape (recognisable or amorphous) and morphological features; the new classification carried out has resulted in: n. four morphotypes among the cakes (A = small round cakes, with or without central knob decoration, B = cakes edged, C = ring shaped cakes 'tarallino', D = cakes with knobs on rim) and n. three morphotypes in reference to the amorphous dough (1 = compact, 2 = porous, 3 = layered) (Table 2).

Different samples from each morphotype were collected and analysed in order to test the hypothesis of a connection

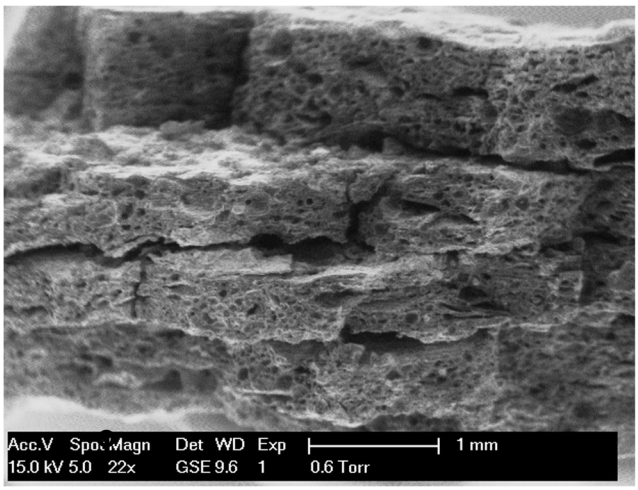


Fig. 3 Particular of the fractured surface of a very compact dough for which the use of faba bean flour has been supposed

Table 2 New classification of sacrificial cakes from the Sanctuary of Oria Monte Papalucio based on their shape and morphology

Shape	Morphology		ID
Recognisable	A	Small round cake (central knob)	A IX A3
			A IX A4
			AIX B4
			A IX B2
	B	Small round cake	B VI A3
			B VIII B3
			B IX B3
			B VI A1
			B IV B2
	C	Cake edged	C VIII A1
			C IX A2
			C X
			C IX B6
			C VIII A3
			C VI B1
		Ring shaped	D IX A5
			D IX B5
			D IX A6
			D VI A1
		Ring shaped decorated	E IX A1
		Cake (knobs around the rim)	F VI B3
Amorphous	1	Compact	G IX B1
	2	Porous	H VIII B2/1
			H VIII B2/2
			H IV A1
	3	Layered	I IV B2

between their shapes, morphological features, production techniques (grinding, sieving, leavening, boiling, baking, charring) and ingredients, taking also into account the cereal and pulse species identified in the archaeobotanical assemblages (whether barley, wheat or faba bean flour).

The approach used in the analysis of food remains was based on Environmental Scanning Electron Microscope investigations and Image Analysis of pictures captured using XL30 ESEM equipment (FEI company). *Environmental Scanning Electron Microscope* (ESEM) technology allows the study of objects made up of organic matter in its natural state (also in hydrate conditions) without the need to apply a conductive coater and overall, without damaging the sample. The ESEM technology is based on the presence of gas (in this case, it is water vapour) inside the sample chamber which allows to discharge the surface of the samples (McKinlay et al. 2004). The images were taken using a gaseous secondary electron detector (GSED) to produce a surface image. The operative conditions were those of low *vacuum* with different values of gas pressure and electronic beam voltage, depending on the type of the sample. In the majority of the performed analyses, the voltage of electron beam and that of the gas pressure were 15 kV and 0.6 Torr, respectively. In such operative conditions, the analysed samples did not show damage on the surface allowing us to gather good quality images for further analysis.

More specifically, the aim of the ESEM examination is to reveal the cereals (in this case, wheat and/or barley) or other possible plant-based ingredients (in particular faba bean) contained in bread-like specimen examined using micro-anatomical tissue analysis, according to criteria initially developed for food science (e.g. Winton and Winton 1932, 1935), later adapted for archaeobotanical finds (e.g. Körber-Grohne and Piening 1980; Dickson 1987), and formalised in recent years by Heiss (see Heiss 2008, 2010, 2012, 2014; Heiss et al. 2015, 2017) and González Carretero et al. (2017). Even in a charred state, the cell patterns of certain characteristic pericarp, testa and more inward tissue layers allow the identification of some of the species used as components. In addition, measurements of their particle sizes and the recording of different patterns of the damage in endosperm cells (modification in starch granules; see e.g. Crowther 2012) were performed in order to shed light on the techniques employed in the flour production (grinding, sieving) as well as in the cooking processes (boiling, baking, charring).

Image analysis of fractured surfaces of eight objects (one for each class of finds) was carried out in order to measure the size distribution of the gas bubbles observable in the dough, allowing for an estimation of the role of microbial fermentation of the objects prior to baking (Scanlon and Zghal 2001; later adapted in Heiss et al. 2015, 2017). Images were captured under the stereo microscope with illumination in a steep angle, resulting in high-contrast imagery of reflecting charred dough (bright) versus cavities (black). These images were then converted to grayscale, and blurred parts were manually removed in Photoshop. Image analysis was then carried out using ImageJ (Rasband 1997–2009), measuring particle sizes using the 'fit ellipse' function on the thresholded black-and-white versions of the images. Only the maximum diameters of the measurements were evaluated.

Results

A total of 160 pictures, pointing out cereal tissue remains, were captured by ESEM and examined in their features. Measuring the tissue remains resulted in the observation that most of the fragments of bran and chaff residues ranged between 150 and 300 μm in size, while only few fragments, notably large grain chunks, exceeded 500 μm in length. The results of the analysis are presented in Table 3 and in Figs. 4 and 5, categorised according to the morphotypes of cakes and dough:

Type A = all the samples examined indicate that the most frequent finds are patches of aleurone tissue arranged in a single layer as in most cereals, excluding barley. In some cases, numerous fragments of transversal cells were observed and their thickened walls, characterised by conspicuous pitting, reveal the use of wheat (*Triticum*) as a component of the cakes type A. In addition, one of the sample shows a grain fragment included into the dough, whose shape in cross-section seems to resemble a naked wheat.

Type B = the results obtained by the micro-analysis of edged cakes indicate the recurring presence of typical single-layered aleurone tissue fragments. The recovery in only one case (ID = C VI B1) of multi-layered aleurone cells, exclusive of barley, found together with transversal cell layers characteristic of wheat (thick and pit walls) suggests the use of both cereals into the flour.

Type C = as regards the ring shaped cakes, defined 'Tarallini', the all-observed tissue fragments, mainly single-layered aleurone cells, are not related to particular cereals; however, they allow to exclude their belonging to barley.

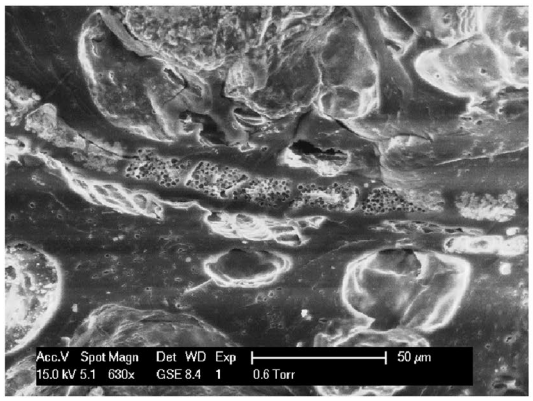
Type D = the identification of transversal cells (defined by thickened and pitted walls), together with aleurone cells arranged in single-layers, suggests for the cakes with knobs on the rim, their origin from wheat bran.

As regards the amorphous dough—whether compact (1), porous (2) or layered (3)—the analyses via ESEM allow to recognise several cereal cell tissue fragments; these are

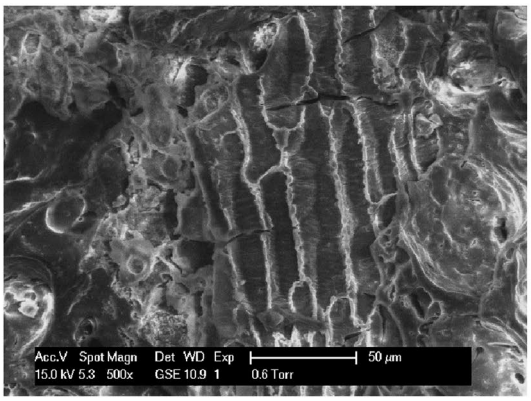
Table 3 List of the main cereal tissue remains observed into the cakes and dough from Oria: Data are summarised according to the different samples (ID) and grouped according to morphotypes

Morphotype		Bran			Chaff	Starch grains	Other	Components
	ID	Long. cells	Transv. cells	Aleur. cells				
Recognisable								
A	A IX A3	x	Thickened and pitted	Single-layer				Cereals; *Triticum* sp.
	A IX A4		Thickened and pitted	Single-layer				Cereals *(excluded Hordeum); Triticum* sp.
	AIX B4	x	Thickened and pitted	Single-layer				Cereals (excluded *Hordeum);Triticum* sp.
	A IX B2	x		Single-layer			Fungal hypha	Cereals; Cereals (excluding *Hordeum*); *Triticum* sp.
	B VI A3		Thickened and pitted	Single-layer			Grain micro-fragment	Cereals (excluded *Hordeum*);*Triticum*; Naked Wheat
	B VIII B3			x				Cereals
	B IX B3	x	Thickened and pitted	Single-layer			Fungal hypha	Cereals; Cereals (excluded *Hordeum);Triticum* sp.
	B VI A1		Thickened and pitted	Single-layer			Grain micro-fragment	Cereals (excluded *Hordeum*); *Triticum* sp.
	B IV B2	x		Single-layer			Fungal hypha	Cereals (excluding *Hordeum*)
B	C VIII A1		x	Single-layer			Grain micro-fragment	Cereals (excluding *Hordeum*)
	C IX A2		Thickened and pitted	Single-layer	Glume/palea			Cereals; *Triticum*
	C X	Square pits		Single-layer	Glume tissue	x		Cereals (excluded *Hordeum*); *Triticum*
	C IX B6	x	Thickened and pitted	Single-layer				Cereals (excluded *Hordeum);Triticum*
	C VIII A3	x	x	Single-layer				Cereals (excluded *Hordeum)*
	C VI B1	x	Some thick-walled	Multi-layered			Fungal hypha	*Hordeum; Triticum*
C	D IX A5	x		Single-layer	Xilem tissue			Cereals (excluded *Hordeum)*
	D IX B5			Single-layer				Cereals (excluded *Hordeum)*
	D IX A6	x		Single-layer				Cereals (excluded *Hordeum)*
	D VI A1			Single-layer				Cereals (excluded *Hordeum)*
	E IX A1		x	Single-layer		x	Grain micro-fragment	Cereals (excluded *Hordeum*)
D	F VI B3		Some thickened and pitted	Single-layer	Glume tissue	x	Fungal hypha	Cereals (excluded *Hordeum*);*Triticum*
Amorphous								
1	G IX B1	x		Single-layer		x		Cereals (excluded Hordeum)
2	H VIII B2/1		x	Single-layer				Cereals (excluded *Hordeum)*
	H VIII B2/2		x	Single-layer			Grain micro-fragment	Cereals (excluded *Hordeum)*
	H IV A1	x		Single-layer	Glume tissue		Grain micro-fragment	Cereals (excluded *Hordeum*)
3	I IV B2	x	Thickened and pitted	Single-layer	Glume/palea tissue			Cereals (excluded *Hordeum); Triticum*

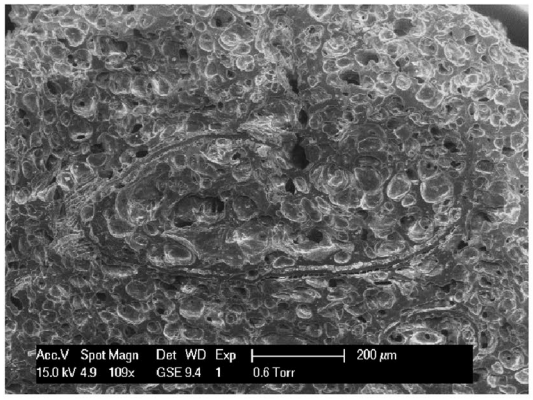
x indicate that the cells were recognised during the ESEM analysis, but their pattern are not diagnostic for components identification


Acc.V Spot Magn Det WD Exp 50 μm
15.0 kV 5.1 630x GSE 8.4 1 0.6 Torr

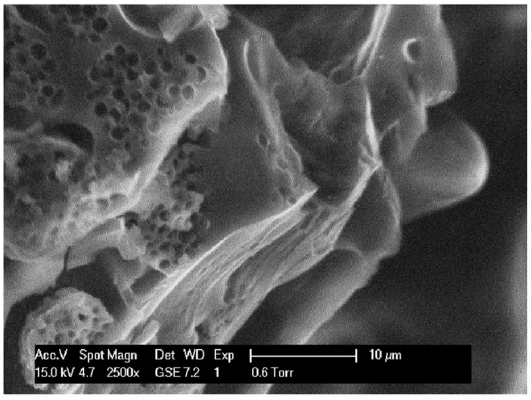
a


Acc.V Spot Magn Det WD Exp 50 μm
15.0 kV 5.3 500x GSE 10.9 1 0.6 Torr

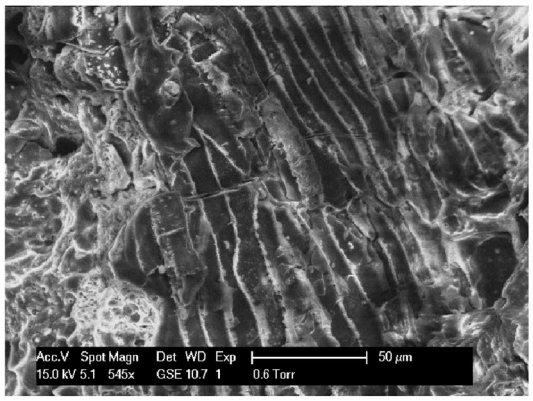
b


Acc.V Spot Magn Det WD Exp 200 μm
15.0 kV 4.9 109x GSE 9.4 1 0.6 Torr

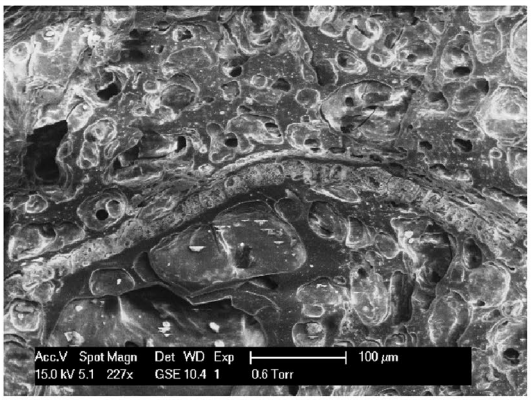
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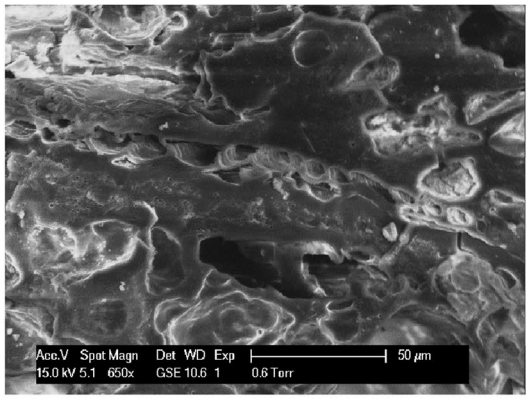
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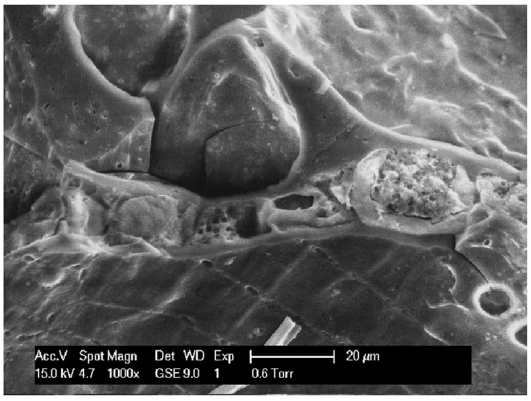
e


Acc.V Spot Magn Det WD Exp 100 μm
15.0 kV 5.1 227x GSE 10.4 1 0.6 Torr

f


Acc.V Spot Magn Det WD Exp 50 μm
15.0 kV 5.1 650x GSE 10.6 1 0.6 Torr

g


Acc.V Spot Magn Det WD Exp 20 μm
15.0 kV 4.7 1000x GSE 9.0 1 0.6 Torr

h

◀ **Fig. 4** ESEM Micro-anatomical tissue image analysis of the different cake morphotypes. Cake type A: **a** well-preserved single-layered aleurone cells, transversal cells and endosperm molten are also visible; **b** transversal cell layers with thickened and pitted cell walls; and **c** cereal grain fragment into the dough, all around the aleurone cells in a single layer. Cake type B: **d** multi-layered aleurone cells, **e** transversal cells thickened and pitted and **f** aleurone cells in cross section arranged in a single layer. Cake type C: **g** single-layered aleurone cells and endosperm structure heavily fused. Cake type D: **h** aleurone cells in a single layer

sometimes identified as wheat, but generally, we have no positive evidence for barley or any other plants.

In some cases, the endosperm cells appear modified at various degrees. Figure 6 describes the different patterns of the damage in endosperm cells and starch granules as well: Generally, the endosperm is molten and starch grains fused into a glassy continuous matrix; in rare cases, the starch granules, likely swell, occur even preserved inside the endosperm cell even if their original morphological characteristics appear modified.

The histograms of particle (i.e. maximum diameters of measured bubbles) measurements are given in Fig. 7 as histograms for the measured seven samples. In contrast to the initial hypothesis, bubble sizes were rather uniform throughout the sample material, with cavity sizes ranging between 20 and 250 μm, with only minor numbers exceeding 100 μm.

Discussion

Food can be anthropologically seen as an expression of identity, an expression of traditionalism, social status or social differentiation. Food is in fact culturally driven and culturally specific, so its study could reveal information about how humans manage their relationship both within and across cultural groups.

Food is not only the dish that is consumed; therefore, studies of ancient food remains require both analytical methods, in order to investigate its 'materiality', as well as contextual approaches able to understand the culture that led to its production and consumption; in this sense, we need to explore its materiality (different aspects of production) within its sociocultural context (Dietler and Hayden 2001; Fuller and Rowlands 2011; Hastorf 2017; Jones 2007; Twiss 2007; Valamoti 2017).

The detailed study carried out on the Oria finds allowed the collection of important data preserved inside the cakes, on the basis of which we can offer new insights into aspects of production as well as into the cultural dimension of ritual food offerings (Samuel 1999; Twiss 2012).

Components and flours

The results obtained according to micro-anatomical analysis via ESEM have revealed that as regards components, the flour used for making the Oria cakes and dough was, at least, cereal based. The frequency of wheat (*Triticum*) remains suggests that it may have been a regular component of the flour, even though we cannot fully exclude other possible cereals as ingredients; barley cell tissue (*Hordeum vulgare*) was also found inside a single sample, together with wheat tissue remains. As regards the supposed use of faba bean flour in the production of the compact dough (1), the analysis has not found any evidence for legume/pulses, at any rate on the investigated surfaces.

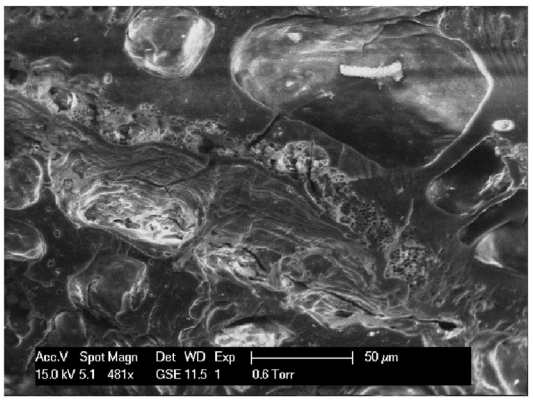
The measurements of the particle size range (bran and chaff tissues) indicate that the flour used for the cakes and dough must have been repeatedly milled or sieved after milling. Taking an example of modern standards as a reference, the used cereal meals would range between flour (particle size smaller than 212 μm, FAO 2016, CODEX STAN 152-1985) and semolina (particle size smaller than 315 μm, FAO 2016, CODEX STAN 178-1991).

Milling is the principal operation that generates different types of semolina and flour that go into the preparation of cereal-based foods (for direct consumption or for long-term preservation). As suggested by ethnographical examples in literature, the milling procedure involves different steps which depend on the type of cereals (naked vs hulled), type of querns and grinding actions, number and type of sievings (Alonso et al. 2014).

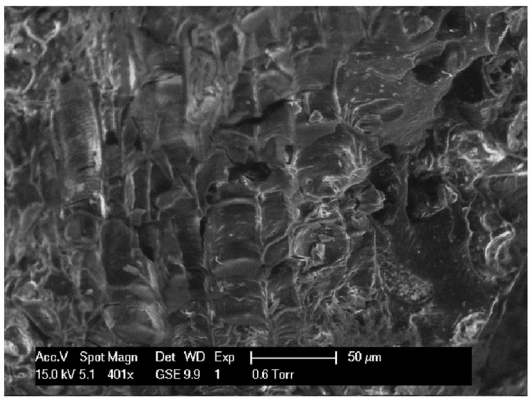
The preparation of ritual breads as those found at Monte Papalucio might have involved ritual grinding, as suggested by the recovery of saddle querns and mortars at the Oria sanctuary (Mastronuzzi 2013, pp. 98, 212, 231). This is indeed mentioned in the ancient Greek texts we examined, whereby the association between noble virgins and the grinding of ritual breads is made (Lowe 1998). Thus, food, cuisine, gender issues and social status would have been embodied by the ritual breads themselves.

Leavening and fermentation

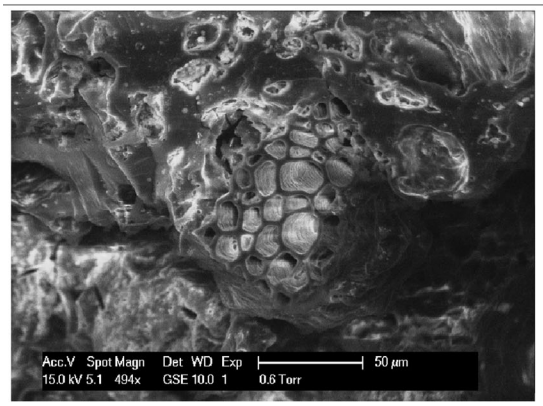
Thanks to the structure preserved in charred finds of cereal preparations, indirect evidence for dough fermentation can be obtained by the evaluation of the cavities observable in the objects (Heiss et al. 2015), applying methods used for modern bread (Scanlon and Zghal 2001). The observed overall dominance of small (< 100 μm) gas bubbles in all eight measured objects is a strong indication for an insufficient or altogether lacking leavening of the dough. This interpretation is confirmed by previous studies, where similar diagnoses were also supported by other traits of the analysed objects, such as the visual impression of high dough density and lacking crust/crumb formation (Heiss et al. 2015; Heiss et al. 2017), and the low overall height interpreted as characteristic for flat (unleavened) bread (Lannoy et al. 2002).


Acc.V Spot Magn Det WD Exp 50 µm
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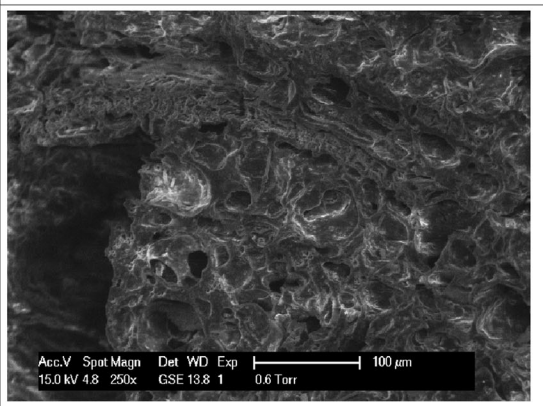
a


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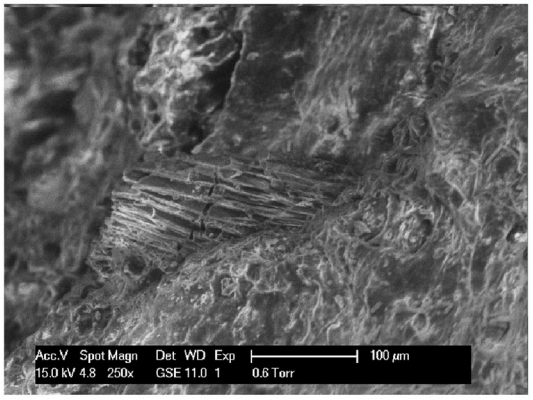
b


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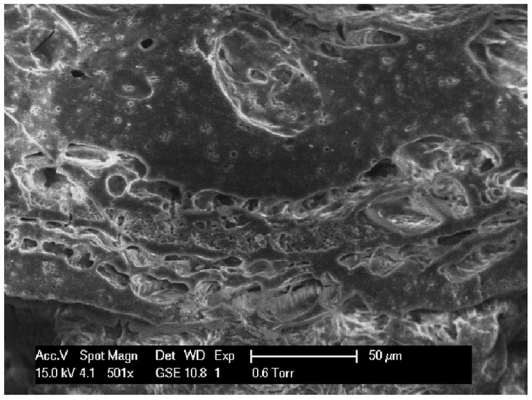
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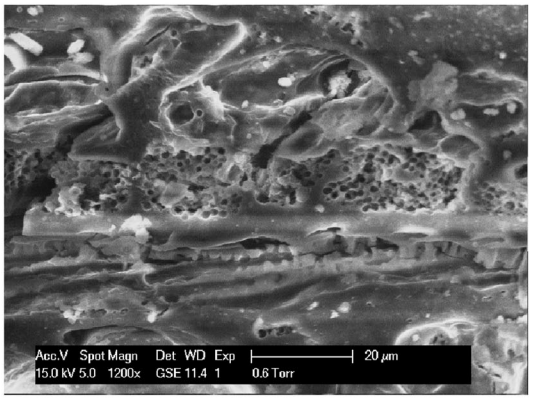
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Acc.V Spot Magn Det WD Exp 100 µm
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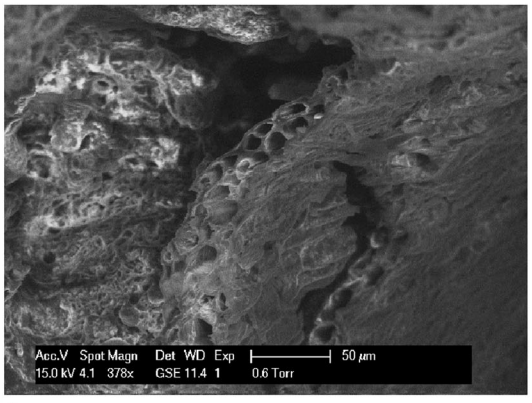
e


Acc.V Spot Magn Det WD Exp 50 µm
15.0 kV 4.1 501x GSE 10.8 1 0.6 Torr

f


Acc.V Spot Magn Det WD Exp 20 µm
15.0 kV 5.0 1200x GSE 11.4 1 0.6 Torr

g


Acc.V Spot Magn Det WD Exp 50 µm
15.0 kV 4.1 378x GSE 11.4 1 0.6 Torr

h

◀ **Fig. 5** ESEM micro-anatomical tissue image analysis of the different dough from Oria Sanctuary. Dough type 1: **a** aleurone cells in cross section arranged in a single layer, **b** cells of xylem tissue and **c** in cross-section is visible the awn fragment. Dough type 2: **d** single-layered aleurone cells and **e** awn fragment in longitudinal section. Dough type 3: **f**–**g** aleurone cells in a single layer together with transversal cells pitted and thickened and **h** fragment of glume/palea

Cooking methods and charring processes

Since ancient times, different kinds of cooking or baking practices were used to transform cereal grain, or flour, into more digestible, palatable or durable food products, while from an anthropological point of view (Lévi-Strauss 1968), these different practices could reflect specific symbolic values, particularly in ritual contexts.

As highlighted by Samuel (1996, 2006), the study of ancient modified starch is one of the techniques able to contribute to an understanding of ancient food technologies and processes. Starch granules are composed of polysaccharides amylose and amylopectin organised in alternating amorphous and crystalline layers; this semi-crystalline structure defines the physicochemical properties of the starch granules and influences its behaviour during cooking/baking processes (Crowther 2012). In recent years, there has been an increase in studies attempting to document this behaviour; food scientist have shown that various cooking methods affect starch grains in number of ways (shape, size and other features): For instance, starch grains will swell and gelatinise with increasing temperature and time when cooking in liquid (Eliasson 1980; Srikaeo et al. 2006); furthermore, different water contents, temperature and other processing conditions lead to various morphological changes in starch granules (Henry et al. 2009; Cunin et al. 1995).

While ancient starch research in archaeology can be considered a well-established discipline (Torrence and Barton 2006) thanks to the preservation of starch grains in different contexts (in soils, on stone tools or ceramic vessels, inside coprolites, within dental calculus and so on), not so many works have applied the results of the studies on changes in the starch grains during various cooking methods on ancient food remains (processed cereal food). A very early work is that of Valamoti et al. (2008) that investigates ancient cereal cooking practices; using a comparative modern set of cooked and charred cereals, the work examines via SEM the microstructure of preserved starch in charred ground cereal remains. A most recent work of Dai et al. (2013) examines the morphological changes in starch grains from wheat using different cooking methods; comparing the experimental cooked starch grains with those from desiccated cakes recovered from Astana cemetery (China, AD 768), the work attempts to define the ancient cooking techniques used.

Both contributions underline the importance of using experimentally generated reference material to compare ancient cereal foods; this approach looks promising, but as regards the burnt cakes from Oria, we have to verify and, if possible, to estimate the degree of starch alteration caused by burning, in addition to alterations caused by cooking process.

It would be interesting to understand why starches in the cakes from Oria show different levels of modification, as well as whether these products were boiled, baked prior to charring or charred directly. In the light of current investigations, we are still unable to answer these important questions; however, it will be appropriate to increase the investigation by combining data collected on the Oria finds (in terms of different survival of starches) with experimentally generated modern dough preparations, baked and charred within the framework of ERC PlantCult Project.

Hidden identity inside sacrificial cakes?

As highlighted previously, of particular interest is the role of food within a place of worship, such as the Sanctuary of

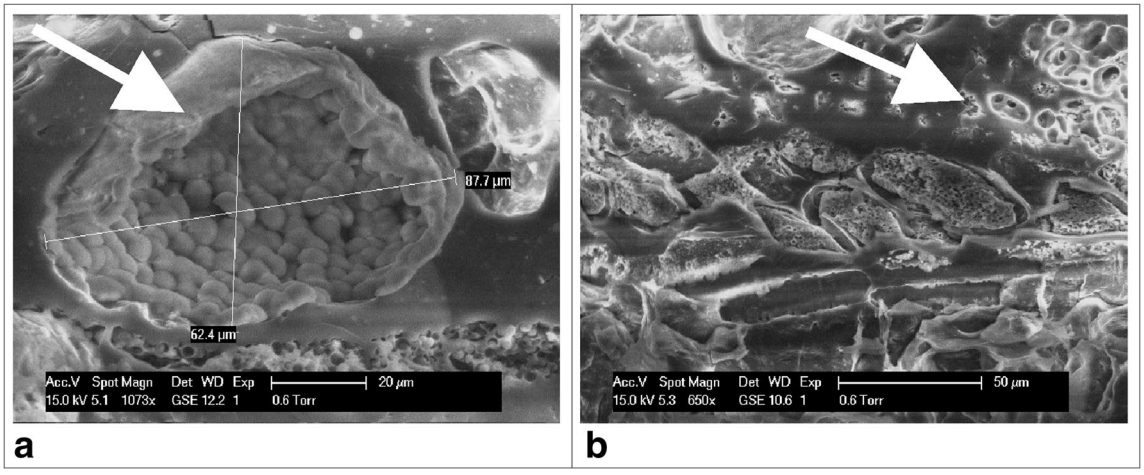
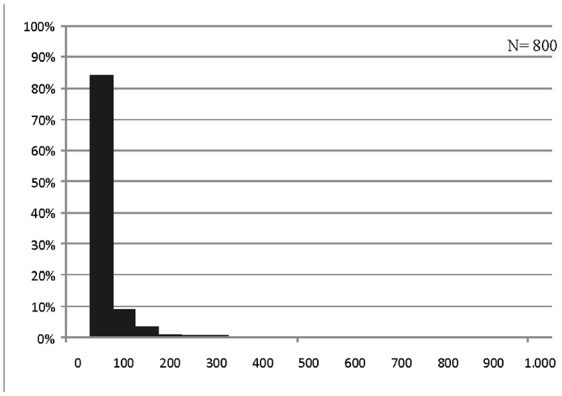
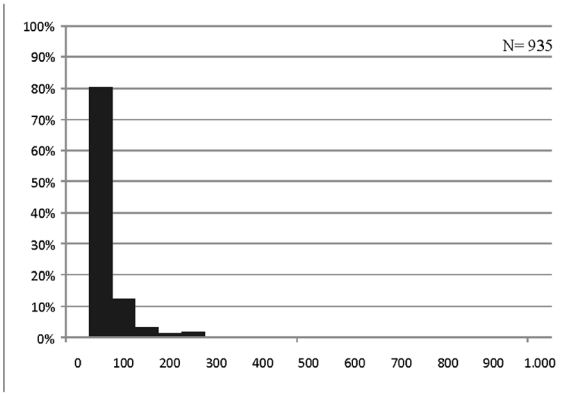


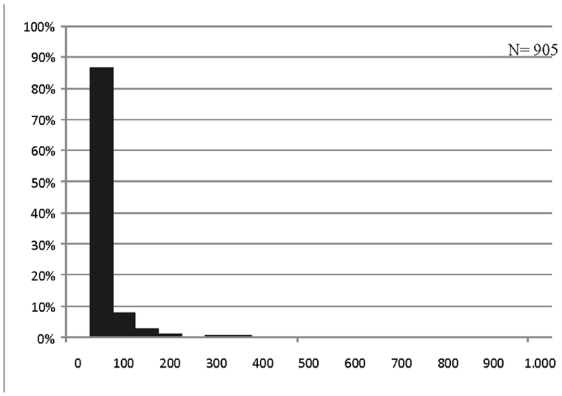
Fig. 6 ESEM images showing the different patterns of damage in endosperm cells and starch granules: **a** starch grain gelatinised and **b** starchy endosperm with different matrix cavities


N= 800
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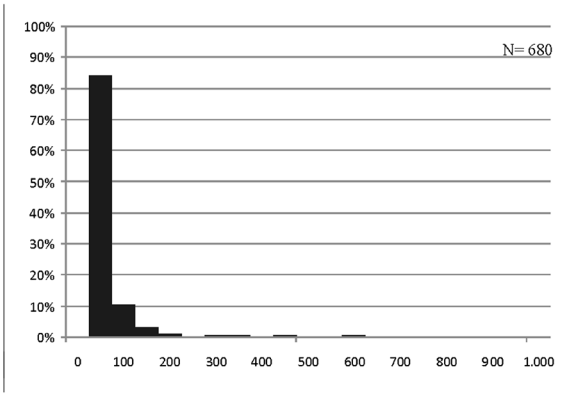
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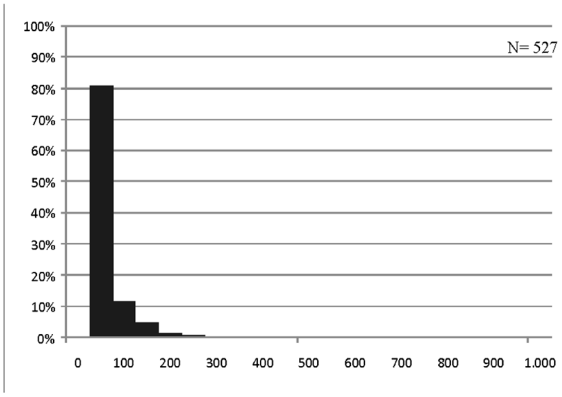
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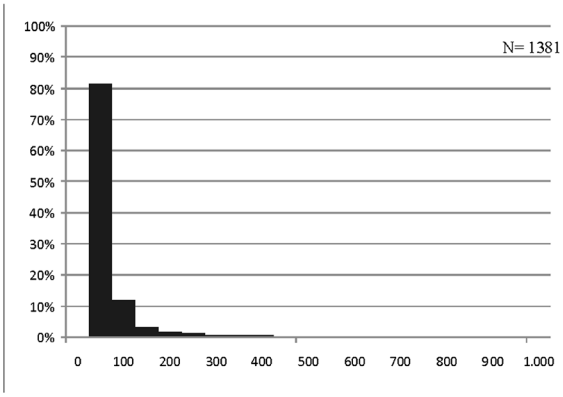
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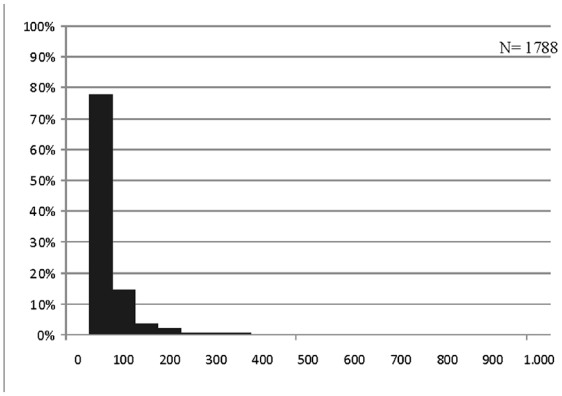
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N= 1381
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N= 1788
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g

◀ **Fig. 7** Histograms of measured bubbles of Oria cereal products: **a** cakes type A, **b** cakes type B, **c** cakes type C, **d** cakes type D, **e** dough type 1, **f** dough type 2 and **g** dough type 3. In *X*-axis is reported size class; in *Y*-axis the number of counts

Monte Papalucio, where both the native and the Greek form of the cult of Demeter intersected in a 'place of encounter', involving also those traits of ritual connected with food offerings.

It is often the case that ingredients contributing towards daily meals are also used for ritual purposes, for example durum wheat used for pasta but also as boiled grain specially prepared for the dead in modern Greece (Valamoti 2011) as well as in northern Apulia (Tragni 2006). It is often the case, however, that ancestral cereals, e.g. the glume wheats, may be used for ritual breads as is the case with emmer bread in modern Asturias in Spain (Peña Chocarro 1999). Food remains from the Oria Sanctuary of Demeter can reveal whether everyday food habits and ritual offerings shared similar ingredients or not, but even more so, it may reveal cultural value and ritual dimensions of plant-based food offerings.

Can our results on sacrificial cakes and dough from Oria reveal influences, or divergences, in ritual use of foods and even contribute to define an indigenous identity?

Based on archaeobotanical data from Greek colonies and indigenous settlements in Italy, it seems that both wheat, naked and emmer, and barley were the cereals grown.

A recent synthesis of archaeobotanical analysis by Lentjes (2013) has focused on the organisation of agricultural production in southern Italy during the different phases of Greek colonisation (Archaic/Classical, 600–325 B.C., and Early Hellenistic Period, 325–200 B.C.) in terms of crop specialisation and of the relationship with indigenous societies. According to this study, no clear differences appear in the crop spectra between Greek colonies and indigenous settlements which are both dominated by hulled barley as well as naked wheat and emmer production.

A contrast is nevertheless observed in western Sicily where, even though a similar range of species is observed among the archaeobotanical evidence (dated to the 7th/6th centuries B.C.) from the Greek colony of Selinunte and the Elymian site of Monte Polizzo, Stika et al. (2008) argue that barley dominated the indigenous site, while free-threshing wheat the colony; presumably, free-threshing wheat was grown by both indigenous people and Greek but was consumed by the colonies.

Going back to our study area, the southern Apulia, intense archaeological research has underlined a remarkable diffusion and a deep knowledge of the Cult of Demeter in Messapia during the Archaic and Hellenistic period (Mastronuzzi and Ciuchini 2011). The goddess was called with a different indigenous name, suggesting very specific features in the form of cult from place to place. This phenomena is explained in the light of the processes of 'selective acquisition' hypothesised by Semeraro (1997) and Burgers (1998) according to which 'prominent social groups imported selected innovative practices in rituals, in order to stress their dominance over the rest of the community' (Mastronuzzi and Ciuchini 2011).

During the centuries, the cult practices were enriched with features coming from the Greek world such as, in our opinion, the sacrificial cakes from Oria which, at least in shape, correspond to those represented in the *likna* from the coeval Sanctuary of Acrocorinth in Greece. Although Greek written sources are very specific at times about the ingredients used in Demeter's ritual breads, namely barley meal, our material examined here shows that in practice, different ingredients might have been used to produce the same result and that, in 'local sacrificial', cake barley was most likely a very minor component, absent in most cases examined here.

This is somewhat in contrast to the information provided by the ancient authors in relation to the special ritual breads, or even, the sacrificial cakes offered to Demeter in ancient Greece.

Considering that the archaeological research is lacking similar finds from Greek sacred contexts, while, by contrast, the Messapian culture is lacking direct written sources at this regards, we can only tentatively interpret these differences in cake ingredients as an established expression of indigenous identity, but neither keep out the possibility of a cultural value related to the different choices.

Conclusions

The detailed study carried out on the Oria finds allowed the collection of important data preserved inside the cakes, on the base of which we can now give new insights:

> Firstly, the flour used for making the sacrificial cakes was, at any rate, cereal based and wheat may have been the major plant component; ESEM recognition of the examined cakes and dough has not provided any evidence for the use of legumes or other plants. Only in one case, a barley tissue fragment was found together with wheat tissue suggesting the use of both cereals into flour.
>
> Secondly, the cereal meals used for making these products range between modern flour and semolina, and the pastry obtained by kneading appears lacking of any signs of the leavening processes.
>
> Thirdly, all these data suggest that probably, there is no correlation between the cake shapes and components and above all, there was no specific attention to barley; these may appear somehow in contrast to what the written sources tell us about the special ritual bread, or even, the sacrificial cakes offered to Demeter in ancient Greece.

In conclusion, Messapian ritual breads seem to diverge from the stereotypical use of barley in offering to Demeter, mentioned in ancient texts. This could suggest more freedom as regards ingredients chosen for rituals (wheat) than that inferred from the texts (barley). Alternatively, it could point towards a local Messapian identity, expressed through the ritual breads offered to the goddess. In any case, our contribution shows that careful analytical work on archaeological food remains can unlock subtle processes of identity expression, through the selection of food ingredients, in this case of cereal species for ritual cakes.

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Prehistoric cereal foods of southeastern Europe: An archaeobotanical exploration

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A B S T R A C T

This paper addresses for the first time a large body of archaeobotanical data from prehistoric Southeastern Europe, mostly published for the first time, that correspond to cereal food preparations. The evidence presented here comes from 20 sites situated in Greece and Bulgaria, spanning the Early Neolithic through to the Iron Age (7th millennium B.C.-1st millennium B.C.). The remains correspond to cereal fragments or agglomerations of fragments that resulted from ancient food preparation steps such as grinding, boiling, sprouting/malting, mixing in bread-like or porridge-like foodstuffs. The article builds on previous pilot studies and with the aid of stereomicroscopy and scanning electron microscopy offers a first classification and possible interpretations of the finds leading to the recipes that might have generated them. At the same time the article highlights the significance of retrieving and studying in depth such rare archaeobotanical finds, points out the interpretative problems stemming from such material and suggests ways forward to address similar archaeological finds in different parts of the world. The paper demonstrates the potential of the systematic study of cereal-based food remains, in our case prehistoric Southeastern Europe, to reveal a wide variability in cereal food transformation practices, suggestive of the interplay between available ingredients, cultural traditions and the complex interaction between society and environment.

1. Introduction

Studies targeting ancient food have begun to acquire a significant position in archaeological inquiry, building up on what Sherratt (1991) had very perceptively argued for, nearly 30 years ago, that *people do not eat species, they eat meals*. Conferences, papers and books have addressed food preparation and consumption, focusing on luxury foods (Van der Veen, 2003), particular consumption practices like feasting on meat and alcohol (Jones, 2007; Miracle and Milner, 2002; Wright, 2004) or variable social, economic and symbolic dimensions of food

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across the globe (Gosden and Hather, 1999). Research projects have investigated food globalisation in prehistory (Jones et al., 2011), the role of the environment and culture into shaping Early Neolithic food ingredients of Southeastern Europe (Ivanova et al., 2018; Kreuz and Marinova, 2017) or the consumption of particular foods, e.g. dairy products (Craig et al., 2005; Evershed et al., 2008). At the same time, edited volumes on the subject of food, embraced a wide array of methods, approaches and case studies in various regions and time periods, including methods and analytical tools like chemical residue and isotopic analysis, often innovatively combined with experimentation, ethnoarchaeology and associated processing equipment (e.g. Anderson et al., 2013; Capparelli et al., 2011; Chevalier et al., 2014; Hastorf and DeNiro, 1985; Parker-Pearson, 2003; Mee and Renard, 2007; Tzedakis et al., 2008; Voutsaki and Valamoti, 2013). Yet, the culinary transformation of plants has rarely been the focus of a systematic inquiry and even less so as regards more integrated approaches (cf. Fechner and Mesnil, 2002).

The importance of plant foods has been underlined in recent archaeological discourse with special emphasis placed on cereal staples, luxury foods and diet enhancers such as wine and oil, condiments and spices or hallucinogenic plants like opium poppy (e.g. Fuller and Rowlands, 2011; Hamilakis, 1996; Sherratt, 1995; Van der Veen, 2003). Prehistoric culinary and food consumption practices have been at the heart of discussions on the emergence of Bronze and Iron Age elites in prehistoric Europe (e.g. Arnold, 1999; Renfrew, 1972; Wright, 2004), wine and oil in particular, relating power appropriation and access to certain types of plant foods and associated processing technologies. Species selection and their transformation into meals involves the interaction of natural vegetation and human culture, whereby the former is shaped, named and incorporated in each society's belief systems, transliterated into daily and life experiences, collective memory and identity. Food preparation and consumption form arenas where social roles are learnt, power relations forged, negotiated and renewed (e.g. Dietler and Hayden, 2001; Jones, 2007). Yet, ancient plant foods, despite their major dietary role, as staples or for special contexts of consumption, remain underexplored as regards individual recipes and processes underlying the preparation of specific prehistoric foods. They are little discussed in terms of their contribution to social cohesion and differentiation through daily, communal or special contexts of consumption, as well as their role in elite emergence and cultural transformation through time. Moreover, culinary practices have been poorly integrated on a regional and temporal scale that would allow for culinary trends and their change through time to be observed in a coherent way. As a result, the dynamic role of culinary transformation of plant ingredients into shaping social and cultural identity in prehistory remains little explored and comprehended.

Archaeobotanical research in Southeastern Europe over the last 20 years has brought to light a wealth of new evidence on actual plant food remains based on cereals, pulses and fruit. In this paper we focus on prehistoric cereal foods from southeastern Europe, offering an overview of the types of food remains encountered in the archaeological record and a first discussion of the potential recipes that led to their production. Cereals have formed the staples of prehistoric communities of the area since the appearance of the first farming communities in the 7th millennium B.C. The ways into which cereals were transformed into food we believe are closely linked to the interplay of environmental and cultural parameters. They can be consumed whole, smoked, roasted, boiled, ground coarsely or finely, then further processed through the intervention of fire and liquids such as milk or water. There is ample ethnographic evidence from Europe, Western Asia and Northern Africa to suggest that human societies have devised many ways of transforming cereals into food, either for short-term or long-term consumption (Capparelli et al., 2011; d'Andrea and Mitiku-Haile, 2002). Moreover, ancient texts reveal a wealth of cereal food preparations, varying not only in terms of the ingredients but also in terms of the steps involved in the preparation of the recipes (cf. Dalby, 1996; Valamoti, in press). Inevitably, archaeological finds of cereal foods are classified on the basis of our current knowledge of potential ways of food transformation. Pilot studies and preliminary publications on such types of foods have suggested food preparations like bulgur and/or trachanas, corresponding to pre-cooked, ground cereal fragments (Marinova, 2006; Valamoti, 2002, 2011; Valamoti et al., 2008). Other types of cereal food remains retrieved have been described as bread or porridge (Carretero et al., 2017; Heiss, 2008; Nikov et al., 2018; Popov et al., 2018; Popova, 2016) and exciting new investigations have further explored the contents and structure of these 'bread/porridge'-like remains, yielding promising results (Heiss et al., 2017; Primavera et al., 2018). At the same time alternative interpretations for cereal-based lumps are emerging, pointing towards the direction of brewing a cereal based alcoholic produce, possibly beer (Valamoti, 2017a,b).

Building upon the pioneering work on processed cereal foods by Hansson (Hansson, 1996; Hansson and Isaksson, 1994) and extant works on cereal bran identification (e.g. Dickson, 1987; Körber-Grohne and Piening, 1980; Winton and Winton, 1932), Heiss et al. (2015) applied a detailed SEM analysis for the identification of the cereal components of a Gallo-Roman bread find. They used specific traits such as drying cracks and pore diameters as well as identification of plant tissue preserved in the bread to decipher the preparation steps involved in its making. Pore size distribution and the presence of fissures was associated to leavening and baking conditions. No experimental observations were taken into consideration in this paper and the inferences were made on the basis of criteria describing modern flat and raised breads, respectively. Information about the processing techniques, like grinding and sieving, could also be drawn based on bran and chaff size measurements, while quantification of pore/bubble size was proposed as a method for identification of fermented dough. Carretero et al. (2017) also used SEM analysis, building upon the suggestions put forward by Heiss et al. (2015), in an attempt to investigate amorphous charred food remains from Neolithic Çatalhöyük, with similar goals: To determine the plant components and potential processing and cooking methods. They applied qualitative estimations of size and number of visible plant material, as well as air bubble size and their distribution in the food matrix, comparing archaeological food remains with experimental cereal preparations. They examined the archaeological material together with a series of experimentally generated cereal-based preparations: dough, bread, porridge. In building their methodology they recorded voids in the amorphous mass matrix and visible plant components.

This ambitious new work by Carretero et al. (2017) that aspires to offer a methodological tool for analysing ancient cereal food remains from archaeological sites reveals the manifold problems involved in attempting to decipher ancient cereal based recipes. The experimental material used to build the methodology in this work is based on assumptions that in part at least lack support from the ethnographic literature or ancient sources, e.g. boiling the grain for the production of fine flour, associating coarse meal with porridge and fine meal with bread, assuming that bulgur is just any coarsely ground grain. Pore size and shape in the experimental and ancient food matrix are used in this study as a main tool to detect cooking processes. It is unclear, however, how pore-size was indeed measured on irregular surfaces and the fact that the authors use pore-size average rather than the size-range, obscures any understanding of the potential variability in the size of pores in individual specimens. Moreover, the effects of charring as regards pore formation are not taken into consideration and therefore it is unclear whether the characteristics recorded are the result of charring or leavening. Thus, although in principle the features that the authors select to record in ancient food remains are potentially indicative of different cereal food preparation methods, the methods used to explore these features are problematic and need rigorous re-assessment, taking into consideration a wide range of experimental variables as regards the food preparation steps, the charring temperatures and the methods of describing and measuring the shape of pores in the cereal food matrix.

It is imperative that a range of experimental variables are taken into consideration before a widely applicable method can be developped and used to study similar archaeological material. Recently, Primavera et al. (2018) applied SEM analysis on exceptional finds of ritual 'cakes' deposited in the Sanctuary of Oria in Monte Papalucio offering novel insights into ritual bread preparation practices thanks to the integration of archaeobotanical, artefactual and textual evidence. This ongoing research could potentially offer fascinating information as regards past culinary practices, yet, no systematic methodology exists to facilitate the study of archaeological cereal food remains. In some of the previous studies, for example, it has been assumed that a) pore size is related to the use of yeast and b) the size of particles visible on the Scanning Electron Microscopy image reflect the entire inclusion. The latter, however, in reality, might be largely hidden in its most part in the interior of the observed surface. The main problem with all the work conducted so far is that many of the variables that might have influenced the structures observed in archaeological cereal foods still remain poorly investigated and understood. At the same time there is inadequate consideration in the literature of alternative possible food preparation steps and subsequent depositional taphonomic processes that would result in similar-looking food products, for example cracked wheat, bulgur and trachanas or bread, flat-bread, porridge, dough. Building on the suggestion put forward by Heiss et al. (2017) we here combine macroscopic and microscopic structure analysis in order to provide insights as regards aspects of prehistoric cereal food preparation and to raise awareness of the variability of food preparations that might have existed in prehistoric times and opens up the way towards classifications beyond the two “global” categories suggested previously, i.e. 'cereal product' and 'bread-like object' (Heiss et al., 2017), at the same time trying to avoid over-interpretation of the structures visible in the material.

Our paper offers for the first time a systematic and comprehensive examination of archaeological finds of cereal based foods originating from 20 sites situated in Northern Greece and Bulgaria spanning the Neolithic through to the Iron Age, i.e. the 7th millennium through to the 1st millennium B.C. This exceptional material, examined in the context of ERC funded project PLANTCULT (Valamoti et al., 2017, http://plantcult.web.auth.gr/index.php/en/) forms the basis for a first attempt to classify these objects taking into consideration a wide range of alternative cereal foodstuffs recorded ethnographically or in ancient texts. Based on a combination of macroscopic and microscopic observations, aided by SEM, we argue that this classification is the first necessary step towards deciphering ancient recipes and the processing steps that led to their preparation, in the context of a wider exploration of prehistoric culinary practice in Southeastern Europe.

2. Materials and methods

Cereal based food remains from prehistoric sites in Northern Greece and Bulgaria are presented in a systematic and comprehensive way. The material originates from nine Greek and eleven Bulgarian sites spanning the Neolithic through to the Iron Age, while one has a Classical-Early Hellenistic dating (Table 1, Fig. 1).

The Greek sites with rich archaeobotanical assemblages that include cereal food remains are located in Northern Greece and span the Late Neolithic through to the Late Bronze Age. The Neolithic finds derive from the sites of Limnochori II, Anarghiri III, Limnochori III, situated in the Amindeon Basin, Western Macedonia, at the northern shore of Lake Chimaditis (Chrysotomou et al., 2015) and Dikili Tash in Eastern Macedonia (Darcque et al., 2007; Darcque, 2013; Kokkidou, 2018; Koukouli-Chryssanthaki and Treuil, 2008; Matterne, 1993; Valamoti, 2004, 2015). Cereal based food remains dating to the Bronze Age from Northern Greece have been retrieved from a number of sites: Anarghiri I (Chrysotomou et al., 2015) Armenochori (Chrysotomou, 1998), Archondiko (Papadopoulou et al., 2010; Papaefthymiou-Papanthimou, 2010, Pilali-Papasteriou et al., 2001), Mesimeriani Toumba (Grammenos and Kotsos, 2002) and Angelochori (Maniatis, 2010; Stefani, 2010; Stefani and Merousis, 2010; Valamoti, 2010), located in Western and Central Macedonia. The Bronze Age sites are all tell settlements, with the exception of the lakeshore settlement of Anarghiri I at Lake Chimaditis. Both the Neolithic and Bronze Age assemblages considered here originate from the burnt destruction layers of buildings

Table 1
Basic qualitative classification categories used for the cereal foods from northern Greece and Bulgaria discussed in the paper.

Overall Appearance: morphological criteria			Potential Food Type
Macroscopic	Stereomicroscopic	Microscopic	
Loose fragments	*fracture surface characteristics*	*Features observed under SEM*	*cracked wheat/bulgur/trahanas/ ground malt*
	bulging	gelatinised endosperm	
	flat	other	
	concave		
Fragment agglomerations			*cracked wheat/bulgur/trahanas*
Fragments clearly visible	*fracture surface characteristics*	*Features observed under SEM*	*/ground malt cakes*
	bulging	gelatinised endosperm	
	flat	other	
	concave		
	components	*components (metallographic and SEM)*	
	grain		
	chaff		
	other		
Fragments in amorphus matrix	Fragments		*bread/porridge/*
	fracture surface characteristics	*Features observed under SEM*	*cooked food containing cereal fragments*
	bulging	gelatinised endosperm	
	flat	other	
	concave		
	size		
	components	*components (metallographic and SEM)*	
	grain	species/type identification and size	
	chaff	species identification and size	
	other	species identification and size	
Amorphus matrix	*components*	*components (metallographic and SEM)*	*bread/porridge*
	grain	species/type identification and size	
	chaff	species identification and size	
	other	species identification and size	

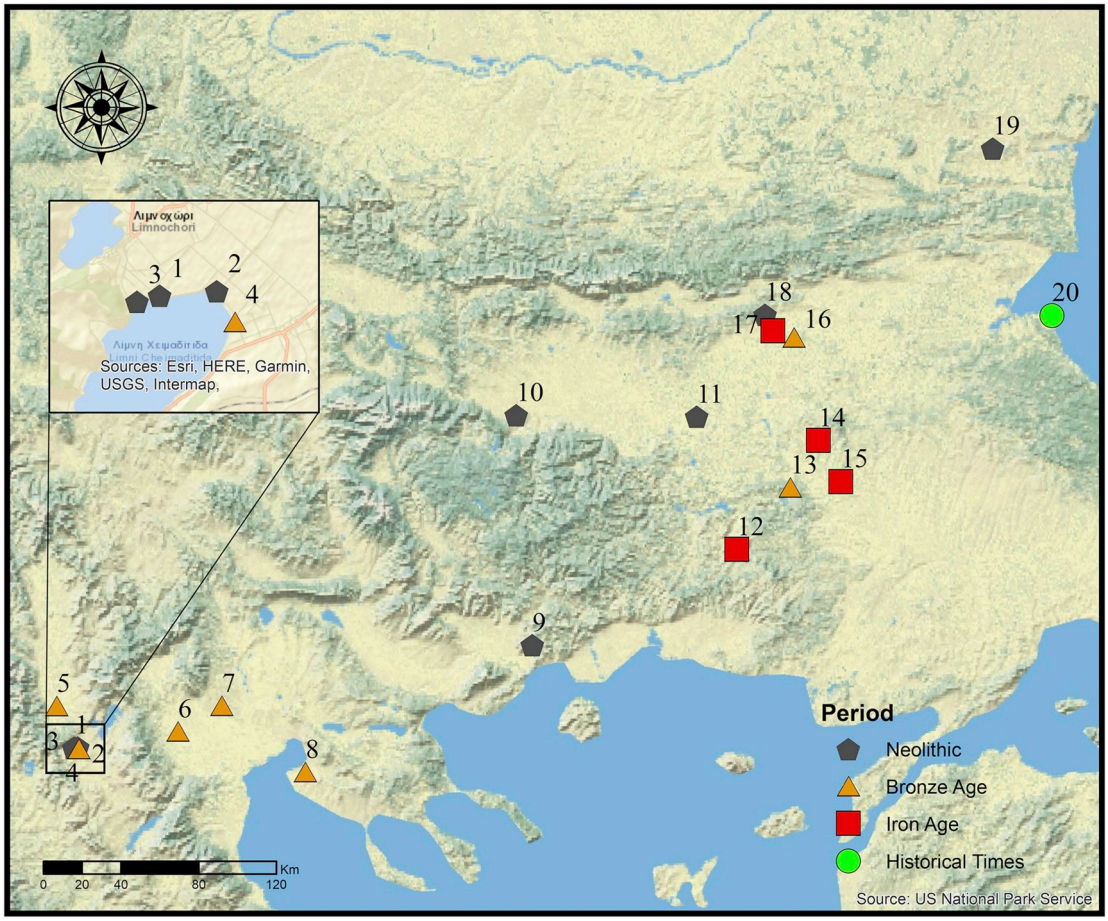


Fig. 1. Map of study area indicating Greek and Bulgarian sites that yielded cereal food remains presented in this paper. 1. Limnochori II, 2. Anarghiri III, 3. Limnochori III, 4. Anarghiri I, 5. Armenochori, 6. Angelochori, 7. Arhcondiko, 8. Mesimeriani Toumba, 9. Dikili Tash, 10. Kapitan Dimitrievo, 11. Yabalkovo, 12. Ada Tepe, 13. Kush Kaya, 14. Vaskovo, 15. Kapitan Andreevo, 16. Sokol, 17. Yurta, 18. Karanovo, 19. Provadia-Solnitsata, 20. Apollonia Pontica.

while the artefactual and other contextual evidence suggest crop storage.

The Bulgarian Neolithic/Chalcolithic sites that have yielded cereal food remains and are included in the paper are Early Neolithic II Kapitan Dimitrievo (Nikolov, 2000) and Early Neolithic Yabalkovo (Leshtakov, 2014), Early Chalcolithic Karanovo (Nikolov, 2002), and Middle Chalcolithic Provadia-Solnitsata (Nikolov, 2008). The food remains presented here are retrieved from house interiors. The vast majority of the Bulgarian sites which yielded actual food remains in our study area is dated, however, to the Bronze and Iron Age periods. The Bronze age sites included in the study are Sokol in Southeastern Bulgaria (Leshtakov et al., 2014) and Kush Kaya in the Eastern Rhodope Mountains (Popov, 2016; Popov et al., 2018). The Iron Age Bulgarian sites are as follows: Vaskovo (Iliev, 2015), Kapitan Andreevo (Popov et al., 2007; Popov and Grozdanova, 2008), Ada Tepe (Nikov et al., 2018) and Yurta (Kancheva-Ruseva and Koleva, 2011).

Besides the prehistoric finds, the study also expands to slightly later food remains from the Necropolis of Apollonia Pontica (present day Sozopol) on the Western Black Sea coast of Bulgaria, dating to the 4th century BC (Panajotova et al., 2006).

The archaeobotanical cereal food remains from the above mentioned prehistoric sites have been retrieved by flotation using a variant of the Ankara machine (French, 1971) for Greek sites and manual flotation and hand picking for Bulgarian sites where they were recognized during excavation as concentrations of plant remains or possible plant food. All the specimens presented in this paper are preserved through charring and in their majority were mostly found in rich, dense concentrations corresponding mainly to stored products while some correspond to lumps contained in pits with food and other 'refuse' (Table 2). As the analysis of each specimen is a very time consuming process, only representative specimens were subject to a detailed SEM examination and imaging with microphotographs.

The suspected cereal food remains were initially examined using a binocular stereomicroscope with magnifications X8-X80. They were subsequently examined with the aid of a metallographic microscope and on the basis of these observations the selected specimens were subjected to SEM imaging. SEM analysis was carried at the Aristotle University of Thessaloniki using a JEOL JSM-840A and a JEOL JSM-6390LV scanning electron microscope. Samples were coated with carbon – average thickness of 200 Å – using a vacuum evaporator JEOL-4X. Few specimens from Karanovo and Kush Kaya were observed under JEOL JSM 840, coated with 20–25 nm of gold at the Royal Belgian Institute for Natural Sciences.

The material examined in this paper could correspond to a range of cereal-based food remains both in terms of their components as regards a) species, b) overall size and c) type of processing (e.g. sprouting, boiling, grinding etc) as well as in terms of the intended end product. The categories we have adopted to classify our material, however, are broad and encompass a range of possible cereal food preparations. For the purposes of this paper we have selected from each site under consideration those specimens that were most likely to correspond to different broad categories of cereal food preparations in order to provide the full range of variability present in our assemblages. The material presented in this paper is representative of each type of food remains and not exhaustive, a task impossible to achieve given the time consuming process of SEM imaging. We believe, however, that by our selective approach and basic classification categories, we offer for the first

Table 2
Overview of archaeobotanical finds of cereal food remains discussed in the paper.

Country	Site	Period	Date range	Site type	Preservation conditions	Context	Taxon component(s)	Overal consistency	Fragment characteristics	Suggested food category
Bulgaria	Yabalkovo	Early Neolithic II	5840-5670 BC	flat site	charred	pithoi interior	cereal (wheat, barley)	loose grain fragments		bulgur/trachanas
Bulgaria	Kapitan Dimitrievo	Early Neolithic II	5650-5450 BC	tell	charred	storage vessel	cereals (einkorn, barley)	loose grain fragments	flat	bulgur/trachanas
Greece	Limnochori II	Late Neolithic	5500-3300/ 3200 BC	lakeshore settlement	charred	house destruction layer (associated with pots, clay structures)	cereal	agglomerations of fragments/ porous mass/ porous mass with fragments		bread/ porridge
Greece	Anarghiri III	Late Neolithic	5300-4000 BC	lakeshore settlement	charred	house destruction layer (associated with pot concentration)	cereal	porous mass/ porous mass with fragments		bread/ porridge
Bulgaria	Karanovo	Early Chalcolithic	4900-4700 BC	tell	charred	vessel	cereals	agglomerations of fragments		bulgur/trachanas
Bulgaria	Provadia-Solnitsata	Middle Chalcolithic	4700-4600 BC	tell	charred	vessel	cereal	agglomerations of fragments	flat	porridge
Greece	Limnochori III	Final Neolithic	4500-4000 BC	lakeshore settlement	charred	house destruction layer/ pot interior	cereal	porous mass/ porous mass with fragments		bread/ porridge
Greece	Dikili Tash	Late Neolithic I	5000-4800 BC	tell	charred	house destruction layer	cereal	porous mass with fragments		bread/porridge
Bulgaria	Sokol	Early Bronze Age	3500 – 1900 BC	tell	charred	pot interior	cereal (wheat)	porous mass with fragments		bread/ porridge
Greece	Mesimeriani	Early Bronze Age	2196-1925 BC	tell	charred	pot interior	cereal	loose	bulging	bulgur/trachanas
Greece	Archondiko	Early Bronze Age	2135-2020 BC	tell	charred	house destruction layer	cereal	loose/ agglomerations of fragments/ porous mass/ porous mass with fragments	bulging/flat	bread/ porridge/ bulgur/ trachanas/ malt
Greece	Armenochori	Early Bronze Age	end 3rd mill. BC	tell	charred	storage room	cereal	porous mass		bread/porridge
Greece	Anarghiri I	Early-Middle Bronze Age	2000 BC	lakeshore settlement	charred	house destruction layer	cereal	porous mass/ porous mass with fragments		bread/ porridge
Greece	Angelochori	Late Bronze Age	1630-1495 BC	tell	charred	burnt layer	cereal	porous mass with fragments		bread/ porridge
Bulgaria	Kush Kaya	Late Bronze Age	1500-1375 BC	hiltop site	charred	vessel	cereals	porous mass with fragments		bread/ porridge
Bulgaria	Ada Tepe	Early Iron Age	1100-850 BC	hiltop site	charred	dwelling	cereals	porous mass		bread/ porridge
Bulgaria	Kapitan Andreevo	Early Iron Age	1000-850 BC	pits	charred	pit	cereals	porous mass		bread/ porridge
Bulgaria	Vaskovo	Early Iron Age	1000-850 BC	farm settlement	charred	dwelling	cereal	porous mass		bread/ porridge
Bulgaria	Yurta	Late Iron Age			charred	ritual pit	cereal	porous mass		bread
Bulgaria	Necropolis of Apollonia	Classical period	first half of 4th century BC		charred	ritual hearth	cereal	porous mass		bread

time a thorough overview of the range of potential cereal food preparations of prehistoric southeastern Europe, emphasizing the significance of similar finds in the archaeobotanical record.

3. Results and interpretation

3.1. Classification of cereal food remains

The archaeobotanical material examined here can be grouped in different categories on the basis of the various morphological characteristics of its components, macroscopic and microscopic. Different components or combinations of components visible in the archaeobotanical specimens could signify different categories of food products, on the basis of our current knowledge regarding the ways in which cereal ingredients can be transformed into cereal food preparations. In order to explore this variability in the archaeobotanical cereal food finds, the macroscopic observations performed on the archaeobotanical material, together with the SEM micrographs, formed the basis for grouping the archaeological food remains in different categories according to a) macroscopic appearance, i.e. whether the remains preserve loose or in lumps, b) microscopic features of surface and internal structure/composition (Table 1). Category (b) is only presented here on a coarse, qualitative level and needs further refinement that will only be possible when a sound methodology has been developped that will allow a better understanding of such archaeological finds. This is work in progress aiming ultimately to the preparation of an open-access data-base comprising detailed SEM images of a wide range of experimental cereal food preparations charred under controlled charring conditions (in preparation by the PLANTCULT project team), informed by ethnography and ancient texts, along the lines proposed by Valamoti (2002), Valamoti et al. (2008), Heiss et al. (2015) and Heiss et al. (2017). The groups we have established here allow an 'inside' view of the components and structure of the archaeological finds without imposing assumptions based on what 'bread' or 'porridge' should look like. These categories of finds we have identified can be associated with different possible food types to which these finds could correspond, inferred with the aid of ethnography and experimental pilot studies. Thus the archaeological specimens could belong to some of the following food categories: a) ground cereals used as such, b) ground pre-cooked cereals (bulgur/trachanas type, see Valamoti, 2011 for a detailed description of variants), c) 'bread' remains (in the broader sense of the word), d) porridge remains, e) ground malt, f) malt 'buns' for the preparation of beer (Table 2). Other preparations and combinations of ingredients are also possible but here we limit ourselves to some common, basic cereal food categories. In most cases it is still impossible to distinguish among the different categories, e.g. between bulgur and trahanas (see Valamoti et al., 2008) or between bread and porridge (see Heiss et al., 2017). These classifications constitute working analytical categories which may be modified in the process of ongoing research, depending on future, more detailed analyses of this and similar material. In the absence of a detailed and tested methodological tool that will 'unlock' recipes of the past we adopt a cautious approach to the archaeological material considered here, an approach that combines macroscopic observations and a first level of analysis using Scanning Electron Microscopy to describe the overall structure of the observed surface. Our proposed categories avoid the pitfalls of projecting to the prehistoric past practices that are closer to our modern cereal food classifications (.e.g. bread made of fine flour-cf Carretero et al., 2017). Moreover they offer an analytical tool that can be easily applied in routine mainstream archaeobotanical work without the need for sophisticated analytical techniques. Needless to say that some of the food categories we use could have constituted ingredients themselves (see discussion below) used towards the preparation of other recipes, increasing thus the food categories to which our finds potentially could correspond to.

3.2. Category 1: loose cereal fragments

This category includes cereal fragments generated prior to charring on the basis of previous research that has shown that the main criterion for identifying grinding prior to charring is the characteristic bulging observed on the fracture surface of the cereal grain (Valamoti, 2002). Such cereal fragments, generated through deliberate actions in prehistory, could correspond to at least three different types based on grain treatment prior to the actual cooking/food preparation: a) cereal grain that appears to have been broken prior to charring without any evidence for further processing, b) ground cereal grain that has been boiled/parboiled/simmered in some form of liquid, milk or water, c) cereal grain that has been converted into malt by sprouting, then ground. Furthermore, in category (b) the relationship between boiling and grinding can vary: grain can be first parboiled whole, then ground or the reverse. Boiling of grain can be identified in the archaeobotanical record through the macroscopic observation of shiny, glassy surfaces (Valamoti, 2002) and gelatinised grain endosperm (Valamoti et al., 2008).

In the assemblages we have studied from Greece and Bulgaria, we

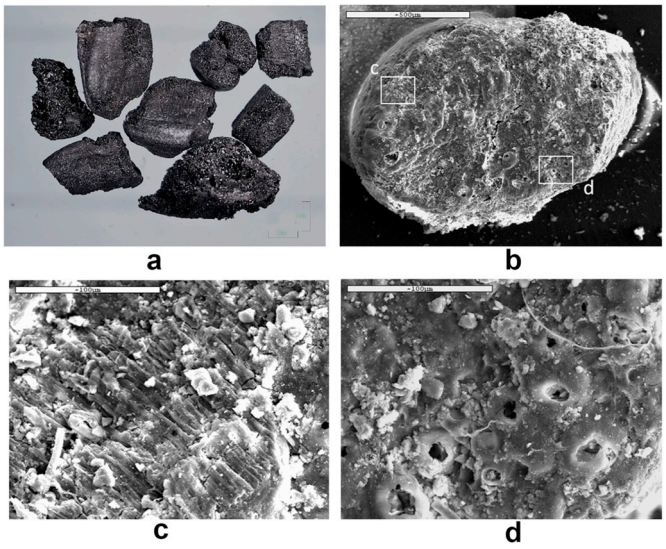


Fig. 2. Loose cereal fragments from Early Neolithic II Kapitan Dimitrievo. a) macroscopic overview of food fragments under low magnification binocular, b) macroscopic overview of a food fragment under SEM (x30 magnification), c) transverse cells of cereal pericarp and d) gelatinised endosperm a view of the microstructure under SEM (x400 magnification).
(working distance for SEM images 20 mm).

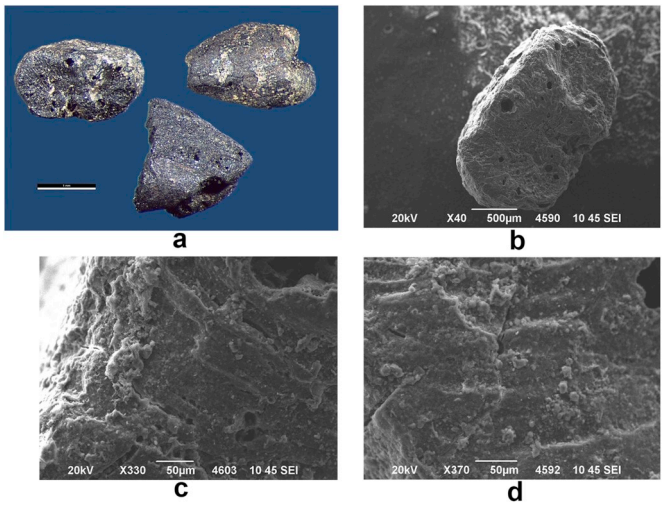


Fig. 3. Loose cereal fragments with bulging fracture surface from Early Neolithic Yabalkovo. a) the grain fragments under low magnification binocular (scale bar 1 mm), b) overview of a grain fragment under SEM, c) and d) view of the fracture surface microstructure under SEM.

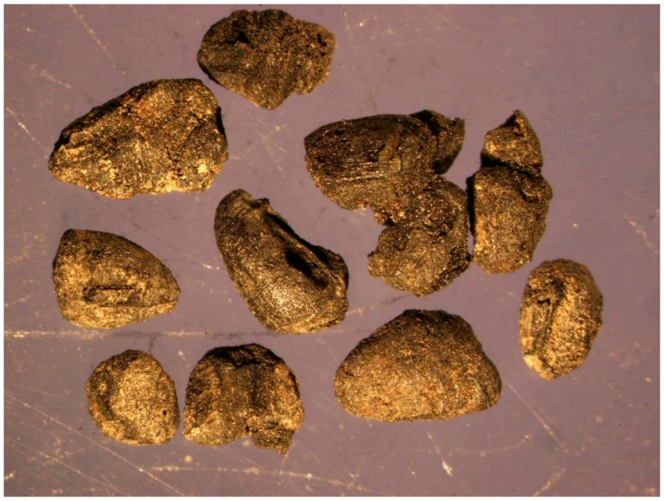


Fig. 4. Loose cereal fragments with bulging non-shiny fracture surface from Early Bronze Age Archondiko.

have identified loose cereal fragments at the following sites: Kapitan Dimitrievo, Yabalkovo, Archondiko and Mesimeriani (Fig. 2, Fig. 3, Fig. 4, Fig. 5). On the basis of the previous pilot studies referred to above, the Mesimeriani finds, stored inside a pot, correspond to pre-cooked wheat grains, probably einkorn, as some of the larger grain fragments were identified as such: The shiny bulging surfaces of the grain fragments, indicate that they had received some kind of treatment with some liquid, like boiling or soaking in water, before grinding (Valamoti, 2002).

The Kapitan Dimitrievo fragments include a) fragments with bulging surfaces (Fig. 2d) with SEM micrographs showing a gelatinised endosperm (after Valamoti et al., 2008) as well as b) fragments with no visible diagnostic features that need further investigation. As it was a dense rich concentration of fragmented cereal grains kept inside a storage vessel, it has been interpreted as intentionally processed and deposited there (Marinova, 2006). At the sites of Yabalkovo and Archondiko, it is observed that fragments with different morphologies of the fracture surface usually coexist in the same samples: the fragments might demonstrate either a bulging, flat, or slightly concave surface. Unlike the finds from Mesimeriani and Kapitan Dimitrievo, these particles have matt surfaces. It is therefore important to explore the possible pre-depositional processes related to cooking as well as the possible taphonomic factors (e.g. charring) that might have resulted in these assemblages through further experimentation considering more variables (currently under way in the context of ERC project PLANTCULT, Valamoti et al. in preparation). Further analysis of more archaeological fragments with the aid of SEM, informed by experimental material will help understand the processes that led to these assemblages.

At Archondiko different types of ground fragments have been retrieved and their combined examination of morphological characteristics and spatial distribution, informed by ethnography and experimentation will potentially reveal different ways of transforming cereals for food (Valamoti, 2002, 2017a; Valamoti et al., 2008). One possibility raised in the past was that they might correspond to some form of bulgur/trachanas (Valamoti, 2002, 2011; Valamoti et al., 2008). Alternatively or in addition to this, some of these steps may be related to beer making, a suggestion recently put forward in a re-examination of the archaeobotanical finds from Archondiko (Valamoti, 2017a). Although ground cereal fragments are often uncritically described as 'bulgur', this is a hasty and potentially wrong interpretation. Depending on surface characteristics, it could correspond to cracked wheat, bulgur, trachanas and in light of recent finds, pontentially ground malt. This possibility has not been previously raised in the literature, yet recent rich finds of charred malt, together with contextual evidence for facilities where malting was possible, raise ground malt as an alternative interpretation of such fragments. Thus some of the cereal fragments encountered at Archondiko could be considered as ground malt, a possibility currently investigated in detail, stemming from the recent finds of sprouted cereal grains in the same archaeological contexts as the ground fragments (Valamoti, 2017a; Valamoti et al. in preparation). Future research may help refine these categories, add new ones and

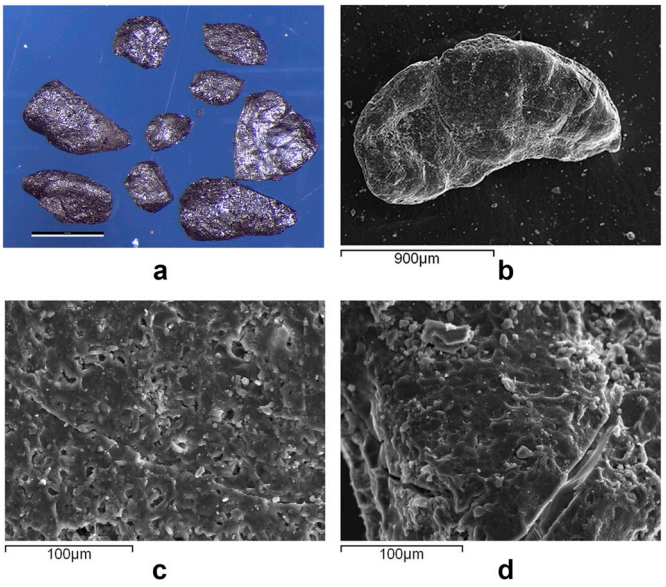


Fig. 5. Loose wheat/barley fragments with bulging/shiny fracture surface from Early Bronze Age Mesimeriani Toumba. a) grain fragments under low magnification binocular (scale bar 1 mm), b) overview of a grain fragment under SEM (x60 magnification), c) and d) view of the fracture surface microstructure under SEM (x650 magnification). (working distance for SEM images 20 mm).

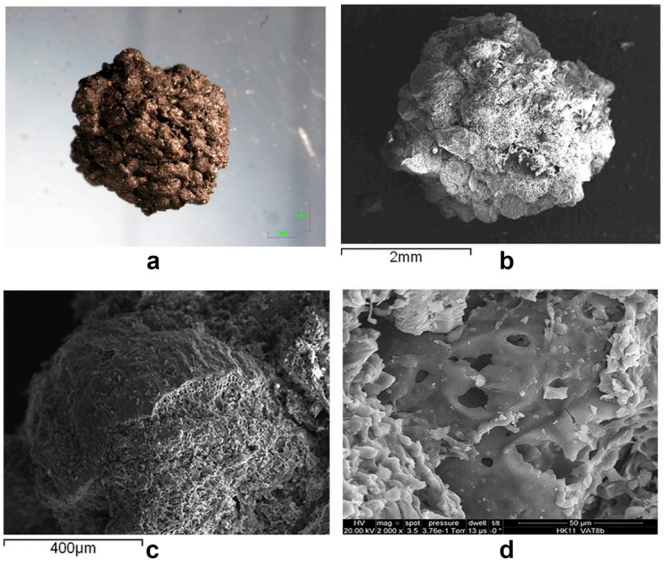


Fig. 6. Microphotographs of the finds of food remains from Early Chalcolithic Karanovo. a) macroscopic overview of a food fragment under low magnification binocular, b) macroscopic overview of a food fragment under SEM (x23 magnification), c) close view on the surface of a food remain with preserved grain fragment (x120 magnification), d) microstructure of the food tissue with indications for boiling.
(working distance for SEM images 20 mm).

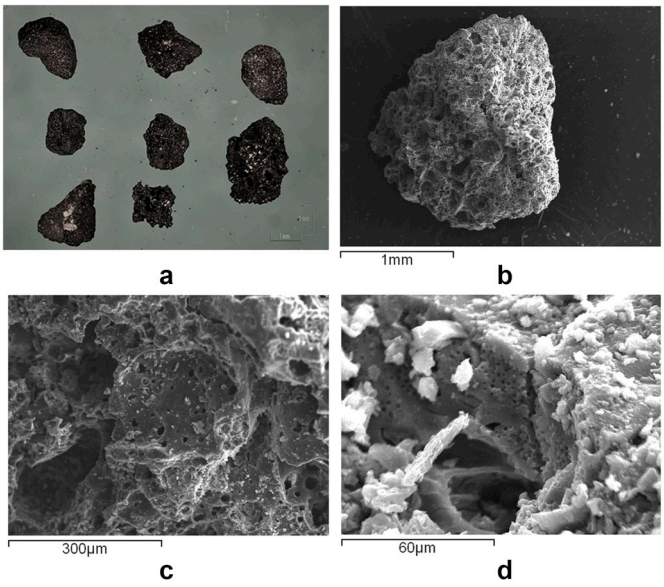


Fig. 7. Microphotographs of the finds of food remains from Middle Chalcolithic Provadia-Solnitsata. a) macroscopic overview of food fragments under low magnification binocular, b) macroscopic overview of a food fragments under SEM (x40 magnification), c) close view on the surface of a food remain (x180 magnification), d) preserved multi-layered aleurone (x900 magnification). (working distance for SEM images 20 mm).

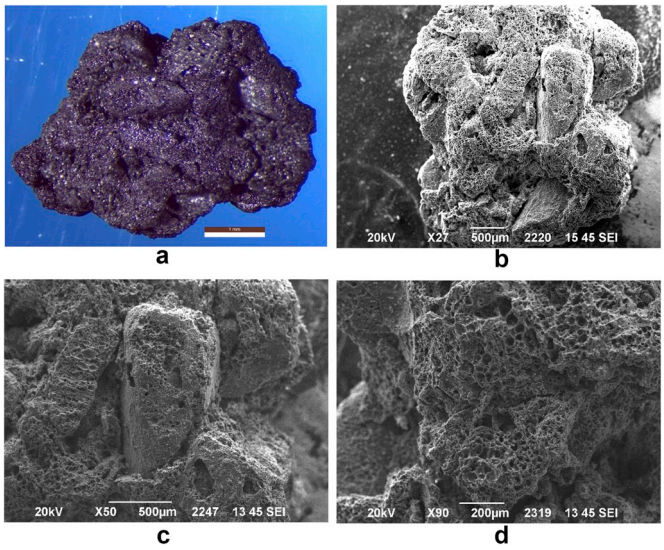


Fig. 8. Early Bronze Age Archondiko, agglomerations of cereal fragments. a) overview under low magnification binocular, b) overview under SEM, c) and d) closer view of the food fragment structure.

develop criteria for their identification in the archaeological record.

Similar finds of possible ground/cracked cereal grains reported for the Neolithic site of Avgi in Northern Greece (Margariti, 2007) and Drakaina Cave in Kephalonia (Sarpaki, 2009), as well as Late Bronze Age Akrotiri in Santorini (Sarpaki, 2001), constitute further indications for the processing of cereal foods in the study area. These are not included in Table 2 as little information is provided in the preliminary publications, lacking images of the fracture surfaces. The Akrotiri finds demonstrate a shredded fracture surface that does not match any of the archaeobotanical material we have considered here and the available, published experimental specimens.

The range of the materials that we have examined and correspond to cereal fragments indicate that grinding of cereals may not always result to bulging of the fracture surface, as previously suggested (Valamoti,

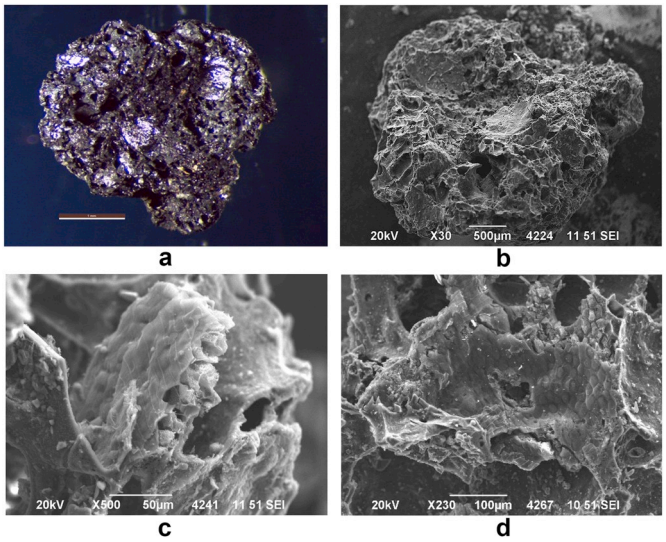


Fig. 9. Porous mass of plant foods form Late Neolithic Limnochori II. a) overview under low magnification binocular (scale bar 1 mm), b) overview under SEM, c) and d) SEM micrographs showing cereal pericarp longitudinal cells and single-layered aleurone.

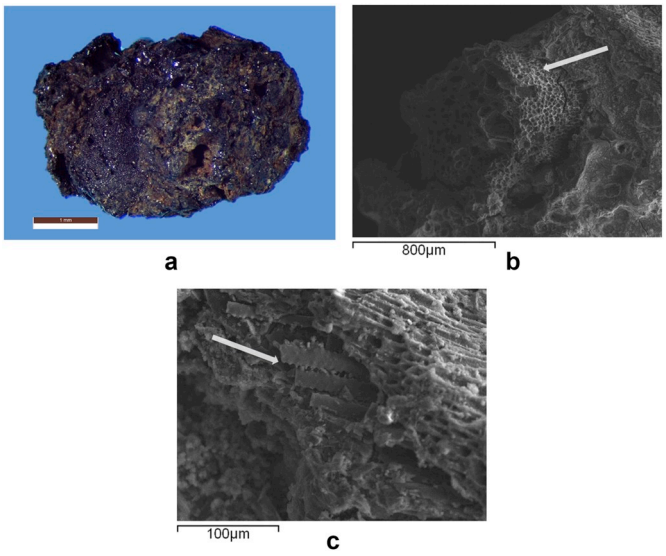


Fig. 10. Fragment of plant food from Final Neolithic Limnochori III. a) overview under low magnification binocular (left). SEM micrographs showing b) aleurone layer remains (x65 magnification) and c) wheat species glume fragments (x370 magnification). (working distance for SEM images 20 mm).

2002) and the taphonomic and/or processing parametres involved in this are currently investigated experimentally in the context of the PLANTCULT project.

3.3. Category 2: agglomerations of cereal fragments or food 'lumps'

The second category includes agglomerations of cereal fragments a) fused together but still clearly visible as distinct fragments and b) embedded in a more or less homogeneous matrix.

3.3.1. Agglomerations of fragments

Cereal fragments of small size are found lumped together at Karanovo as the contents of a vessel. They consist of small fragments (between 0,5 and 1 mm) and they could correspond to pre-cooked cereals or simply ground cereals that were lumped together during

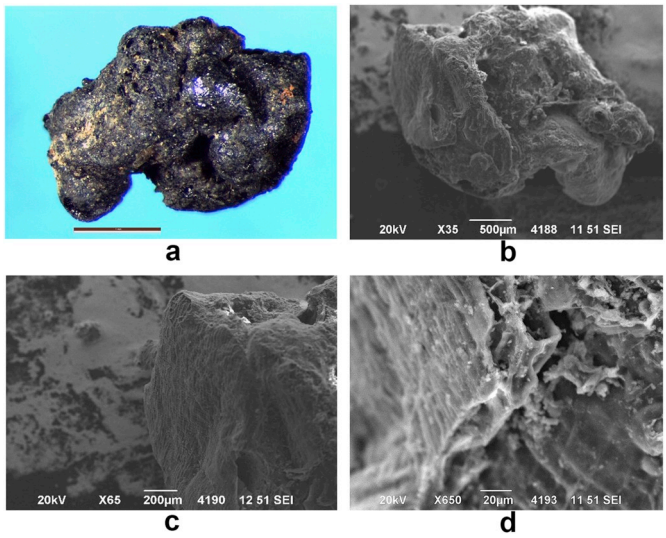


Fig. 11. Fragment of processed cereal food from Late Neolithic Anarghiri III. a) overview under low magnification binocular (scale bar 1 mm), b) overview under SEM, SEM images showing c) cereal grain fragment and d) multicellular aleurone layer.

charring. (Fig. 6). SEM images of individual fragments show the modified starchy endosperm observed in experimentally boiled grains (Valamoti et al., 2008) thus they could correspond to cooked cereals. It is impossible, however, on present state of the art to determine whether the gelatinised endosperm was generated as part of a pre-treatment (as in parboiling to make bulgur) or during an accident (destruction by fire or cooking accident) during the preparation of some foodstuff.

The Provadia-Solnitsata (Fig. 7) material is very interesting as it clearly shows cereal fragments fused together and a homogeneous surface that indicates a discrete lump of fragments. Therefore the Provadia-Solnitsata specimen corresponds to grain that had been ground and most likely formed into a lump or the lump is the result of some cooking process. We should, however, also consider the possibility that the loose fragments became fused together due to charring.

At Archondiko, some of the samples consist of lumps of cereals processed by grinding, with relatively large fragments of cereal grains and chaff (Fig. 8). These lumps of ground grain could have resulted either from intentional processing or could be the outcome of fusing of grain fragments due to charring conditions. If intentionally formed, they could correspond to some form of processing/cooking steps such as grinding, mixing with some liquid and forming lumps of the xinochondros/kishk type (see Valamoti, 2011 for an overview of the different types of food preparations consisting of cereal fragments and water/or milk). The shiny glassy surfaces of boiled specimens have not been identified on this material. A new possibility of interpretation has recently emerged in light of recently published evidence from Archondiko (Valamoti, 2017a,b) and these finds could alternatively correspond to dried malt cakes, used as starters for the preparation of a fermented beverage. Experimental investigations underway may help clarify these alternative processes generating this type of archaeobotanical food remains.

3.3.2. *Agglomerations of fragments in an amorphous matrix*

Our second group in this category includes mixtures of a fine, amorphous matrix with cereal fragments embedded in it, when examined with stereomicroscopy. Mixtures that may include fragments generated from the steps described above, together with more finely ground material may constitute more complex preparations such as 'breads', porridges, thick soups or other foodstuffs of similar consistency. These food remains could be interpreted as possible bread/porridge remains and are the most common category (regarding plant food remains), encountered in most of the sites from Northern Greece and Bulgaria, considered in the study.

Neolithic finds corresponding to this category come from the sites of Limnochori II and Limnochori III and Anarghiri III (Figs. 9–11) in the

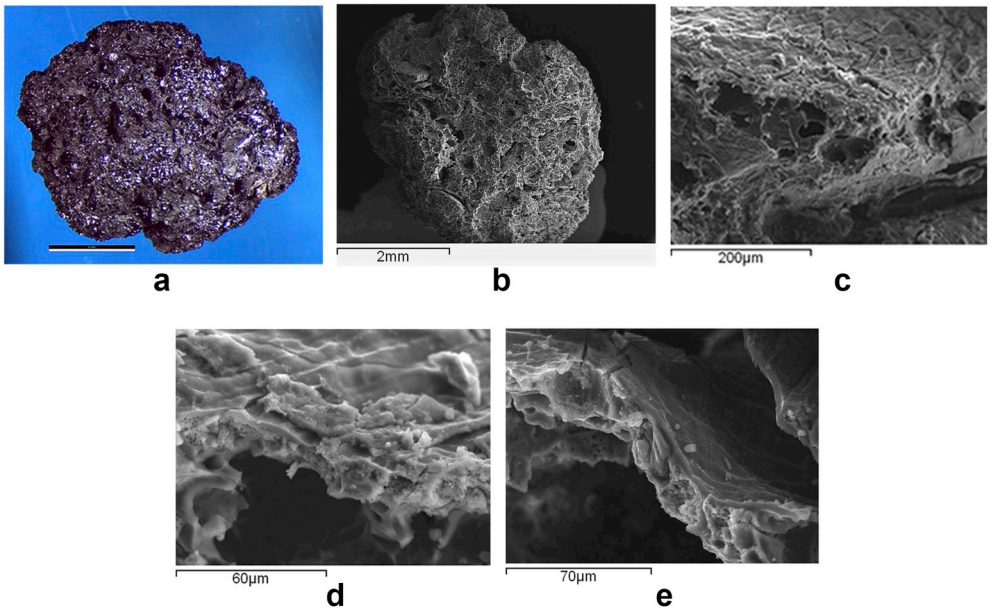


Fig. 12. Fragment of food remains from Early Bronze Age Archondiko. a) overview of the fragment under low magnification binocular, b) overview under SEM (x23 magnification), c) part of cereal grain showing at least sinlge-cell aleurone layer (x250 magnification), d) magnification of c (x800 magnification), e) remains of aleurone layer, possibly multi-layered (x850 magnification).
(working distance for SEM images 20 mm).

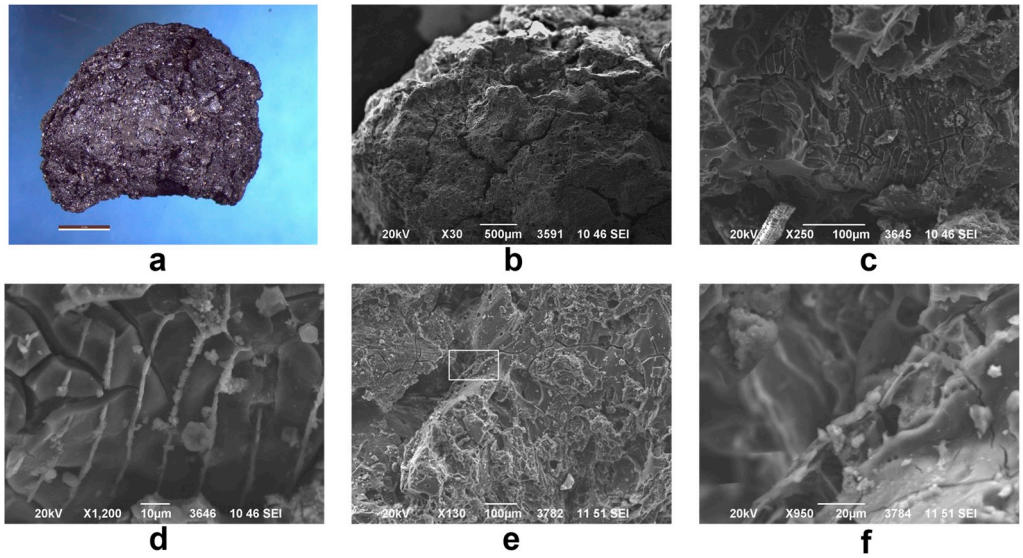


Fig. 13. Finds of food remains from Early Bronze Age Armenochori. a) overview under low magnification binocular (scale bar 2 mm), b) view of the find under SEM, c) patch of *Triticum* sp. transverse cells, d) magnification of c., e) remains of sinlge-layered-aleurone, f) magnification of e.

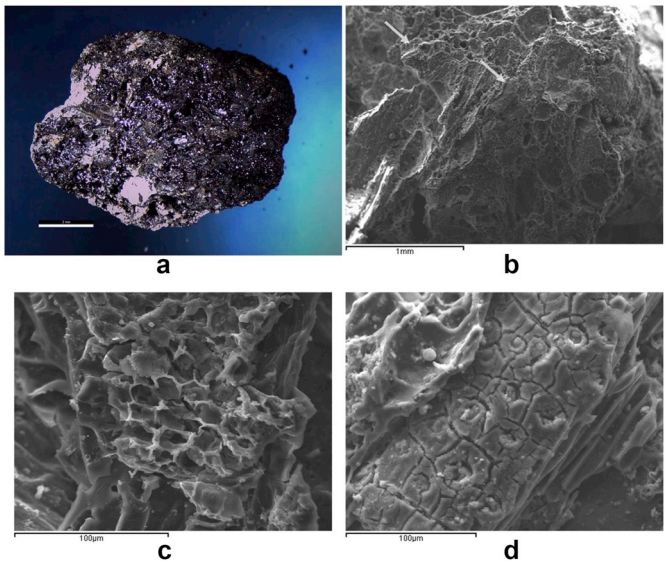


Fig. 14. Cereal fragment agglomeration in matrix from Late Bronze Age Angelochori. a) overview under low magnification binocular (scale bar 2 mm), b) view under SEM (x50 magnification). Arrows indicating areas of interest: c) remains of (possibly multi-layered) aleurone (x650 magnification), d) barley glume fragment (x550 magnification).
(working distance for SEM images 10 mm).

regions of Western and Eastern Macedonia in Northern Greece. In the Bronze Age, similar finds come from Archondiko, Armenochori and Angelochori in Northern Greece (Figs. 12–14) and Sokol and Kush Kaya in Bulgaria (Figs. 15 and 16). Further Bulgarian finds from Ada Tepe, Vaskovo, Kapitan Andreevo and Yurta belong to the Iron Age while the Necropolis of Apollonia to the Classical period (Figs. 17–21). At Archondiko, grain and chaff fragments are embedded in a porous, starchy matrix. Among the most common finds of identifiable tissues are parts of the aleurone layer, found in the pericarp of cereal grains (Fig. 12). Both single-layered (as in wheat, millet, oat and rye), and multi-layered aleurone tissue, found in barley, were visible. Food fragments with similar structure of coarsely pounded or ground cereal grain fragments embedded in a starchy matrix were also found in Limnochori II, Limnochori III, Anarghiri III and Armenochori (Figs. 9–11, 13). In the food fragments from Angelochori (Fig. 14), barley was recognized as the main component. In the cases where parts of the original outer surface were preserved, no differentiation between crust and crumb could be detected.

The Bulgarian finds that demonstrate this feature of an amorphous matrix including cereal fragments are dated to the Bronze and Iron Age. Food fragments from Early Bronze Age Sokol consist of masses with fragments of cereal grain and chaff. Some of the grain fragments have been recognized as wheat. The porous matrix appears to be shiny and somewhat vitrified in some parts (Fig. 15).

Agglomerations of cereal fragments were found in the Late Bronze Age layers of the site of Kush Kaya *in situ* in a deep vessel in a dwelling. The crust has a porous texture, which contains whole and fragmented cereal grains (millet and barley). Less frequent but well recognizable is linseed (Fig. 16). The fragmented grain and chaff of millet indicate that some processing related to dehusking or pounding/grinding took place prior to charring. Similar to the millet grains, also the barley remains indicate that they were partly fragmented or ground before mixing and becoming charred. This is attested by a variety of barley pericarp fragments, some still associated with multi-layered aleurone, which is typical for barley (Koërber-Grohne and Piening, 1980). Linseed was added to the mixture for its high content of oil, which would increase the nutritional value of the porridge.

Few samples with preserved cereal pericarp fragments were found in the Early Iron Age site of Ada Tepe (Fig. 17) and Kapitan Andreevo (Fig. 19). The texture of the fragments is quite homogenous which could be evidence of more controlled grinding and perhaps sieving of the ingredients prior further processing/cooking. In the material of Ada Tepe the preserved pericarp was identified as wheat (*Triticum* sp.) while that from Kapitan Andreevo was most probably barley.

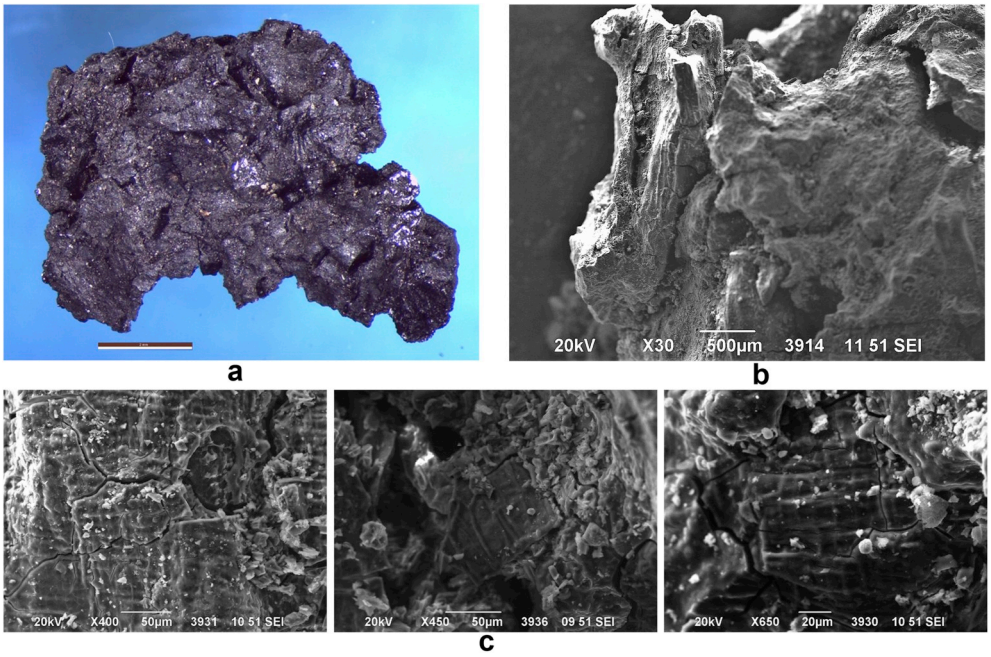


Fig. 15. Fragment of food remain from Early Bronze Age Sokol. a) overview of food fragment under low magnification binocular (scale bar 2 mm), b) view of food fragments under SEM, c) patches of cereal bran embedded in the matrix.

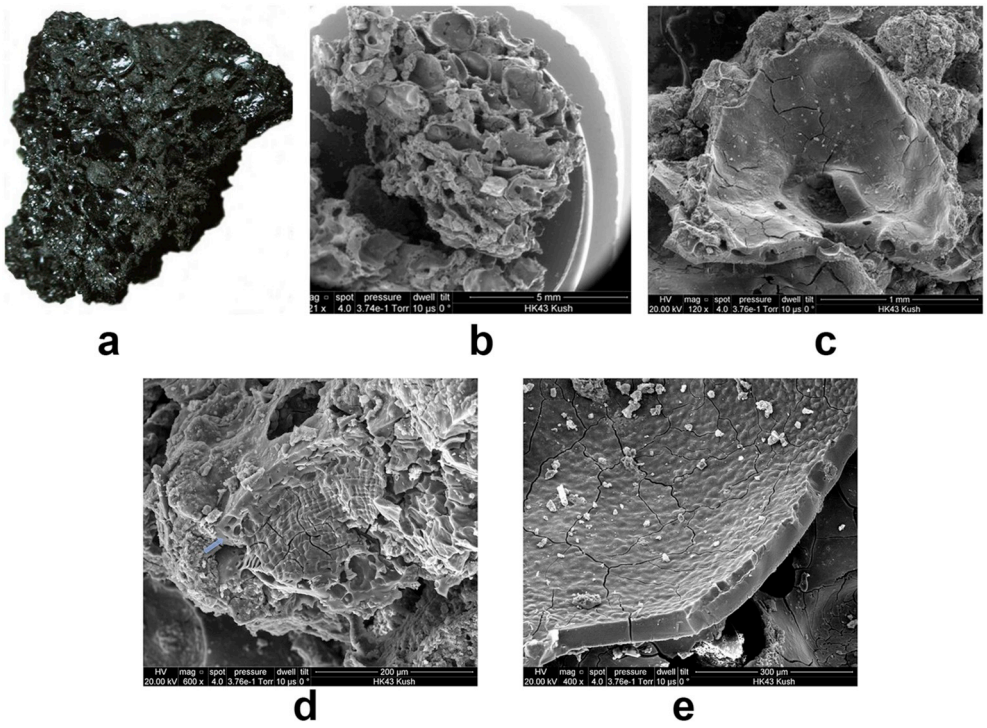


Fig. 16. Microphotographs of the finds of food remains from Late Bronze Age Kush Kaya. a) macroscopic overview of a food fragment under low magnification binocular, b) macroscopic overview of a food fragment under SEM, c) common millet – glumes fused with pericarp, d) preservation of cereal pericarp (arrow indicating remains of multicellular aleurone), e) linseed – seed coat surface fragment.

Food fragments from Late Iron Age Yurta and classical period Necropolis of Apollonia are characterized by a similar homogeneous structure. Cereal bran fragments, most commonly aleurone layer remains, were found in the SEM samples (Figs. 20 and 21).

Several very small fragments (approx. 0,5 cm) from the Early Iron Age site of Vaskovo were studied (Fig. 18). These possible food remains represent a homogenous structure. The texture is very similar to those from the other Early Iron Age sites Kapitan Andreevo and Ada Tepe, but traces of preserved cereal pericarp and/or aleurone layers were barely found. It should be noted that in some of the fragments a wooden

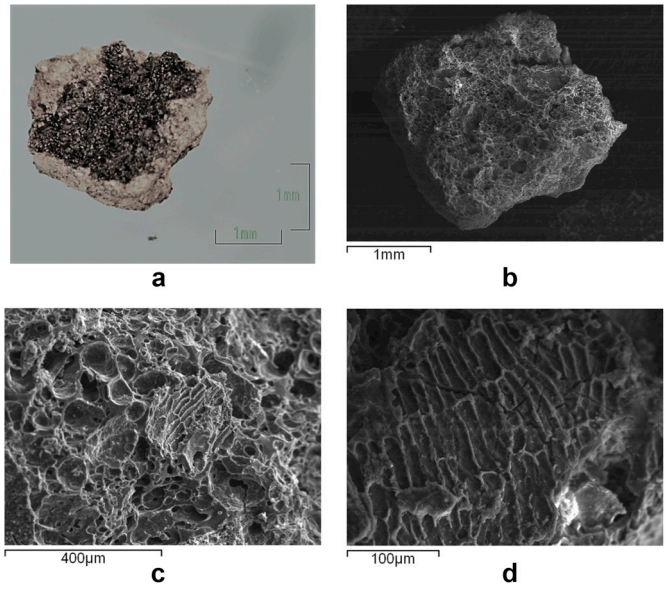


Fig. 17. Microphotographs of the finds of food remains from Early Iron Age Ada Tepe. a) macroscopic overview of a food fragment under low magnification binocular, b) macroscopic overview of a food fragment under SEM (x30 magnification), c) close view of the porous structure of a fragment with preserved pericarp cells (x140 magnification), d) detailed view of transverse cell layer of wheat (*Triticum* sp.) pericarp (x330 magnification).
(working distance for SEM images 20 mm).

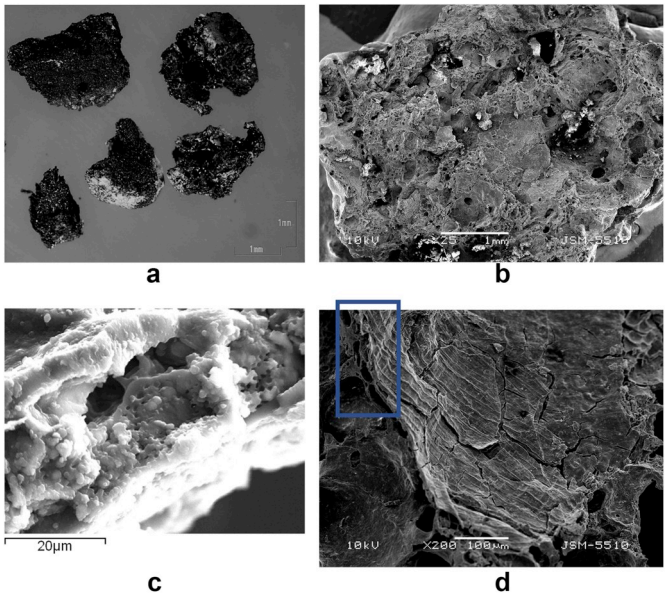


Fig. 19. Microphotographs of the finds of food remains from Early Iron Age Kapitan Andreevo. a) macroscopic overview of food fragments under low magnification binocular, b) macroscopic overview of a food fragment under SEM, c) and d) view of preserved aleurone layer and cereal pericarp (possibly barley) (c: x1900 magnification).

structure was also identified. Having in mind that the samples come from a house floor near the fireplace, most probably wood fragments have been mixed with the food remains.

3.3.3. Amorphous masses with 'bubbles'

The material in this category corresponds to a fine structure with no cereal fragments visible. This group of remains is quite frequently encountered at sites like Dikili Tash and Anarghiri I and consists of featureless masses of homogeneous structure with large bubbles or small pores (Figs. 22 and 23). In some fragments, possible remains of cereal pericarp could be observed under SEM, but their poor and fragmented state of preservation does not allow for a conclusive identification of

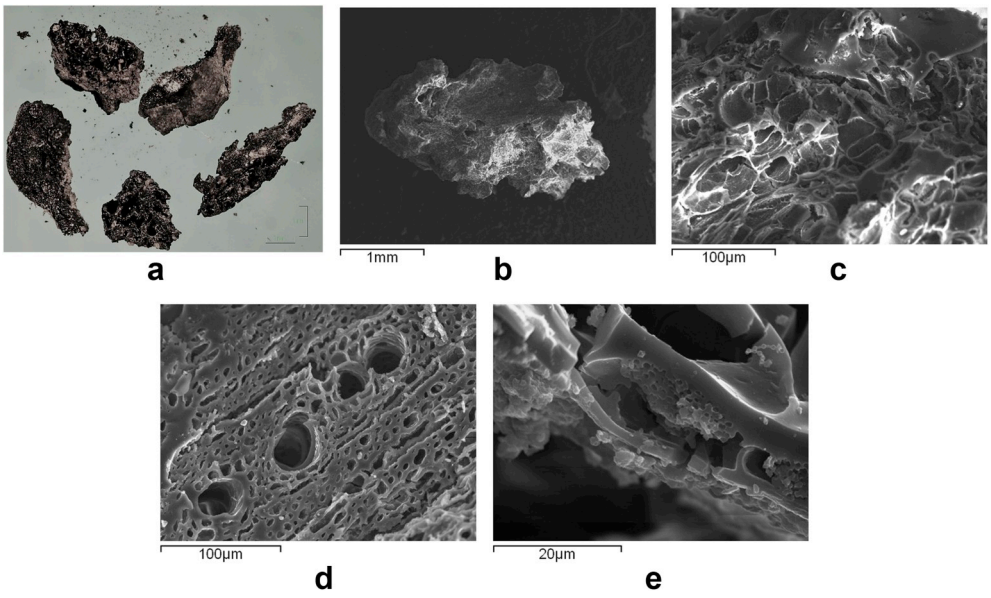


Fig. 18. Microphotographs of the finds of food remains from Early Iron Age Vaskovo. a) macroscopic overview of possible food fragments under low magnification binocular, b) macroscopic overview of a food fragments under SEM (x30 magnification), c) close view of the porous structure of a fragment (x400 magnification), d) close view of wood structure (x430 magnification), e) preserved aleurone layer (x2300 magnification).
(working distance for SEM images 20 mm).

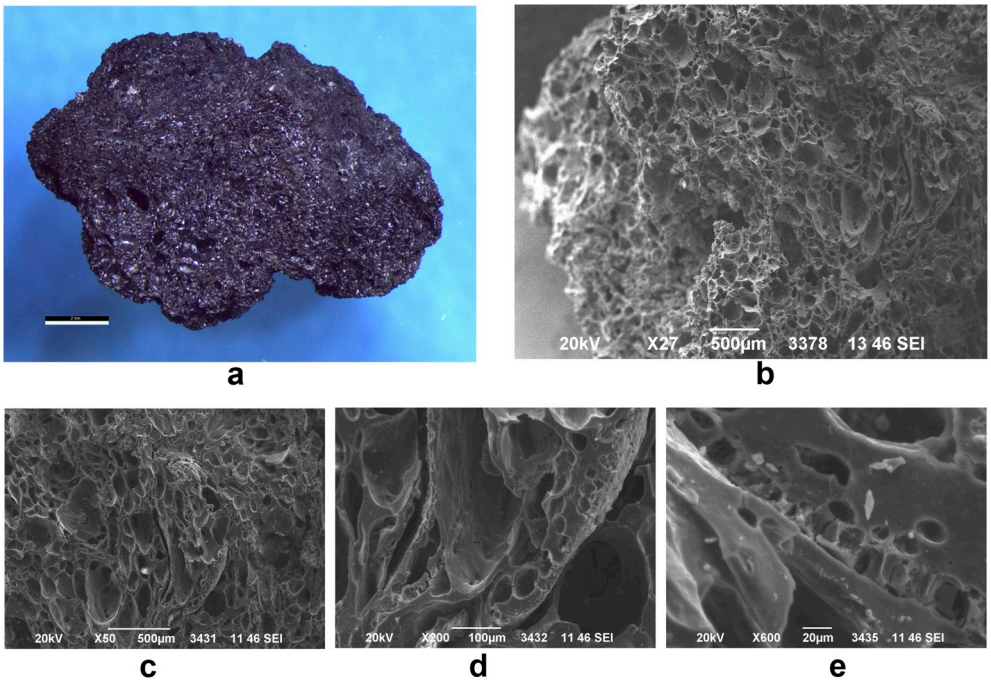


Fig. 20. Fragment of food remains from Late Iron Age Yurta settlement. a) overview of food fragment under low magnification binocular, b) view of the food fragment under SEM, c) remains of aleurone layer embedded in the matrix, d) and e) details of c.

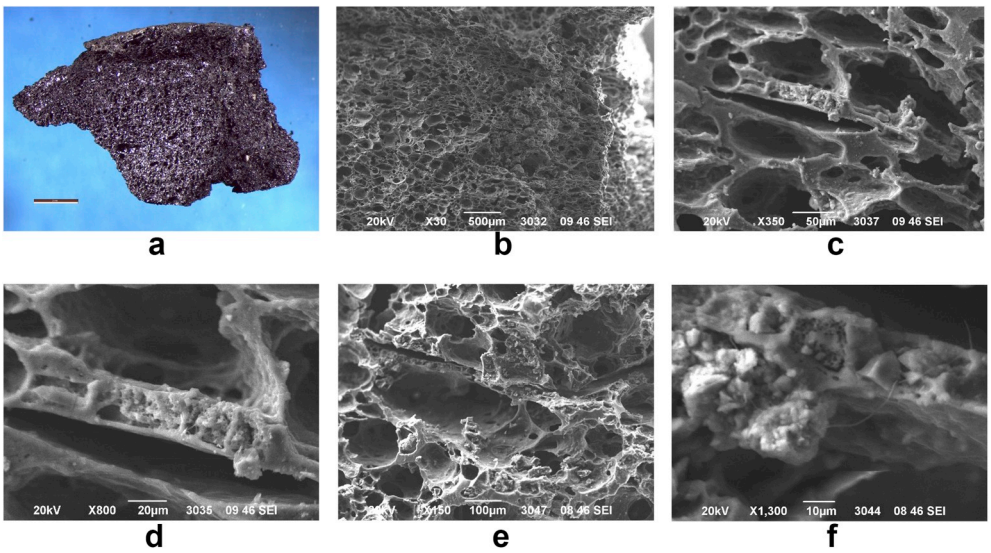


Fig. 21. Fragment of food remains from Necropolis of Apollonia, classical period. a) overview of food fragment under low magnification binocular (scale bar 2 mm), b) view of food fragment under SEM, c) and e) remains of aleurone layer embedded in porous matrix, d) and f) magnification of c and e respectively.

cereals as a component of the food remains. In most cases, their examination has not revealed any identifiable plant tissues, it is therefore not certain that they are cereal based. In several of the presented here sites (Kush Kaya, Kapitan Andreevo, Ada Tepe and Vaskovo) amorphous matter portions are available together with recognizable plant tissues. However when no morphological structures are visible such amorphous material is more difficult to interpret and the possibility that parenchyma or other kinds of tissues of plant origin are present has not yet been excluded. An aid to solve this question could be further methodological approaches like residue or chemical analyses.

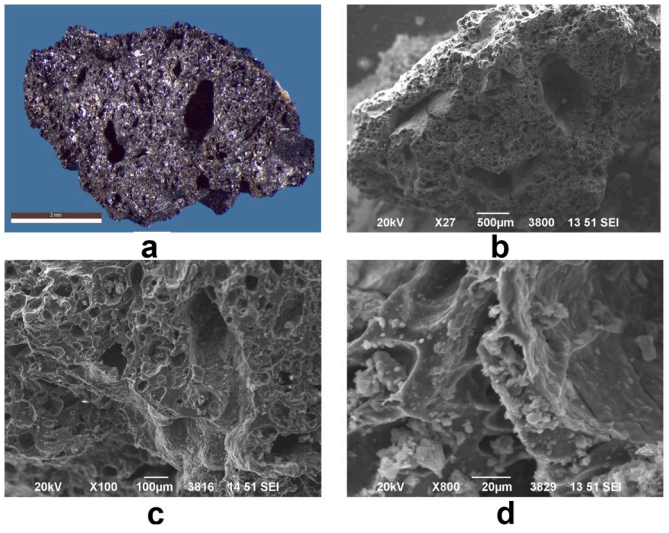


Fig. 22. Fragment of possible processed cereal food from Late Neolithic I Dikili Tash. a) overview of food fragment under low magnification binocular (scale bar 2 mm), b) and c) view of food fragment under SEM, d) possible remains of aleurone layer.

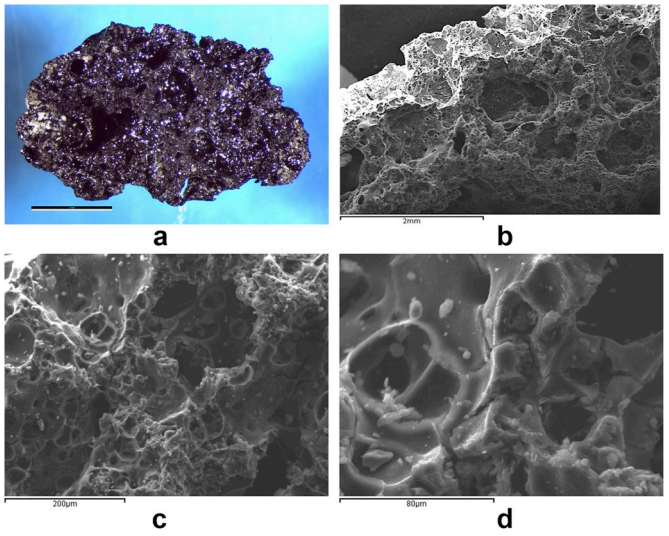


Fig. 23. Fragment of food remains from Early-Middle Bronze Age Anarghiri I. a) overview of the fragment under low magnification binocular (scale bar 2 mm), b) and c) view of the fragment under SEM (x30 and x250 magnification respectively), d) possible remains of aleurone layer from food fragment (x800 magnification).
(working distance for SEM images 10 mm).

4. Discussion

A wide range of possible plant food ingredients could have been used as food components, including various cereal and pulse species as well as oil plants, fruits, nuts, medicinal and aromatic plants in Southeastern Europe during the Neolithic and the Bronze Age. Turning to cereal ingredients in our study area, the main component of the material studied here, glume wheats, einkorn (*Triticum monococcum*), emmer (*Triticum dicoccum*) and the "new glume wheat-type", as well barley (*Hordeum vulgare*) are the most common finds (Hansen, 2000; Jones et al., 2000; Marinova and Valamoti, 2014; Sarpaki, 2000; Valamoti, 2009). Free threshing wheat, although very sporadically encountered in Neolithic sites from Greece it has been found in rich concentrations in Bulgarian Chalcolithic sites, especially in the Eastern part of Bulgaria (Gleser and Marinova, 2018).

The Neolithic prevalence of the glume wheats in our study area continues into the Bronze Age. The presence of free-threshing wheat increases, and it is present as a prominent crop in Archondiko, yet it is absent from the archaeobotanical assemblages of Bulgaria (Marinova and Valamoti, 2014; Valamoti et al., 2008). Barley also emerges as the dominant crop at sites such as Mesimeriani Toumba (Valamoti, 2009) and Agios Athanasios (Moniaki, 2009). To the species known from the Neolithic, two more are added: spelt wheat (*Triticum spelta*) during the Early Bronze Age and millet (*Panicum miliaceum*) during Late Bronze Age (Marinova and Valamoti, 2014; Valamoti, 2003, 2013). Among the sites with rich finds of millet are Archondiko and Angelochori (Valamoti, 2010, 2013), while in Kush Kaya it appears as a dominant crop along with hulled wheats (Popov et al., 2018).

During the Early Iron Age, cereal crops include millet, barley, hulled wheats, especially einkorn, and free threshing wheat (Hristova et al., 2017; Valamoti et al., 2018). Regional differences between Greece and Bulgaria are observed, for example unlike Greece, free-threshing wheat makes a limited appearance in Bulgaria with the exception of some sites such as Ada Tepe (Nikov et al., 2018) and Bresto (Marinova unpublished data).

Already since the Neolithic we observe variability in our study area as regards the forms in which cereals were transformed into food in prehistoric SE Europe. Cereal fragment concentrations and agglomerations of fragments in an amorphous matrix could correspond to various forms of cereal preparations such as bulgur or trachanas, bread, porridge or other forms of preparations. When fragments are loose, they could represent some form of cracked wheat, bulgur, trachanas or ground malt, depending on the particular features of the fragments (e.g. glassy, bulging endosperm). When the finds correspond to lumps of fragments they could be either some form of food like bread or porridge or an accidental conglomeration of a coarse meal or a fine meal with coarse inclusions, generated through charring. On present evidence it is not possible to differentiate between bread, porridge or accidentally formed lumps on the basis of morphological features of the archaeological finds. Moreover there is inadequate published comparative experimental material to facilitate a fine resolution categorisation of these ancient food remains. Therefore such lumps or masses are provisionally grouped in a broad category of 'bread/porridge'. The chronologically earliest finds (5840-5670 BC) are cereal fragment concentrations (Table 2), but very soon after that period (from 5500 to 4000 BC) also finds of bread/porridge occur in the study area (Table 2).

The Early Neolithic loose fragments from Bulgarian sites are either bulging (Kapitan Dimitrievo) or undiagnostic (Kapitan Dimitrievo, Yabalkovo). The Early Chalcolithic remains from Karanovo and Middle Chalcolithic from Provadia-Solnitsata demonstrated some traces of cooking (Figs. 6 and 7). It is not known whether a lack of bulging on cereal fragments can be generated under certain processing or charring conditions something that is currently being explored through systematic experimentation in the context of project PLANTCULT.

During the Bronze Age, the same variability continues as regards the types in which cereals are found in the form of food preparations, both in Bulgaria and Greece, with fragments and porridge/bread finds identified in both regions. The ingredients identified in the cereal food remains are in agreement with the appearance of millet as a new ingredient introduced during the Bronze Age in the area. Iron Age food remains are at present reported only from Bulgaria (Kapitan Andreevo, Ada Tepe, Vaskovo, Yurta) and may suggest standardised grinding and/or sieving prior to cooking.

Any regional differences observed between the different periods, e.g. the later occurrence of 'bread/porridge' finds from Bulgarian sites, is still difficult to evaluate, as such finds corresponding to cereal foods are quite rare and their preservation in the archaeological record depends on a series of taphonomic factors that may vary from site to site. Therefore, before enough data has been collected, it would be premature to discuss regional differences in culinary practices in respect to the cereal food preparations presented in this paper.

Despite the difficulties encountered in interpreting the material we have studied and deciphering the underlying 'recipes', we can safely argue that a range of different ways of transforming cereals into food were used in our study area. The variability observed concerns both ingredients and forms of food remains and would have served different requirements, seasonal, nutritional and social. The ethnographic record of our study area and beyond, offers a wealth of options as regards converting plant ingredients, in our case cereals, into foods. Solid forms with a long shelf life include ground cereals, precooked cereals in various forms known as bulgur or trachanas/kishk (see Palmer, 2002 and Valamoti, 2011 for a review of the literature as regards nutrient properties and variability in the ethnographic record), unripe grain roasted or smoked known as frikee and Grünkörn (Bayram, 2008; Palmer, 2002; Berihuete-Azorin in preparation), barley or other cereal based rusks (Procopiou, 2003). Cereals can also be transformed into liquid forms in fermented or alcoholic drinks as is the case of beer and millet boza (e.g. Valamoti, 2009, 2013) and such practices may well be represented by the material under consideration here (e.g. beer, see Valamoti, 2017a). Parboiling and grinding cereal grain in a coarse form in a bulgur/trachanas preparation as identified at Mesimeriani would have taken advantage of seasonally available ingredients and the hot summer sun to convert these ingredients into a product with a long shelf life, easily transformed into a nutritious meal throughout the year (Valamoti, 2011). Grinding grain into fine or coarse meal could have taken place piecemeal throughout the year to produce bread or porridges. The potential range of cereal food preparations that may correspond to the archaeological specimens we have examined so far might have had different advantages in terms of nutrient content, nutrient uptake and shelf-life as well as of labour investment in preparation, seasonality of cooking activities, ease of cooking etc. Transforming cereals into foods in different ways would have allowed not only a variety in cuisine *per se* but a means to better manage the available ingredients in terms of cooking time, nutrient availability, seasonal distribution of tasks, e.g. bulgur making in the summer, beer making in winter.

Which of these preparations correspond to the material we have examined remains unclear for most of them and apart from bulgur/trachanas, the other food remains could correspond to one or a range of pre-processed cereals (e.g. of the kishk/trachanas type, ground malt, dry bread) or of foodstuffs that happened to be charred as left overs or during cooking porridge and baking bread. However, several of them (Table 2) were found in contexts which strongly suggest their relation to processed food products. As already stated above the materials we have studied correspond to an extremely small portion of the foods prepared in prehistoric times in the region and consumed as food. In our discussion we should not forget that particular tastes might have prescribed regional preferences in the ingredients used and the ways those ingredients were transformed into foods. This interplay of available and selected ingredients and recipes would have contributed to the creation of regional culinary identities (Valamoti, 2017b). The ground cereal food ingredients we have investigated in the archaeobotanical record of Southeastern Europe could, in themselves, have been very flexible ingredients as they could have been converted into a savory or sweet meal, depending on what is added in the dish, e.g. salted cheese or dried fruit.

5. Conclusions

At the level of our analysis attempted here, the food products found could correspond to two broad categories: ground/pounded grains and bread/porridge preparations. These could correspond to many food products attested ethnographically. On current evidence the potential foodstuffs represented by the studied material could correspond to a) cracked wheat, b) bulgur/trachanas, c) ground malt, d) conglomerations of a-b-c-d, accidental or intentional, e) bread/porridge like preparations. Whether indeed such a variability in preparations existed in prehistoric times, is the subject of future research. Our paper offers a coarse-grained classification of archaeologically found cereal foods on the basis of morphology, informed by ethnographic studies. This classification provides a tool for routine archaeobotanical examination of such finds, avoiding at the same time the projection of modern perceptions about cereal foods to the prehistoric past. This is a first step in classifying such remains, in agreement with the wide range of possibilities in transforming cereals into food. Our work has shown that the characterisation of such cereal food preparations as bread or bulgur should be done with great caution or even be avoided, before reliable methodological steps for the examination of the different food processing stages has been developed.

As stated in the beginning of our paper it is crucial to carefully record the different forms of the archaeological specimens that are currently lumped under general categories such as cereal food, bulgur, bread/porridge. It is also very important to note that these general categories widely used in the literature, sometimes interchangeably, mask a multitude of recipes leading to similar looking preparations in the archaeobotanical finds, thus further ethnographic data backed up by experimental data will help understand the nature of the ancient cereal foods examined under the microscope. A systematic key for classifying such objects is much needed and is currently under way in the context of ERC project PLANTCULT (Heiss et al. in preparation). Detailed classification categories of archaeological finds of cereal foods, backed up by experimental replications will allow more refined interpretations of the processing steps involved in their preparation. It is probably uncertain that experimental replication could cover the full range of types of fragmented grain, pre-cooked cereals, flours or fermented cereal products that were used in prehistoric times or the ways in which they were further mixed and cooked. Moreover, our study has shown that behind the visible surface observed each time, there will always be an underlying matrix that is invisible and non-quantifiable. Yet, this coarse grain classification we offer here, based on 'internal' evidence provided by this rarely preserved archaeobotanical material, is a first step towards the classification of archaeological cereal foods that allow associations between these finds and a range of possible food categories. Devising detailed classification categories opens up the way to decipher prehistoric cereal based recipes. Our work presented here highlights a multitude of possible cereal-based food products that may correspond to the finds analysed. The food remains we have identified and presented in a first regional overview of prehistoric cereal food preparations open up the possibility to explore and comprehend the factors that may have led to this wealth of food preparations, the complex outcome of interactions between the natural and cultural environments of these farming communities over a long period of time. Integrating the archaeobotanical macro- and micro-remains with the available food technologies used for grinding, cooking/baking etc, informed by residue and use-wear analyses, will hopefully facilitate our understanding of the cereal food preparations discussed here (Valamoti et al., 2017).

Further analysis of these finds, integrated with evidence from functional analyses of pottery, residue analyses and ethnography, underway in the context of ERC project PLANTCULT will hopefully reveal in detail the particular characteristics of the prehistoric forerunners of foods that still survive today in the traditional cuisines of the study area. The refinement of the methods and variables that need to be taken into consideration will allow in the future the exploration of shared culinary trends and their potential changes over time opening the path towards an investigation of the factors that led to culinary traditions and innovations in this part of Europe.

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The Hoard of the Rings. "Odd" annular bread-like objects as a case study for cereal-product diversity at the Late Bronze Age hillfort site of Stillfried (Lower Austria)

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Abstract

Cereals, in addition to being a major ingredient in daily meals, also play a role in the preparation of foodstuffs for ritual purposes. This paper deals with finds that may correspond to such ritual preparations retrieved from the hillfort site of Stillfried an der March. The site, spreading across an area of ca. 23 ha, held a very important position among settlements of Late Urnfield period (particularly during the 10th – 9th c. BCE), acting as a central place where large scale storage of grain as well as textile and metal production took place under the control of local elites. Three incomplete ring-shaped charred organic objects, found together with 14 rings and ring fragments made of clay were discovered in a secondary filled silo pit, excavated among a total of about 100 pits of this kind at the site. The overall good state of preservation of the organic ring fragments suggests that they were deposited intact on the bottom of the pit and covered well so that no re-deposition or damage occurred. This could be indicate their intentional placement in this position. Light and scanning electron microscopy revealed that the charred organic rings are cereal products containing hulled barley and a wheat species. Indications that the objects were shaped from a wet cereal mixture and had been subsequently dried without baking are discussed, as well as the possible significance of the find assemblage. The annular objects are put in context with the contemporary cereal spectrum as well as other cereal preparations from Stillfried, outlining their different *chaînes opératoires* for handling cereal food.

Key words

air-dried dough

bread-like object

cereal preparation

culinary diversity

eastern central Europe

grain storage pit

hillfort site

Hordeum vulgare

Late Bronze Age

Triticum sp.

Introduction

The importance of food, or rather, of different meals, for the constitution of individual and collective identities, and likewise as a means of social stratification, has long been a topic in the philosophy of culture and in social and historical anthropology [1-3], becoming a key topic in archaeology with ever-increasing importance [4-6]. However, in stark contrast to the vast evidence on crop diversity [7, 8], the scarcity of archaeological finds of food preparations and the even scarcer evidence on their ways of production has left a large component of past

meals poorly understood and investigated, while conclusions from the archaeobotanical side had to remain on the level of anecdotic evidence. Luckily, interdisciplinary research into food transformation has gained momentum recently [9-11] and, in particular for south-eastern Europe, the awareness of the significance of research into the diversity of cereal-based dishes in the prehistoric archaeological record has been substantially improved [12, 13].

The cultural importance of the transformation of raw ingredients into food has probably been emphasised best by Sherratt, stating that "people do not eat species, they eat meals" [4]. The choices of plant species, their respective parts to be consumed [14-16] and the transformation of those into meals involves their incorporation into the social space of a civilization. Each of those meals reflects individual life experiences, collective memory, and identity [5, 17-19]. By human action and creativity, ecofacts [20] are transformed into artefacts [21-23] of defined structures and shapes in specific *chaînes opératoires* [24, 25]. Archaeological remains of meals in whatever form shall therefore clearly be regarded as parts of a material culture [26], requiring no less concise classification criteria and typologies than artefacts made of metal, ceramics, or glass [27, 28].

The archaeological remains of supposed "everyday food" and the insight into their composition and ways of production can tell us a lot about the nutrition value and sensory quality of this food, as well as the kind of tools involved and the amount of time invested in its production [10, 29, 30]. Altogether, these sets of information may also allow for conclusions about the social significance of the food preparations concerned. Yet when interpreting food remains from certain – or at least presumable – cultic contexts, understanding their sociocultural role is only possible when understanding respective *chaînes opératoires* involved in their production. Ethnography and history demonstrate how even a single aspect in either the components or processing can be decisive for the role of a food preparation in a particular rite: again taking fermentation as an example, leavening would be unthinkable in the *matzah* bread of Jewish Passover rites [31, 32], just as it would be for the altar bread of the Catholic Eucharist [33]. Concerning components, the Roman *mola salsa* [34] should certainly not be made of barley, while most Ancient Greek votive breads or cakes such as the *megalomazos* and the *hygieiai* should certainly be barley-based [35, 36]. Until now, only a few in-depth archaeobotanical studies have been able to contribute to such aspects of the respective ritual, the gestures and the knowledge behind it, and their embodiment in the final offerings [26, 30, 37].

Research goals

Systematised scientific analyses of charred annular organic finds from a Late Bronze Age context were carried out in order to elucidate their composition and the processes involved in their production in order to test the hypothesis of them representing food in the widest sense. The results shall then be set in relation to extant data on remains of food plants and foodstuffs. The possible roles and significances of the three annular objects shall be elaborated against the background of the find context and its depositional history. Finally, the finds will be put within the wider context of the central European Late Bronze Age in regards to food processing practices and the role of food preparations in ritual activities. Purposes of food preparations other than consumption shall be discussed briefly.

The site

The hillfort site of Stillfried an der March is situated on a prominent knoll oriented in a north-south direction on the border between the gentle hills of the Weinviertel to the west, and the lowlands to the east, overlooking the banks of river March/Morava (Fig 1). The settlement shared its fortification and its strategic elevated position with other settlements of the Middle Danubian Urnfield culture [38, 39], yet was outstanding due to its location at the crossroads between the later so-called "amber road" running north-south, and a trade route running east-west leading towards the Little Carpathians.

Fig 1. Aerial view of Stillfried an der March, as seen from the west. River March/Morava is visible in the upper part of the image. The reconstructed former fortification ramparts of the late Bronze Age hillfort are outlined in red. Insets indicate the location of the site at the Austrian-Slovakian border, and Austria's location within Europe. Aerial Image No. 02030701.096 reprinted under a CC-BY license with permission from the Aerial Archive, Department of Prehistoric and Historical Archaeology, University of Vienna. Map sources: Wikimedia Commons, users TUBS and NordNordWest, CC BY-SA 3.0.

About 2.5 % of the 22 ha (220,000 m^2) plateau has been excavated by the University of Vienna continuously from 1969 until 1989 [38]. From the Late Bronze Age, a large number of pits (about 100) were found distributed relatively evenly across the excavated parts of the hillfort (Fig 2). These share a general common shape of truncated cones, but vary in volume from 2 to 10 m^3. They are interpreted as former storage pits for grain, and it is assumed that most of them were used repeatedly. None of the excavated storage pits contained major amounts of refuse as would have been the case had they been used for waste disposal [40], they had obviously been filled with rather homogeneous soil within short periods. Still, their excavation yielded a relatively large number and diversity of objects, often in unusual states or combinations: in at least two of the pits, human skulls were deposited [41] as were seven dead bodies in another pit [42, 43]. Eighteen terminated storage pits contained the deliberately deposited carcasses of domestic animals, as well as apparently tamed wild animals, some of which had died of old age such as wolves, hares and red deer [44]. Finds of daub fragments in some of the pits indicate dwelling houses nearby, but the connection between houses and pits is unknown: only very few postholes were found as the terrain has undergone severe ablation, most probably during the Middle Ages, only preserving the deeply dug pits.

Following D. Garrow's definitions, most of these find assemblages correspond to "odd deposits" [45], which are outlined by one or more of the following characteristics: a) an extraordinary selection of finds, b) an exceptional state of preservation, c) a remarkable number or combination of finds, or d) exceptional find situations within a deposit or an unusual location of the find assemblage itself. These "odd" deposits from the secondary fillings of the storage pits probably cannot be understood without implying ritualised processes for placing those objects in the pits [42, 46-48].

Fig 2. Elevation map of the northern area of the Late Bronze Age hillfort, indicating the location of pit V5400. Brown rectangles mark excavation trenches while blue lines indicate excavated structures. Toponyms indicated (e. g. Küssleracker, Wagneracker) are referred to in the text. Image: ÖAW-OREA / B. Biederer, I. Hellerschmid, I. Petschko.

Food plants and plant foods from the settlement

Extensive archaeobotanical analyses on samples from various archaeological contexts in the hillfort site, mostly the above-mentioned storage pits, but also from ovens and vessel contents, have resulted in a wide spectrum of crop plants [49-51]. As also observed in other sites of the region during Late Bronze Age [52, 53], the cereal spectrum is strongly dominated by broomcorn millet (*Panicum miliaceum*) comprising ca. 60% of all identified cereal grains (Fig 3), followed by more or less equal quantities (7 – 9% each) of hulled barley (*Hordeum vulgare*), einkorn (*Triticum monococcum*), spelt (*T. spelta*), and the "new" glume wheat most probably corresponding to modern Sanduri wheat (*T.* cf. *timopheevii*) [54-56]. Foxtail millet (*Setaria italica*), emmer (*Triticum dicoccum*) and free-threshing wheats (*T. aestivum*/*T. durum*/*T. turgidum*) only occur in minor quantities.

Among the other domesticates found at Stillfried, only the remarkably early finds of domesticated grapevine (*Vitis vinifera* subsp. *vinifera*) shall be highlighted here, which are interpreted as imports from the Mediterranean [49].

Aside from seeds and fruits, these archaeobotanical analyses have also resulted in rich evidence of various charred cereal preparations (Table 1): fragments of porridge are documented, as are chunks of bread showing clear differentiation between crumb and crust. The third type of material (nicknamed "Hirsotto") was identified as a porridge-like preparation of coarsely crushed grains of barley, broomcorn millet and rye brome (*Bromus secalinus*), and it has already been the research focus of experimental approaches in order to infer its possible production steps and taste [49, 57, 58].

Fig 3. Simplified spectrum of cereal grain finds at Late Bronze Age Stillfried. The original data of M. Kohler-Schneider [49] were processed following the scheme of Stika & Heiss [52, 53]: included are only grain finds of taxa definitely or at least probably (cf.) identified to species level. Chaff finds as well as grains identified only to genus level are excluded, as are intermediate groups. Naked wheats which are not satisfactorily discernible by their grains are treated as a single species. Percentages are rounded to whole numbers. N = 4,256. Image: ÖAW-ÖAI / A. G. Heiss.

Table 1. Known occurrences of cereal preparations in Late Bronze Age pits from Stillfried. Identifications by M. Kohler-Schneider [49]. The localities "Hügelfeld" and "Wagneracker" are indicated in Fig 2 and the radiocarbon dates obtained there are given in Table 3.

	Hügelfeld			Wagneracker			
	V887	**V888**	**V949**	**V5001**	**V5003**	**V5005**	**V5006**
porridge	+	+	+	+	+	+	+
bread	+	+	+	+	+	+	+
"Hirsotto"	-	-	-	+	-	-	+

The find context

The finds analysed in the current paper originate from the secondary filling of a Late Bronze Age former grain storage pit (V5400) from the eastern part of the hillfort (Fig 2). It was already excavated in 1978, but will be published the first time within the course of the ongoing Austrian Science Fund (FWF) project "Resource management, power and cult in Stillfried?" (Project No. P 28005-G25).

The structure is a 1.55 m deep pit, widening to a diameter of 2 m towards its bottom. Its volume of ca. 2.8 m³ lies in the lower range of the pits at Stillfried. In the basal layer, a charred wooden plank was found. The filling above (Fig 4) contained elements of a burnt-down house, such as a massive layer of burnt rubble with large pieces of daub (about 20 kg), charred wood and broken pottery. The latter is dominated by rough houseware (cooking pots, storage vessels, in total about 8 kg), most of the pieces bearing traces of fire. In contrast, the fine tableware from the same layer shows mostly no evidence of burning. A similar composition of the secondary filling as well as a similar state of preservation of the ceramics was found in storage pit V5001 of the same hillfort [47]. Typological dating of the ceramics is in congruence with Hallstatt B2 and B3, corresponding to c. 960 – 800 BCE [59].

Fig 4. Annotated profile photo (above) and plan (below) through Pit V5400 at Küssleracker, 1978 excavation campaign. The grey layer at the bottom is the burnt debris which contained the rings. In the foreground, the charred plank (find number ST 12050.1) is visible. Image: excavation documentation Stillfried, State Collections of Lower Austria, Department of Prehistory, Protohistory, and Medieval Archaeology.

From the layer of burnt debris, 14 rings made of clay were recovered, as well as three fragments of rings made of charred organic matter, which are interpreted as originating from three individual rings (Fig 5). The clay rings have outer diameters of 8.6 – 10.5 cm and 6.2 – 7.7 cm. Two were found in complete state, another four can be reassembled completely from two or three pieces, while the remaining ones are fragmentary. These had been only weakly fired and had probably been used as loom weights [47], as is also indicated by traces of use. Similar clay rings are documented from pits V5003 and V5004.

The three charred organic rings are significantly smaller, with outer diameters ranging from 2.6 to 3.6 cm. From the same layer, other interesting finds also came to the light: two deviant ceramic finds – a vertically halved vessel with a conical neck used for scooping liquid (Fig 6) and a stamp-like object made of a lid – as well as grinding stones (Fig 7), a bronze needle, a processed antler and daub fragments (Fig 8). Above this layer only a few finds were detected in a filling dominated by the local humus soils and loess [46, 47].

The overall composition of finds from pit V5400 clearly speaks against tertiary refuse, i.e. the diachronic accumulation of materials eventually constituting the pit's filling [40], but rather indicates a singular event of deposition. Like in the other terminated storage pits mentioned above, the unusual combination of objects in a particular state qualifies the find assemblage as an "odd deposit" [45]. An intentional and deliberate (ritual) deposition of the pit's contents shall therefore serve as a working hypothesis.

Fig 5. The annular objects from the find assemblage in the debris layer of pit V5400. Twelve of the 14 rings made of clay (find numbers ST 12044.1–9, 12116.1, 12266.1–2, box 10/60044) are shown, as well as the charred organic rings (find numbers ST 12050.2–4, box 9/60043) which are the focus of this contribution. Scale bar units: centimetres. Image: ÖAW-OREA / B. Biederer.

Fig 6. Vessel with conical neck (*Kegelhalsgefäß*) and handle from the burnt debris layer. This deviant ceramic object, split in half vertically (find number ST 12051.1/box 1/60001), was possibly used for scooping liquid. Scale bar units: decimetres/centimetres. Image: ÖAW-OREA / M. Griebl.

Fig 7. Edge piece of a grinding stone with preserved top surfaces and side edges, broken in halves. The marked burning traces of this object (find number ST 12260.5, box 3/60048) may derive from the same fire as the remaining burnt debris. Scale bar units: decimetres/centimetres. Image: ÖAW-OREA / B. Biederer.

Fig 8. Burnt daub, interpreted as architectural elements. These elongated daub fragments (find number ST 12049.11, boxes 2/60028 and 2/60033) are comparable to finds out of the burnt rubble-layer in storage pit V5001 of the same hillfort. Scale bar units: decimetres/centimetres. Image: ÖAW-OREA / B. Biederer.

Materials and methods

The three incomplete charred rings (Find Nos. ST 12050.2-4 / Box 6004) covered by the current study are the property of the Provincial Government of Lower Austria. Like the other mentioned finds from Stillfried, they are stored in the archaeological depot (Kulturfabrik), Donaulände 33, 2410 Hainburg an der Donau, Austria. The material is accessible on request for re-examination. Several of the mentioned archaeological finds are part of the permanent exhibition in the Museum Stillfried in Stillfried an der March [60]. No permits were required for the described study.

Conservational considerations: Some challenges in the analysis of museal objects

The surfaces of all three charred organic rings exhibited an opaque and glossy appearance, apparently deriving from a consolidating agent applied immediately after excavation in the late 1970s. As the diagnostic features of the surface where not readable due to this treatment, the consolidant had to be removed to some extent in order to enable microscopical analysis. Preliminary tests showed a slight swelling in water while the application of a range of other polar and non-polar solvents did not show any effect. In order to gain detailed information on the composition of this consolidating agent, chemical analysis was carried out by means of FTIR (Fourier-Transform Infrared Spectroscopy). A portion of the swollen glossy coating of Sample A was taken, air-dried, and directly analysed in a diamond cell (transmission mode) using a Bruker Tensor 27, coupled with a Hyperion 2000 microscope, resolution: 4 cm^{-1}, measurement range: 4000–550cm^{-1}.

The results (Fig 9) show the presence of polyvinyl acetate (PVAC) [61], which is commonly used as wood glue and which has apparently been applied onto the find as consolidant. Contrary to a number of synthetic resins which were also in use during the 1970s, PVAC is soluble in aqueous solution as well as in some solvents and is therefore removable to some extent. Since its first reported use in conservation in 1932 [62], it has been in use as consolidant throughout the 20th century for objects made of a broad range of materials including glass [63], ceramics [64], textiles [65], leather [66], paper [67], and wood [68]. It is still in use as a consolidant for archaeological finds [69-71], with a particular focus on the consolidation of human bone material [72-74].

In addition, traces of a translucent reddish brown coating were identified as shellac [61] which is interpreted as a secondary addition. Shellac has commonly been used as varnish for many

centuries and is nowadays still used in conservation-restoration for special applications. Apparently shellac was still in use as consolidant in the 1980s in central Europe – despite the fact that some of its properties are highly problematic for this kind of application [75].

Fig 9. FTIR spectra of the surface coating of sample A. a) PVAC. red: sample curve, blue: reference material, b) Shellac. red: sample curve, grey: reference material. Image: BDA / R. Linke.

The observed low solubility of the consolidant on sample A may be linked to the ageing of the PVAC, as photochemical degradation leads to cross-linking and chain scission in the material, under release of volatile compounds [76]. Issues regarding the removal of PVAC are, however, not limited to conservation: Especially in the field of radiocarbon dating PVAC can be problematic [77, 78]. As the PVAC used for consolidation on Sample A was not sufficiently removable by solvent treatments but swellable with water, the decision was made to manually remove it from a part of the surface of Sample A after the application of water soaked cellulose fibres. The surface of the object showed enough strength to lift the softened consolidant with a set of very fine metal tools under the stereomicroscope. The fragments of the charred material (2.8 mg) which came off during this procedure were labelled sample B and kept for radiocarbon dating. As a consequence of the observed changes in surface caused by the removal of the consolidating agent, namely the loss of the glossy appearance, we decided to limit this procedure, and consequently in-depth analysis, to sample A.

Chemical analyses were not carried out in the current study due to the limited results to be expected in comparison to tissue-based approaches [9, 79, 80], as well as due to the known contamination of the finds with consolidating agents. In contrast to method sets involving chemical dissolution of the material [81-83], we followed a less invasive approach by identifying components via tissue remains visible on fractured faces as already established [10, 30]. Aside from the samples for SEM analysis and AMS dating, no fresh fractures were produced due to conservation considerations regarding the uniqueness of the finds.

Radiocarbon dating

AMS dating was carried out at BETA Analytic, Miami. As a preventive measure against the above-mentioned organic contaminants, standard acid-alkali-acid treatment as well as solvent extraction were applied prior to dating. The results as well as all other radiocarbon dates mentioned in this article were calibrated with OxCal 4.3 [84], basing on the IntCal13 calibration curve [85].

Microscopy and photography

Photo documentation was carried out with a Canon EOS 5DS R equipped with a Canon EF 100 mm/2.8 L Macro IS USM objective, using a Broncolor Siros 400 WiFi / RFS 2.1 illumination device in order to maintain constant colour temperature.

Light microscopic observations of the objects' supposedly post-depositional fractured faces were carried out using integrated solutions by Olympus: an SZX-10 stereo microscope at magnifications up to 63-fold, and a BX53M metallurgical microscope with up to 500-fold magnification, both with integrated camera UC909 and the software Olympus Stream Basic,

applying its Instant EFI (Extended Focal Imaging) image stacking function in order to improve depth-of-field of the photographed irregular surfaces.

The cleaned surfaces of ring A were additionally analysed using a Quanta 250 FEG environmental SEM in 'Low Vacuum Mode' and without prior sputter coating. We used acceleration voltages ranging from 5 to 15 kV in the generation of secondary electron images. Depth-of-field was enhanced in some cases by combining an image stack with the software Helicon Focus 7 [86].

Experimental reference material

Some aspects of the analysis required experimentally charred reference material, in particular the preservability of starch granules in charred state and the formation of cavities during charring.

Triticum spelta 'Bauländer Spelz' was cultivated in autumn sowing by the Mechler family in Altheim-Walldürn, southwestern Germany, and harvested as *Grünkern*, i.e. in an unripe state [87] after nine months of growth. The grains were charred in a Nabertherm NA 15/65 muffle furnace under various charring regimes: at low temperature (230° C) for 7, 9, 12, and 24 hours [88], and at high temperature (300°C) for 6 hours.

Sprouted two-rowed hulled barley (*Hordeum vulgare* subsp. *vulgare* f. *distichon*) was acquired from the Durst Malz company, Bruchsal-Heidelsheim, Germany, in various states of germination (3 days and 5 days) and charred using the same muffle furnace under varying conditions (dry, soaked in water, and with water) at low temperature (230° C) for 24 hours [88].

SEM imagery for the *Grünkern* was produced using a Zeiss DSM 940 after sputter coating with gold/palladium in a Balzers SCD 040, for the barley malt with a JEOL JSM-6390LV after carbon coating using a JEOL-4X vacuum evaporator.

Identification of plant components

The histological identification of cereal tissues is based on well-established plant anatomical criteria for the identification of bran and glumes. The criterial typically applied in food analysis [89-92] were adapted for archaeobotanical use [93-96]. We regarded the discriminatory power of cereal transverse cell wall thickness and pitting as limited to the genera *Triticum*, *Secale*, and *Hordeum* – with the concession of incomplete differentiation between barley and the millets – as laid out previously [10, 30].

Measuring

Original diameters of the charred rings were reconstructed using the software ImageJ [97] by manually aligning ellipses to the outlines of each fragment. ImageJ was also used for the measurements of plant tissue fragments visible in the scanning electron micrographs of sample A, as well as in the light micrographs of all three rings. Pore/cavity size distributions were measured in light micrographs of all three rings following the methodology as laid out in [10], i.e. measuring pore sizes with ImageJ's "fit ellipse" function on black and white

photographs of the fractured faces (threshold: 64 out of 255 grayscale values). Obvious cracks were excluded from the measuring, as were Instant EFI-generated visual artefacts on the image margins. Likewise, pores smaller than 100 µm were not measured. The resulting values were evaluated in histograms with constant 100 µm class intervals. Fragments of cereal components were measured only for ring A, as this was the only sample where both light microscopy and SEM images were available. The results, presented in histograms (100 µm steps), are grouped according to modern equivalents of ground cereals [98, 99]: flour and dunst (particles smaller than 300 µm) vs. semolina (300 – 1000 µm) vs. grist (larger than 1000 µm).

Terminology

As laid out previously [10], a precisely defined common terminology is still widely lacking in the analysis of archaeological "bread"-like objects. Building on current works on cereal-based foodstuffs, we suggest the very general definitions of "cereal preparation", synonymous to "cereal product", both following FAO suggestions [100], for any charred find bearing evidence of processed cereals. We suggest the term "bread-like object" for any archaeological find of a cereal product which shows traces of intentional shaping [10]. We suggest this term as a general working title preceding analysis, in order to avoid the use of expressions implicating certain *chaînes opératoires*.

In microstructure, we follow standard terminology in food technology by calling an airspace within a cereal preparation "pore" [101] or "cavity" [10]. The recently published term "close void" [102] may indeed refer to "closed pore" and "closed void" [103] – but is not appropriate in this context, as it refers to the interconnectivity of pores, which can neither be observed nor judged from the surface of such objects [104, 105]. A pore not exceeding 200 µm in diameter is named "micropore" following the suggestion by González et al. [102]. In contrast to previous work [30], we suggest a terminological delimitation between a "crack" as a taphonomical feature, either caused by charring itself or by mechanical stress after charring, and a "furrow" for the elongated hollow spaces with irregular margins which are features of the dough/batter itself and often intergrade with pores. Unless a definition of the term "channel void" [102] becomes available – it may be synonymous with either or both of the aforementioned – so far its use should be avoided.

Results

Dating

The date range proposed in the introduction (c. 950 – 800 BCE) could be further narrowed down by the presence of the older type of vessels with conical necks (*Kegelhalsgefäße*) with a handle [59], in combination with the AMS dating of sample B (Table 2). Altogether, we propose dating the context to Ha B2 (960 – 900 BCE).

Table 2. Radiocarbon dates of the contexts discussed in the text. Samples preceded by an asterisk * come from a previous publication [49]. Pit numbers used in the current publication correspond to those published in 2001 as follows: V5001 = A3/1; V5003 = A/0 18; V5005 = Schnitt 7 Verfärbung 2; V5006 = Schnitt 7 Verfärbung 5. For this publication, all data were (re-)calibrated with OxCal 4 [84] using the IntCal13 calibration curve [85].

Pit number	Laboratory no.	^{14}C Age	δ^{13}C (‰)	Calibrated age ranges (2σ)
V5400 (ST 12050.4 B)	Beta-486379	2780 ± 30 BP	-25.0	1004–844 cal BCE (95.4%)
* V5001	ETH-16498	2880 ± 50 BP	-22.0 ± 1.1	1210–926 cal BC (95.4%)
* V5003	ETH-16497	2750 ± 50 BP	-25.3 ± 1.1	1005–811 cal BC (95.4%)
* V5005	ETH-16499	2830 ± 50 BP	-22.1 ± 1.1	1126–844 cal BC (95.4%)
* V5006	ETH-16500	2840 ± 50 BP	-22.9 ± 1.1	1131–893 cal BC (91.1%)

General Traits

Each of the three samples is interpreted as a fragment of an originally annular, or rather torus-shaped object (Fig 10, Fig 11, Fig 12, Fig 13). All three rings are roughly of the same size, shape, and proportions, their original diameters are reconstructed as ranging from 26 to 36 millimetres (Table 3). Apart from the flaky protrusions caused by the consolidating agent still adhering to samples C and D, their surfaces are all smooth and inconspicuous. Neither particular decorations nor fingerprints could be observed, only sample D shows a thin overlaying structure (Fig 13 a) on the outer side, as well as a marked furrow on the inner side (Fig 13 c).

Fig 10. Line drawing of the three charred organic rings. Image: ÖAW-OREA / B. Biederer, S. Tikatsch.

Fig 11. Charred organic rings, sample A (find no. ST 12050.4). **a** "top", **b** "bottom", **c** inside, **d** outside view. Arrows indicate furrows extending to the surface. Scale bar units: centimetres. Image: ÖAW-ÖAI / N. Gail.

Fig 12. Charred organic rings, sample C (find no. ST 12050.2). **a** "top", **b** "bottom", **c** inside, **d** outside view. Bright surface features originate from the consolidating agent (wood glue). Arrows indicate furrows extending to the surface. Scale bar units: centimetres. Image: ÖAW-ÖAI / N. Gail.

Fig 13. Charred organic rings, sample D (find no. ST 12050.3). **a** "top", **b** "bottom", **c** inside, with visible furrow, **d** outside view. Bright surface features originate from the consolidating agent (wood glue). Arrows indicate furrows extending to the surface. Scale bar units: centimetres. Image: ÖAW-ÖAI / N. Gail.

Table 3. General traits of the three annular objects.

	Sample A (Fig 11)	Sample C (Fig 12)	Sample D (Fig 13)
Shape	torus ($^1/_4$)	torus ($^1/_2$)	torus ($^1/_3$)
Ring thickness, range [mm]	12.1–15.8	10.1–14.2	11.2–18.9
Outer diameter, range [mm]	26–36	31–33	27–36
Ratio max. diameter : max. height/thickness	2.28 : 1	2.32 : 1	1.9 : 1
Weight [g]	1.37	2.45	3.01

When observed with the naked eye, the rings' irregularly broken faces appear very dense. Neither pores nor plant parts are visible, but the otherwise compact and seemingly homogeneous matrix is traversed by conspicuous furrows similar to the superficial furrow in sample D. Under low magnification (10x), a few supposed grain fragments as well as the very

small pores became visible (Fig 14, Fig 15, Fig 16). None of the three rings showed a differentiation of crumb and crust.

Fig 14. The two fractured faces of sample A under the binocular (10x). Scale bar lengths: 1 mm. Image: ÖAW-ÖAI / A. G. Heiss.

Fig 15. The two fractured faces of sample C under the binocular (10x). Scale bar lengths: 1 mm. Image: ÖAW-ÖAI / A. G. Heiss.

Fig 16. The two fractured faces of sample D under the binocular (10x). Scale bar lengths: 1 mm. Image: ÖAW-ÖAI / A. G. Heiss.

Plant tissues in sample A

When observed under magnification (50x – 500x) numerous fragments of cereal bran could be observed (Fig 17) in the porous, starchy matrix of sample A. Here they shall be listed following their arrangement in the cereal grain from the outside inwards: patches of transverse cells, sometimes with tubular cells still adhering (Fig 18), were the predominant bran parts observed. The majority could not be sufficiently identified to genus level in most cases as their cell wall thicknesses could only be observed indirectly. Most of them at least closely resembled barley (cf. *Hordeum vulgare*) transverse cells (Fig 18 a–c). A single fragment was identifiable as *Triticum* sp. (Fig 18 d). All observed aleurone tissue was single-layered (Fig 19), therefore giving evidence for some cereal other than barley. Close to former grain surfaces, even a few portions of relatively intact endosperm tissue were found. In some of these endosperm cells, spherical subcellular structures were observed, which we interpret as non-gelatinised or partially gelatinised starch granules (Fig 20). Full gelatinisation of starch granules is the result of (reversible) swelling of starch grains by soaking in water, followed by elevated temperatures of at least 55 to 75°C (see section “Soaking and kneading”). A single fragment of a barley (*Hordeum vulgare*) glume could be identified by the characteristic “double” (crescent-shaped plus orbicular) short cells (Fig 21).

The distribution of grain sizes of the tissue fragments recorded under light (N = 122) and scanning electron microscope (N = 65) are presented in Fig 22. 86% of the measured particles do not exceed 1 mm.

Fig 17. SEM overview of one of the fractured faces in sample A. Arrows indicate cereal bran fragments. Image: die Angewandte / R. Erlach.

Fig 18. SEM of patches of transverse cells in sample A, **a** and **b** with overlaying tubular cells. **a**, **b**, **c**, probably thin-walled transverse cells of the barley type (cf. *Hordeum vulgare*). **d** transverse cells of *Triticum* sp. in cross-section, arrows indicating the conspicuous wall thickenings and “wavy” aspect of the pitted thick walls. Image composed from a stack of 3 images using Helicon Focus 7. Image: die Angewandte / R. Erlach.

Fig 19. Patches of aleurone tissue (with still intact aleurone granules) in cross-section. The single layer indicates a cereal other than barley. Image: die Angewandte / R. Erlach.

Fig 20. Partly gelatinised starch granules in the endosperm of sample A. a Overview and position in relation to the aleurone layer (close-up of **Fig 19 b**). Arrows indicate structures resembling incompletely gelatinised starch granules, the rectangle indicates the position of image **b**. **b** Magnified area as indicated in **a**. Image: die Angewandte / R. Erlach.

Fig 21. Glume of hulled barley (*Hordeum vulgare*). Image composed from a stack of 3 images using Helicon Focus 7. Image: die Angewandte / R. Erlach.

Fig 22. Histogram of the recorded maximum dimensions of components (N = 187) in sample A. X axis: number of occurrences, Y axis: size class in micrometres (100 µm steps). Grouping is according to grain sizes of modern grain products: a) flour and dunst (smaller than 300 µm), b) semolina (300 – 1000 µm), and c) grist (larger than 1000 µm). Raw data is given in S1 Table.

Pores

All three samples are characterised by very high and nearly identical proportions of micropores, i.e. cavities not exceeding 200 µm in diameter: While in sample A, 66% of the measured pores fall into this category, it is 70% in sample C and 67% in sample D. In all three annular objects, the proportion of pores exceeding 1 mm lies around 2% (Fig 23).

Fig 23. Histogram of the pores measured in a) sample A (N = 1,341), b) sample C (N = 328) and c) sample D (N = 875). X axis: number of occurrences, Y axis: size class in micrometres (100 µm steps). Raw data is given in S2 Table.

Discussion

Ingredients of sample A

Hulled barley is without doubt an ingredient of the bread-like object, as concluded from the evidence of a *Hordeum vulgare* glume remain. Furthermore, a wheat species (*Triticum* sp.) was clearly identified by the characteristic patches of transverse cells. Taking the quite relevant proportions of einkorn (*Triticum monococcum*), spelt (*T. spelta*), and Sanduri wheat ("new" glume wheat, *Triticum* cf. *timopheevii*) in the overall cereal spectrum of the settlement [49-51], it is very likely that one of these three glume wheats forms the second constituent of sample A.

The other cereal remains require a bit more caution in their interpretation due to their low discriminatory power: the single-layered non-*Hordeum* aleurone patches may very well derive from the above-mentioned wheat species, but could also be from virtually any other cereal. Likewise, the transverse cells identified as cf. *Hordeum vulgare* leave at least some room for interpretation, as e.g. millet transverse cells look very similar to those of barley [89]. Considering the dominance of *Panicum miliaceum* in the archaeobotanical record of the site, we should therefore at least give a thought to the hypothesis of broomcorn millet being an additional component of the annular object(s). However, millets are difficult to dehusk completely [106], and experience in archaeobotany has shown that at least some fragments of their characteristic glumes [107, 108] are usually preserved in processed cereal preparations [37]. No such evidence was found whatsoever.

As a conclusion, unless future investigations of the rings should result in positive evidence for other cereals, hulled barley and some (probably hulled) wheat species in unknown proportions [10] shall be considered as the cereal ingredients of sample A and quite likely also of the other two charred rings. No evidence for additional plant-based components such as intentionally added condiments [10] or accidentally processed weeds was found. As liquid or soluble

components ranging from dairy products to salt cannot be traced via the chosen set of methods, no statements can be made on this topic.

Involved processes

Grinding and sieving (sample A)

Considering the overall grain size distribution as given in Fig 23, 34% of the measured particles would classify as flour or dunst when compared to modern standards [98, 99]. An additional 52% would range within the modern grain size classification as semolina. The remaining 14% remain in the lower range of grist, the largest measured particle hardly exceeding 2.5 mm. If intended for consumption, the flour quality of the three Stillfried rings would be considered as rather fine quality, and comparable to modern wholemeal breads [109]. When comparing the measurements to the (still only scarcely available) extant data from other archaeological finds, sample A corresponds best to find no. 2010.012.2907.5 from the Neolithic site of Parkhaus-Opéra, Zürich, Switzerland [10]. A considerable amount of care [110] has been invested in grinding and sieving the flour used in the production of this ring, and most probably also of the other two annular objects.

Soaking and kneading

Mechanical stress during kneading or subsequent drying processes can easily lead to ruptures of doughs with low water contents, which requires extra caution in the kneading of e.g. biscuit [111] or pasta [112] doughs. As in previous archaeological finds [30], the numerous large furrows observed in the charred samples from pit V5400 are interpreted as hints in this direction.

In the SEM micrograph, structures were visible which are interpreted as non-gelatinised or partly gelatinised starch granules. Full gelatinisation of starch granules is the result of (reversible) swelling of starch grains by soaking in water, followed by elevated temperatures of at least 55 to 75°C [113-115]. Experimental studies have demonstrated that the degree of gelatinisation of starch granules is not only preserved in uncharred archaeological remains [115] but also in charred material [116], at least if charred in dry state (Fig 24).

As a conclusion, we assume that the starch granules observed in sample A indicate a cereal preparation either heated at rather low moisture content [117], or not heated at all. The annular objects could therefore have been shaped from uncooked/unbaked dough or grain-paste [118], and were either cooked/baked in dry state, or air-dried. The question still remains whether the partial gelatinisation of starch granules observed in the sample may be an artefact of the charring process or bear some other significance.

Fig 24. Cross section of charred "*Grünkern*" spelt (immature *Triticum spelta* 'Bauländer Spelz'). After charring of the dry grains at 230° C for 7 hours, starch granules are still easily discernible. Images: Universität Hohenheim, M. Berihuete Azorín. Images: Universität Hohenheim, M. Berihuete Azorín.

Fermenting

Modern and historical examples show that there is a wide continuum between the extremes of hard and dense (unfermented) and fluffy (thoroughly fermented) dough. Yet until now, no systematised catalogue of criteria exists to describe the degree of fermentation of

archaeological cereal preparations. Key features [119] need to be defined. Extant data from bread research need to be transferred onto charred archaeological finds. These topics are being worked on in within the scope of the project PLANTCULT. For now, and until a database allowing for statistical comparison with experimental data will be available, we have to rely on a comparative approach relating to known finds of archaeological material.

Overall pore size distribution in the Stillfried rings is basically comparable to other cereal products interpreted as non-fermented [10, 30, 120]. In a more detailed comparison with bread-like objects from which pore distribution data have been recorded using the same methodology as in the current paper, the proportion of micropores (66–70%) in the three Stillfried rings is the same as in the sacrificial "cakes" from the Archaic/Hellenistic sanctuary at Monte Papalucio, Oria, Italy (66–82%) [26], but twice as high as in the bread-like object from the Gallo-Roman cemetery of St. Memmie, France (33%) [30] or those from the Neolithic lakeshore settlement Parkhaus-Opéra (26–29%). The proportion of pores exceeding 1 mm (roughly 2% in each of the rings) is comparable to the find of St. Memmie, while measuring the Monte Papalucio finds had not resulted in any values of this size class [26]. Density and degree of fermentation of the Stillfried rings therefore seems to lie somewhere between the aforementioned finds.

It must be stressed that the chosen cut-off value, i.e. omitting pores with diameters under 100 µm, affects the resulting data and its interpretation. We chose the value for two main reasons, the first being that a) any microscope-mounted camera has limited resolution. If counted, single pixels in the image will strongly bias the measurements towards cavities even smaller than micropores [10]. Secondly, b) the authors are convinced that very small pores are consequences of charring and do not contribute to the knowledge of the degree of fermentation of a cereal product.

The reason for this shall briefly be highlighted: charring leads to the formation of pyrolysis gas predominantly of carbon dioxide, carbon monoxide and methane [121, 122], as well as water vapour. The latter originates from both residual bound water and from the chemical breakdown of starch [123]. Together, the expanding gases inevitably lead to the formation of cavities in the intermediate liquid phase of biopolymers breaking down [124]. The irregular bubbly structures found in most archaeological finds of intact cereal grains may be taken as examples for this process of cavity formation. This also occurs in grains experimentally charred at elevated temperatures (Fig 25).

It must be stressed that even higher cut-off values than the ones applied in the current and previous studies may be required in the future. Experimental work within the scope of the project PLANTCULT is ongoing, but preliminary results already suggest that great caution is required in the interpretation of pore sizes, in particular when using smaller pores, or even micropores, as a diagnostic character for the presence of (leavened) "bread".

Fig 25. Cross section of charred "*Grünkern*" spelt (immature *Triticum spelta* 'Bauländer Spelz'). After charring a) at low temperature (230° C) for 7 hours, wide portions of the endosperm have fused into an amorphous glassy matrix while others have formed irregular cavities. Charring b) at high temperature (300° C) for 6 hours has led to extensive formation of cavities with a broad range of sizes, the largest of these "pores" slightly surpassing the category of micropores. Images: Universität Hohenheim, M. Berihuete Azorín.

Shaping

The aforementioned furrows indicate an overall low water content in the dough during preparation. The deep length-wise furrows extending to the surfaces of all three annular objects may directly derive from the process of rolling the dough into a tube before connecting its ends into a ring-like shape. It is, however, important to point out that no remains of such connective points are preserved.

A ring is a ring is a ring. Daring a description

As with fermentation in particular, the general criteria for the classification of archaeological finds of cereal preparations are still in an early stage. Extant pioneering work requires 1) refinement, 2) an increase in complexity of characters, and 3) general applicability. Taking the criteria proposed for the Çatalhöyük material as a reference, for example, the rings from Stillfried show traits comparable to the published Matrix Types 2 and 4 [102], resembling a finely ground porridge. Combining the features of 1) a rather unfermented dough and 2) the raw state before charring with 3) the low initial water content, we would consequently categorize the material of the Stillfried rings as air-dried dough [118] made from finely ground barley and wheat flour.

Using modern cereal preparations as references, the rings' *chaîne opératoire* is most similar to that of modern pasta, or of *tarhana*/*tarhonya*/*trahanas* [125-127], while they roughly share shape and size with Italian *tarallini* [26] and Russian *sushki* [128]. Unless a better solution for a terminology is found, we propose to limit denominations of archaeological cereal preparations to this approach, i.e. to give separate comparative descriptions for components, shape, and making.

Further interpretative approaches

Taphonomy of the find assemblage

In her review article, T. Popova states "It has been established that bread fragments are among the most common finds in ceremonial/ritual fireplaces, burial mounds, and sanctuaries (…)" [129]. This is statement is certainly correct, but in the authors' opinion it should by no means be understood by the reader as a postulate of a scarcity of "bread" use in "profane" contexts. Cereal products are indeed a very frequent archaeological find category, yet due to their fragility they are highly prone to fragmentation [130, 131], with their fragments usually not allowing for any inference to the original artefact such as bread in the broadest sense, porridges, and the like [118, 125, 132]. Even worse, as D. Fuller stated, they are also "more often than not set aside by archaeobotanists as indeterminate fragments" [131].

The reason for the seemingly rare occurrence of intact "bread" in such ritual contexts may simply lie in taphonomical processes, and of sample treatment; aside from ritual depositions [26, 30, 133, 134], large numbers of more or less intact charred bread-like objects also originate from lakeshore settlements [10, 135-137] and from burned-down bakeries [138, 139]. These find situations share the common trait of reduced mechanical stress affecting the fragile charred finds, either because the objects a) had been deliberately and carefully deposited, b) were embedded in soft lakeshore sediments, or c) were charred and embedded *in situ*. Furthermore, all these finds have in common that they are usually grab finds: the

destructive potential which flotation can have on charred plant material [140] has just recently been reconfirmed [141].

Were we to interpret the genesis of the pit's secondary filling against the background of an entirely "profane" scenario versus one also involving ritualised ("ceremonial/cultic") activities, one of the key differences in their respective taphonomies would concern the way the finds were deposited: disposing of the debris of a burnt-down house and using it as the backfill for a no longer used storage pit would probably not involve much care, in contrast to a structured and ritualised process [142, 143]. Taking into account these considerations together with the "odd" inventory of the pit, as well as the rather good state of preservation of the three annular bread-like objects from pit V5400, may indicate careful deposition and serve as a indication of a ritual/cultic interpretation of the filling process.

If we accept deliberate deposition of the objects in pit V5400, this inevitably begs the question of the purpose of the dough rings themselves: do they represent "everyday food" deposited in the pit? Were they made for a certain symbolic purpose?

Modern dough rings

In general, historical and ethnographic sources document a rich wealth of ring-shaped breads and pastry across Europe. The most prominent and best known ones today are indeed "everyday food", sharing the characteristic of leavened dough which is boiled before baking, such as the *bagel* of the Polish Jews, documented since early Modern Times [144] and its Russian counterparts such as the *sushki* [128]. The *simit* in Turkey and the *koulouria* in Greece, both supposedly of Ottoman origin [145], are produced the same way.

In contrast, other types of ring-shaped cereal products are documented as distinct elements of specific festive and ritual contexts, such as the early Christian *corona* [33] of unknown components and production traits. The *sa pertusitta* is a traditional baked ring in Sardinia's New Year's Eve [146], just as southern Italy's *raffiuoli* – a particular sweet variant of *taralli* – are produced for religious feast days [147, 148]. For the days around Christmas and New Year, the Alpine region knows deep-fried annular *kiachl* [149], while Styrian [150] and Lower Austrian [151] folklore includes *Beugel*, a variant of the bagel, during carnival. Greek *kerkelia* are produced for Lazarus Saturday by Pontic Greeks [152]. The kolač, in its innumerable spelling variants and preparation techniques, is part of religious feast days throughout Slavic countries [153, 154] and beyond. It should be mentioned, however, that the Romanian [155] and Moldvian [156] *colaci* have their principal purpose in serving as offerings for the dead [157].

All of the aforementioned examples only share a roughly annular shape as common character, yet they are produced by following strongly diverging *chaînes opératoires* and intended to serve a wide range of different purposes. Consequently, the ring shape alone is an insufficient interpretive element for elucidating the nature of the Stillfried rings.

Archaeological finds

If we consider archaeological finds of ring-shaped "bread" in the widest sense across Europe, i.e. bread-like objects, we find that the evidence is generally very limited. Find no. 2010.012.2285.3 from the late Neolithic site of Parkhaus-Opéra might be the oldest documented find from central Europe to date, but it is of unknown purpose and unspecific find context [10]. Several ring-shaped "biscuits" are documented as offerings in an Archaic/Hellenistic sanctuary in southern Italy [134] which have recently been revised [26].

Finally, there is thorough analysis and documentation available for a large number of annular bread-like objects, some on metal strings, as grave goods in Viking Age cremation graves in Sweden [133].

The annular object from a Late Iron Age cremation grave at Wederath in Germany [158], initially published as "ring cookie" (*Ringgebäck*) [159, 160], has unfortunately been proven recently to be entirely made of beeswax [161].

Possible significance of the Stillfried rings

In comparison to the other cereal preparations (Table 1) from Stillfried an der March which have already been published [49], the three annular objects from pit V5400 differ in both their shape and the production processes involved. Their finely ground flour and intentional shaping certainly indicate that more time was invested in their production than necessary for subsistence. The rings may therefore have been of higher value than the other cereal preparations described from Stillfried.

The overall "odd" assemblage [45] in the secondary filling of pit V5400 may or may not be a valid argument against the dough rings representing everyday food. In the authors' opinion, the strongest point lies in the context of clay rings and dough rings deposited together which seems highly unlikely to have happened by sheer chance. Like similar finds from synchronous sites in the region [162], the clay rings are interpreted as loom weights [47, 163], and they bear actual traces of use.

Any practical use for the dough rings found in context with them is hard to imagine. We therefore suggest the hypothesis that the dough rings were created on purpose as imitations of the clay loom weights of the same shape and probably were not produced for consumption in the first place. The exact purpose of the Stillfried cereal rings remains unknown, as well as the time of their charring – during the catastrophic fire which destroyed the house, or within the course of the ritualised filling of the pit.

No literature on directly comparable finds was available to the authors, yet some approximations shall be attempted; to a certain extent, cultic aspects of loom weights have frequently been postulated and discussed, and there are numerous examples of intentionally deposited loom weights – annular, truncated pyramid shaped, or irregular – in central European Late Bronze Age settlements [162], and likewise as grave goods. The latter are, however, usually miniatures, and they all resemble the truncated pyramid type. Archaeological finds of dough imitations of loom weights are, however, entirely unknown up to now – in the view of all the adverse preservation conditions for processed cereals [10] and even more so for entire bread-like objects (see above), this is not entirely surprising.

Conclusions

The three annular charred finds from former storage pit V5400 at Late Bronze Age Stillfried were made of dough from rather finely ground wheat and barley meal which was most likely air-dried or baked at low temperature prior to charring.

Comparison to the extant data on food preparations at the site, combined with the "odd" find context strongly suggest that the three annular objects had most likely not been produced for

consumption, but had rather served some specific purpose prior to or during the deposition of the remainders of the burnt house in the pit.

In view of the general difficulties in differentiating “profane” domestic refuse from remainders of ritual activities at all – or rather, of highlighting both aspects if present at the same time, the role of food preparations in these past activities is even more difficult to investigate. Without favourable preservation conditions, thorough sampling and in-depth scientific investigations, such organic remains may simply go unnoticed in the archaeological record.

In order to recognise and preserve such “odd” objects, we strongly recommend direct sampling of charred plant concentrations, especially in “odd” contexts. Avoiding not only exposure to mechanical tensions but also to flotation seems to be crucial for gaining all available information on cereal food preparations.

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Supporting information

S1 Table. Particle measurements of Sample A. Raw data of the histogram in Fig 21.

S2 Table. Pore measurements of the three annular objects. Raw data of the histograms in Fig 21.

Fig1

Click here to access/download;Figure;Fig1.tif

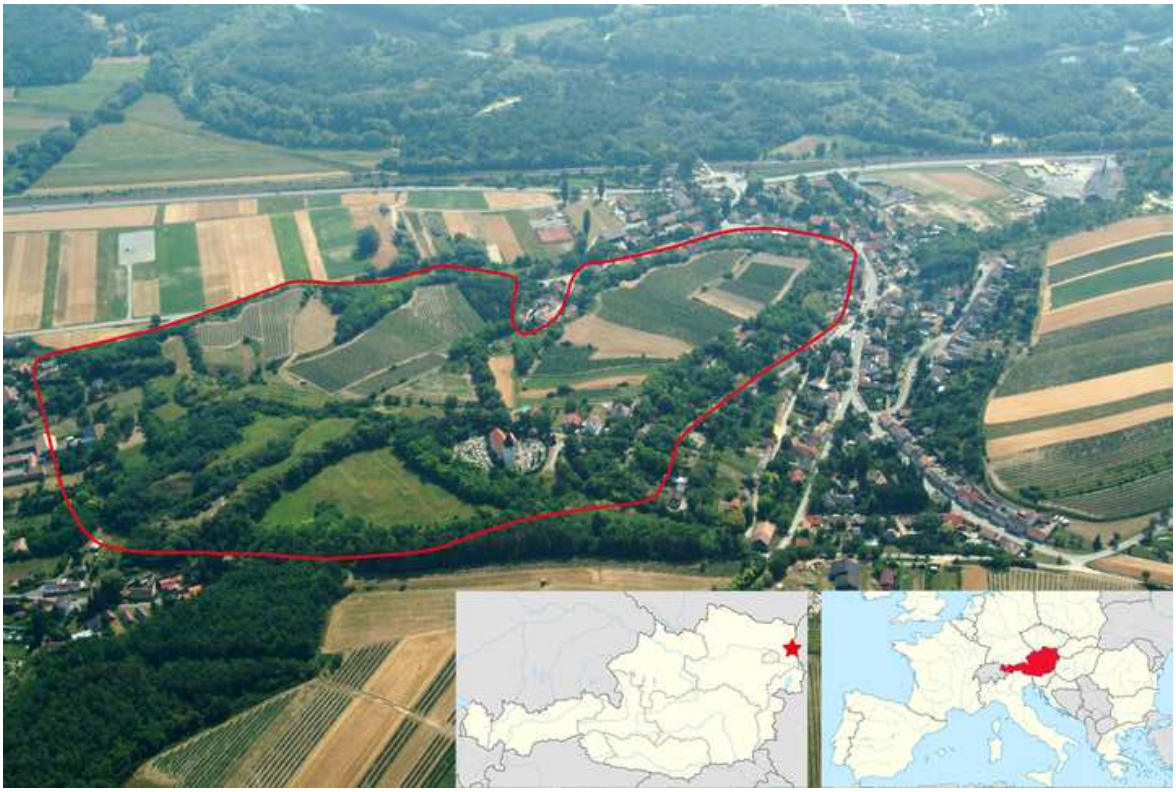


Fig2

Click here to access/download;Figure;Fig2.tif

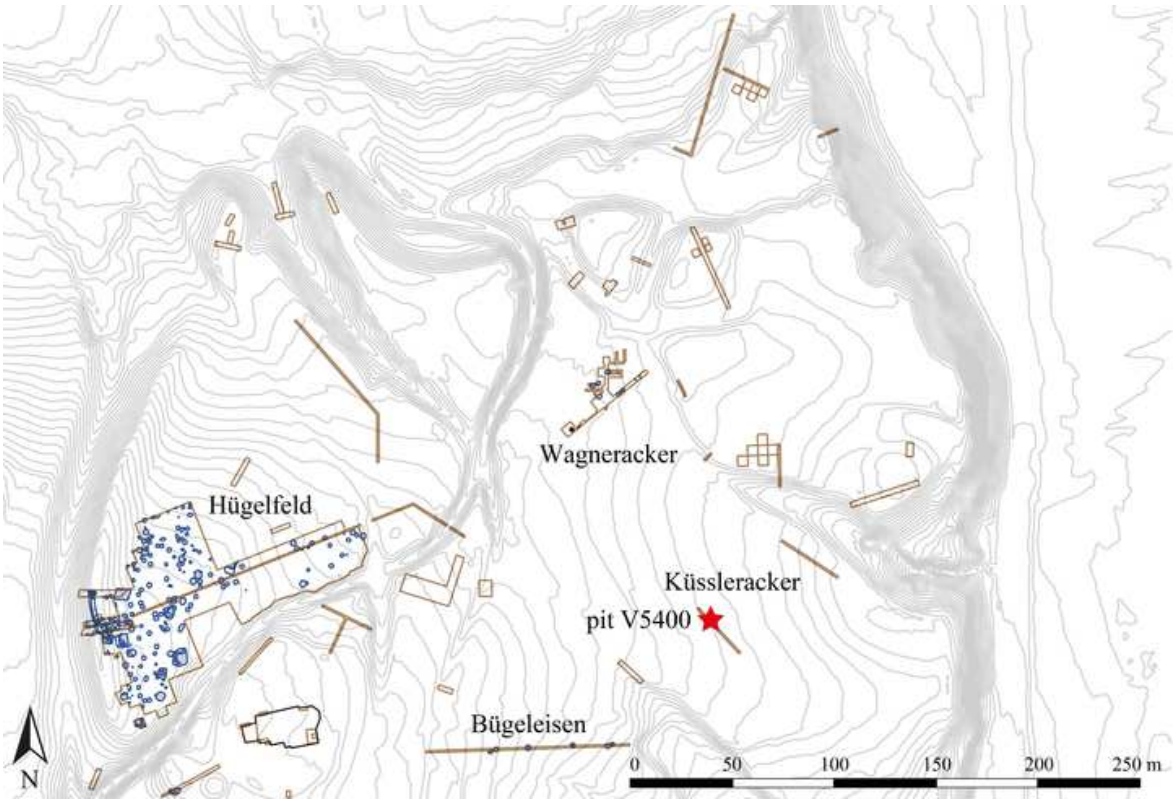


Fig3

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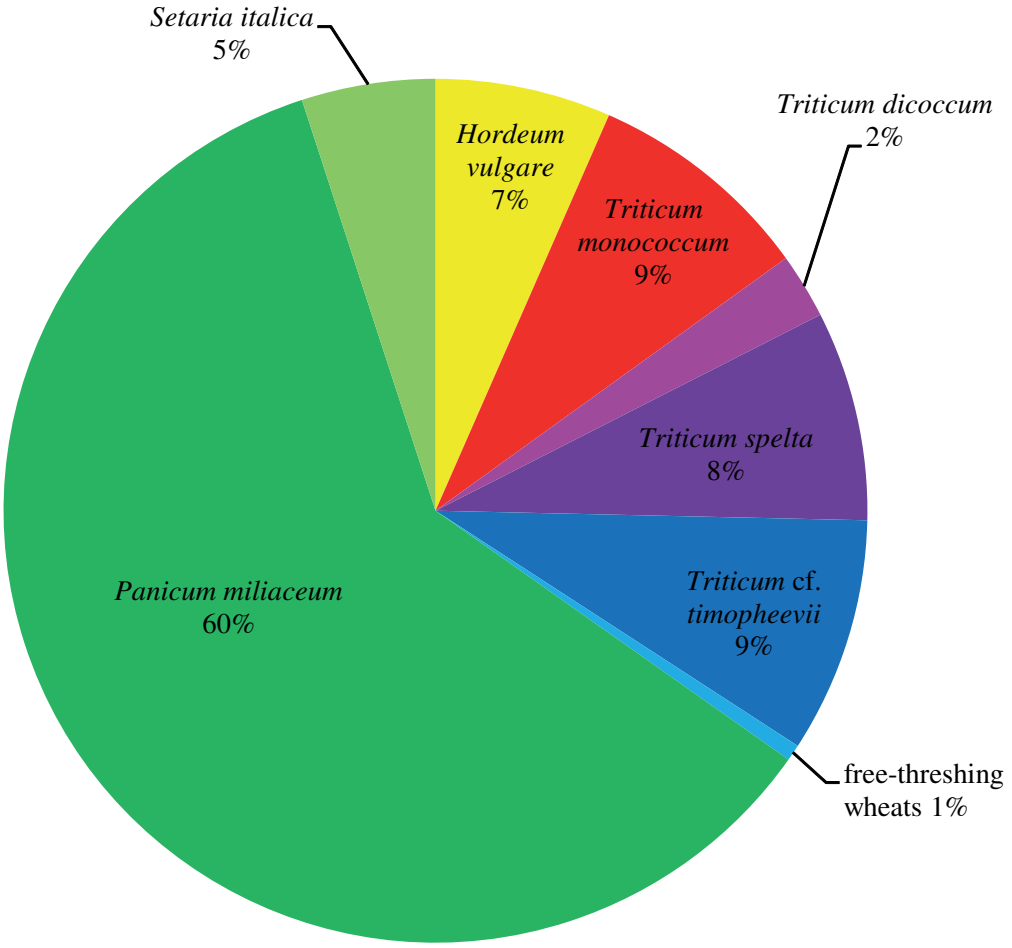
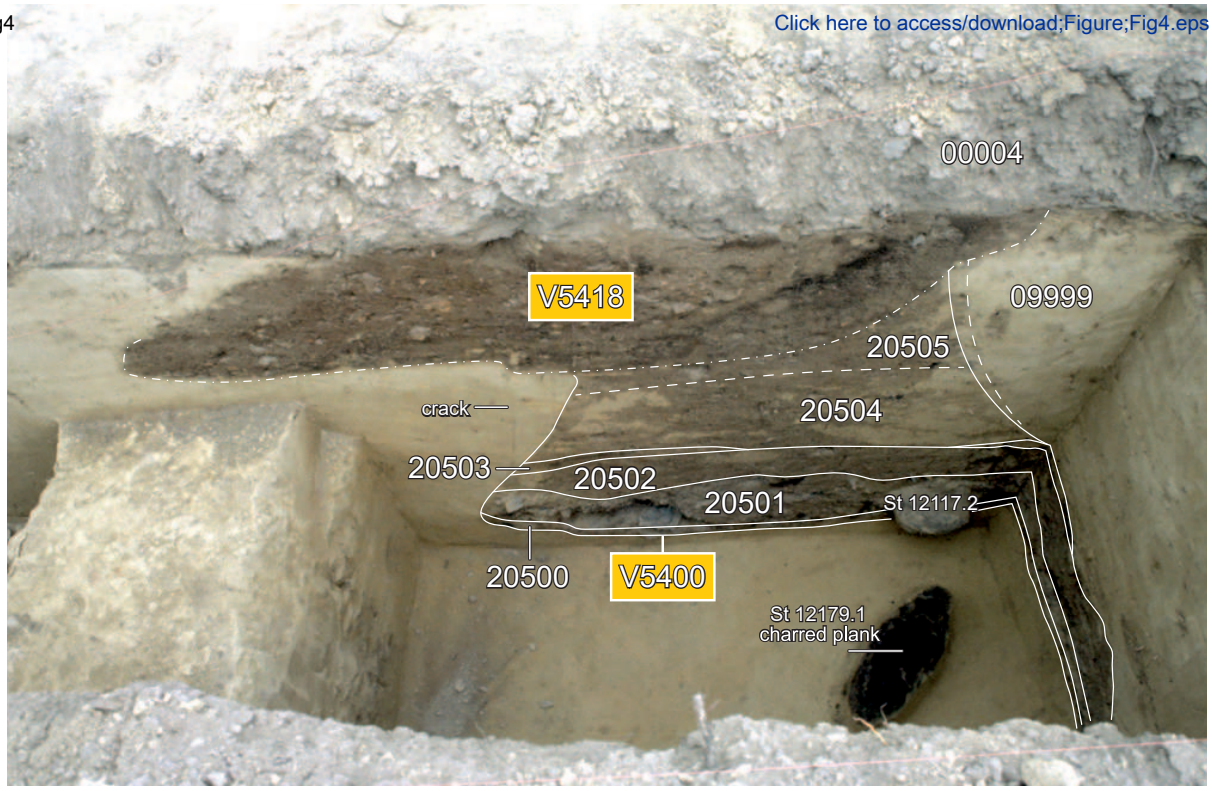
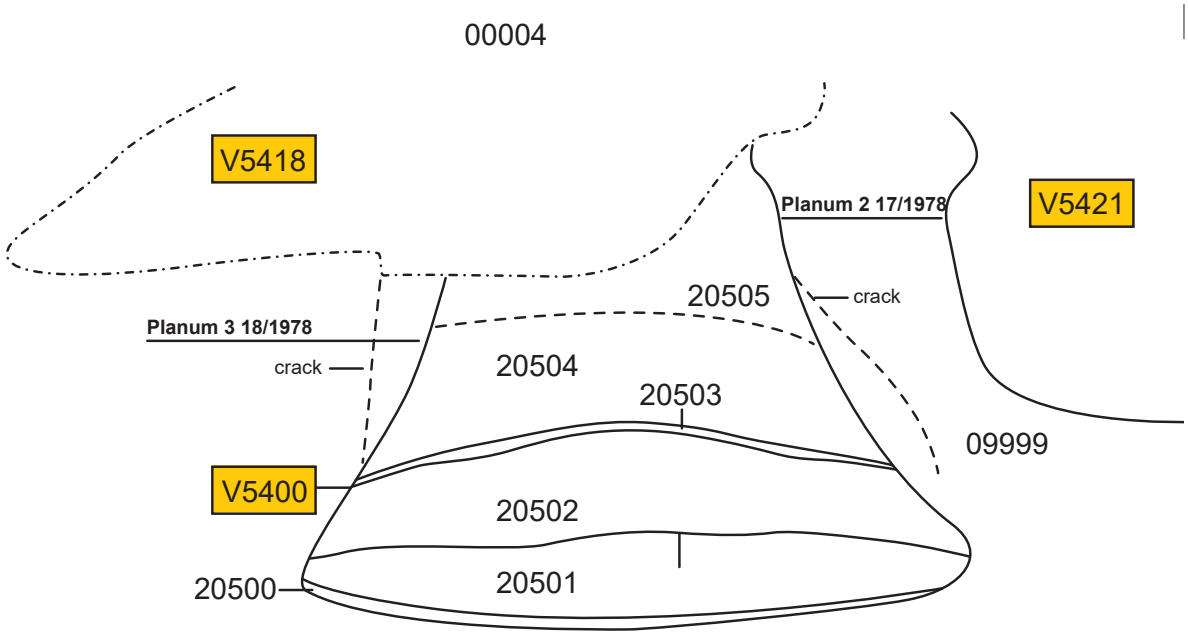


Fig4 Click here to access/download;Figure;Fig4.eps



V5400, eastward profile (photo no. 1764)

Northwest Southeast



V5400, eastward profile (plan KÜ 8/1978)

0 100 cm

Fig5

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Fig6

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Fig7

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Fig8

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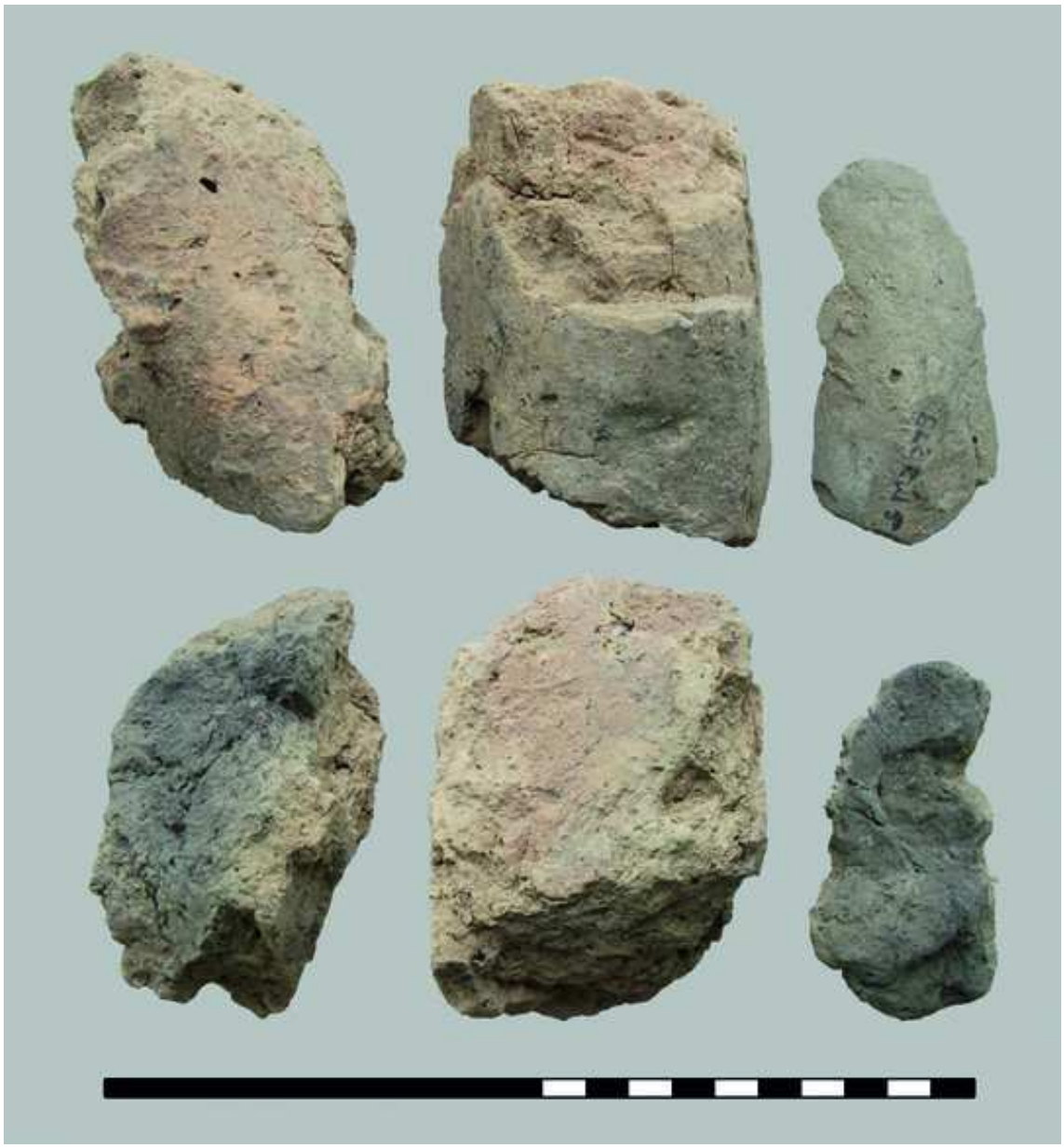


Fig9

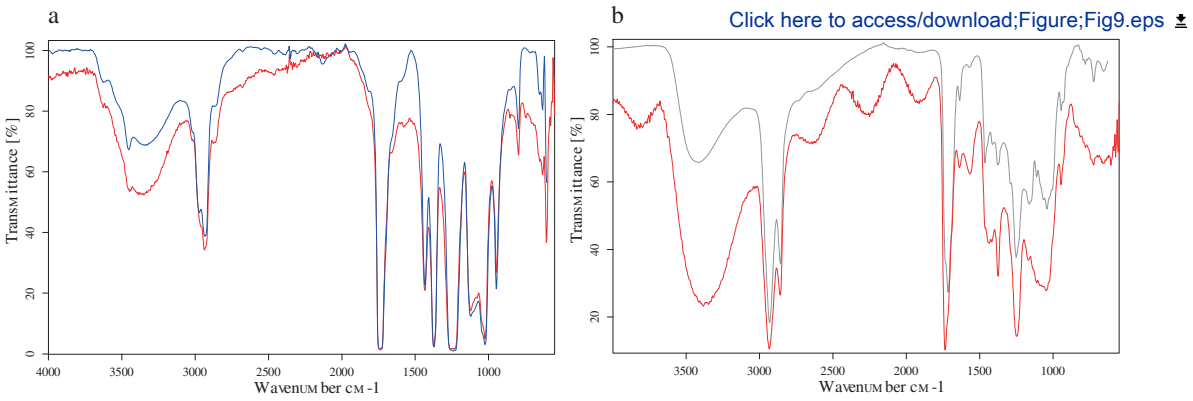
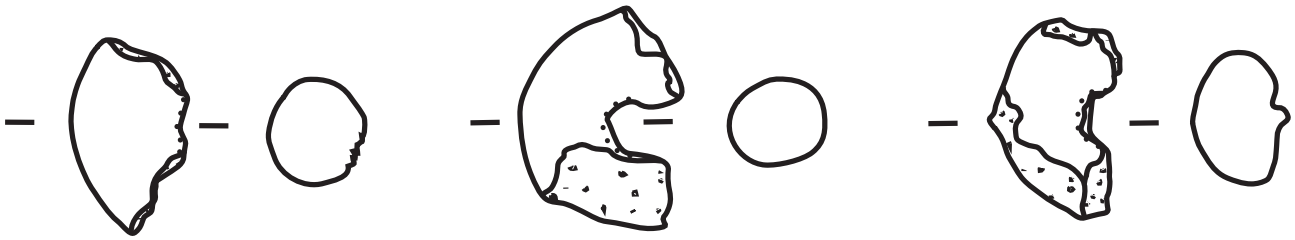

a
b
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Transmittance [%]
Wavenumber cm-1
4000
3500
3000
2500
2000
1500
1000
0
20
40
60
80
100

Fig10

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Sample A
ST 12050.4

Sample C
ST 12050.2

Sample D
ST 12050.3

Fig11

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Fig12

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Fig13

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Fig14

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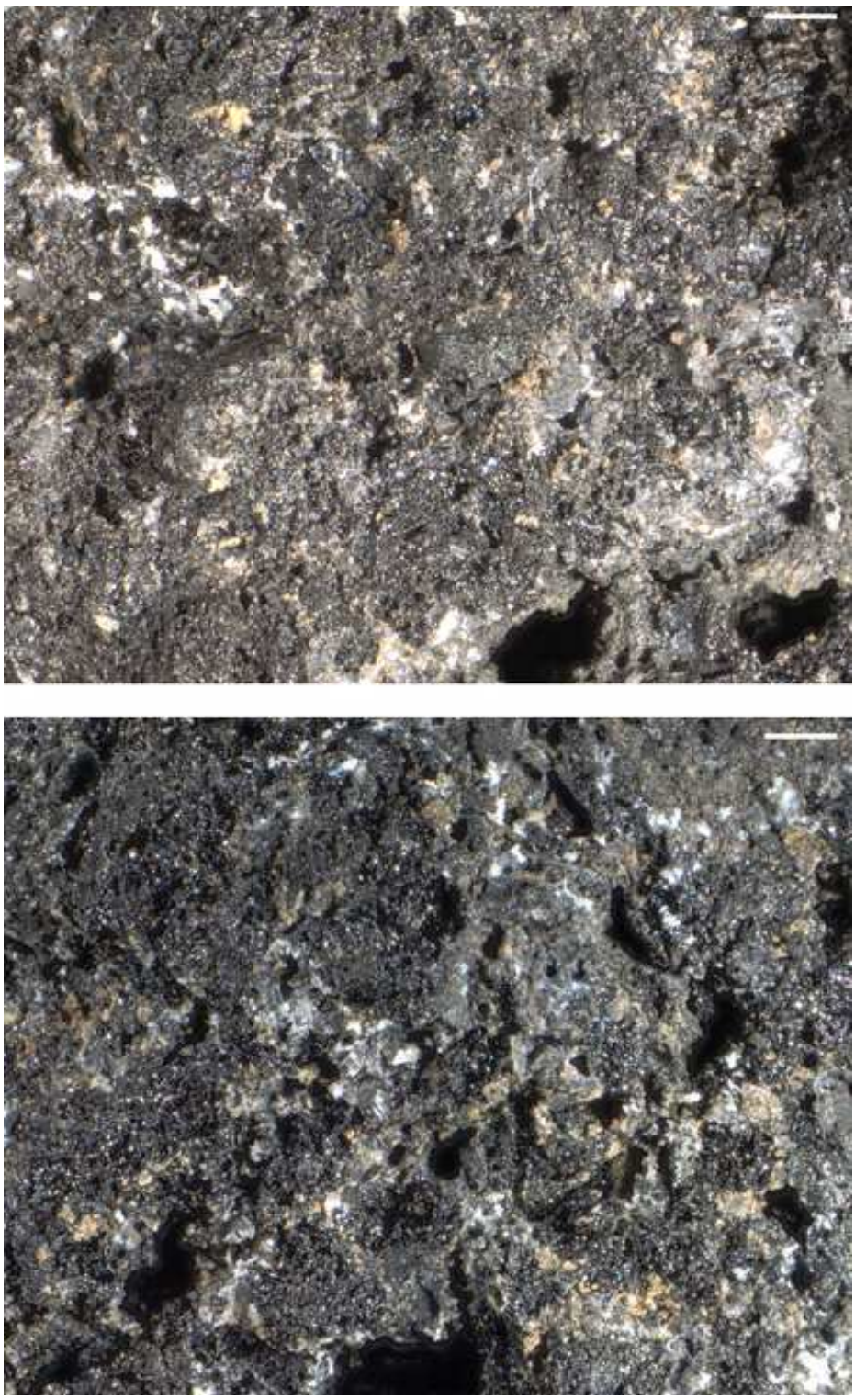


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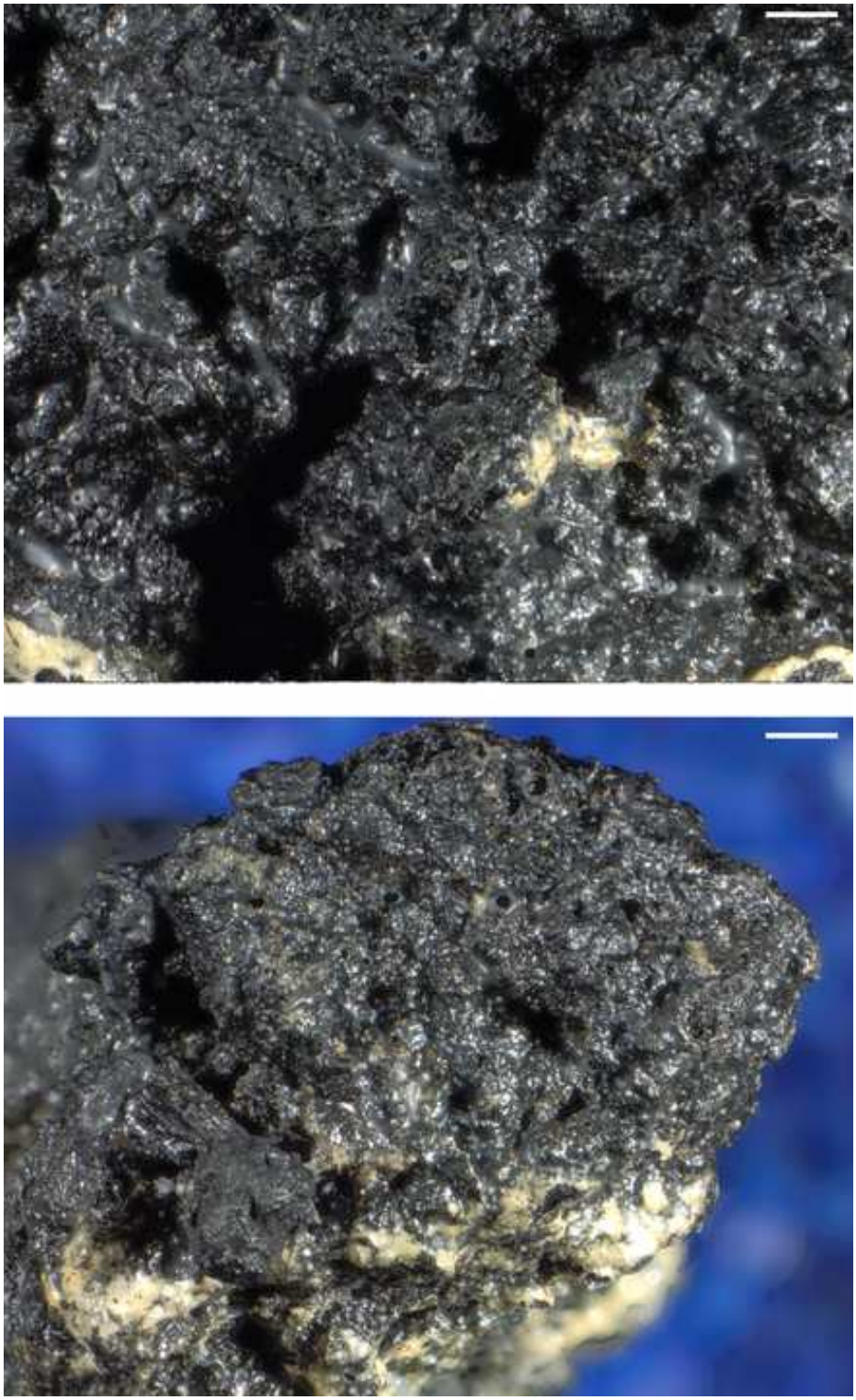


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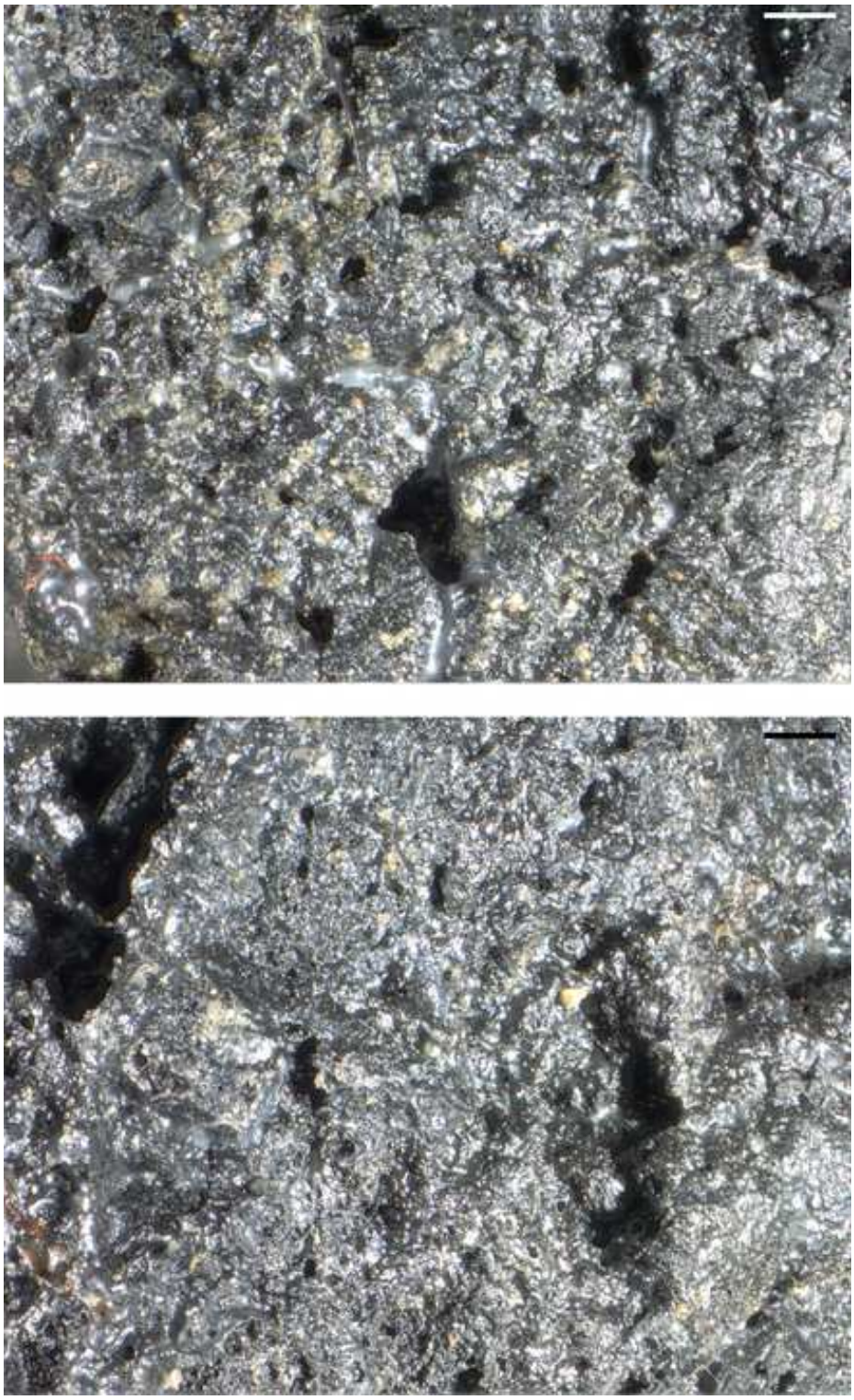


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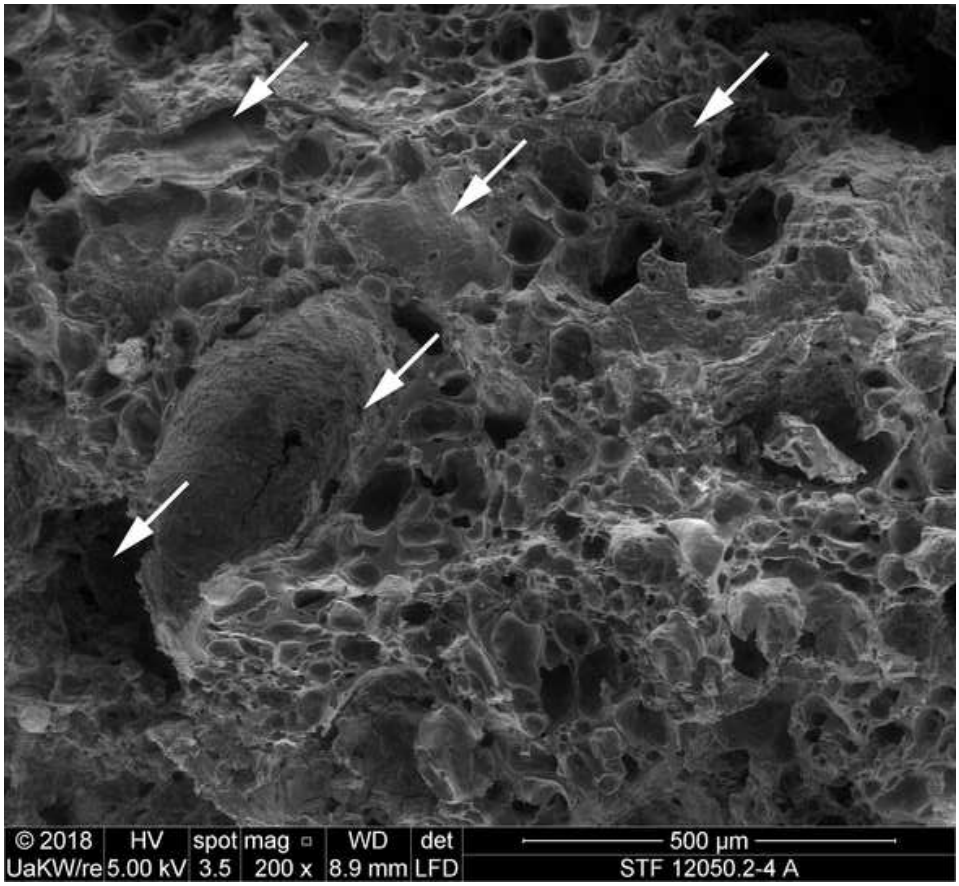


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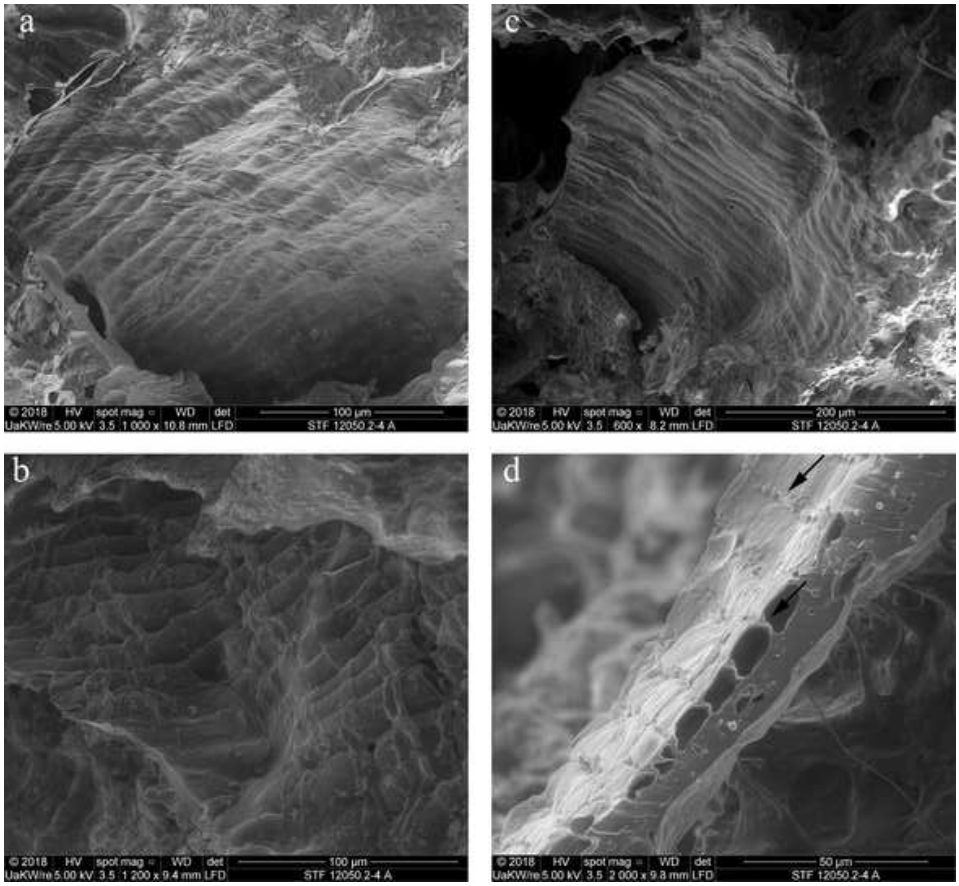


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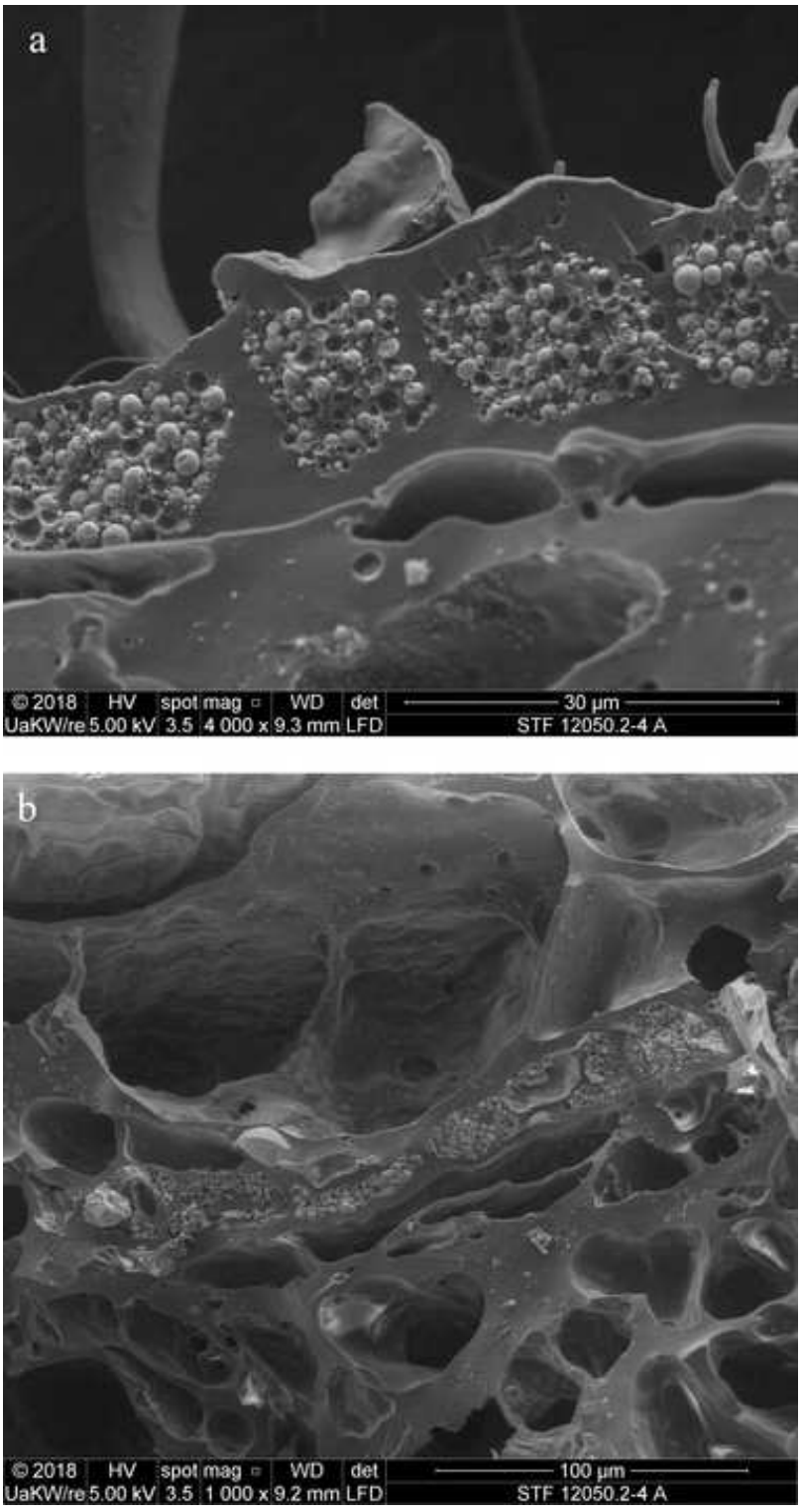
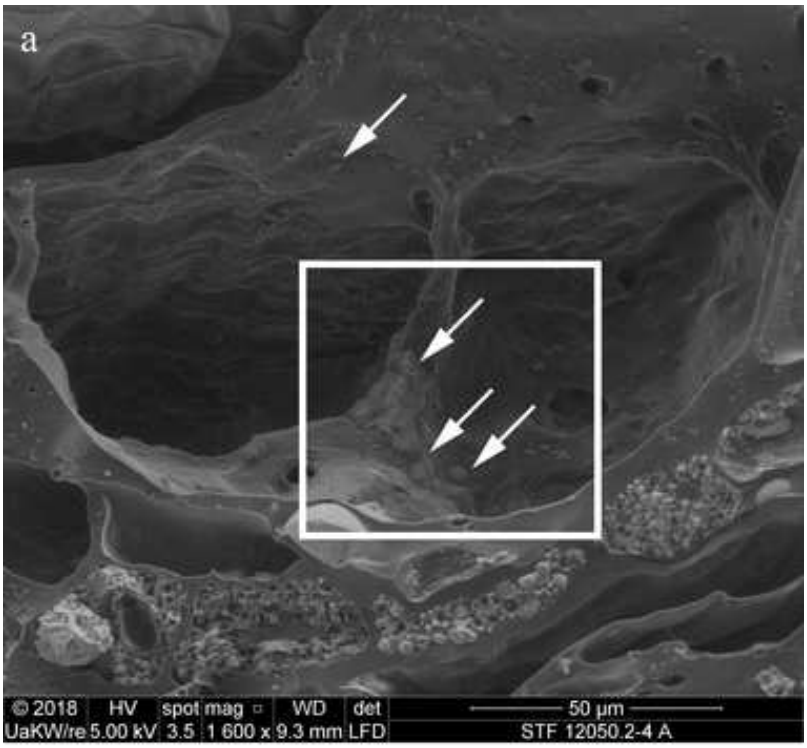


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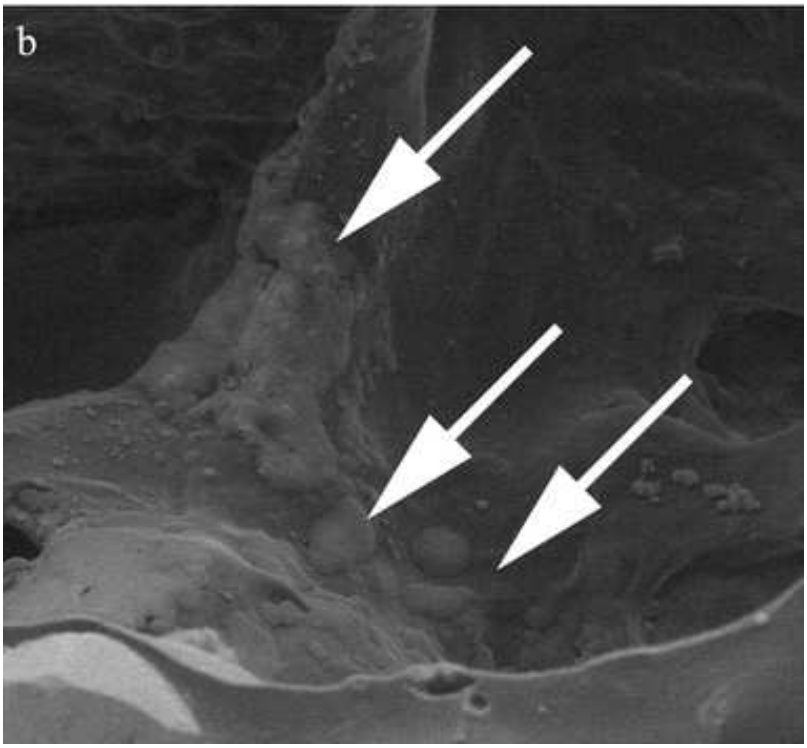


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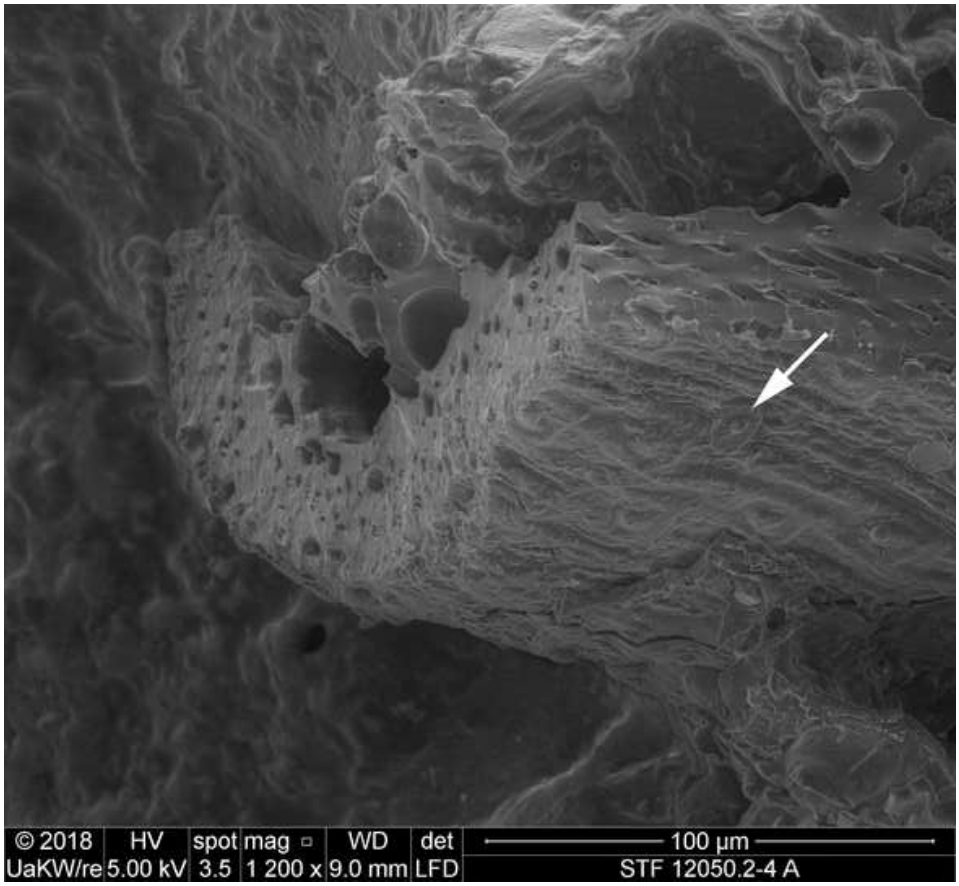


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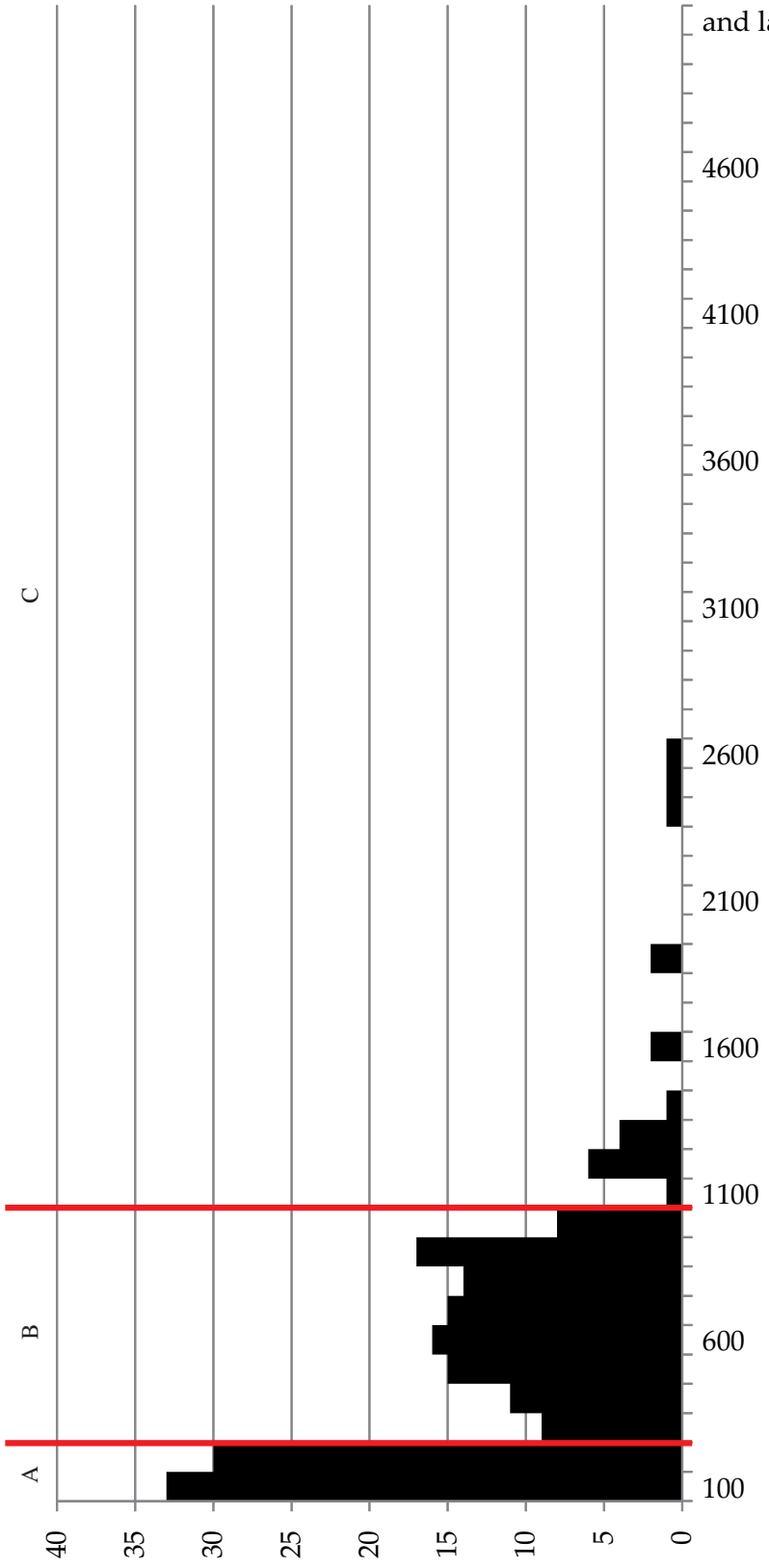


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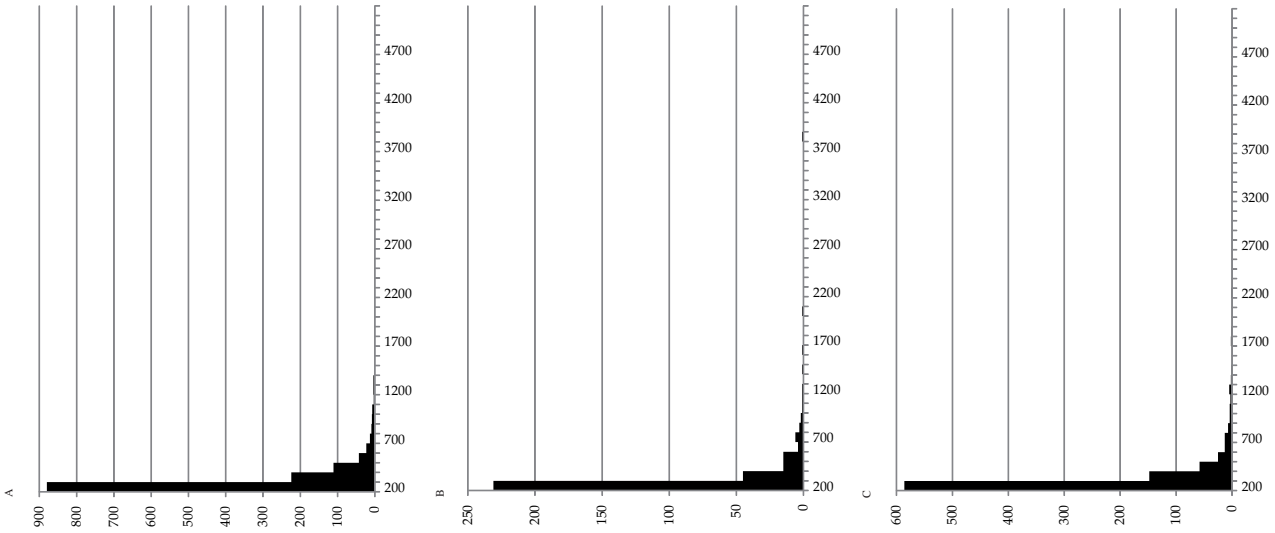


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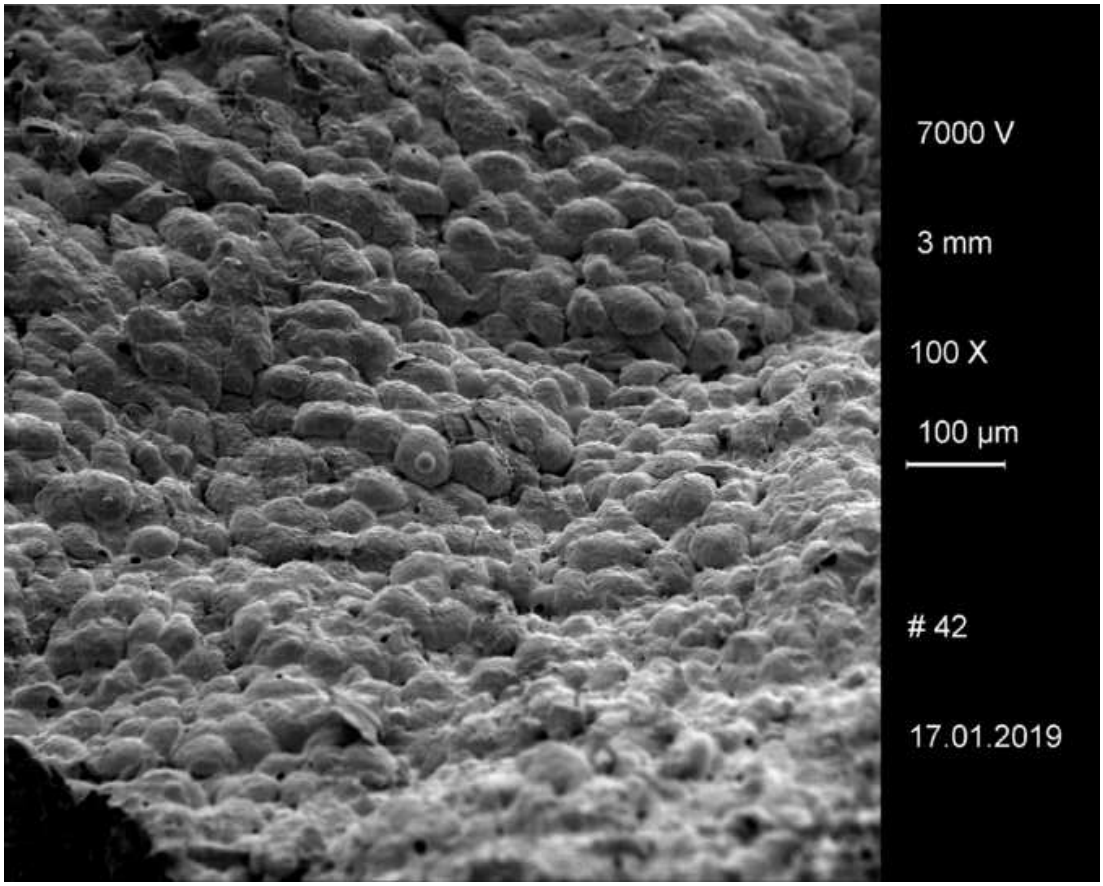
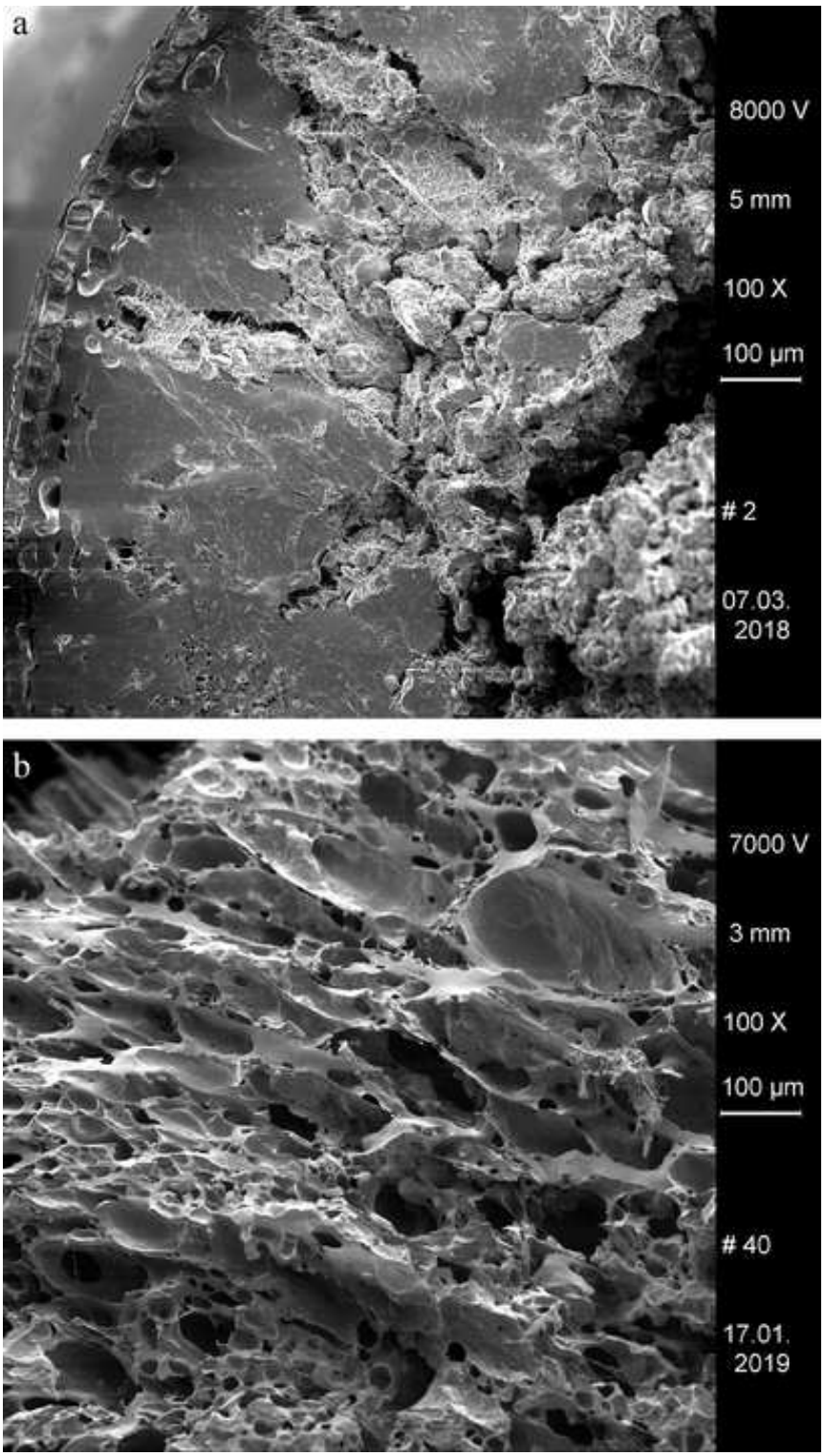


Fig25

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Appendix II
Selected Additional Original Papers

Short citation	Journal / Book title, Series	Impact	Peer Review	Estimated personal contribution
Heiss & Oeggl 2008	Vegetation History and Archaeobotany	1,908	yes	90%
Heiss & Oeggl 2009	Vegetation History and Archaeobotany	1,908	yes	50%
Heiss et al. 2011	International Journal of Plant Sciences	1,748	yes	75%
Stika & Heiss 2013	Oxford Handbook of the European Bronze Age, Oxford Handbooks in Archaeology	-	yes	50%
Heiss & Kohler-Schneider	Produktion — Distribution — Ökonomie	-	yes	50%
Heiss et al. 2014	Folk Life	-	yes	75%
Kohler-Schneider et al. 2015	Vegetation History and Archaeobotany	1,908	yes	33%
Stock et al. 2016	Earth Surface Processes and Landforms	3,697	yes	
Farag et al. 2019	Food Research International	3,52	yes	15%

Table 2. Personal contributions to the additional publications.

Heiss & Oeggl 2008

Heiss A. G. & Oeggl K. (2008) Analysis of the fuel wood used in Late Bronze Age and Early Iron Age copper mining sites of the Schwaz and Brixlegg area (Tyrol, Austria). *Vegetation History and Archaeobotany* **17** (2): 211–221. doi: 10.1007/s00334-007-0096-8

Veget Hist Archaeobot (2008) 17:211–221
DOI 10.1007/s00334-007-0096-8

ORIGINAL ARTICLE

Analysis of the fuel wood used in Late Bronze Age and Early Iron Age copper mining sites of the Schwaz and Brixlegg area (Tyrol, Austria)

Andreas G. Heiss · Klaus Oeggl

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Abstract Charcoal analysis was carried out as part of an interdisciplinary project focusing on the copper mining history of the former mining area of Schwaz and Brixlegg, a region pivotal as a copper source in prehistoric Europe. The goal was to use remains of carbonised wood to investigate environmental implications of prehistoric mining, as well as to gain new insight about the ancient mining technique of fire-setting. Charcoal samples from seven copper mining sites (Late Bronze Age to Early Iron Age) were analysed. The results reveal a strong preference for coniferous wood as fuel in fire-setting, but not in ore smelting/roasting processes. Species composition at the ore-processing sites indicates moderate forest degradation processes caused by human intervention.

Keywords Charcoal analysis · Bronze Age · Iron Age · Fire-setting · Copper mining history · Alps

Introduction

The Eastern Alps contain a high number of profitable ore deposits and are thus a region with a long tradition of mining (Eibner 1992; Höppner et al. 2005). The most prominent prehistoric mining areas were the Mitterberg near Salzburg, the region of Schwaz and Brixlegg in the lower Inntal, and the Kelchalpe near Kitzbühel. In the area of Schwaz/Brixlegg, man has been extracting copper ores from the bedrock since at least the Early to Middle Bronze Age (Goldenberg 1998, 2001), and the local use of copper for creating artefacts is already documented for the beginning of the fourth millennium B.C. (Matuschik 1997; Huijsmans et al. 2004).

The local geology is dominated by the Northern Alpine Greywacke zone (Fig. 1 inset, hatched areas; Brandner 1980) which holds deposits of the tetrahedrite–tennantite type (fahlore/grey copper ore), a mineral closely associated with dolomite rock (Rieser 2000). Dolomite is represented in this area by a local variety, the Schwazer Dolomit. Prehistorical and historical exploitation of these deposits has left traces across the landscapes around Schwaz and Brixlegg (Pirkl 1961; Gstrein 1986, 1988; Goldenberg and Rieser 2004). Along the south bank of the lower Inntal, hundreds of former mines and pits from prehistoric times (Fig. 2) to the Middle Ages can still be found up to high altitudes, for example, the mines of Gratlspitze at 1,899 m a.s.l., a site which is also included in this investigation.

Most of the prehistoric mines close to the surface seem to have been created using the fire-setting technique (Goldenberg 1998). Aside from tools driven by human strength, this was one of the principal methods of working into the rock during the millennia preceding the use of explosives. This did not occur until the seventeenth century, when in 1627 the first confirmed use of gunpowder in mining took place in Banska Stiavnica, Slovakia (Weiss 2005).

Fire-setting takes advantage of the susceptibility of dolomitic rock to heat. A fire is lit close to the wall (Fig. 3) causing the surface layers to crack, thus easing further processing with stone or metal tools. The pits created in dolomite in this way are of a characteristic, dome-like shape. As demonstrated in an experimental approach by Rieser (2000), this treatment can cause ra-

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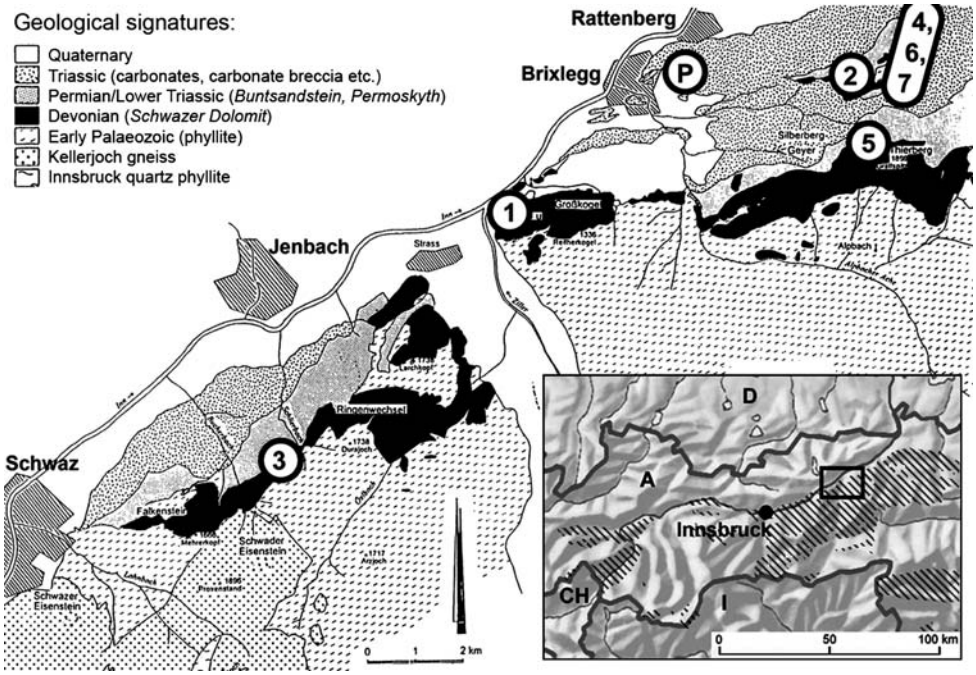


Fig. 1 Site locations (Arlt 1994, modified). *Inset* area investigated, *hatched pattern* Alpine Greywacke zone (Spiess 2002, modified; Brandner 1980, modified). *1* Kleinkogel (970 m a.s.l.), *2* Moosschrofen (1,150 m), *3* Blutskopf (1,200 m), *4* Mauken B (1,200 m), *5* Gratlspitze (1,899 m), *6* Mauken A (950 m), *7* Mauken D (1,020 m), *P* Oberkienberg pollen profile (757 m)

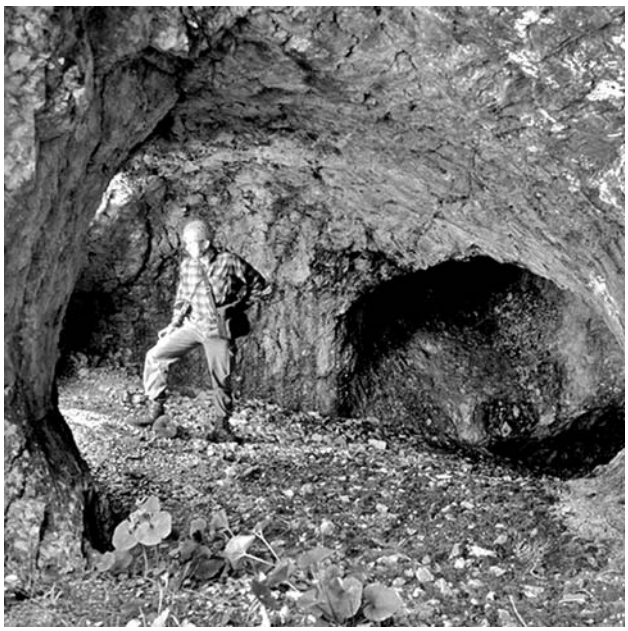


Fig. 2 The pit ''Zwei Fenster'' at Gratlspitze (*photo* Gert Goldenberg)



Fig. 3 Fire-setting as depicted by Georgius Agricola in his *De re metallica libri XII* from 1549 (Schiffner 1928). A burning pile of wood, *B* Bärte (frayed pieces of wood for kindling fire), *C* mine shaft

ther large chunks (up to 10 cm in diameter) to come off the rock by themselves, and allows the miner to process the now-fissured dolomite wall with tools as simple as wooden rods and stone mallets. Historical sources frequently mention the use of cold water for quenching the heated rock and thus enhancing the effect. Roman authors such as Titus Livius (*Ab urbe condita*, *Liber XXI*, *XXXVII*; Spillan and Edmonds 1868) and Gaius Plinius Secundus (*Naturalis historia*, *Liber XXXIII*, *LXXI*; von Jan 1860) even wrote of vinegar as a quenching agent instead of water. However, experimental approaches have not been able to verify unequivocally the efficacy of quenching (Rieser 2000; Craddock 1995, cited by Rieser 2000).

During Middle to Late Bronze Age new technological and cultural influences coming from the Mediterranean

spread across Europe. Archaeological evidence suggests a kind of ''early industrialisation'' impulse in the Eastern Alps based on the rising demand for bronze in Europe and also newly introduced techniques of smelting and alloying (Goldenberg 1998). It is to be expected that during this period

1. a higher demand for copper led to an increase in copper production, which resulted in
2. a higher population and larger settlements, and
3. an increase in agriculture and trade, leading to the expansion of arable land and of the road network.

Furthermore, a noticeable impact on local forest ecosystems in the mining areas is to be expected because of the timber needed for ore winning and processing.

To investigate these cultural and social as well as environmental changes, an interdisciplinary project on Bronze Age fahlore mining in the Schwaz and Brixlegg region was launched in 1997. Since then, test excavations have been carried out at numerous mining sites throughout the area, resulting in a number of publications on copper ore mining in the Eastern Alps (Goldenberg 1998, 2001; Goldenberg and Rieser 2004; Höppner et al. 2005; Rieser 2000). Similar multidisciplinary investigations including charcoal analysis are available from, for example, Cabrières in southern France (Ambert 2002; Ambert et al. 2002), or from Goleen in south-eastern Ireland (O'Brien 2003).

The goal of the charcoal analyses performed in the current project was to investigate some of the general conditions and consequences of mining, and of fire-setting in particular:

- Does the species composition of the fuel wood reflect local vegetation at Late Bronze Age and Early Iron Age, derived from the available pollen record?
- Is there any evidence on changes in forest cover or even on vegetation degradation?
- Could the data possibly contain any evidence on specific selection of certain woody taxa?
- What do dendrological features tell us about the quality of wood used?

Similar anthracological investigations of human impact and forestry management, as well as of details of the underlying technical processes have already been carried out for other periods: Imperial Roman bloomery furnaces in northern Germany (Dörfler and Wiethold 2000), Roman to modern times settlements, mining and kiln sites in the Black Forest (Ludemann 1996, 1999, 2002, 2003; Ludemann et al. 2004) and in the Bavarian Forest (Nelle 2003), and various sites from modern times analysed in large-scale investigations in Great Britain (Gale 2003).

The area investigated

Charcoal was collected from five fire-set pits at different locations (Fig. 1) and at different altitudes as described below, as well as from two other archaeological sites. These were a Middle to Late Bronze Age ore-processing site and the surroundings of a late Bronze Age mine shaft (Fig. 1). Detailed account of the topography, geology and actual vegetation can be found in Rieser (2000) and in Heiss (2001).

The first pit is located at *Kleinkogel* (970 m a.s.l.), the most north-westerly outpost of the Kitzbüheler Alpen at the entrance of the Zillertal. Its northern aspect is characterised by numerous screes and steep rock faces (*Heidstein*, the ''heathen rock'') pierced with prehistoric mines. Actual vegetation on the northern face is a mixed montane forest similar to that described for the Mauken area, but interrupted by azonal stands of mugo pine (*Pinus mugo*) in the screes.

The *Moosschrofen* is a small inselberg in the Mauken region, completely composed of Schwazer Dolomit and with numerous fire-set pits. Samples were taken from the pit ''Grube Ost'' (1,150 m a.s.l.) at the northern face of Moosschrofen (Rieser 2000). The rocky areas contain Scots pine (*P. sylvestris*), whereas the surrounding vegetation is composed of spruce forest and pastures.

The pit sampled at *Blutskopf*, a mountain at Hochgallzein in the east of Schwaz, lies about 100 m below the peak (at 1,200 m a.s.l.), on a scarp called Vogelsang. Local vegetation is dominated today by (supposedly) natural spruce woods, with frequent occurrence of larch.

Mauken (Hintersommerau) is a small region on the south bank of the Inntal, in the vicinity of Brixlegg. In a narrow, gorge-like valley in that area, the Maukengraben, a fire-set pit (*Mauken B*) at about 1,200 m a.s.l., was sampled. Some distance downhill, excavation campaigns revealed the slag dump from an ore-processing site (*Mauken A*, 950 m a.s.l.) and several collapsed mine shafts (*Mauken D*, 1,020 m a.s.l.). Charcoal was collected from both sites for analyses. The actual vegetation of the area is very heterogeneous due to debris cones and anthropogenic clearings (e.g. the gravel access road). However, it is dominated by a montane mixed forest of spruce (*Picea abies*), fir (*Abies alba*) and beech (*Fagus sylvatica*), with Scots pine (*P. sylvestris*) and larch (*Larix decidua*) occurring frequently.

The prehistoric mines at *Gratlspitze* (1,899 m a.s.l.) are also very close to the peak, where a pit (''Zwei Fenster'', Rieser 2000) on the northern face was sampled. Local woody vegetation is restricted to patches of mugo pine (*P. mugo*). Beneath the timberline (at about 1,800 m), woods of the typical subalpine spruce–larch type dominate the landscape.

Materials and methods

Sampling

The excavator (G. Goldenberg) took 11 samples of fire-setting rubble from the 5 fire-set pits, their volumes ranging between 25 and 120 ml. The soil samples from the Mauken A and D sites were significantly larger and ranged between 42 and 2,660 ml. All material was packed in airtight polyethylene bags immediately after sampling and stored at +5°C until analysis.

Radiocarbon dating

Several charcoal samples were AMS dated at the Vienna Environmental Research Accelerator (VERA) laboratory at the Institute for Isotope Research and Nuclear Physics of the University of Vienna. Radiocarbon data calibration was carried out with OxCal 3.10 (Bronk Ramsey 1995, 2001) using the IntCal04 calibration curve (Reimer et al. 2004).

Sample processing and identification

Extraction of plant macro remains from the soil material followed standard flotation procedure (Jacomet and Kreuz 1999), and the resulting material was split into four fractions using staggered sieves at mesh sizes of 0.25, 0.5, 1 and 2 mm. Uncarbonised and carbonised plant remains from all fractions were then analysed. Results from the macrofossil analyses from Mauken have already been published (Heiss 2001; Schatz et al. 2002; Heiss and Oeggl 2005).

As charcoal analysis had originally only been planned as a minor component of the investigations, the following measures were taken in order to keep within the scheduled time frame:

- Charcoal analysis was limited to fragments from the largest fraction (>2 mm)
- Subsamples of 50 fragments (where possible; Table 1) per sample were randomly collected and analysed.

Identification of the charcoal fragments was carried out using an episcopic microscope (Zeiss Axioskop). An interactive identification key (Heiss 2000 onwards) was also used in addition to the standard literature (Schweingruber 1990).

In addition to identification, some dendrological and taphonomical features were recorded for the charcoal analysed to gain some insight into the quality of wood used. The radius of the outermost growth ring for each charcoal fragment was measured by adjusting the growth ring curvature and wood ray angle of the charcoal pieces to a diameter stencil (Ludemann 1996). As a simplified stencil was used, only a qualitative differentiation between ''small'' (≤25 mm) and ''large'' (>25 mm) radii was made in this current study. Additionally, the maximum growth ring width per fragment (i.e. the dimension of the widest growth ring) was recorded.

Wood-decaying fungi are destroyed during carbonisation, but their former presence is often indicated by imprints of hyphae in the cell wall tissue of the host plant. This fact can be used to gain further information on the quality of the fuel wood, and whether intact or decaying wood had been used (Schweingruber 1976). Unidentified fragments (recorded as ''hardwood indet.'' and ''softwood indet.'') were excluded from this analysis. Charcoal pieces containing modern hyphae material (probably from edaphic fungi) were considered as not containing any ancient hyphae imprints. This approach implies a bias, possibly causing under-representation of fungus-infested material in the data.

Results

Radiocarbon dating

The results indicate ages ranging from Late Bronze Age to Early Iron Age (Fig. 4) and an obvious temporal difference between the ore-processing sites at Mauken A and D and the five fire-set pits. However, these seemingly younger sites lie within the Hallstatt plateau of the calibration curve. This is caused by a sudden rise in atmospheric ^{14}C content between ca. 2750 B.P. and 2450 B.P. (van Geel et al. 1996; Reimer et al. 2004; Guilderson et al. 2005) which renders radiocarbon data from that period rather unreliable. Consequently, it cannot be stated with certainty whether the material from the fire-set pits investigated is of Late Bronze Age (Urnfield Culture) or Early Iron Age (Hallstatt) origin.

Moreover, the charcoal material from Kleinkogel dates to modern times. Although sampling focused on the lower layers of the fire-setting rubble (G. Goldenberg, personal communication), the charcoal had most probably been contaminated with modern material. This may be explained by the fact that both tourists and locals sometimes use the prehistoric mines as campfire sites. Nevertheless, the results from the Kleinkogel samples are also included in this study as a modern analogue for the prehistoric sites.

Charcoal analysis

A total of 520 charcoal fragments was analysed from the Late Bronze Age (LBA) sites of Mauken A and D (Table 1). The samples were dominated by the taxa *Abies*, *Picea/Larix* type and *Fagus*. Small quantities of the light-demanding pioneer woody taxa *Betula*, *Pinus* and *Sambucus* occurred, as well as the highly shade-tolerant *Taxus*.

Table 1 Results of the charcoal analyses for the Late Bronze Age mining sites

	Mauken A: ore-processing site											Mauken D: mine shaft surroundings								
												Fireplace				Refuse pit				
Sample no.	1	2	14	19	21	25	30	31	32		%	35	36		%	26	33	34		%
Total sample volume (ml)	790	610	42	2,634	1,330	2,125	1,405	430	590	9,956		2,660	690	3,350		1,430	1,630	2,090	5,150	
Total charcoal weight >2 mm (g)	2.30	1.33	0.1	27.56	2.98	57.34	12.18	0.58	3.92	108	100	1.35	6.29	8	100	12.04	7.14	4.41	24	100
Analysed charcoal weight >2 mm (g)	0.35	0.43	0.1	5	0.58	9.25	2.31	0.27	2.12	20	19	0.69	1.92	3	34	2.1	2.57	1.88	7	28
Mean fragment weight (mg)	7	9	10	100	12	185	46	27	42			23	38	33		42	51	38	44	
Abies alba	28	26	5	22	24	40	25	7	21	198	53.5	13	15	28	35	7	9	11	27	18
Larix decidua	2	–	–	–	4	–	–	–	3	9	2.4	–	–	–	–	–	1	5	6	4
Picea/Larix type	15	16	2	13	12	3	7	1	9	78	21.1	8	21	29	36.3	24	19	20	63	42
Pinus non *cembra*	–	–	–	–	–	–	2	–	1	3	0.8	3	1	4	5	–	1	–	1	0.7
Taxus baccata	–	–	–	–	–	–	–	–	–	–	–	2	–	2	2.5	–	–	–	–	–
Coniferous wood (indet.)	2	4	1	3	1	–	3	–	4	18	4.9	–	–	–	–	2	3	2	7	4.7
Betula sp.	–	–	–	–	–	–	2	–	–	2	0.5	–	–	–	–	–	–	2	2	1.3
Fagus sylvatica	3	4	–	10	7	5	10	2	10	51	13.8	4	8	12	15	16	16	9	41	27.3
Sambucus sp.	–	–	–	–	–	–	–	–	–	–	–	–	2	2	2.5	–	–	–	–	–
Broad-leaved wood (indet.)	–	–	2	2	2	2	1	–	2	11	3	–	3	3	3.8	1	1	1	3	2
Analysed charcoal (total)	50	50	10	50	50	50	50	10	50	370	100	30	50	80	100	50	50	50	150	100

Values given are fragment numbers unless otherwise stated

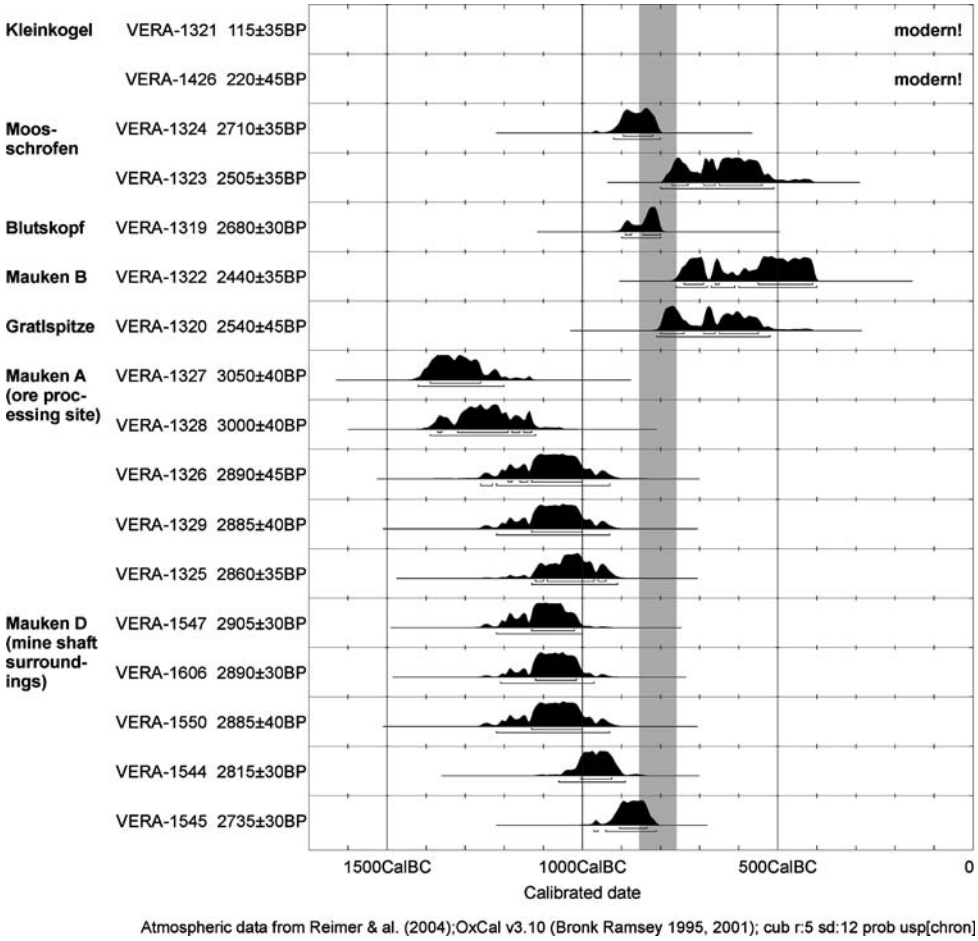


Fig. 4 Results of the radiocarbon dating. The *grey bar* indicates the Hallstatt plateau

From the fire-set pits, 476 specimens of charcoal were analysed. In comparison to the LBA sites, the results for the prehistoric samples display a starkly diverging species composition: all the charcoal originated exclusively from softwoods (Table 2, Fig. 6) with either *Abies* or the *Picea/Larix* type dominating. The modern samples from Kleinkogel pit show in turn an additional proportion of *Fagus* wood similar to the LBA sites.

Discussion

Species composition

According to the palynological analyses performed on a peat profile from the nearby Oberkienberg (Walde 1998, 1999), forest vegetation in the Brixlegg area during the LBA was very similar to modern conditions. After the arrival of *Fagus* during the transition Atlantic-Subboreal (ca. 4000 cal B.C.), all main tree taxa were present in the area, indicating that montane mixed forests were already fully formed at the beginning of LBA.

Proportions of the dominant tree taxa in the LBA sites of Mauken A and D (*Abies*, *Picea/Larix* type, *Fagus*; Table 1, Fig. 5) more or less match the expected natural composition of montane mixed-forest stands. Species composition at these two sites does not give any evidence of selection of fuel wood.

The presence of some pioneer taxa in the Mauken A and D charcoal samples might indicate that succession processes were taking place, probably induced by anthropogenic influence on the local forest ecosystems (comparable to the modern situation at Mauken). As expressed in the basic hypothesis stated above, small-scale clearings are to be expected in the surroundings of ore-processing and mining facilities, as there was need for fuel wood and traffic routes to be set up in order to facilitate work and transport. However, the obviously very small proportion of these pioneer taxa (0.54–2.5% of charcoal fragments per site) is within the range of natural conditions and does not necessarily imply human impact (T. Ludemann, personal communication). In any case, their low proportions in the firewood point to sufficient availability of the taxa forming the climax forest, and consequently a rather low or, at the most, a moderate influence of mining activities on the local forest ecosystems.

As already described, hardwoods were completely missing from the prehistoric material from the fire-set pits. Widely varying amounts of *Abies* were recorded, from a

Table 2 Results of the charcoal analyses for the Early Iron Age fire-set pits

	Kleinkogel (modern!)			Moosschrofen			Blutskopf			Mauken B			Gratlspitze		
Sample no.	6	11	%	4	5	7	8	9	%	3	10	%	12	13	%
Total sample volume (ml)	120	66	186	31	67	25	39	86	125	74	35	109	46	29	75
Total charcoal weight >2 mm (g)	17.39	27.58	44.97	14.56	19.92	9.97	13.60	27.26	40.86	18.48	13.88	32.36	28.48	13.62	42.1
Analysed charcoal weight >2 mm (g)	3.03	15.96	18.99	14.56	12.95	5.15	5.35	17.39	22.74	7.27	5.03	12.3	20.92	12.21	33.13
Mean fragment weight (mg)	61	319	190	14,560	259	103	107	348	227	145	101	123	418	488	442
Abies alba	32	13	45	–	36	5	8	4	12	11	35	46	1	–	1
Larix decidua	–	–	–	–	–	–	1	–	1	–	–	–	5	2	7
Picea/Larix type	13	31	44	1	14	43	58	57	35	45	80	80	39	12	51	43	23	66	88
Coniferous wood (indet.)	–	–	–	–	–	2	2	2	6	1	7	7	–	3	3	1	–	1	1
Fagus sylvatica	2	6	8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Broad-leaved wood (indet.)	3	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Analysed charcoal (total)	50	50	100	1	50	50	101	100	50	50	50	100	100	50	25	75	100

Values given are fragment numbers unless otherwise stated

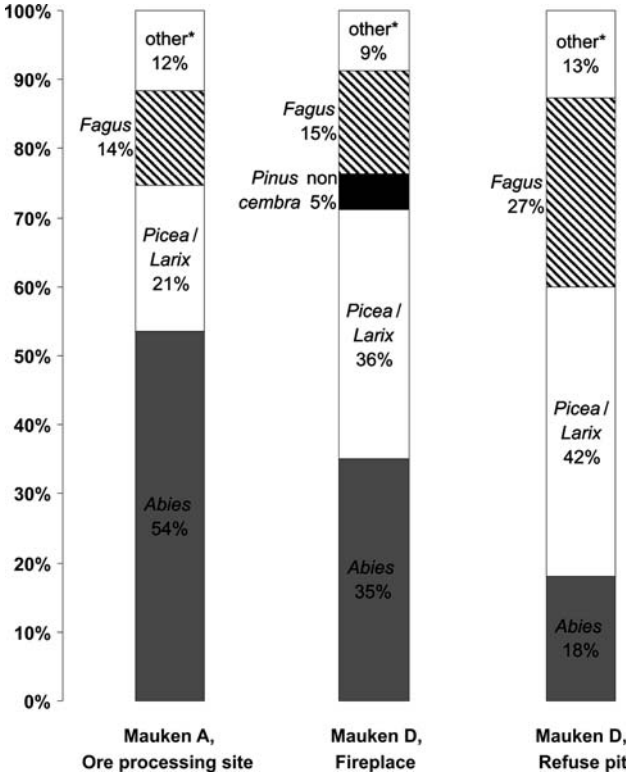


Fig. 5 Taxon percentages for the Late Bronze Age (LBA) mining sites. * = Taxa with per-site percentages below 5%, subsumed as ''other'' (see Table 1 for details)

maximum of 46% at Mauken B to only a single find at the Gratlspitze pit. When considering the differences in altitudes between the sites (bottom of Fig. 6), it becomes obvious that natural altitudinal distribution of *A. alba* may

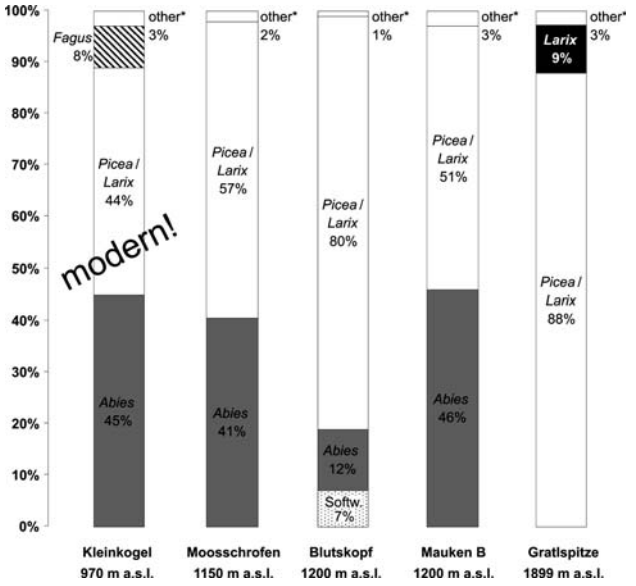


Fig. 6 Taxon percentages for the Early Iron Age fire-set pits. * = Taxa with per-site percentages below 5%, subsumed as ''other'' (see Table 2 for details)

be the reason. Noteworthy amounts of *Abies* charcoal occur only in the material from the montane pits.

By and large two approaches seem possible when seeking explanations for the species compositions being so markedly different to the LBA sites. Either these divergences are the consequence of the very different archaeological contexts and the different uses of the fuel wood (ore smelting/roasting in contrast to fire-setting), or major changes in local vegetation must have taken place between the LBA and Early Iron Age.

Taking the pollen record into account, then at least for the surroundings of the three Iron Age pits at montane altitudinal zones (Moosschrofen, Mauken B, and Blutskopf) the availability of sufficient wood from hardwood species (e.g. *F. sylvatica*) for fire-setting can be considered. The Oberkienberg pollen profile (Walde 1998, 1999) documents human impact on local vegetation by a steady increase of anthropogenic indicators (Cerealia, *Plantago lanceolata* and *Rumex* pollen types) and decreasing values for arboreal pollen since the Subboreal. However, there is apparently no evidence whatsoever for major degradation processes in local forest vegetation during the Bronze and Iron Ages, such as would result in a collapse of hardwood species populations. Consequently, their complete absence in all of the charcoal samples ought to be interpreted as evidence of the deliberate selection of coniferous taxa for fuel wood.

This possible evidence for the selection of fuel wood in fire-setting may also be corroborated by historical written sources, for example, Rösler (1700) cited by Rieser (2000) strongly suggests the exclusive use of fir and spruce wood for fire-setting, due to their ''hotter flames''. Such preference for coniferous wood cannot be substantiated by measurement—in reality burning temperatures are not species dependent (Ten Wolde et al. 1988, cited by Ragland et al. 1991). Nevertheless, if our conclusions on Early Iron Age fire-setting in the Schwaz/Brixlegg area are correct, taking these together with the sixteenth century document, we have a strong indication of a tradition of fire-setting remaining nearly unchanged for more than two millennia, at least in terms of fuel wood selection.

The modern charcoal material from Kleinkogel pit, strongly deviating from this pattern of an exclusive presence of softwood taxa, more or less resembles the taxa proportions typical of the modern, montane mixed-forest stands in the area (Table 2). It can be presumed that no selective processes had guided the wood gatherers.

Wood quality

The data resulting from the dendrological analyses are displayed in Figs. 7 and 8. For each site, the maximum growth ring radius, a histogram of maximum growth ring

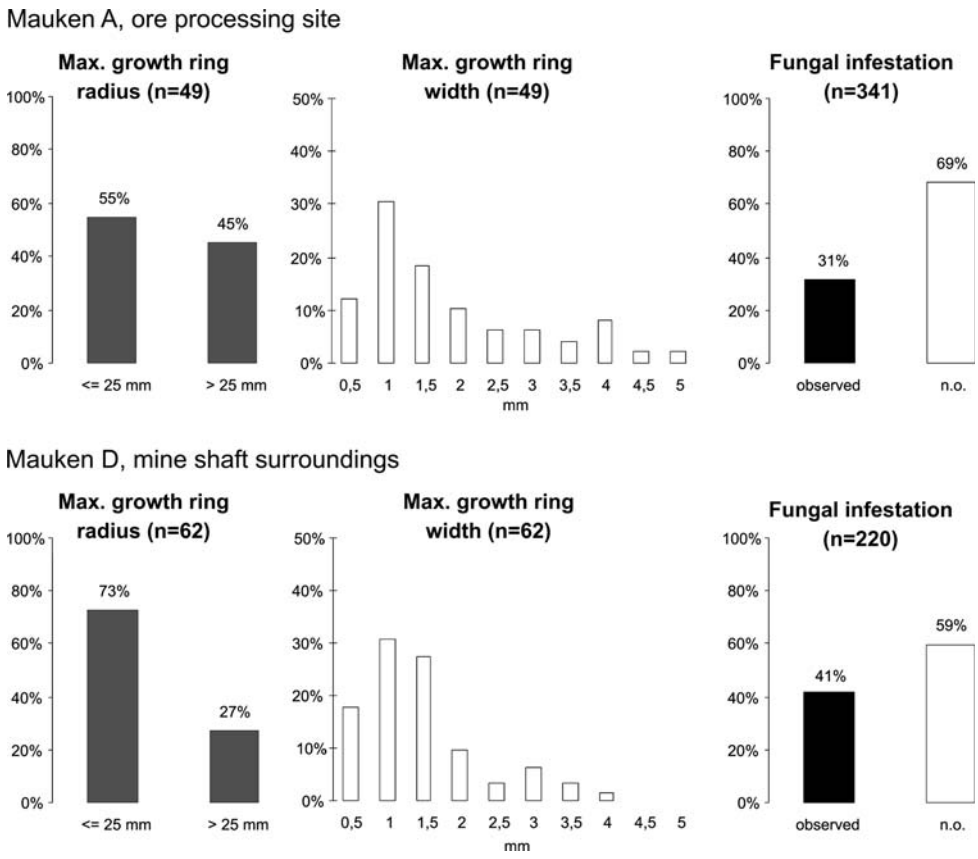


Fig. 7 Dendrological features of the LBA mining sites charcoal. n.o. = not observed

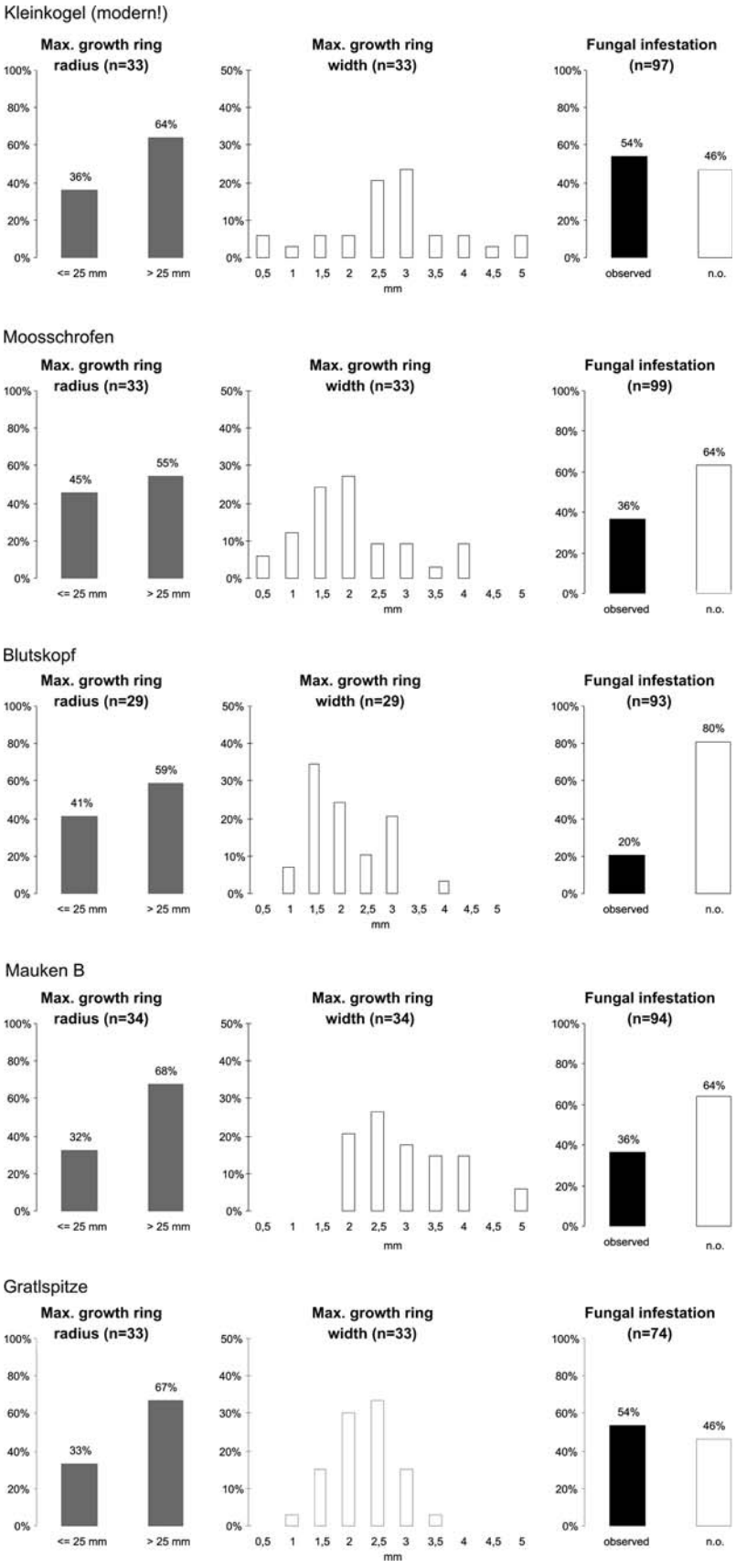


Fig. 8 Dendrological features of the Early Iron Age fire-set pits charcoal. n.o. = not observed

widths and the proportion of fungus-infested wood are shown.

As for the wood radii, only very limited interpretation is possible since only two radius categories were used. As a significant volumetric loss in wood tissue during carbonisation has to be considered, especially in the radial and tangential directions (12–25%, Schweingruber 1976; Slocum et al. 1978), the measured growth ring data (radius as well as growth ring width) also cannot be equated with uncarbonised wood.

Generally, for the fire-set pits the amount of ''large'' radius wood is above 50%, suggesting the presence of thicker stems and branches (>5 cm diameter) in the charcoal material. However, the Mauken A and D sites display a reverse proportion, with a dominance of ''small'' radius wood. Analyses with a higher resolution (e.g. using five radius categories instead of only two) should reveal whether there has been any preference for twigs and thin branches at Mauken A and D.

The histograms show the distribution of growth ring width categories in the charcoal material. Branches commonly display less radial growth than do young stems of the same diameter. The figures show markedly heterogeneous results that do not display a common trend within the fire-set pits, very unlike the species composition or the wood diameters. However, the LBA sites at Mauken A and D again stand out, because of the increased occurrence of low radial growth with a simultaneous decrease in large growth rings. This, too, points to a prevalent use of twigs and thin branches in the fuel wood.

The presence of fungus-infested charcoal fragments was also recorded for all the sites investigated. The proportions in the fire-set pits are rather heterogeneous, with 20 to 54% of the material containing hyphae imprints, indicating varying quantities of gathered/stored wood in contrast to freshly felled material.

The only prehistoric site exceeding a value of 50% was Gratlspitze (54%). Given a possible under-representation of hyphae-containing fragments (see Methods section) we have to consider the use of a substantial amount of fungus-infested (and thus, partly decayed) wood/charcoal for fire-setting. Considering the altitude of the mine it seems very plausible to assume that the low availability of fuel wood had led the miners to use (gathered?) wood of poor quality, which they had to transport to the pit from the forests below.

The same analyses carried out for the Mauken A and D sites resulted in roughly one-third of the charcoal material showing hyphae imprints, indicating a moderate proportion of gathered/stored wood.

Conclusions

The results from the LBA sites of Mauken A and D suggest that the fuel wood utilised for smelting/roasting processes as well as for daily use (Mauken A, D) was most probably taken from the environment at random, but may have undergone a selection process by branch thickness. The implication of the charcoal record of human impact on local forest ecosystems points to a possible influence due to clearings and wood use, but still suggests a broad availability of climax forest taxa and consequently the presence of more or less intact forest vegetation.

The situation at the Early Iron Age fire-set pits is rather different, clearly showing deliberate selection of fuel material on the basis of hardwood/softwood, with the sole use of coniferous woods for setting fire possibly being due to their putative combustion properties.

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ORIGINAL ARTICLE

The plant macro-remains from the Iceman site (Tisenjoch, Italian–Austrian border, eastern Alps): new results on the glacier mummy's environment

Andreas G. Heiss · Klaus Oeggl

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Abstract Archaeobotanical studies are currently being carried out on all the plant remains retrieved from the high alpine site where the Iceman "Ötzi" was found (3,210 m a.s.l.). Preliminary results already show a great diversity of species (121 taxa) mainly originating from lower regions, which must have been transported to the Tisenjoch site by a number of vectors. Spatial modelling has been carried out for one part of the plant remains unequivocally assignable to the Iceman. The resulting patterns indicate that post-depositional displacement processes have affected the material, and even the mummified body itself. It is demonstrated that the influence of cross-contamination resulting from the recovery attempts preceding the excavations can be ruled out by thorough selection of sampled areas and layers. The archaeobotanical results, together with current data from other research fields, strongly suggest that the Iceman had died in an area about 5 m south-west of the position where he was discovered in 1991.

Keywords Neolithic · Alps · Iceman · Archaeobotany · Taphonomy · Palaeo-forensics

Introduction

The Iceman "Ötzi" represents the unique find of a perfectly preserved corpse dating back to the late Neolithic. Radiocarbon data (3370–3100 cal B.C.; see Bonani et al. 1994; Hedges et al. 1992; Kutschera 2002) suggest that he was a contemporary of the Cham and Horgen cultures north of the Alps (Jacomet 2006).

The body has been subject to detailed multidisciplinary scientific research for more than a decade, dealing with issues as different as his geographical and cultural backgrounds, health and state of nutrition, and many more. Various results on plant remains have already been published, such as analyses of the wooden artefacts (Oeggl and Schoch 1995, 2000), the binding material (Pfeifer and Oeggl 2000), the remains of retrieved mosses and liverworts (Dickson 2003; Dickson et al. 1996, 2000, 2005), or of the grasses used (Acs et al. 2005). Even the body's intestine contents (Oeggl 1998, 2000, 2001; Rollo et al. 2002) have successfully been examined for plant and animal remains, and resulted in valuable data on the living conditions of Ötzi.

The discovery site of the Neolithic glacier mummy is located in a flat and rocky area of the Tisenjoch (3,210 m a.s.l.), a pass in the Ötztal Alps, in the municipality of Schnals/Senales in Italy, close to the Austrian border (Fig. 1). The rocky hollow where the body has been found lies in a level part of the pass, in the accumulation area of the Niederjoch glacier. The flat local topography and the orientation of the rocky hollow, crosswise to the ice flow's direction (Baroni and Orombelli 1996), were conditions decreasing the influence of glacial movement (Bagolini et al. 1995). Also, the only slight deformations of the corpse's soft tissues suggested that the find assemblage had probably not been subject to massive ice-flow (Seidler et al. 1992a), as to be expected in steeper areas of the glacier.

The gully is orientated in a southwest–northeast direction, and about 40 m long, but only the southern part of the gully, in which the mummy had been discovered, was excavated. Its width varies from 3.5 m at the western end

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Fig. 1 The location of the Iceman site south of the Ötztal

to about 8 m in the centre of the gully, its depth being about 2.5 m (Figs. 2, 3). In the centre of the gully, to the south-east, the limiting rock ridge is lower and becomes an overflow for melt-water, which in case of melting allows water levels of up to about 1.4 m in the gully (Bagolini et al. 1995).

During two archaeological excavations (see the "Materials and methods") at the Iceman's discovery site a huge amount of plant material, which had been embedded in the ice and sediments of the gully, was collected and taken to the Botanical Institute of Innsbruck University for analysis following the excavations in 1992. Unfortunately, a comprehensive study of all plant remains from the Iceman's discovery site has not been done until now: this kind of analysis could contribute essential information on the post-mortem fate of the organic remains and on the formation of the find assemblage (the taphonomy) in the gully at the Tisenjoch. Furthermore, the results of this study could also help with a scientific interpretation of the last moments in the life of the Iceman. Both topics are still under controversial discussion. Originally, Spindler (1993, 1996; see also Zur Nedden et al. 1994) suggested that the extraordinarily good preservation of the body and the other finds was due to an immediate incorporation in the snow slowly transforming into ice after years, and then never thawing again until the glacier mummy's discovery in 1991. Anyhow, first studies on the wooden artefacts and their positions in the gully indicated that they had possibly been displaced by wind or water (Oeggl and Schoch 1995). This suggestion was corroborated by further detailed analyses of the wooden artefacts found in the gully (Oeggl and Schoch 2000; Oeggl 2003), as well as by a pedological investigation of the soils at the Tisenjoch site carried out by Baroni and Orombelli (1996). Climatological interpretation of the latter study implied that the ice in the gully, where the Iceman had been discovered, had melted several times since the late Neolithic.

Once more it has to be stressed that the cause of Ötzi's death is still ambiguous. The original suggestion that he had possibly died from exhaustion and hypothermia (Seidler et al. 1992a) is seriously opposed by the recent discovery of a fresh arrow wound in his back, with the arrowhead still trapped between the rib cage and the left shoulder blade which it had perforated (Gostner and Egarter-Vigl 2002; Murphy et al. 2003). This severe injury indicates a trauma of the large axilla (armpit) vessels caused by the arrow, the resulting haemorrhage leading to death within a short time (P. Gostner, personal communication). Where the attack had taken place—either in the gully at the Tisenjoch or elsewhere—is still a subject of speculation.

Anyway, knowledge of the taphonomy of the find assemblage can contribute data to clarify whether the find positions of the corpse and the other finds correspond to their original positions at the time of Ötzi's death, and thus provide cogent evidence of the last moments of his life.

The reconstruction of the Iceman's death is hampered by the indication that parts of the find assemblage were displaced on freezing/thawing cycles which took place post-mortem, as already suggested by archaeologists during the excavation in 1992 (Bagolini et al. 1995). However, precise data on the site's taphonomy has been scarce up to now, although there is some evidence of the processes which took place there:

- The Iceman's equipment was scattered across the whole rock gully where he had been lying (Fig. 2) which does not seem to be a typical situation to be expected at a resting place or at a camp site. Nevertheless, the possibly violent death of the Iceman might constitute exceptional circumstances.
- The corpse was lying in a prone position on a stone slab (Fig. 3), left arm beneath him, right hand trapped under a stone. This has initially been interpreted as a "resting position" (Lippert 1992). In consideration of the arrowhead in his left shoulder, this position might also be explained as resulting from the pain caused by the injury (Gostner and Egarter-Vigl 2002).

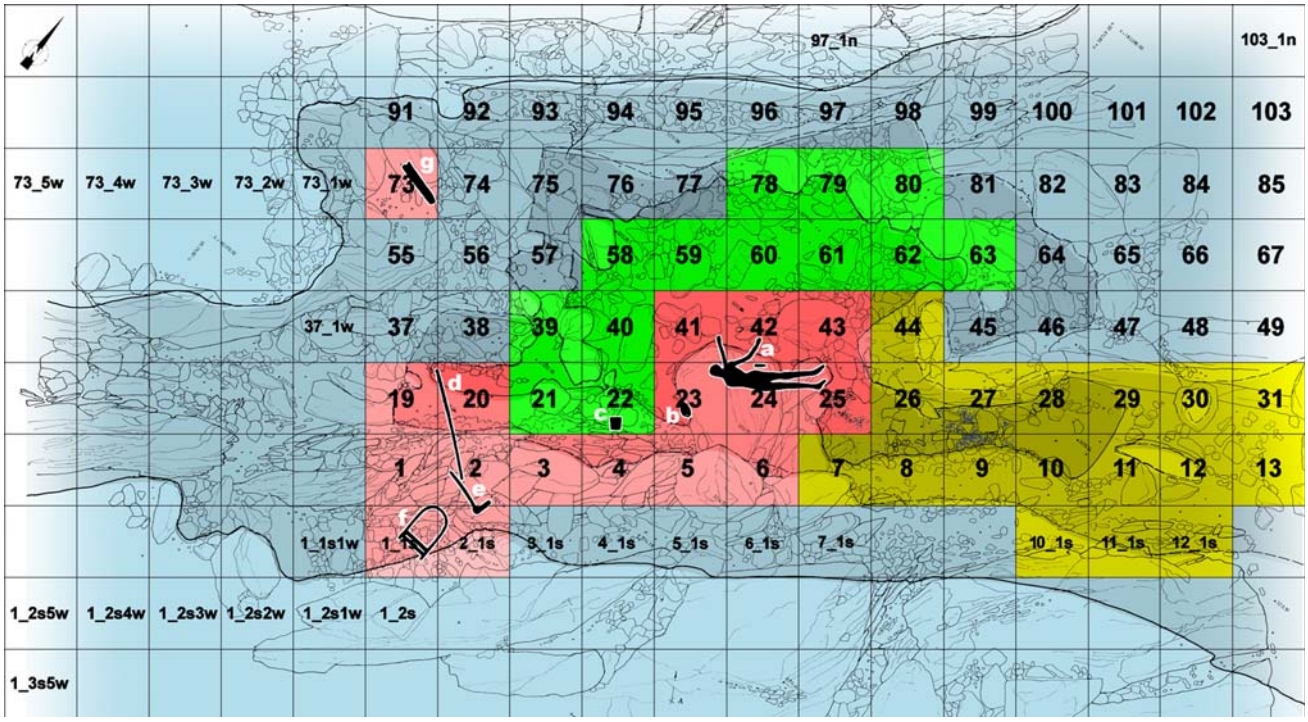


Fig. 2 The Iceman site with the 1 m^2 grid. Additional quadrant numbers in the west and east (indicated with "*s*", "*w*" or "*n*") were added as supplements to the original plan. Marginal areas are not displayed. *Darker shades* of blue indicate deeper areas of the rocky hollow. *Red* area excavated during the 1991 campaign. *Yellow* quadrants within the melt-water stream of the 1992 excavation. *Green* quadrants with undisturbed sediments selected for preliminary assessment of spatial distribution. **a** Iceman body and dagger, **b** bearskin cap, **c** birch bark container, **d** bow, **e** axe, **f** backpack frame, **g** quiver

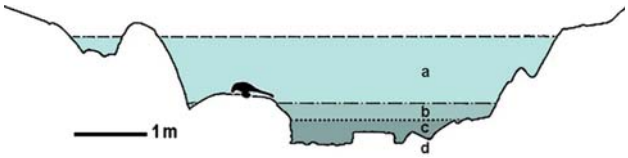


Fig. 3 North–south transect of the Iceman site. **a** Maximum depth of water, flooded after the excavation in 1991, **b** upper ice layer excavated in 1992, **c** lower, "dirty" ice layer incorporating the find assemblage, **d** bedrock (Bagolini et al. 1995, modified)

- The body's outermost epidermis layers had come off due to the body having been submerged in water for short episodes (Bereuter et al. 1996; Murphy et al. 2003), causing a loss of epidermal appendages such as hair, fingernails and toenails.

All this evidence remains isolated at the moment and can only be corroborated (or vitiated) by an integrated and large-scale study of plant remains in the gully. The current archaeobotanical study deals with the features of how the find assemblage at the discovery site had been formed by evaluating the distribution patterns of plant remains in the ice and sediments inside the gully, to reconstruct the circumstances of deposition and possible post-depositional alterations of the Iceman's find assemblage.

Materials and methods

Field work and sampling

The archaeological excavations at the site of the Iceman's discovery were conducted by Andreas Lippert (University of Vienna) under exceptional conditions (Lippert 1992; Lippert and Spindler 1992; Bagolini et al. 1995). The first excavation, immediately after the discovery in autumn 1991, was restricted to the south-eastern part of the gully, in the immediate vicinity of the body and the artefacts. The campaign lasted only three days and had to be abandoned because of the late season. Finally, the gully was flooded with water to create a sterile ice layer sealing the site, and thus avoiding unauthorized interference.

An extensive second excavation campaign then took place in the summer of 1992, aiming to study the complete southern part of the gully. Before, tons of snow and the sterile ice layer had to be removed. The snow and ice were mainly melted by the sun; only in the case of artefacts visible in the ice was a steam blower used to melt the objects from the ice. All melt-water was siphoned from the gully and brought via a system of tubes and gutters into a set of sieves with defined mesh sizes to collect all finds from the site. Precise spatial information was obtained

using GPS and theodolite coordinates: at the beginning of the excavation, a 1 m grid was calibrated and projected onto the site to ensure the precise location of all material retrieved from the site and consequently to allow detailed documentation and analysis. The main focus of the excavation campaign was the "dirty" bottom ice layer which contained most of the finds (Bagolini et al. 1995). After all of this ice had been removed, the sediment of each quadrant was also sampled and taken to the Institute of Botany in Innsbruck for further analysis.

Sample types and their processing

The plant material analysed originated from a variety of sources:

1. The Iceman's equipment itself: clothing components made of plant material, such as the grass cape/mat and shoe insulating material, or the wooden tools and weapons, such as the bow and the axe shaft, both made of yew wood.
2. Plant macro-remains picked from and washed off the Iceman's clothes and implements. This material had been retrieved at the Römisch-Germanisches Zentralmuseum in Mainz (RGZM) and was later sent to the Botanical Institute at Innsbruck University for further studies.
3. The botanical material melted from the surrounding ice layers in the gully by using a steam blower.
4. Plant fragments extracted from the sediment at the bottom of the gully by using wet-sieving and flotation techniques (Jacomet and Kreuz 1999). The mesh sizes used for fractioning the material were 7.0, 5.0, 3.15, 2.0, 0.71, 0.5, 0.25, and 0.125 mm.

All extracted plant material was stored at the institute's refrigerator chamber at a constant temperature of +4°C, immersed in Strasburger's preserving agent (Gerlach 1969), a 1:1:1 solution of distilled water, ethanol 96%, and glycerine. A small amount of phenol (0.4–0.6% by weight), serving as a fungicide, had also been added.

Identification of the plant remains was carried out using standard literature on diaspores (Anderberg 1994; Berggren 1969, 1981), leaf surfaces (Westerkamp and Demmelmeyer 1997) and wood (Schweingruber 1990; Heiss 2000 onwards) as well as the comprehensive reference collection of Alpine plant material at the Institute of Botany in Innsbruck. Nomenclature follows Fischer et al. (2005).

Spatial modelling

After the identification of the plant remains, the exact topographic sample positions first had to be allocated by integrating the find positions from the 1991 excavation into the coordinate system used in the 1992 campaign (Lippert and Spindler 1992; Lippert 1992; Bagolini et al. 1995; Zissernig 1992), and by placing the 1991 data in the 1 m^2 grid (Fig. 4).

In order to ensure sufficient reliability of the spatial modelling, it was crucial to make a deliberate selection of the areas and layers to be assessed. Consequently, all events after the Iceman's discovery that might have affected possible distribution patterns of the finds had to be considered:

- The events prior to the archaeological excavation, when laymen tried to recover the glacier mummy from the ice, as well as the rescue of the body by the official medico-legal expert (Zissernig 1992), increasing the chance of distortions in the distribution of plant remains in the immediate vicinity of the Iceman's body.
- The 1991 rescue excavation conducted by Lippert (1992) focused on the stone slab where the body had been lying, as well as on areas in the south of the gully where the Iceman's weapons and carrying frame were retrieved from the ice. The quadrants lying within this excavation area are displayed in Figs. 2 and 4 (red areas).
- After the 1991 campaign, the gully was flooded with water to seal unexcavated parts and the remaining find material from access. This ice was removed before the excavation campaign in 1992. The original ice layers beneath were only a 50–80 cm thick, with a clearly distinguishable upper (bright, sterile) and lower (grey, "dirty") layer (Fig. 3b), the latter containing the Iceman artefacts (Bagolini et al. 1995). Thus, it was reasonable to primarily focus on the plant material from the lower ("dirty") ice and the sediment layers below this level (Fig. 3c).
- During the 1992 excavation campaign the north-eastern parts of the gully served as a drain for the melt-water. Possible material movements and cross-contamination between the quadrants could have occurred in these places (Fig. 2, yellow areas).

Bearing in mind these determining factors, the preliminary study for spatial distribution patterns was focused on the undisturbed layers in the quadrants 21, 22, 39, 40, 58–63, and 78–80 (Figs. 2, 4, green areas).

As the immediate vicinity of the mummy had been sampled more intensively by the archaeological teams, the resulting sample frequencies varied from 1 to 17 samples per m^2. Neither were the sampled amounts constant, with sample volumes per m^2 ranging from 55 to 9,855 ml (average 1,106 ml). To compensate these biases, the total sample volume per m^2 will have to be standardised prior to

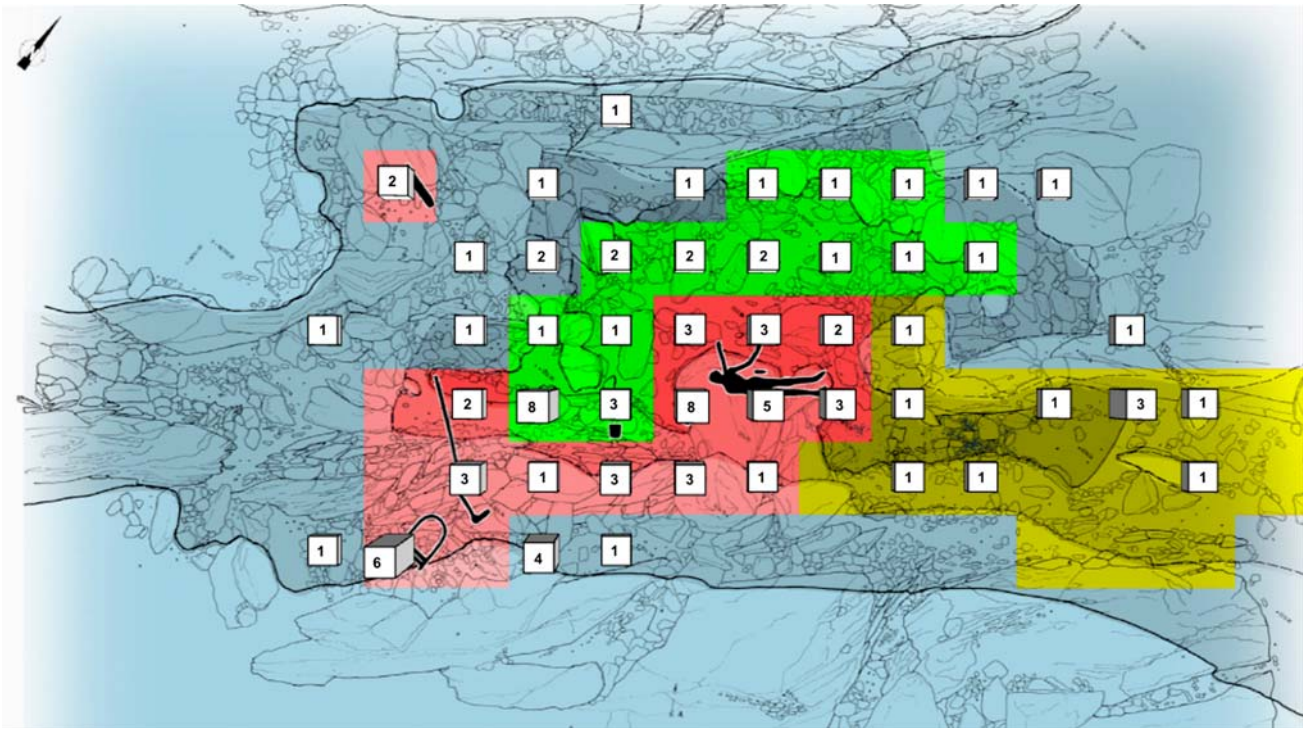


Fig. 4 Current state of archaeobotanical analysis. The *numbers* in the bars show the analysed samples per square metre. For meanings of colours, see Fig. 2

quantification and statistical analysis of the data. Consequently, these operations are postponed until the complete dataset of the plant remains from the gully sediments is available.

Up to now, 107 samples out of 291 have already been analysed, 97 of which were assignable to precise positions within the grid. Ten samples originated from the meltwater obtained from whole site sectors, which are larger units representing north–south transects through the site, with widths of 2–3 m.

Results

The 107 samples analysed up to now have resulted in a total of 40,612 plant remains from 121 vascular plant taxa. These were attributable to 32 families and a minimum of 66 species. Together with at least 80 species of mosses and liverworts identified by Dickson (2003), the Iceman site has up to now yielded the highest plant diversity ever found from an archaeological site above the tree line (Tables 1, 2).

It has to be stressed that a whole variety of ecosystems ranging from the valley bottoms up to the snow line is represented in the plant material from the site. Considering the fact that six of the identified vascular plant taxa have the ecophysiological potential to grow on-site (grey bar in Table 1; Fig. 5), it becomes evident that the vast majority of the plant material originated from lower altitudes (see also under "taphonomical considerations" below). Figure 5 displays an overview of all plant taxa found in the samples, assigned to phytosociological class groups (Oberdorfer 1990).

A detailed account of the recovered cultivated plants is shown in Table 1. Two cereals, *Hordeum vulgare* (hulled barley) and *Triticum monococcum* (einkorn), have already been found before, adhering to the body's garments (Oeggl and Schoch 1995; Oeggl 2000). Two new finds of millet caryopses were discovered in the sediments of quadrants 82 and 42, the latter one within immediate vicinity of the corpse (Figs. 2, 4): the carbonised grains could not be identified with certainty as they were in a very bad state of preservation, and no chaff remains were found. Thus, their identification has to remain cf. *Panicum miliaceum* (cf. broomcorn millet).

However, another two cultivated crops have newly been discovered: two seeds of *Papaver somniferum* (opium poppy) were retrieved from the ice (sample no 92/166 which comes from sector 4/5, a north–south transect through the site). Also a single seed of *Linum usitatissimum* (flax) was found, embedded in the sediments of quadrant 21, 2 m west of the Iceman's corpse. As for the literature (Kroll 2004), these can be considered the earliest oilseed finds in this central part of the Alps.

Table 1 Plant remains, in phytosociological class groups (Oberdorfer 1990)

		Se, Fr	Wood	Charc	Bast	Le, Ne	Other	Total
Rocky meadows and rock crevices								
sn	*Achillea moschata* Wulfen	2						**2**
sn	*Cerastium uniflorum* Clairv.	24						**24**
sn	*Kobresia myosuroides* (Vill.) Fiori	41						**41**
*sn	*Poa laxa* Haenke	874					8	**882**
sn	*Poa* cf. *laxa* Haenke						3	**3**
*sn-n	*Ranunculus glacialis* L.	129						**129**
sn-n	*Salix herbacea* L.					85	1	**86**
a	*Salix* cf. *reticulata* L.			1				**1**
a	*Hieracium intybaceum* All.	9						**9**
a	*Leucanthemopsis alpina* (L.) Heywood	11						**11**
a	*Luzula spicata* (L.) DC.	2						**2**
a	*Saxifraga bryoides* L.	1						**1**
a	*Sibbaldia procumbens* L.	6						**6**
a	*Silene acaulis* (L.) Jacq. s.l.	6						**6**
a	*Silene acaulis* (L.) Jacq. subsp. *exscapa* (All.) Braun-Blanq.	23						**23**
Anthropogenic/zoogenic heaths and meadows								
a	*Achillea millefolium* L. agg.	23						**23**
a	*Alchemilla vulgaris* L. agg.	1						**1**
m	*Aster linosyris* (L.) Bernh.	1						**1**
m	*Brachypodium pinnatum* (L.) P. Beauv. s.l.	14				125	2cf.	**141**
m	*Bromus hordeaceus* L.	12						**12**
sa	*Dactylis glomerata* L.	3						**3**
a	*Hieracium aurantiacum/pilosella* L./L.	2						**2**
a	*Leontodon helveticus* Mérat	16						**16**
sa	*Molinia caerulea* (L.) Moench					16		**16**
a	*Nardus stricta* L.					9		**9**
sa	*Taraxacum officinale* Weber agg.	8						**8**
sa	*Trifolium montanum* L.						1	**1**
Herbaceous and shrubby vegetation of woodland margins								
sa	*Alnus viridis* (Chaix) DC.	29	1	7			2	**39**
m	*Bromus ramosus* Huds. agg.	2						**2**
m	*Sambucus racemosa* L.	6						**6**
Coniferous woods and associated heathland								
a	*Arctostaphylos uva-ursi* (L.) Spreng.	9					1	**10**
m	*Betula pubescens* Ehrh.	1						**1**
a	*Empetrum nigrum* L. s.l.	7						**7**
sa	*Erica carnea* L.					1		**1**
sa	*Larix decidua* Mill.		18			1,314		**1,332**
sa	cf. *Larix decidua* Mill.		1					**1**
a	*Loiseleuria procumbens* (L.) Desv.	2				1		**3**
a	*Picea abies* (L.) H. Karst.	4				235	10	**249**
a	cf. *Picea abies* (L.) H. Karst.		12	201				**213**
a/sa	*Picea* sp./*Larix* sp.		5	1				6
sa	*Pinus cembra* L.		1			17		**18**
a	*Vaccinium vitis-idaea* L.	8				1		**9**
Deciduous woods and associated brushwood								
m	*Abies alba* Mill.					9		**9**
m	*Acer platanoides* L.					3		**3**
m	*Cornus* sp.		1					**1**
m	*Corylus avellana* L.		11					**11**
sa	*Deschampsia* cf. *flexuosa* Trin.	5						**5**
m	*Fraxinus* cf. *excelsior* L.		1					**1**
sa	*Luzula sylvatica* (Huds.) Gaudin	1						**1**
m	*Sanicula europaea* L.	1						**1**
m	*Taxus baccata* L.		5					**5**
m	*Viburnum lantana* L.		17					**17**
Herbaceous plants in frequently disturbed habitats								
m	*Carduus nutans* L.	3						**3**
m	*Cirsium arvense* (L.) Scop.	1						**1**
a	*Cirsium spinosissimum* (L.) Scop.	1						**1**
m	*Lappula squarrosa* (Retz.) Dum.	1						**1**
m	*Picris hieracioides* L.	1						**1**
Cultivated crops								
	Hordeum vulgare L.	5						**5**
	Hordeum vulgare L. var. *nudum*	14						**14**
	Linum usitatissimum L.	1						**1**
	cf. *Panicum miliaceum*	2						**2**
	Papaver somniferum L.	2						**2**
	Triticum dicoccon Schrank	2						**2**
	Triticum monococcum L.	9						**9**
Total		**1,325**	**73**	**210**		**1,816**	**26**	**3,452**

The grey bar highlights taxa from the potentially local flora (in subnival and nival zones). Asterisks indicate plants growing on-site, observed by the authors on a recent survey (21 September 2005). Letters in leftmost row indicate maximum altitudinal zones of the taxa: *sn–n* subnival to nival (above 2,500 m a.s.l.), *a* alpine (ca. 1,800–2,500 m a.s.l.), *sa* subalpine (ca. 1,500–1,800 m a.s.l.), *m* montane (ca. 500–1,500 m a.s.l.); data from Fischer et al. (2005); *Se, Fr* seeds, fruits (+ chaff, cone scales); *Wood* wood fragments (mainly of artefacts); *Charc* charcoal; *Bast* lime bast; *Le, Ne* leaves, needles (+ bud scales), *Other* other remains (flowers, periderm...)

Table 2 Plant remains not assignable to phytosociological class groups

		Se, Fr	Wood	Charc	Bast	Le, Ne	Other	Total
Asteraceae								
	Achillea sp.	1						**1**
m	*Bidens* sp.	1						**1**
	Cirsium sp.	1						**1**
	Leontodon sp.	2						**2**
sa	*Solidago virgaurea* L.	1						**1**
	Taraxacum sp.	2						**2**
	Asteraceae Subfam. Asteroideae						1	**1**
	Asteraceae indet.	17						**17**
Betulaceae								
	Alnus sp.	15						**15**
sa	*Betula pendula* Roth	3						**3**
sa	*Betula* Sect. Albae	12		1				**13**
	Betula sp.	40	3			2	2	**47**
Pinaceae								
sa	*Pinus mugo* Turra/*P. sylvestris* L.					4		**4**
sa	*Pinus* cf. *mugo* Turra			22				**22**
sa	*Pinus* sp. (*P.* non *cembra*)		1	2				**3**
sa	*Pinus* sp.		1			1	1	**3**
	Pinaceae indet.		1			2		**3**
Poaceae								
	Agrostis sp.	1						**1**
a	*Anthoxanthum alpinum* A. & D. Löve	1						**1**
a	*Avenula pubescens/versicolor* (Huds.) Dumort./(Vill.) M. Laínz	5						**5**
a	cf. *Bellardiochloa violacea* (Bellardi) Chiov.						2	**2**
	Brachypodium sp./*Molinia* sp.					3		**3**
	Bromus sp.	7						**7**
	Festuca sp.	7						**7**
a	*Poa annua* L. agg.	1						**1**
a	*Poa chaixii* Vill.	2						**2**
a	*Poa* cf. *chaixii* Vill.	7						**7**
	Poa sp.	41						**41**
	Poaceae indet.	32				18	1,906	**1,956**
Rosaceae								
m	cf. *Amelanchier ovalis*			4				**4**
a	*Dryas octopetala* L./*Geum montanum* L.	6						**6**
	Maloideae			1				**1**
a	*Potentilla aurea/crantzii* L./(Crantz) Beck ex Fritsch	3						**3**
	Rosa sp.	1						**1**
Mosses								
	Hydrogrimmia mollis (Bruch & Schimp.) Loeske						2	**2**
	Neckera complanata (Hedw.) Hüb.						5	**5**
	Paraleucobryum enerve (Thedenius) Loeske						2	**2**
	Polytrichum piliferum Schreb. ex Hedw.					1	47	**48**
	Polytrichum sexangulare Brid.						43	**43**
	Racomitrium lanuginosum (Hedw.) Brid.						14	**14**
	Musci indet.						39	**39**
Others								
m	*Acer* sp.			2				**2**
m	cf. *Acer* sp.			1		3		**4**
	Carex sp.	4						**4**
	Epilobium sp.	7						**7**
	Epilobium Subgen. *Epilobium*	1						**1**
a	*Juniperus communis* L.	1				9		**10**
	Rumex sp.						1	**1**
	Salix sp.	1	6					**7**
	cf. *Salix* sp.		1					**1**
m	*Sambucus nigra* L.	1						**1**
m	*Sambucus* sp.	5						**5**
a	*Saxifraga oppositifolia* L.					37	17	**54**
m	*Tilia* sp.		8		12,033		1	**12,042**
m	*Ulmus* sp.			22				**22**
	Apiaceae indet.	2						**2**
	Cyperaceae indet.	156				21		**177**
	Dryopteridaceae indet.						1	**1**
	Juncaceae indet.	3						**3**
	Broad-leaved wood indet.		1				1	**2**
	Coniferous wood indet.		1	29				**30**
	Grasses (Poaceae/Cyperaceae/Juncaceae) indet.					20,484		**20,484**
	indet.	9	2	292		191	1,463	**1,957**
Total		**399**	**25**	**376**	**12,033**	**20,776**	**3,548**	**37,157**

Letters in leftmost row indicate maximum altitudinal zones of the taxa: *sn–n* subnival to nival (above 2,500 m a.s.l.), *a* alpine (ca. 1,800–2,500 m a.s.l.), *sa* subalpine (ca. 1,500–1,800 m a.s.l.), *m* montane (ca. 500–1,500 m a.s.l.); data from Fischer et al. (2005)

Fig. 5 Overview of the identified taxa, in phytosociological class groups (Oberdorfer 1990). The *grey bar* shows taxa growing in subnival and nival altitudinal zones



Fig. 6 Stand of *Ranunculus glacialis* and *Poa laxa* in a rock crevice on the southern slope of the Hauslabjoch (ca. 3,250 m a.s.l.)

an additional potential source of plant material. According to Oeggl et al. 2008 (this volume), macrofossils of *Leucanthemopsis alpina* (alpine daisy), *Ranunculus glacialis* (glacier buttercup), *Salix herbacea* (dwarf willow), and *Saxifraga oppositifolia* (purple saxifrage) are recorded from these droppings. Furthermore, faecal material has to be considered a source for the identified fragmented needles of *Juniperus communis* (juniper), *Larix decidua* (larch) and *Picea abies* (spruce), as well as for a minor part of grass remains. These grass fragments can be differentiated from other grassy material by their poor preservation, supposedly caused by the effects of ruminant digestion, while the major part of Poaceae leaf remains is clearly assignable to the Iceman's equipment.



Fig. 7 Bird droppings on a rock on the peak of Hauslabjoch (3,280 m a.s.l.), with protruding seeds of *Juniperus* sp.

– Other mammals or humans: the vectors for the discovered epizoochorously propagated diaspores are unclear. The spiny fruits of *Lappula squarrosa* (bur forget-me-not) and *Sanicula europaea* (sanicle) may have been transported attached to the Iceman's clothes or hair, but maybe also to some animal's fur.

Taking these considerations into account, only the remains of cultivated plants and the plant material belonging to the Iceman's equipment were regarded as (a) being contemporary with "Ötzi" and (b) with a high probability of having been brought to the find place by the Iceman himself (cf. extensive radiocarbon data of the implements: Kutschera et al. 2000; Kutschera and Müller 2003).

Distribution patterns

The gully on the Tisen pass is small and shallow and is fed by melt-water from the south-eastern slopes of the Hauslabjoch. Over a ridge it drains to the southeast into the Ötztal. Usually the water depth in the gully is low, but when all the ice is melted, water levels may reach about 1.4 m. The current energy as well as the sedimentation rates are low to moderate inside the gully, and bioturbation virtually does not exist at such altitudes. According to this, a dislocation of organic remains is possible by wind, water, and/or glacier movement. The latter seems to have had little impact due to the topography of the site, as shown by the intact state and the excellent preservation of the Iceman (Barfield et al. 1992; Seidler et al. 1992b; Bagolini et al. 1995).

Nevertheless, the Iceman find assemblage clearly displays an impact of various mechanical processes like fragmentation, dispersion and re-orientation, which took place at the time of his death and/or in the long period between the deposition and the archaeological excavation: for example the torn quiver cap, the broken quiver strut, the fractured arrow shafts, and the distant location of some of their pieces well away from the quiver suggest that considerable mechanical forces were involved. It is a fact that the conditions for an excavation at such altitudes are difficult and also that the first attempted recovery carried out by laymen involved the use of force. Still, there can be no doubt that the artefacts must have been broken at the time of deposition because they were recovered in that damaged condition from the undisturbed ice (cf. Zissernig 1992; Lippert 1992; Egg et al. 1992; Bagolini et al. 1995; Spindler 1996).

The dispersed distribution pattern of the artefacts can also be observed in other plant remains of the find

assemblage. For the time being, distribution patterns were generated and analysed only for two categories of plant remains: the *Tilia* sp. (lime) bast used as a binding material throughout the Iceman's equipment (Pfeifer and Oeggl 2000), and the *Taxus baccata* (yew) wood of which the Iceman's bow was made (Oeggl and Schoch 2000).

The distribution of lime bast fragments shows two distinct peaks: the highest concentrations of these were observed in the quadrants where the backpack frame, axe and bow were found, followed by a second peak at the find place of the glacier mummy itself (Fig. 8), originating from bast remains adhering to the Iceman's clothes. Together with these two peaks in lime bast concentration, the accumulation of several heavier pieces of the Iceman's equipment (bow, axe, backpack frame, leather fragments) on the rock ridge south of the gully suggests that Ötzi's body had originally been deposited in this place, well away from where it was discovered.

Small amounts of bast fragments were found scattered across the whole investigated area, even in places rather far away from their potential sources. The probability of displacement of plant material caused by activities of the excavators is high in certain areas of the rock gully, indicated by different colours in the figures (Figs. 2, 3c, 4, 8, 9). The occurrence of lime fragments in the green areas (Fig. 8) suggests that the deposition pattern of lime bast is a result of natural causes and not one biased by excavation activities.

The remains of *Taxus baccata* (yew) wood were analysed in order to test the amount of possible material displaced by excavation activities. The bow may contribute to this matter because it was broken during an attempted rescue by laymen, about a week before the first excavation. The splinters resulting from this damage were recovered from the ice both in the 1991 and 1992 campaigns. Figure 9 shows that all the splinters had stayed within the same quadrant as the bow. This suggests that archaeological and rescue activities have had little effect on the distribution pattern of the find assemblage.

Anyhow, due to the fact that the Iceman was hit by an arrow and most probably died within a short time (P. Gostner, personal communication), it seems unlikely that he had enough time to arrange his equipment in such a scattered way. The distribution patterns of the artefacts and the plant remains in the rocky hollow were thus most probably caused by a dislocation either by wind, by melting snow and/or by water in a resulting melting water pool (Oeggl 2003). It has to be considered that Ötzi died in late spring (Oeggl 2000), at a time when the gully was presumably covered with several metres of snow. Thus the body must have lain in or on the snow at first and then, during the following thawing, sank to the bottom of the gully. Forensic investigations corroborate this hypothesis, basing on the skin alterations observed in the body: these indicate that the Iceman was not embedded in ice immediately, but rather was first submerged in water for one to

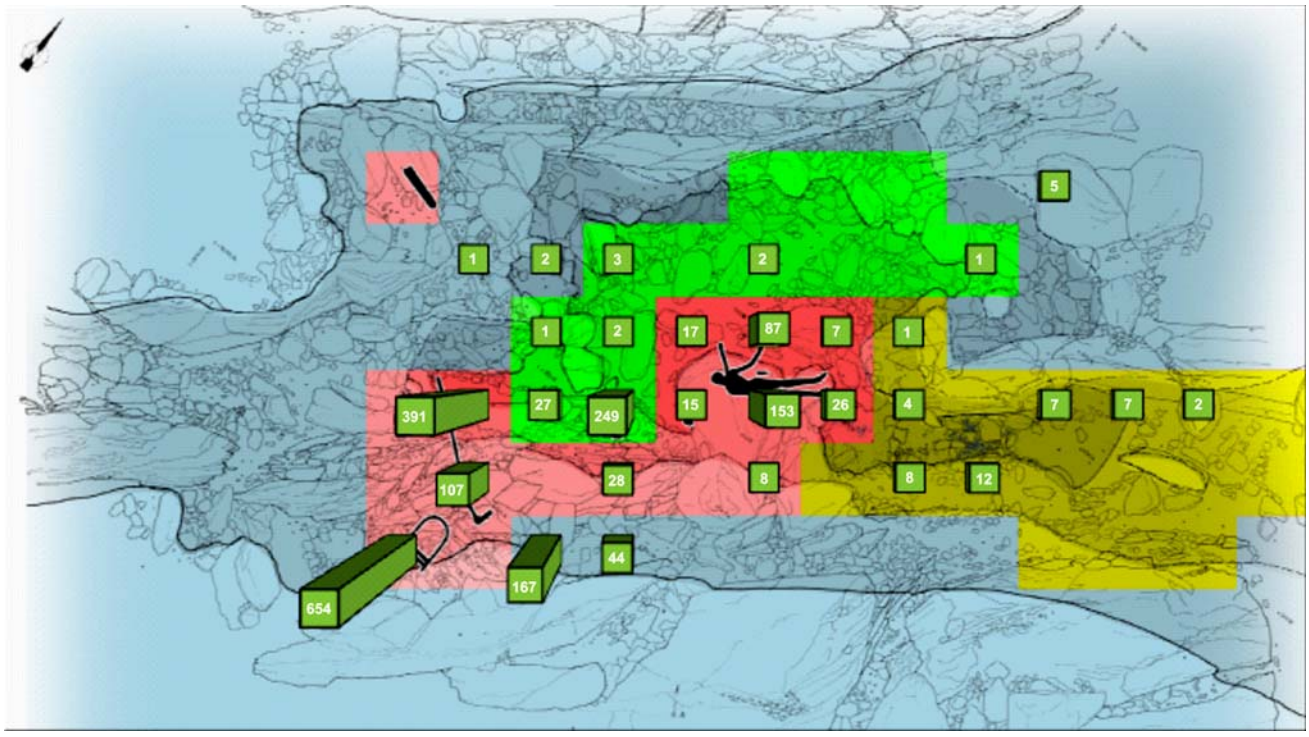


Fig. 8 Distribution of lime bast. The *numbers* in the bars represent the total fragments. For meanings of colours, see Fig. 2

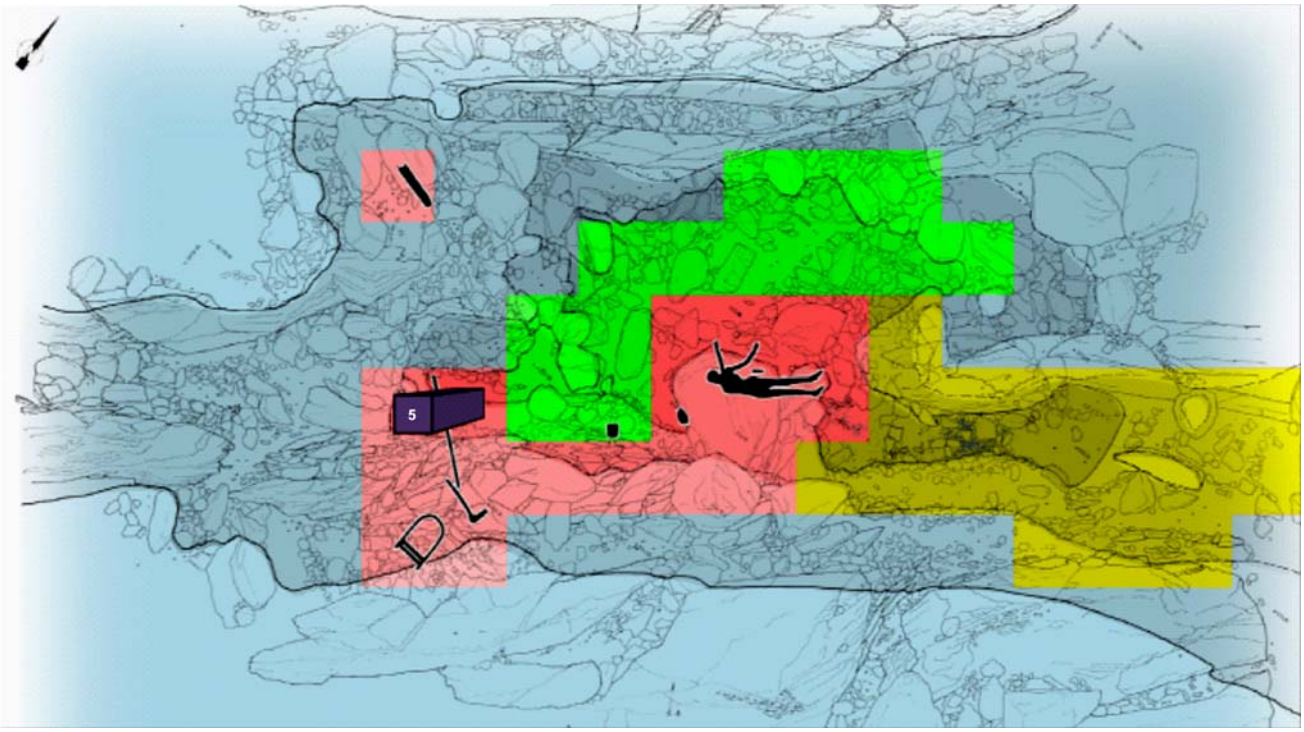


Fig. 9 Distribution of *Taxus baccata* (yew) splinters. For meanings of colours, see Fig. 2

three months, and only then was exposed to drying winds causing mummification (Bereuter et al. 1997). This again means that either the Iceman must have floated in the melting snow and water of the gully immediately after his death or that the ice melted at least once between his death and final discovery in 1991. This assumption is strengthened by the fact that several fragments of artefacts were discovered on the boulders outside the gully (Zissernigg 1992) and that some of the Iceman's equipment is still missing, such as parts of the birch-bark containers, fragments of the wooden backpack frame, pieces of leather from the quiver cap, etc.

Conclusions

Analysis of more than 40,000 plant remains from the find site of the Tyrolean Iceman has yielded plants from a great variety of ecosystems from different altitudes, and also from many taxonomic groups. Most of these plants were transported to their find place by long-distance transport either by wind or by human/animal action. The spectrum of identified cultivated Neolithic plants has now been extended by the cereal cf. *Panicum miliaceum*, as well as by the two oilseeds *Papaver somniferum* and *Linum usitatissimum*, so far the oldest finds in the Eastern Alps.

The first analyses of plant remain distribution patterns carried out for the "Ötzi" site suggest that plant remains have been subject to movement by snow and/or melting water, but most probably not resulting from excavation activities. It is to be expected that a clearer image of the site's taphonomy and of the processes involved is going to be gained from the ongoing full analysis of the remains.

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SEED MORPHOLOGY OF *NIGELLA* S.L. (RANUNCULACEAE): IDENTIFICATION, DIAGNOSTIC TRAITS, AND THEIR POTENTIAL PHYLOGENETIC RELEVANCE

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A comprehensive morphological and anatomical analysis was carried out on seeds of all 15 species currently recognized in the genus *Nigella* s.l. (including *Komaroffia* and *Garidella*). In addition, a selection of six infraspecific taxa was examined. Using testa thin sections, morphometry, and SEM imaging, seed coat characters proved to be a highly diagnostic and powerful tool in species identification. A dichotomous identification key is presented along with seed descriptions, measurements and anatomical details, LM photos, and SEM micrographs. Analyses using maximum parsimony and character mapping onto a DNA-based phylogeny suggest that seed characters will be useful for ongoing phylogenetic studies in the genus. The importance of properly identifying *Nigella* seeds is highlighted for applied use in archaeobotany and pharmacognosy.

Keywords: *Garidella*, *Komaroffia*, *Nigella*, phylogeny, Ranunculaceae, seed morphology.

Online enhancements: appendixes.

Introduction

Seed morphology has developed into an important source of useful phylogenetic information, following the work of Barthlott (1981, 1984) and increasing throughout the 1990s. A number of angiosperm taxa have already been studied intensively in terms of their seed micromorphology, in combination with phenetic or phylogenetic analyses at the genus level. Data of this kind are now available across a broad evolutionary range of plant families, such as Schisandraceae (*Schisandra* and *Kadsura*; Denk and Oh 2006), Cactaceae (*Stenocereus*; Arroyo-Cosultchi et al. 2006), Oxalidaceae (*Oxalis*; Obone 2005), Melastomataceae (*Leandra*, *Miconia*, *Ossaea*, and *Clidemia*; Martin et al. 2008), Gentianaceae (*Gentiana*; Davitashvili and Karrer 2010), Lamiaceae (*Hemigenia* and *Microcorys*; Guerin 2005), Plantaginaceae (*Veronica*; Muñoz-Centeno et al. 2006), and Orchidaceae (*Liparis*; Tsutsumi et al. 2007). In Ranunculaceae, most such work has focused on *Aconitum* (Tamura 1993; Luo et al. 2005). Seed and fruit morphological data, if only of selected species, have also been included in the most recent works on Ranunculaceae phylogeny (Wang et al. 2009; Emadzade et al. 2010).

However, there are additional fields in which seed morphology is of increasing interest. In pharmacognosy, proper identification is crucial for quality control of seed accessions. Detailed information on seed identification is often still missing, especially in the case of the taxa recently studied for pharmacological research, such as some *Nigella* species; we will therefore provide that information for *Nigella*. Another applied use of seed morphological data lies in the interdisciplinary field of archaeobotany/paleoethnobotany: together with their archaeological contexts, correctly identified plant remains are the basis for the reconstruction of migrations of human and plant populations as well as for general investigations into the cultural history of plants through human history (see Renfrew 1973; Hastorf and Popper 1988; Jacomet and Kreuz 1999; Zohary and Hopf 2000).

Nigella L. (fennel flower, nigella) is a small genus within the buttercup family (Ranunculaceae), comprising ~15 species (Zohary 1983; Dönmez and Mutlu 2004) distributed from the Middle East (the center of diversity for the genus) to Spain. It is remarkable in several academic and applied respects: (1) it is the only genus of Ranunculaceae with a truly syncarpous gynoecium (Rohweder 1967); (2) the flowers of the advanced species within the genus exhibit an interesting and complex pollination mechanism, representing highly specialized "roundabout flowers" (Sprengel 1793; Weber 1993, 1995); (3) some species, especially *Nigella damascena* L., are popular ornamental plants (Burnie et al. 2008); (4) the seeds of several species have been in use as a condiment since prehistoric times (Hepper 1990; Heiss and Oeggl 2005; Salih et al. 2009); and (5) seed oils of *N. sativa* L. and *N. damascena* are of high commercial interest to the pharmaceutical and cosmetics industries (Agradi et al. 2002; Ali and Blunden 2003; Anwar 2005). In recent years, additional *Nigella* species have moved into the focus of pharmaceutical research, such as *N. arvensis* L., *N. integrifolia* Regel, *N. nigellastrum* (L.) Willk. in Willk. et Lange, *N. orientalis* L., and *N. segetalis* M. Bieb. (Aitzetmüller et al. 1997; Aitzetmüller 1998; Kökdil and Yılmaz 2005; Kökdil et al. 2006*b*).

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The taxonomic position of *Nigella* s.l. within Ranunculaceae as well as the number of species included and their respective delimitations have changed repeatedly. For instance, previous investigations have placed *Nigella* and its segregates *Garidella* and *Komaroffia* in the subfamily Ranunculoideae, tribe Delphinieae (Hoot 1991; Frohne and Jensen 1998; Stevens 2001–), or in the Aconitoideae (Takhtajan 2009). However, a recent synopsis of molecular and morphological data suggests that the group's affinities within the Ranunculaceae are only weakly supported and must be considered uncertain (Wang et al. 2009).

Taxonomy within the genus has also undergone many changes in recent decades. Currently, *Nigella* s.l. is commonly divided into three genera: *Komaroffia* Kuntze, *Garidella* L., and *Nigella* L. s.str., as done by Tamura (1993) and Tutin et al. (1964–1983). For overviews of alternative classifications, see Gregory (1941) and Zohary (1983). In this work, we used the monograph of Zohary (1983) as a reference, which recognizes 14 species, essentially on the basis of morphological (mainly floral and fruit) and karyological criteria. *Nigella* s.l. sensu Zohary includes *Komaroffia* and *Garidella* at the rank of sections (see table 1). For taxa within the *N. arvensis* aggregate, the work by Strid (1970) deserves mention, since it differs from the approach of Zohary (1983) and has been used in various recent studies, such as that of Bittkau and Comes (2008).

Molecular investigations at the genus level have been carried out only very recently—namely, the analysis of DNA sequences of the internal transcribed spacer (ITS) region representing 25 taxa, 11 of which belong to the *N. arvensis* aggregate (Bittkau and Comes 2008)—while analyses of chloroplast DNA are still in progress (*trnL-trnF*, *trnK-matK* intron, *atpB-rbcL* intron; C. Bittkau and H. P. Comes, unpublished data). However, comprehensive and multidisciplinary studies of the taxonomy of *Nigella* are missing, and there is still no consensus as to whether *Nigella* should be treated as a single genus or split into three.

Seed morphology, representing a potential set of taxonomically informative features, has only rarely been considered in taxonomic descriptions of *Nigella* species. To some degree, particular aspects of seed morphology and testa anatomy have been included in general treatments of angiosperm seeds, including species such as *N. nigellastrum* (Netolitzky 1926) and *N. damascena* (Corner 1976). Rough macroscopic identification criteria for *N. sativa* and *N. damascena*, occasionally also for *N. arvensis*, are given in agronomical and archaeobotanical seed identification guides (Beijerinck 1947; Brouwer and Stählin 1955; Montégut 1971; Berggren 1981; Bojňanský and Fargašová 2007). Curiously, in pharmacognosy, criteria for identifying and discriminating the seeds of *Nigella* have been largely neglected or ignored. Wichtl (2004, p. 417), for instance, stated for *N. sativa*, "Due to the characteristic morphology, odor and taste of the drug, a microscopic examination seems unnecessary," ignoring similarities between species in taste or odor (*N. sativa* vs. *N. arvensis* agg.; A. G. Heiss, personal observation) or in seed shape (*N. sativa* vs. *N. arvensis* agg., *N. damascena*, *N. elata*, or *N. turcica*). This could easily lead to the misidentification of seed accessions or prevent the recognition of adulterated material.

Seed identification criteria for *Nigella* have become available only very recently (see table 1). Three studies on *Nigella* seed morphology have been published, two of them considering six taxa (Bahadur et al. 1984; Karcz and Tomczok 1987*a*), with the third and most recent study covering 12 taxa (Dadandi et al. 2009). In comparison to these, not only is this article more comprehensive in terms of the number of *Nigella* taxa studied (21 taxa in 15 species) but also it integrates a wider range of methods, namely microscopic sections, SEM imaging, morphometry, a standardized documentation of the observed features, and an evolutionary perspective based on character mapping onto a previously published phylogenetic tree.

Our primary goal in the current study is to demonstrate and document the variability of seed morphology within the genus *Nigella* s.l. and to provide quantitative data for a future phylogenetic reassessment of the whole genus. We attempt to identify seed characters that might prove useful for this purpose through phylogenetic analyses and also to document possible differences in taxonomic groupings on the basis of seed morphology and recent classifications, including the most recent monograph (Zohary 1983) and the evolutionary lineages inferred from a recent molecular analyses (Bittkau and Comes 2008). As a second core part of the article, an identification key for the seeds of *Nigella* is provided. This will serve as a useful tool in the fields of pharmacology and archaeobotany.

Material and Methods

Seed Material

In total, 2229 seeds from 40 seed accessions were investigated, corresponding to 21 taxa (15 species) and originating from a wide variety of sources: commercial products as well as seeds from herbaria, collections of botanical gardens, and material collected by the authors (app. A). However, only a single accession was available for 10 of the included taxa, namely, *Nigella ciliaris*, *N. oxypetala*, *N. stellaris*, *N. turcica*, *N. unguicularis*, and several varieties from the *N. arvensis* group (accessions Nar000, Narar0, Naras0, Narin0, and Nartr0). In these cases, we had to make the initial assumption that infraspecific or infravarietal variability would not mask interspecific or intervariety differences in seed morphology. In addition to the 14 *Nigella* species recognized by Zohary (1983), the recently described species *N. turcica* was also included; according to the taxon's authorities (Dönmez and Mutlu 2004), it is closely related to *N. sativa*. All of the taxa belonging to the *N. arvensis* group treated in this study were covered in the most recent monograph (Zohary 1983), except for *N. arvensis* var. *trachycarpa* Borb.; this taxon has been described as a distinct variety occurring in eastern and southeastern Europe (von Borbás 1887).

Two species covered by the Index Kewensis (Hooker and Jackson 1893–) and some other authors were not analyzed in this study and must be mentioned. (1) *Nigella atropurpurea* Huber is, with high probability, an illegitimate synonym of *N. hispanica* L.; the name was introduced in an 1866 nursery catalog by the company Huber and Co. in Hyères, France (Mabberley 1985). (2) *Nigella glandulifera* Freyn and Sint. ex Freyn is reported as being "cultivated (not native) in China" (Wang et al. 2001), but no information on its geographical origin is given. The species is frequently referred to by pharmacologists

Table 1

Overview of Previous Studies of Seed Macro- and Micromorphology of *Nigella* Species

Taxon	Important synonyms	Bahadur et al. 1984	Karcz and Tomczok 1987*a*	Dadandi et al. 2009	This study
Sect. Komaroffia (O.Ktze) Brand:					
Nigella integrifolia Regel	*Komaroffia diversifolia* (Franchet) O.Ktze	+	−	−	+
Sect. *Garidella* (L.) Spenn.:					
N. nigellastrum (L.) Willk.	*Garidella nigellastrum* L.	+	−	+	+
N. unguicularis (Lam.) Spenn.	*G. unguicularis* Lam.	−	−	+	+
Sect. *Nigella* L.:					
Subsect. *Nigellaria* (DC.) Terracc.:					
Nigella arvensis L.		−	+	−	+
N. arvensis L. var. *arvensis*	*N. arvensis* L. subsp. *arvensis*	−	−	−	+
N. arvensis L. var. *assyriaca* (Boiss.) Zoh.		−	−	+	+
N. arvensis L. var. *glauca* (Schkuhr) Boiss.	*N. arvensis* L. subsp. *glauca* (Boiss.) Terracc. p.p., *N. carpatha* Strid, *N. degenii* Vierh., *N. degenii* Vierh. subsp. *barbro* Strid, *N. degenii* Vierh. subsp. *jenny* Strid, *N. doerfleri* Vierh., *N. icarica* Strid, *N. stricta* Strid	−	−	+	+
N. arvensis L. var. *involucrata* Boiss.	*N. arvensis* L. subsp. *aristata* (Sibth. & Sm.) Nyman	−	−	−	+
N. arvensis L. var. *trachycarpa* Borb.[a]		−	−	−	+
N. fumariifolia Kotschy		−	−	−	+
N. glandulifera Freyn & Sint. ex Freyn[a]		−	−	−	−
N. hispanica L. var. *hispanica*	*N. hispanica* L., *N. papillosa* G. López	−		−	+
N. hispanica L. var. *intermedia* Coss.	*N. papillosa* G. López *subsp. atlantica (Murb.) Amich*	−	+	−	−
N. hispanica L. var. *parviflora* Coss.	*N. gallica* Jord.	−		−	+
N. sativa L.		"*N. hispanica*," *N. sativa*	+	−	+
N. segetalis M.Bieb.		−	−	+	+
N. stellaris Boiss.		−	−	+	+
N. turcica Dönmez & Mutlu[a]		−	−	−	+
Subsect. *Erobathos* (DC.) Zoh.:					
N. damascena L.		"*N. arvensis*," "*N. orientalis*"	+	+	+
N. elata Boiss.		−	−	+	+
Subsect. *Nigellastrum* (DC.) Zoh.:					
N. ciliaris DC.		−	+	−	+
N. orientalis L.		−	+	+	+
N. oxypetala Boiss.		−	−	*N. lancifolia* Hub.-Mor., *N. latisecta* P.H.Davis, *N. oxypetala* Boiss.	+

Note. Studies grouped according to the classification by Zohary (1983). Synonyms are given referring to the work by Strid (1970). Underlined synonyms are accepted by the Flora Europaea (Tutin et al. 1964–1983). For taxa in quotation marks, refer to the seed descriptions in appendix A and the "Discussion."

[a] For taxa not covered by Zohary's revision, their assumed positions are according to the notes of Freyn (1903) and Dönmez and Mutlu (2004).

from Southeast Asia (Liu et al. 2004; Tian et al. 2006; Nguyen et al. 2007). According to the taxon's authorities, *N. glandulifera* seems to be closely related to—if not conspecific with—*N. sativa* (Freyn 1903). Riedl and Nasir (1991) indeed synonymize *N. glandulifera* with *N. sativa* L. var. *hispidula* Boiss. Unfortunately, taxonomic investigations have never been carried out on the species after the initial work of J. Freyn, and no seeds could be obtained for this study. Therefore, the status of this "species" remains doubtful and must be reassessed in the future.

As an outgroup taxon, we chose *Aconitum lycoctonum* L. subsp. *vulparia* (Rchb.) Nyman for several reasons. We intentionally decided not to use *N. integrifolia* as an outgroup, as done by Bittkau and Comes (2008), but to continue using the taxonomy suggested by Zohary (1983), regarding the genus *Komaroffia* as a section of *Nigella* s.l. as a starting hypothesis. Although the phylogenetic analysis by Wang et al. (2009) leaves the position of *Nigella* within the Ranunculaceae rather open, the Delphinieae can still be regarded as a possible sister taxon to *Nigella* s.l., albeit an only weakly supported one. Furthermore, using the ITS sequence of *N. integrifolia* (Bittkau and Comes 2008) in a BLAST search excluding sect. *Nigella* and sect. *Garidella* as the known closest relatives revealed (given a query coverage of 62%–63%) a maximum DNA sequence identity of 87% with eight species of *Hepatica* and 20 species of *Aconitum*. After assessing the published literature on Delphinieae seeds (*Aconitum*: Wojciechowska and Makulec 1969; Cappelletti and Poldini 1984; *Consolida*: Karcz and Tomczok 1987*b*; Constantinidis et al. 2001; *Delphinium*: İlarslan et al. 1997), we found that *Aconitum* shared a roughly comparable testa structure with *Nigella* s.l., which thus enabled us to code the outgroup with as few additional characters as possible. Finally, the limited availability of well-identified herbarium material also influenced our choice. The seed characters of *A. lycoctonum* subsp. *vulparia* were mainly taken from the work of Cappelletti and Poldini (1984) and were complemented by our own observations.

Light Microscopy

Thin sections were prepared with the following procedure: the seeds were soaked in a 4:1 mixture of distilled water and 96% ethanol for 1 h. Cross sections 20 μm thick were prepared using a Reichert microtome without prior embedding of the seeds. The thin sections were bleached in sodium hypochlorite (5% NaOCl) for 30 min and then rinsed in distilled water for 1 h. Staining was carried out by immersing the specimens in a 4:1 mixture of distilled water and Etzold's fuchsin-chrysoidin-astrablue solution (FCA; Etzold 2002) for 15 min, resulting in differential staining of cellulose (blue), lignin (pink), and lipophilous substances (yellow) in the seed coat. Before microscopic investigation, the stained thin sections were rinsed in distilled water and embedded in glycerine.

For the observation of tissue/cell characters, an Olympus BX50 microscope with polarized light was used, and measurements were carried out with an eyepiece micrometer. Microscopic photos were taken using a Canon Powershot A95 camera with an attached eyepiece adapter manufactured by R. Mehnert (Weil der Stadt). In order to avoid blurring due to the limited depth of field, an image stack of 10–50 frames was recorded for each individual image and joined with the software Helicon Focus (Kozub et al. 2000–2008). Macroscopic images of the seeds were created with a Wild/Leica Photomakroskop M400 and the same photographic equipment, also using image stacking. The background was subtracted from the macroscopic photos using Photoshop CS 2 (Adobe Systems 2005).

Scanning Electron Microscopy (SEM)

Seeds used for SEM imaging were desiccated in an ascending ethanol series (50% and 75% for 24 h each), after which they were placed in a drying oven for 24 h at 40°C. They were sputtered with ~1 μm of gold/palladium coating. SEM imaging was carried out with a Philips XL 20 at the Institute of Botany, University of Innsbruck (*N. arvensis* var. *glauca*, *N. elata*, *N. orientalis*, *N. sativa*, and *N. turcica*), and with a JEOL T300 at the (former) Institute of Botany, University of Vienna (remaining taxa). Scale bars in the images were added manually in the latter case.

Morphometry

A total of 1700 seeds were measured. Digital images of whole seeds were created as 600-dpi grayscale images with a Xerox DocuScan flatbed scanner and calibrated with a millimeter scale. Measurement accuracy was ~50 μm. Before image analysis, image corrections (contrast adjustment, elimination of dirt particles and overlapping seeds) were carried out with Photoshop CS 2 (Adobe Systems 2005). The software ImageJ 1.42q (Rasband 1997–2009) was used to measure particle sizes with the "fit ellipse" option: the parameters "major" and "minor" were determinants for maximum length and width of each seed.

In thin sections, the height of epidermal cells and the total thickness of all subepidermal cell layers were measured. These measurements were based on a single transverse seed section in the region between the lateral ridges and were recorded as one maximum and one minimum value per taxon (for character coding, see table D1 in the online edition of the *International Journal of Plant Sciences*).

Character Selection and Coding

The significance of seed shape and sculpture for dispersal, and thus their importance for evolutionary processes, is well known (Barthlott 1981) and has already been applied in phylogenetic studies, as mentioned in the "Introduction." However, their phylogenetic relevance has never been quantified in *Nigella*. Therefore, we chose the maximum parsimony (MP) approach in order to find possible phylogenetically informative characters for future studies. Character coding was based on hypothetical homologies assessed from seed geometry and spermoderm structure, for example, grouping characters according to the categories recognized by Barthlott (1981): characters of primary structure refer to epidermal cell patterns and shapes, which were divided into nine states (see fig. 1), and secondary structure refers to characters of periclinal cell wall ornamentation. Of the morphometric data, the respective 1σ

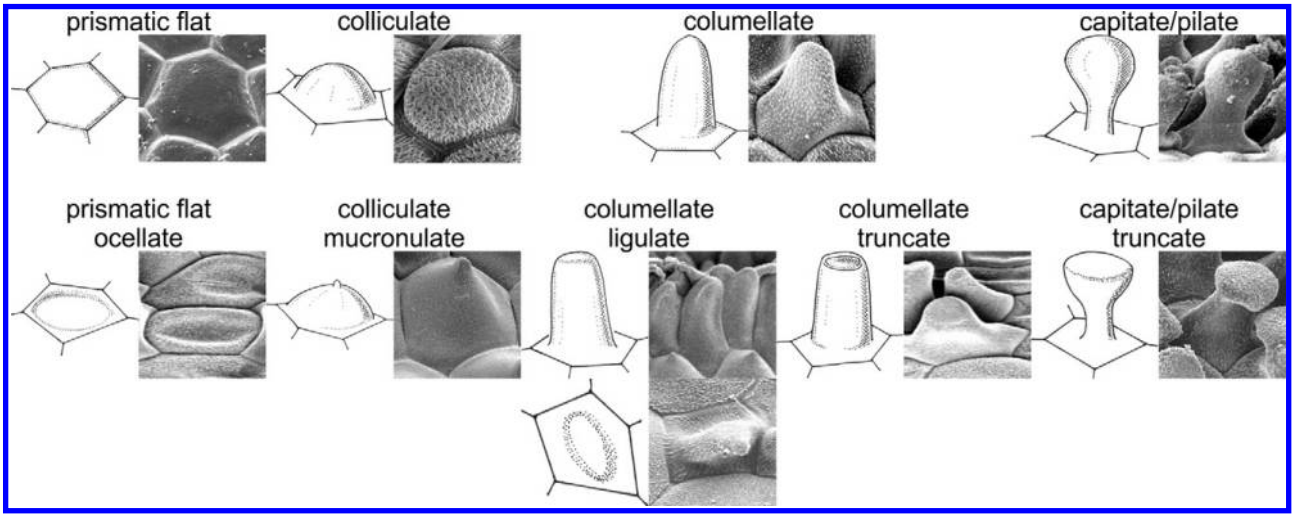


Fig. 1 Types of epidermal cells recorded for *Nigella*, grouped in a hypothetical hierarchy of cell types (top row) and their subtypes (bottom row). The type columellate ligulate is illustrated in lateral and apical view.

intervals of length and width measurements per taxon were obtained using the software SPSS 11 (SPSS 2001). In the data matrix analyzed, they were expressed as size classes (see table D1). These were set up in 1-mm intervals in order to obtain groups containing roughly comparable numbers of individuals.

All measurements were coded as ordered characters on the basis of the hypothesis that a seed would be more likely to evolve toward a neighboring size class than directly to a more remote one. Data matrices were then built using the software DELTA (Dallwitz and Paine 1993–2005; Dallwitz et al. 1993–).

Data Analysis

After export of the data matrix from DELTA via NEXUS files (Maddison et al. 1997), cluster analyses were carried out using PAUP* 4.0b10 (Swofford 1998), assisted by the graphical interface PaupUP (Calendini and Martin 2005). In general, all characters were treated as unweighted, and multiple states were treated as polymorphisms. The outgroup *A. lycoctonum* subsp. *vulparia* was used for rooting. Initial data evaluation was carried out using both distance and MP criteria. The neighbor-joining (NJ) tree (Saitou and Nei 1987) based on 11 characters and total character difference was complemented by bootstrap support (BS) values (Felsenstein 1985), calculated with 50% majority rule, 1000 replicates, and character resampling in effect (Efron et al. 1996). MP trees were calculated for nine parsimony-informative characters in a two-step procedure: in a first full heuristic search with 1000 random addition replicates and tree bisection reconnection (TBR), a limit of 10 trees retained per replicate was used in order to minimize the time spent on suboptimal trees. The resulting 5990 best trees (score 121) were then used as starting trees in the main full heuristic run, again using TBR and 1000 random replicates, with the maximum tree limit increased to 100,000. BS of the resulting clades was calculated with 1000 bootstrap replicates, character resampling, and TBR in effect. Because of the rather low number of parsimony-informative characters (9) and taxa (21), a tree limit of 10,000 was applied. We regarded BS of 50%–74% as weak support, 75%–89% as moderate support, and 90%–100% as strong support for each clade. Tree output was visualized in TreeView (Page 1996) and postprocessed in CorelDRAW X4 (Corel 2008).

Since our data set contained a mixture of ordered and unordered characters and was not coded in a binary way (as suggested by Pleijel 1995), distance is not the ideal optimality criterion. We thus decided to focus on the MP analysis over the distance analysis, since we regarded the former to be a more reliable representation of possible shared characteristics and to allow phylogenetic inferences.

As an additional source of information regarding the possible phylogenetic relevance of seed morphological characters and their likely evolutionary trend within the study group, our data matrix was mapped onto the ITS phylogeny previously published by Bittkau and Comes (2008) using MacClade 3.0 (Maddison and Maddison 1992).

Identification Key

The data matrix generated in DELTA was exported as an HTML identification key with a set of 21 seed characters. The key was then manually adapted to the diacritical method, as suggested by Fischer and Willner (2010). For practical reasons, the focus lay on anatomical features easily observable by light microscopy. In some cases, additional characters (such as seed color or characters observable only via SEM) were added if necessary for identification.

Results

General Seed Morphology

For detailed individual descriptions, see appendix C in the online edition of the *International Journal of Plant Sciences*. In all the taxa we investigated, we observed a multilayered testa (see figs. 2, 3). The number of cell layers, however—and therefore the total testa thickness—varies widely between spe-

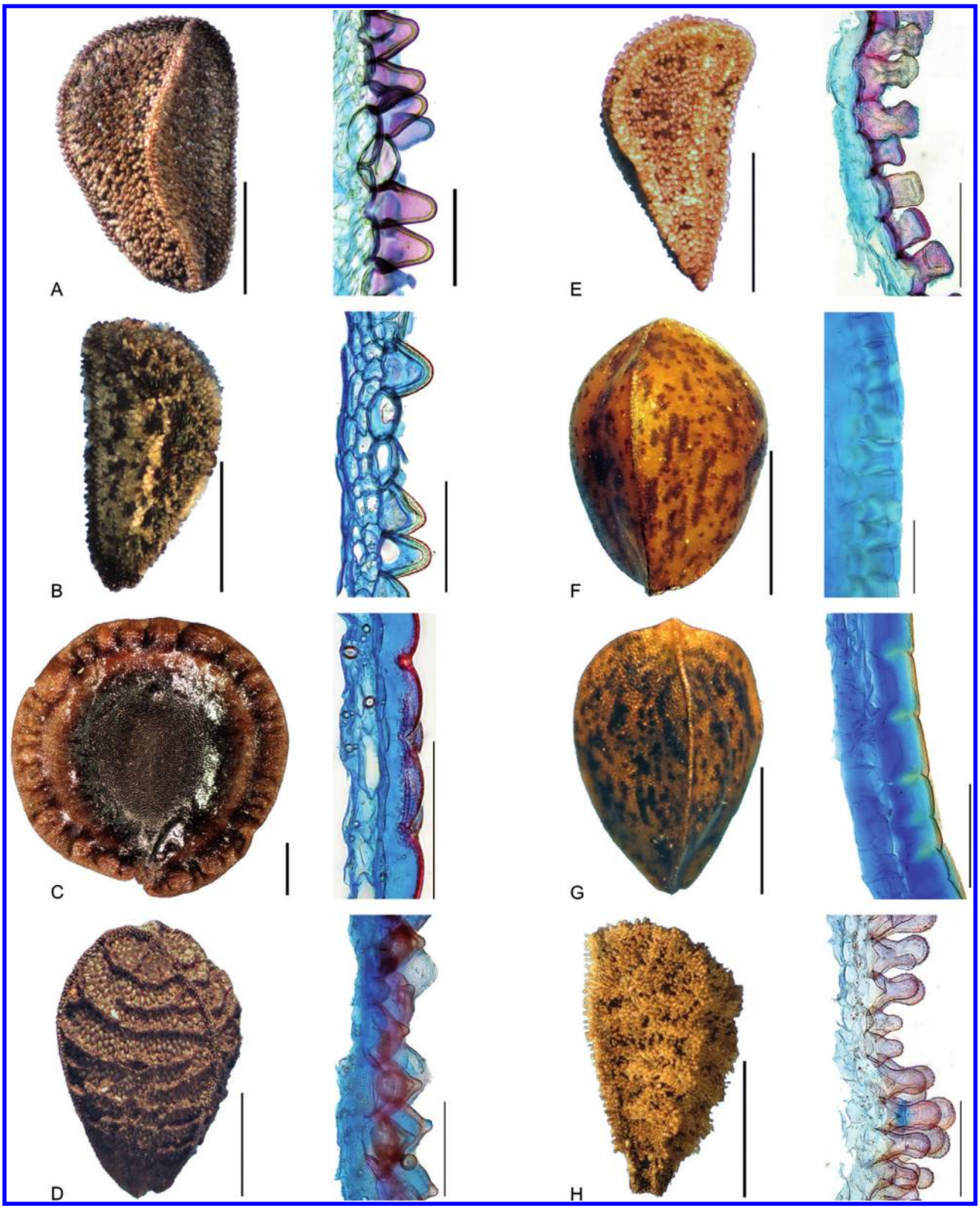


Fig. 2 Light microscope images of *Nigella* species investigated. *A*, *Nigella arvensis*. *B*, *Nigella arvensis* var. *glauca*. *C*, *Nigella ciliaris*. *D*, *Nigella damascena*. *E*, *Nigella fumariifolia*. *F*, *Nigella hispanica*. *G*, *Nigella hispanica* var. *parviflora*. *H*, *Nigella integrifolia*. Scale bars = 1 mm (whole seed view), 100 μm (thin sections).

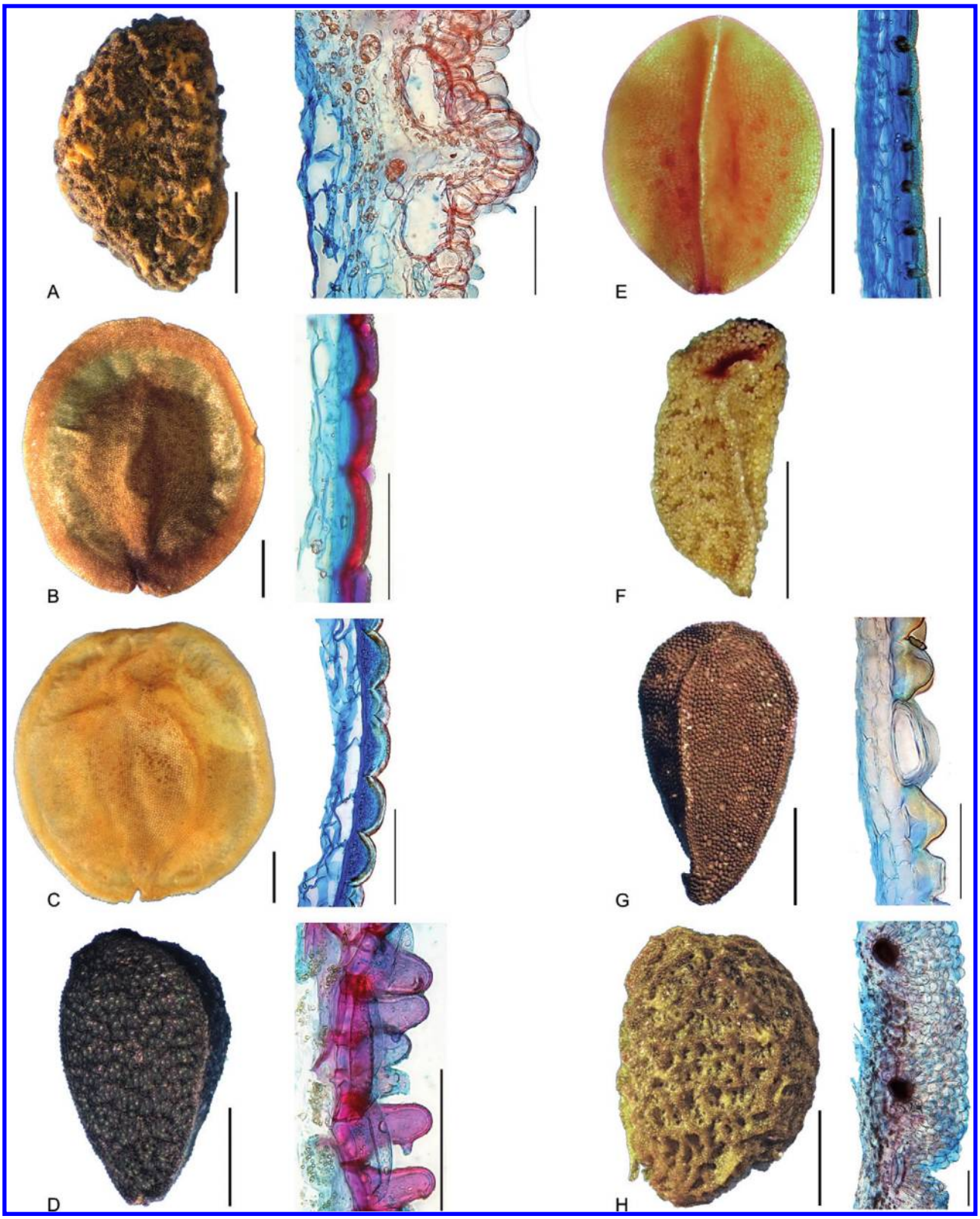


Fig. 3 Light microscope images of *Nigella* species investigated. *A*, *Nigella nigellastrum*. *B*, *Nigella orientalis*. *C*, *Nigella oxypetala*. *D*, *Nigella sativa*. *E*, *Nigella segetalis*. *F*, *Nigella stellaris* (no adequate image of thin section available). *G*, *Nigella turcica*. *H*, *Nigella unguicularis*. Scale bars = 1 mm (whole seed view), 100 μm (thin sections).

cies (tables D1, D2). A single vascular bundle, embedded in a more or less distinct ridge, runs along the seed from the hilum. Thin sections showed the presence of lipophilous substances (apparently oil drops; see figs. 2, 3) in the spermoderm of all investigated taxa.

Seed geometry and size were strongly divergent between taxa: one group, corresponding to subsect. *Nigellastrum*, is characterized by dorsoventrally flattened seeds more than 4 mm long and wide, with an ovate to circular outline (see figs. 2*C*, 3*B*, 3*C*, 4*B*, 5*D*, 5*E*). The second group (identical with sect. *Garidella*) has smaller obovate seeds with a single ventral ridge, and covered by an irregular reticulum up to 250 μm high (figs. 3*A*, 3*H*, 5*C*, 6*E*). The seeds of the remaining taxa display a basically trigonous-ovate shape, some similar to the segments of an orange.

In terms of the general seed surface features and the primary structure, the three taxa in subsect. *Nigellastrum* share the characteristic of having only flat prismatic cells, as do *N. hispanica*—including the ssp. *parviflora* (figs. 2*F*, 2*G*, 5*A*)—and *N. segetalis* (figs. 3*E*, 6*B*). The same five taxa show a thick periclinal cell wall in the outermost epidermal cell layer. The remaining groups are characterized by the presence of various cell types, often arranged in transverse structures, and thinner cell walls. *Nigella damascena* and *N. elata* share a transverse reticulum bordering mucronulate cells; the distinct central mucronulus (fig. 4*C*) separates *N. damascena* from *N. elata*, which has an indistinct and excentric mucronulus (fig. 4*D*). Pilate/capitate cells are characteristic of *N. integrifolia* (fig. 2*H*), as is a truncate type in *N. fumariifolia* (fig. 2*E*) and *N. stellaris*. Collapsed (ocellate) prismatic cells were observed in *N. arvensis* agg., *N. sativa*, *N. stellaris*, and *N. turcica*. This cell type correlates with thinner periclinal cell walls (see figs. 2*A*, 2*B*, 3*G*).

Secondary structure is unspecific in most investigated taxa and typically varies from irregularly granulate to rugulate. However, *N. ciliaris* lacks any secondary structure in seed surfaces (fig. 4*B*), which gives them a shiny appearance (fig. 2*C*). Furthermore, the two species in sect. *Garidella* display distinctly undulate rugulae in the flat prismatic cells lying between the ridges (figs. 5*C*, 6*E*). Another unique character is the secondary structure found in *N. integrifolia*, where the rugulae/striae are radially oriented (fig. 5*B*).

Seed Identification

The results show that it is possible to identify *Nigella* to the species level for most taxa using only seed characters. The resulting dichotomous identification key is given in appendix B. In the few cases where taxa could not be separated, a clear distinction of groups could at least be established. The recorded characters were, for example, not sufficient to clearly discriminate between infraspecific taxa of the *N. arvensis* group. Likewise, it was not possible to efficiently separate the seeds of *N. hispanica* (including its var. *parviflora*) from *N. segetalis* or those of *N. nigellastrum* from *N. unguicularis*.

Phylogenetic Trees

Results from MP analysis (fig. 7) resolved only two well-supported groups, namely sect. *Garidella* (100% BS) and subsect. *Nigellastrum* (89% BS), while moderate support (73%) is available for the clade including all *Nigella* species except subsect. *Nigellastrum*, *N. hispanica* s.l., and *N. segetalis*. One subclade within subsect. *Nigellastrum* has low support (*N. orientalis* and *N. oxypetala*; 58%), while all others have BS values below 50%. A large group incorporating the whole subsect. *Nigellaria* as well as subsect. *Erobathos* and sect. *Komaroffia* therefore remains unresolved.

Character Mapping

Mapping characters onto the existing DNA-based phylogenetic hypothesis (fig. 8) indicated that only a few molecularly defined taxa are characterized by unambiguous autapomorphies in seed morphology. These were the sections *Garidella* and *Komaroffia* and the subsections *Erobathos* and *Nigellastrum*. A few characters (see table D1) represent important autapomorphies, namely characters 1 (seed shape) and 7 (secondary structure), both of which define three separate groups in the phylogeny. Characters 4 (seed surface), 6 (primary structure), 8 (presence of resin-filled idioblasts), 9 (outermost testa layer height), and 10 (underlying testa layers height) each occur a single time as autapomorphies.

Discussion

General Seed Morphology and Species Identification

Despite the difficulties in the separation of taxa within the *Nigella arvensis* group, there are clearly observable (and possibly constant) differences in the proportions of cell types, such as ocellate versus columellate cells or columellate versus ligulate versus truncate cell types. This was also suggested by Dadandi et al. (2009). However, thorough quantification and assessment of these characters would require huge amounts of data and time for setting up both the means of identification and their applied use; total cell counts per seed would be necessary for proper identification.

In contrast to the lack of distinction between *N. nigellastrum* and *N. unguicularis* observed in the current study, Dadandi et al. (2009) report characters useful for differentiating the two species, namely rugulate periclinal cell walls in *N. nigellastrum* versus pitted or microreticulate walls in *N. unguicularis*. We were not able to observe these features in the current study. Neither were we able to reproduce the differentiating canal (*N. nigellastrum*) versus ridge (*N. unguicularis*) of the anticlinal cell wall.

Differing results were also obtained when comparing the current results on subsect. *Nigellastrum* with two previous studies: Karcz and Tomczok (1987*a*) report conical projections in the central portion of *N. orientalis* seeds. Conversely, Dadandi et al. (2009) document nipplelike projections as present in *N. oxypetala* and *N. latisecta* (the latter is commonly considered synonymous to *N. oxypetala*) but as missing in *N. orientalis* and *N. lancifolia* (which, again, is considered synonymous to *N. oxypetala*). The current study found no indications of cell wall projections in either *N. orientalis* or *N. oxypetala*. These differences may well be due to morphological variability within *N. orientalis* and *N. oxypetala*, but the existence of hitherto unidentified subtaxa in both species must

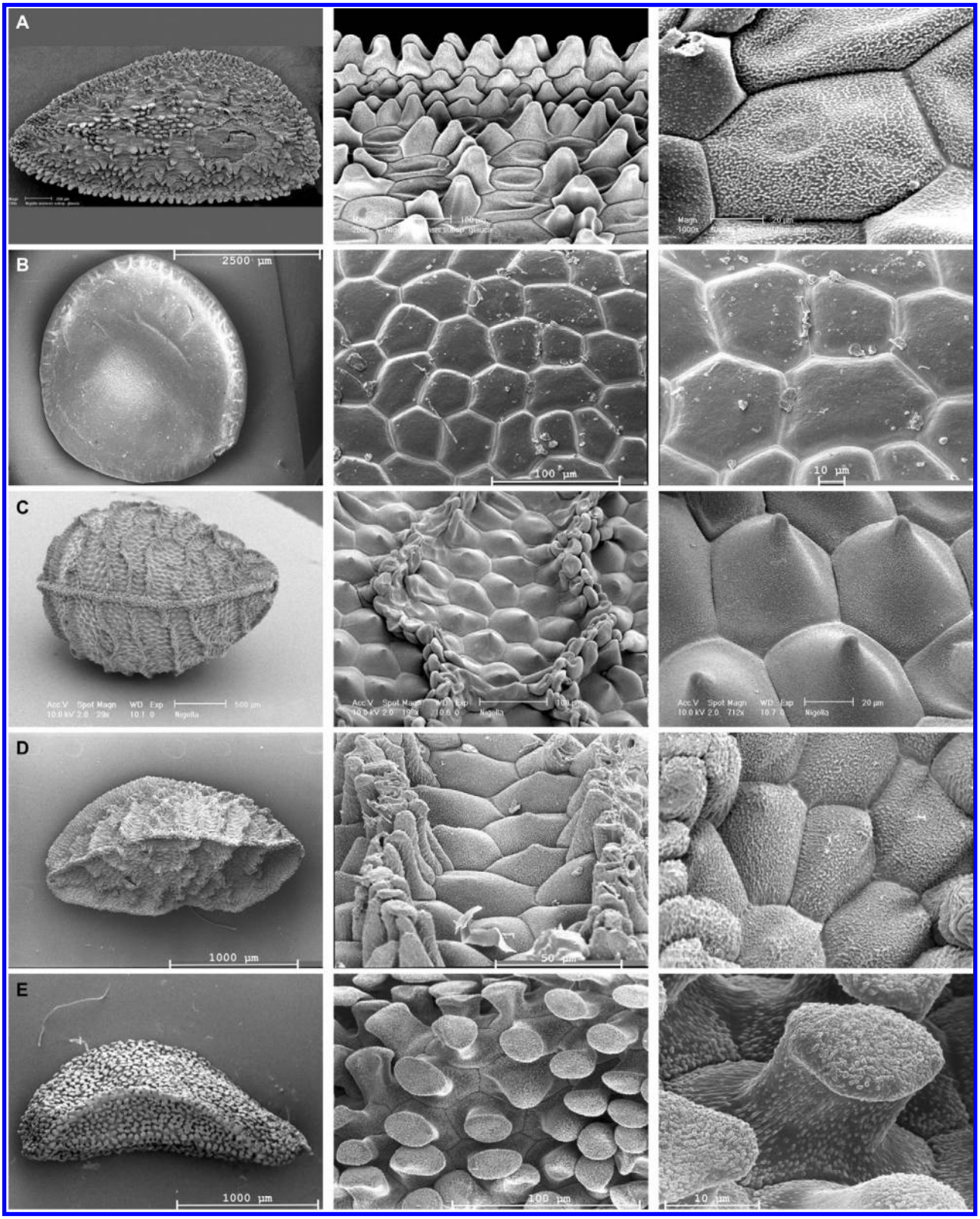


Fig. 4 SEM micrographs of *Nigella* species investigated. *A*, *Nigella arvensis* var. *glauca*. *B*, *Nigella ciliaris*. *C*, *Nigella damascena*. *D*, *Nigella elata*. *E*, *Nigella fumariifolia*.

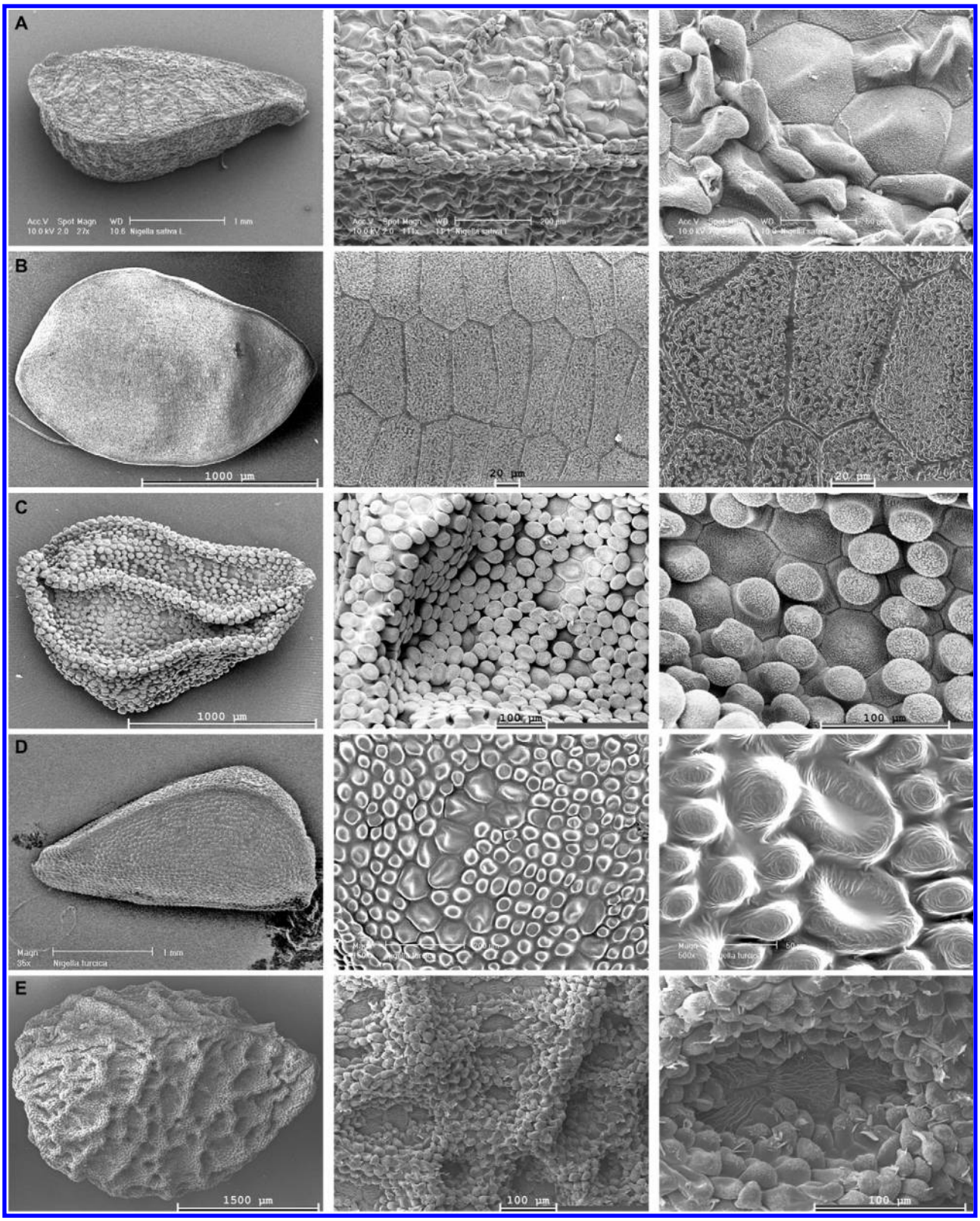


Fig. 6 SEM micrographs of *Nigella* species investigated. *A*, *Nigella sativa*. *B*, *Nigella segetalis*. *C*, *Nigella stellaris*. *D*, *Nigella turcica*. *E*, *Nigella unguicularis*.

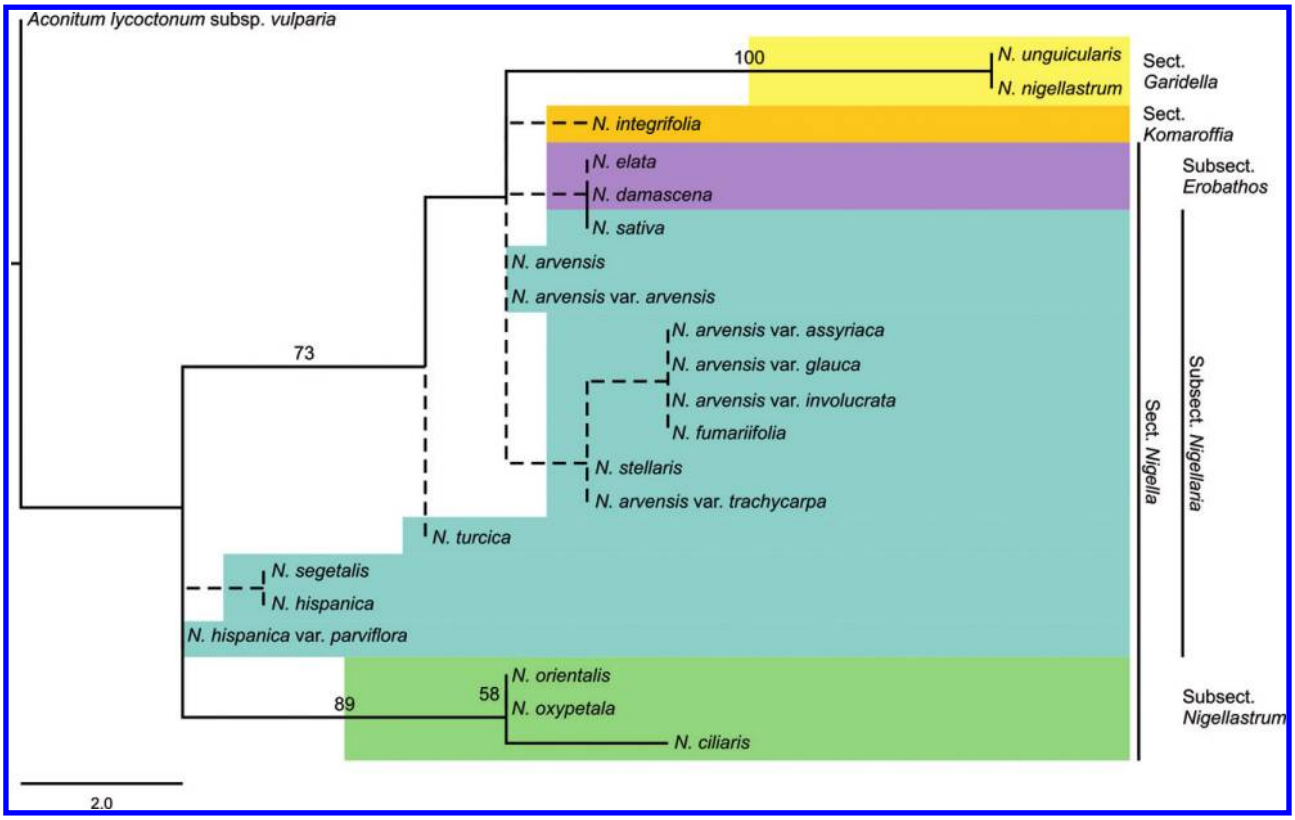


Fig. 7 Tree no. 326 of the 100,000 most parsimonious trees (length 121) resulting from the second run of the heuristic search. Numbers indicate bootstrap percentages, dashed lines indicate branches that collapsed during the bootstrap. Consistency index = 0.957, retention index = 0.971.

also be considered possible. In general, variability within taxa must be considered an important factor in morphological analyses. For 11 taxa in our study (including *N. orientalis*), multiple accessions were available, thus helping to reduce any possible bias caused by infraspecific variability.

The results of the current study, alongside those of Karcz and Tomczok (1987*a*) and Dadandi et al. (2009), differ strikingly from some of the seed descriptions given by Bahadur et al. (1984). This can most likely be explained as misidentifications of the seed accessions in the 1984 study (for details, see app. C). Using the respective descriptions and SEM images in their publication, three of the six described taxa need to be corrected as follows: "*N. arvensis*" → *N. damascena*, "*N. hispanica*" → *N. sativa*, and "*N. orientalis*" → *N. damascena*.

Phylogenetic Implications of MP Analysis and Character Mapping

The MP tree resolved two well-supported groups corresponding to sect. *Garidella* and subsect. *Nigellastrum*, indicating that the taxa included in the respective groups share a significant number of seed morphological traits (fig. 7). The two species of sect. *Garidella* show the greatest phenotypic divergence from all other taxa investigated. Four autapomorphies in seed geometry, surface pattern, testa composition, and secondary structure (fig. 8) place *N. nigellastrum* and *N. unguicularis* in a remote position relative to the remaining *Nigella* taxa. This can be regarded as additional support for their placement in a separate genus *Garidella*, as suggested by flower morphology (Linnaeus 1753; Boissier 1867), palynology (Skvarla and Nowicke 1979; Dönmez and Işık 2008), DNA (Bittkau and Comes 2008), and phytochemistry (Aitzetmüller et al. 1997).

Although not resolved in the MP tree, the monotypic section *Komaroffia* is also separated from *Nigella* by two autapomorphies (fig. 8), namely the capitate/pilate cells and the unique secondary structure with radially oriented rugulae/striae (fig. 5*B*). Against the background of evidence from karyology (2n=14 in *N. integrifolia* vs. 2n=12 in all other species in *Nigella* s.l.; Gregory 1941; Strid 1970), ITS sequence data (Bittkau and Comes 2008), and seed oil characteristics (Aitzetmüller 1998), seed morphology also supports the maintenance of a separate genus *Komaroffia*.

The three taxa contained in sect. *Nigella* subsect. *Nigellastrum* form a well-resolved clade in the MP tree (fig. 7). It is mainly defined by an autapomorphy in seed geometry (fig. 8) but also by the presence of flat prismatic cells only and thick periclinal epidermal cell walls, two homoplasies shared with *N. hispanica* s.l. and *N. segetalis*. The subsection *Nigellastrum*, as defined by Zohary (1983), is supported by seed morphology, and ITS phylogeny (Bittkau and Comes 2008) also suggests a proximity of the taxa *N. ciliaris*, *N. orientalis*, and *N. oxypetala*. The taxonomic implications of Dadandi et al.

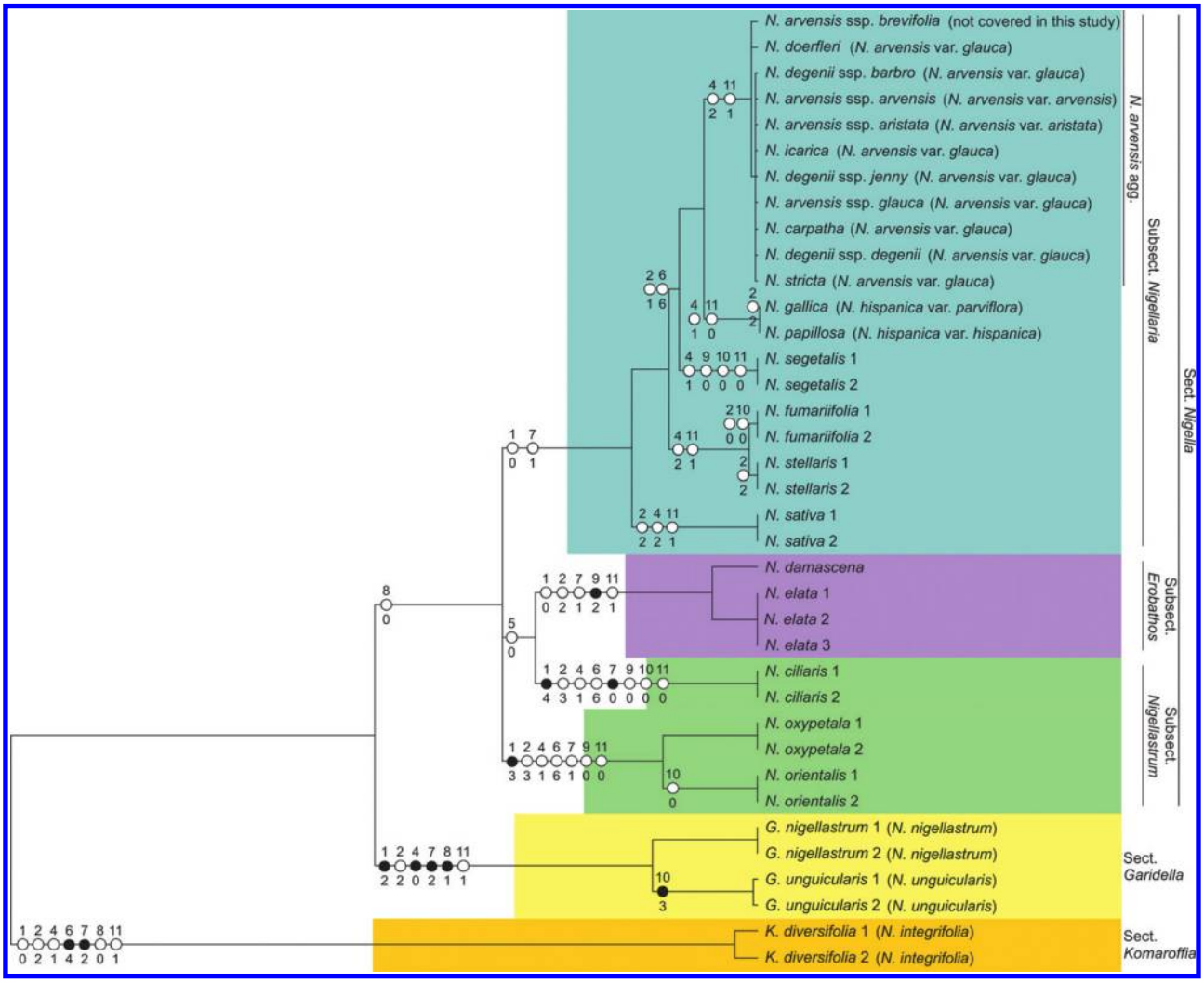


Fig. 8 Characters (top numbers) and their states (bottom numbers) mapped onto the phylogenetic hypothesis based on ITS sequences as previously published by Bittkau and Comes (2008). Only unambiguous character states are given. Apomorphies are indicated by filled circles, homoplasies by open circles. Taxon names and accession numbers follow the original publication (based on Strid 1970); synonyms used in the current study (according to Zohary 1983) are given in parentheses.

(2009) even suggest an independent position of sect. *Nigellastrum* from the other taxa investigated in their study, referring to similar results in a stem anatomy study by the same working group (Kökdil et al. 2006*a*).

Apart from the previously mentioned homoplasies, *N. hispanica* s.l. and *N. segetalis* share other homoplastic characters, such as seed geometry and color. Their seeds could not be efficiently distinguished in this analysis, and although the two species are presently found in disjunct areas of the Mediterranean—*N. hispanica* in southwestern Europe and western North Africa and *N. segetalis* in the Irano-Turanian region (Tutin et al. 1964–1983; Zohary 1983)—they also share a wide range of morphological (Zohary 1983) and DNA characteristics (Bittkau and Comes 2008; C. Bittkau and H.-P. Comes, unpublished data). Taking into account their similarities in seed morphology, they should be regarded as more closely related than has previously been assumed. Likewise, the close similarity of *N. fumariifolia* to *N. stellaris* observed in their seed morphology is not clearly mirrored in traditional *Nigella* taxonomy, although Terracciano (1897; cited in Zohary 1983) treated *N. stellaris* as a subspecies of *N. fumariifolia*. This possible close relationship is also reflected by the results of phylogenetic analyses of ITS data (Bittkau and Comes 2008) and is in need of further investigation.

The monophyly of subsect. *Erobathos*, a taxon accepted by traditional taxonomy (Zohary 1983) and supported by molecular data, is further supported by a seed morphological autapomorphy (testa thickness) and is also characterized by the presence of mucronulate cells, a unique character of its primary structure.

Within the *N. arvensis* aggregate, no clear grouping could be observed. Primary structure proved most variable in this group: a total of four different cell types were observed in varying proportions in the six investigated *N. arvensis* taxa, as documented by Dadandi et al. (2009) for two of the varieties/subspecies.

Conclusions

In the current study, seed shape and secondary structure proved to be the most useful seed morphological characters for characterizing *Nigella* taxa. Other characters, such as the thickness of the underlying testa layers as well as the presence of idioblasts, represent autapomorphies for specific clades (such as the section *Garidella*). The remaining features—seed measurements, the occurrence of pigmented cells, and the primary structure—did not in general reflect a clear evolutionary trend. However, the high variability and homoplastic patterns of primary structure reveal extensive evolutionary plasticity in these surface structures.

The current analysis cannot provide definite conclusions on the phylogenetic status of the genus *Nigella*; a thorough synthesis of the current and other morphological as well as molecular data will be required to accomplish this. We have, however, demonstrated that seed morphology can contribute valuable information for species classification in *Nigella*. As a main result, the considerable phylogenetic distinction between the sections *Garidella*, *Komaroffia*, and *Nigella*, as also shown in other studies, is clearly reflected by seed morphology.

Perspectives

As a result of the current study, proper identification and quality control of seed accessions of *Nigella* will now be possible to a much greater extent. This will hopefully facilitate the accelerating research regarding pharmacologically interesting taxa. Some of these, such as *N. ciliaris*, have not yet been analyzed for their medicinal potential but should be, according to ethnological records (Ali-Shtayeh et al. 2000).

The results from this study might also be valuable for research into archaeobotany: the history and prehistory of cultivated and useful plants. Archaeological finds of *Nigella* species date back to prehistoric times, the oldest dating from the Middle Kingdom in Egypt (*N. sativa*; around nineteenth century BC; Murray 2000) to the Late Bronze Age in central Europe (*N. damascena*; 1410–920 calibrated years BC; Heiss and Oeggl 2005). Together with younger finds and written records from Europe, the Near East, and North Africa (A. G. Heiss, unpublished data) document a long tradition of intentional use, cultivation, and synanthropic long-distance transport of *Nigella* seeds over a wide area, with most of the evidence deriving from *N. sativa*. However, this study now provides the means to better identify almost all of the species of this fascinating genus by their seeds and will hopefully allow researchers to better understand the importance of *Nigella*—not only of *N. sativa* but also of the other species—for past cultures in terms of their economic, environmental, and social value.

Finally, we would like to mention seed dispersal in *Nigella*, which has not been treated in our work but deserves mention as a key issue in future studies. The high degree of seed differentiation we found in this rather small genus (and even within the *N. arvensis* group) must be assessed in terms of its possible relationship with dispersal strategies. Seed characters may have played a crucial role in the differentiation and radiation of this genus and, more specifically, even within the *N. arvensis* group: by investigating pollen pigmentation in *N. degenii*, Jorgensen et al. (2006) have already discovered existing intraspecific variability of a character relevant for reproduction.

Also, the different modes of fruit shape and fruit dehiscence in *Nigella* will require thorough assessment, since they directly influence seed propagation: certain taxa within *Nigella* (*N. arvensis* agg., *N.* subsect. *Nigellastrum*) seem to utilize barochorous/ombrochorous mechanisms as, for instance, also found in the Ranunculaceae genus *Eranthis* (Emig et al. 1999), while *N.* subsect. *Erobathos* seems to resemble more closely the anemoballistic/boleochorous *Papaver* type (Müller-Schneider 1977; Kadereit and Leins 1988). As Römermann et al. (2005) have demonstrated, even taxa not typically known as epizoochorous may produce seeds with a high attachment potential to animal hides. The ample differentiation of seed shapes and surface structures in *Nigella* s.l. will therefore be assessed against this background.

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Appendix A

Seed Accessions of *Nigella* s.l. Investigated in This Study

Seed accessions alphabetically sorted by taxon; taxon names follow Zohary (1983). Question marks indicate doubtful or missing data. Asterisks indicate the number of seeds included in the morphometric analysis. Reference material of the seed accessions used in this study is deposited at WHB herbarium. Further information can be obtained from the authors.

Taxon: laboratory number, number of seeds investigated, collection, specimen details, country, locality, leg. (yyyy-mm-dd) / det. (yyyy-mm-dd).

Aconitum lycoctonoum* L. subsp. *vulparia* (Rchb.) Nyman**: **Alyvu0**, *35, HBG, IS2006/244, ?, ?; ***Nigella arvensis* L.**: **Nar000**, *213, MJG, IS2004/974 (IPEN XX0MJG19—45660), ?, ?; ***N. arvensis* L. var. *arvensis: **Narar0**, *10, WU, 1759, Albania, "Sentari", Baldacci A (1897-08-09) / Strid A (1969); ***N. arvensis* L. var. *assyriaca* (Boiss.) Zoh.**: **Naras0**, *7, WU, 004590, Iraq, Ramadi, Rechinger KH (1957-06-06/07) / Strid A (1969); ***N. arvensis* L. var. *glauca* (Schkuhr) Boiss.**: **Nargl0**, 16, LI, 096499, Turkey, B5 Nevsehir, Göreme, ? (1977-08-26) / Sorger F; **Nargl1**, *108, BRIX, 44, Turkey, A4 Kastamonu, Freyn J (1892-08-04) / Sintenis P / Heiss AG (2006); ***N. arvensis* L. var. *involucrata* Boiss.**: **Narin0**, *14, WU, 1622, Greece, Faliro, von Heldreich T (1895-06-08) / Strid A (1969); ***N. arvensis* L. var. *trachycarpa* Borb.**: **Nartr0**, *43, BRIX, 36, Romania, Ayud, Baenitz C (1894-07-03); ***N. ciliaris* DC.**: **Nci000**, *28, C, S-1977-0977; 279; 183/99; 2581, Israel, ?; ***N. damascena* L.**: **Nda000**, *60, MJG, IS2004/975 (IPEN XX0MJG19—45670), ?, ?; **Nda001**, *11, collection of A.G. Heiss, 2722, ?, Oeggl K (1985-09-27); **Nda002**, 6, BRIX, 13, Croatia, Dubrovnik, Huter R (1867-05-19); **Nda003**, *90, collection of A.G. Heiss, 1249, Italy, Selinunte, Heiss AG (2006-08-07); **Nda004**, 57, HOH, IS1990/1148, ?, ?; ***N. elata* Boiss.**: **Nel000**, *8, LI, 096512, Turkey, A3 Bolu: Kibrisçik, ? (1983-08-20) / Sorger F; **Nel001**, *38, BRIX, 23-24-25, Turkey, A1 Istanbul:Kartal, Aznavour GV (1898-07-02/14) / Dörfler J; ***N. fumariifolia* Kotschy**: **Nfu000**, *23, WU, s.n., Cyprus, Lefkoniko, von Halácsy E (1880-05-06) / Strid A (1969); **Nfu001**, 5, BRIX, 64, Cyprus, Lefkoniko/Arthana, Sintenis P & Rigo G (1880-04-15); ***N. hispanica* L.**: **Nhi000**, *193, MJG, IS2004/976 (IPEN XX0MJG19—45680), ?, ?; **Nhi001**, 53, GAT, IS2004/213, ?, ?; **Nhi002**, 10, BRIX, 34, France, Toulouse, Pech D (1853-08); ***N. hispanica* L. var. *parviflora* Coss.**: **Nhipa0**, *38, MJSD, 1575-19-116/98, ?, ?; **Nhipa1**, 44, BRIX, 47, Spain, Pueblo de San Federique, Porta P & Rigo G (1895); ***N. integrifolia* Regel**: **Nin000**, *260, MJG, IS2004/977 (IPEN XX0MJG19—45690), ?, ?; **Nin001**, 17, IB, s.n., Czech Republic, Olomouc, Laus H (1938-07-01); ***N. nigellastrum* (L.) Willk.**: **Nni000**, *82, MJG, IS2004/978 (IPEN XX0MJG19—45700), ?, ?; **Nni001**, *95, GAT, s.n., ?, ?; **Nni002**, 8, IB, s.n., Czech Republic, Olomouc, Laus H (1938-07-01); ***N. orientalis* L.**: **Nor000**, *8, GAT, IS2004/213, ?, ?; **Nor001**, *38, BRIX, 62, Turkey, ?, Bornmüller J (1889-04-24) / Freyn J; **Nor002**, *161, PRAZ, IS2008/173, ?, ?; ***N. oxypetala* Boiss.**: **Nox000**, *5, LI, 096511, Turkey, B6 Sivas:Divriği, ? (1969-08-09) / Sorger F / Zohary M; ***N. sativa* L.**: **Nsa000**, 160, MJG, IS2004/979 (IPEN XX0MJG19—45710), ?, ?; **Nsa001**, *107, —, spice market, Turkey, C1 Muğla:Bodrum, Turan-Jeschow M (2006) / Heiss AG (2006); **Nsa002**, 99, HOH, IS1991/1077, ?, ?; ***N. segetalis* M.Bieb.**: **Nse000**, *12, WU, s.n., Georgia, Kakheti, Hohenacker RF (1842-06) / Strid A (1970); **Nse001**, 51, BRIX, 56, Turkey, A4 Kastamonu, Freyn J (1892-06-07) / Sintenis P; ***N. stellaris* Boiss.**: **Nst000**, *3, LI, 001173, Turkey, C6 Seyhan:Karatepe, ? (1971-06-23) / Zohary M; ***N. turcica* Dönmez & Mutlu**: **Ntu000**, 5 (*2), collection of A. Dönmez, 11447, ?, Dönmez AA; ***N. unguicularis* (Lam.) Spenn.**: **Nun000**, *8, WU, 2575, Syria, Jabal Abdul Aziz, von Handel-Mazzetti H (1910-06-22) / Strid A (1969)

Appendix B

Key to the Species of *Nigella* s.l., Based on Seed Morphology

1. a) Seed discoid (dorsoventrally compressed, with orbicular outline and one circumferential wing), longer than 4 mm → subsect. *Nigellastrum* 11

   b) Seed shape different, seed shorter than 4 mm 2

2(1). a) Seed trigonous-ovate to orange-segment shaped, three longitudinal ridges 3

   b) Seed obovate, with one ventral ridge—surface covered by a conspicuous, irregular reticulum up to 300 μm high; cell walls with undulate rugulae/striae present ..... *Nigella* sect. *Garidella* (*N. nigellastrum*, *N. unguicularis*)

3(2). a) Distinct surface structures with more or less regular transverse orientation present, seed rough; outermost cell layer thin walled (double periclinal cell wall diameter less than lumen diameter)—seed buff to blackish or mottled 4

   b) Distinct surface structures absent, seed smooth; outermost cell layer thick walled (double periclinal cell wall diameter larger than lumen diameter; sometimes no lumen visible)—seed lustrous, buff to dark brown, frequently mottled ..... *N. hispanica*, *N. hispanica* var. *parviflora*, *N. segetalis*

   a) Capitate/pilate cells present 5

   b) Capitate/pilate cells absent 7

5(4). a) Prismatic cells (with more or less flat periclinal walls, including ocellate types) present; capitate/pilate cells with collapsed periclinal walls/apices (=truncate); cells with radial rugulae/striae absent 6

b) Prismatic cells absent; capitate/pilate cells without any collapsed walls; cells with radial rugulae/striae present ..... *Nigella* sect. *Komaroffia* (*N. integrifolia*)

6(5). a) Ocellate cells (prismatic cells with collapsed periclinal walls) present .....*N. stellaris*

b) Ocellate cells absent ..... *N. fumariifolia*

7(4). a) Colliculate cells (including mucronulate types) present 8

b) Colliculate cells absent 10

8(7). a) Mucronulate cells present; columellate cells with collapsed lateral walls (=ligulate) present; ocellate cells absent (→ subsect. *Erobathos*)..... 9

b) Mucronulate cells absent; columellate cells absent; ocellate cells present .....*N. turcica*

9(8). a) Mucronulate cells with distinct, centered mucronulus..... *N. damascena*

b) Mucronulate cells with indistinct, excentric mucronulus.....*N. elata*

10(7). a) Ocellate cells covering nearly 90% of the seed surface; columellate cells exclusively ligulate—seed blackish .....*N. sativa*

b) Ocellate cells covering much less (~50%) of the seed surface; columellate cells without collapsed walls present—seed dark brown, frequently mottled with brighter cells .....*N. arvensis* agg. (var. *arvensis*, var. *assyriaca*, var. *glauca*, var. *involucrata*, var. *trachycarpa*)

11(1). a) Seed wing entire; cells with irregularly granulate to rugulate cell walls present—seed dull, buff to dark brown, frequently mottled ..... *N. orientalis*, *N. oxypetala* (central portion of *N. oxypetala* sometimes with mucronulate cells; cf. Dadandi et al. 2009)

b) Seed wing undulate-crenate; cells with irregularly granulate to rugulate cell walls absent—seed shiny, blackish ..... *N. ciliaris*

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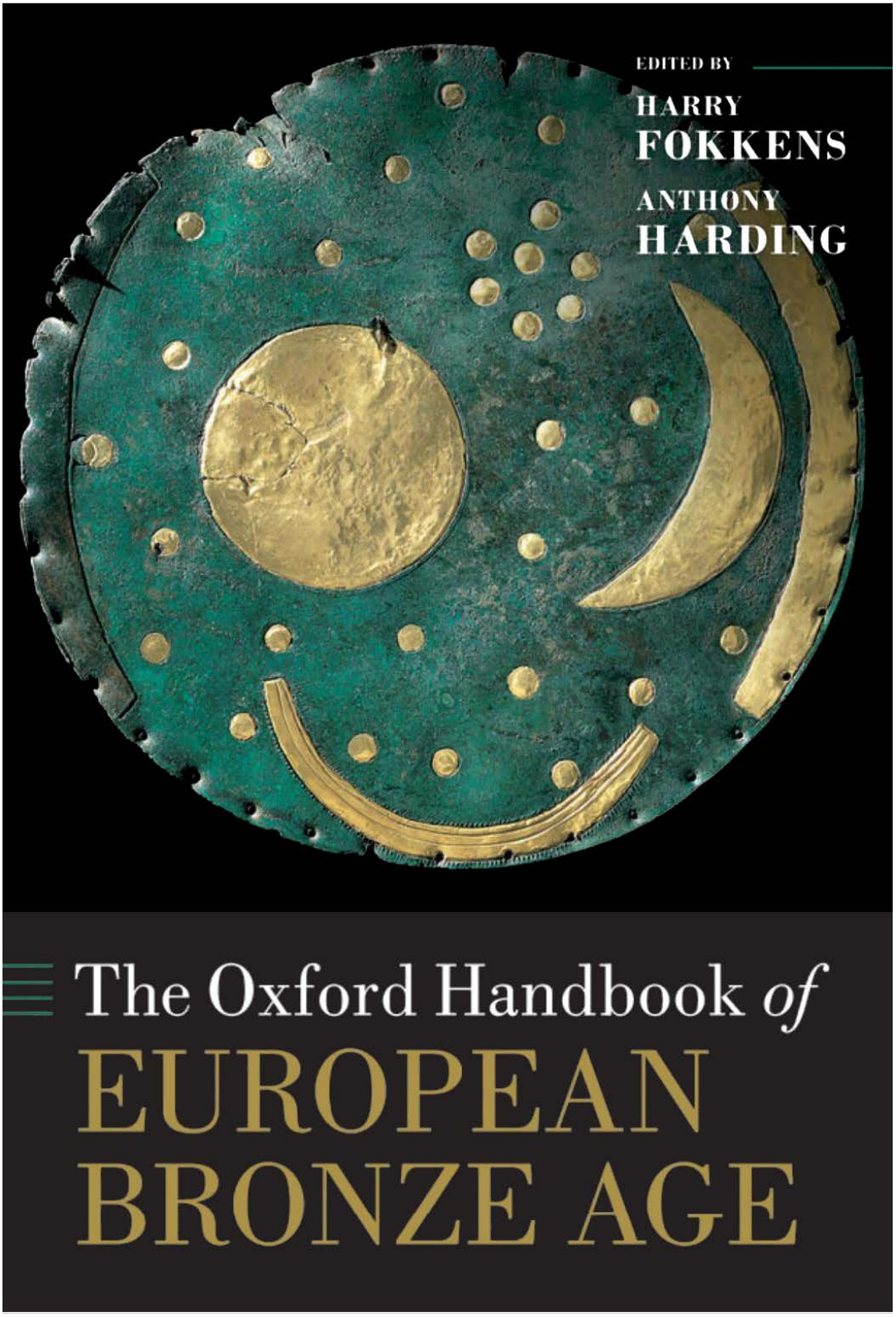
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CHAPTER 19

PLANT CULTIVATION IN THE BRONZE AGE

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Introduction

For millennia, cultivated (or, to be more precise, domesticated) plants have been the main foundation of human nutrition. In Europe, this is true since the Neolithic introduction of a set of several cultivated crops from the 'Fertile Crescent' in the Near East and the accompanying cultural techniques involved in their cultivation, processing, and consumption.

Investigating these present and past interactions of domesticated crop plants with environmental and cultural factors is one of the central questions when researching human history and prehistory. Several compilations on crop cultivation and plant use as staple food exist for different regions of Bronze Age Europe. Of the supraregional studies, one especially well-known publication should be emphasized: *Progress in Old World Palaeoethnobotany: A Retrospective View on the Occasion of 20 Years of International Work Group for Palaeoethnobotany* (Van Zeist, Wasylikowa, and Behre 1991). Twenty years later, we are trying to face the same challenge of compiling data on crop cultivation. Apart from basing ourselves on updated knowledge in archaeobotany, the main difference between the current study and the approach followed in Van Zeist et al. is the use of a semi-quantitative approach, in contrast to mere presence-absence data or a coarse estimation of dominance. Another important change is the referral to site representativeness and thus to the reliability of the conclusions drawn. Our goal, however, is to assess both the regional dominance and the general importance of certain crops in Bronze Age Europe, and to assess the representativeness of the extant data used in the study.

Methods

A problem with the term 'Bronze Age' in an overview of Europe is that it is used in different ways for different parts of the period across Europe, with different durations and varying subdivisions. Therefore we have limited ourselves to rough regional classifications of Early,

Middle, and Late Bronze Age following the chronology compiled in Von Schnurbein (2009: 240). A handicap is that although large numbers of publications are available for most regions in Europe, the habit of publishing tables containing raw data is clearly still not mandatory in archaeobotany. Thus, several regions of Europe either could not be included in our synopsis, or are represented by weaker supporting data than the intensive research carried out by local colleagues would suggest, or could otherwise enable. In total, the data from 229 sites have been integrated into our study. (On the full record of literature used, see Note)

The spectrum of plants included in the current study primarily covers the three main groups of cultivated crops most important for nutrition: 1. cereals; 2. legumes and pulses; 3. oilseeds. Cereals (grasses of the Poaceae family) are the main contributors to human daily calorie intake. Legumes or pulses (Fabaceae family) also provide, apart from their calorie content, essential amino acids. Oilseeds, from different plant families, provide essential fatty acids crucial for human metabolism and hormonal balance. The most important ones in prehistory were flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), gold-of-pleasure (*Camelina sativa*), and opium poppy (*Papaver somniferum)*. Apart from their use as a source of vegetable fat, many of these oilseeds are also multifunctional plants used, for example, in fibres (flax, hemp) or as narcotics (hemp, poppy). In addition to these three main groups, cultivated fruit were also included, as past studies (e.g. Kroll 1991a: 166) have shown that the beginnings of the cultivation of these plants lie in the Bronze Age.

In devising a means of data evaluation, the question was how to deal with the different archaeological contexts, and the different states of preservation of plant remains, and how to maintain comparability across all these data. We decided to evaluate all available sites in a region with a weighted, semi-quantitative approach that respects both the presence of a taxon and its relative quantity per site (i.e. dominance), the total quantity of plant material recovered from a site, and the number of samples analysed. In this way the representativeness of the dominances observed in particular sites could be assessed.

Occurrences of cultivated plants were extracted from the extant archaeobotanical and archaeological literature from across Europe. Only publications with raw data were included in the survey. Seed/fruit counts of charred, subfossil, and mineralized finds of seeds or fruits of cultivated taxa were recorded per site. (For further details about the way in which the data were evaluated see Note.)

Regional Overviews

Continental and Northern Greece, and Southern Bulgaria

In this overview we have combined the data from northern Greece and southern Bulgaria because these regions show a comparable agricultural development and are ecologically close. In spite of the fact that the data available to us from this region only covers 15 sites, the *Representativeness Index* (RI) reaches the highest levels in our study, both for cereals and non-cereals. The mainly diachronic tell sites were excavated with large series of samples producing high numbers of finds. Earlier regional compilations of archaeobotanical results (e.g. Kroll 1991a: 166) already pointed out a certain continuity of the Late Neolithic

Table 19.1 RI (Representativeness Index) Values of Non-Cereals (Pulses, Oilseeds, and Cultivated Fruit) in the Archaeobotanical Record of Continental and Northern Greece and Southern Bulgaria

Plant species		EBA	MBA	LBA
Cicer arietinum	chickpea	10	6	1
Lathyrus sativus/cicera	grass pea	13	11	6
Lens culinaris	lentil	39	21	11
Pisum sativum	garden pea	10	6	6
Vicia ervilia	bitter vetch	78	22	29
Vicia faba	field bean	26	11	7
Camelina sativa	gold-of-pleasure	10	5	26
Carthamus tinctorius	safflower	1		
Lallemantia sp.	lallemantia	13	5	8
Linum usitatissimum	flax	28	6	5
Papaver somniferum s.l.	opium poppy	14	6	10
Cucumis melo	melon		1	
Ficus carica	fig	49	15	16
Olea europaea (undiff.)	olive	1	2	2
Punica granatum	pomegranate		1	
Vitis vinifera (undiff.)	grapevine	25	12	12

agricultural system up to the Middle Bronze Age, while changes become noticeable in the Late Bronze Age.

The main cereal during the Early and Middle Bronze Age was barley (*Hordeum vulgare*). Most remains have been identified as hulled barley (*Hordeum vulgare* var. *vulgare*), and only a few derived from naked barley (*Hordeum vulgare* var. *nudum*). Besides hulled barley, emmer (*Triticum dicoccum*) and einkorn (*T. monococcum*) were subdominant. Spelt (*T. spelta*), free-threshing wheat (*T. aestivum/durum/turgidum*), broomcorn millet (*Panicum miliaceum*), and oats (*Avena* sp.) were recorded, but of minor importance, or in the case of oats of no importance in cultivation terms. From the Neolithic onwards, there are hints of another cereal in Greece: a 'new type' of glume wheat with uncertain taxonomic affiliation, probably closely related to *Triticum timopheevi* Zhuk. (Jones, Valamoti, and Charles 2000: 140–2). During the Middle Bronze Age species percentages are generally comparable to the Early Bronze Age, although seed counts (and thus representativeness) are noticeably lower.

Intensively investigated Late Bronze Age finds document a change in cereal cultivation observable in a marked decrease in barley and a smaller one in emmer, in favour of increasing values of broomcorn millet and spelt.

As with the cereals, the non-cereals records for northern Greece and southern Bulgaria exceed all other regions covered in our study in terms of find numbers, diversity, and representativeness (Table 19.1). For the Early Bronze Age the Representativeness Index of non-cereals (RI = 317) is even higher than that of cereals (RI = 248). This clearly indicates the importance of non-cereals in cultivation and consumption, mainly deriving from finds of

pulses (RI = 176). The same is true for the Middle and Late Bronze Age, with the importance of cereals slightly rising towards the Late Bronze Age. The dominant pulses are bitter vetch (*Vicia ervilia*) and lentil (*Lens culinaris*), followed by field bean (*Vicia faba*). Grass pea (*Lathyrus sativus/cicera*), garden pea (*Pisum sativum*), and chickpea (*Cicer arietinum*) are of less importance. However, the spectrum of pulses does not display any clearly detectable shift between the different Bronze Age periods.

Oilseeds are also very diverse. For the Early and Middle Bronze Age, flax/linseed, opium poppy, lallemantia (*Lallemantia* sp.; s.; Jones and Valamoti 2005), gold-of-pleasure, and a single find of safflower (*Carthamus tinctorius*) are recorded. Towards the Late Bronze Age, gold-of-pleasure rises in importance whereas the others decrease (or go missing altogether, as in safflower). Remains of cultivated fruit are dominated by woody plants: fig (*Ficus carica*) is dominant, while grape (*Vitis vinifera*) is subdominant, and a few finds of olive (*Olea europaea*) occur. Also single records of pomegranate (*Punica granatum*) and melon (*Cucumis melo*) from Tiryns (Kroll 1982: 470, Table 1) are displayed in Table 19.1. In accordance with prior investigations, it seems indeed that fruit (mainly fruit tree) cultivation rose during the Bronze Age in the eastern Mediterranean (Zohary and Hopf 2000: 142–5). Certain aspects, such as oil production from olives, seem however to have been introduced to Europe, and even to the Aegean, after the Bronze Age (Riehl 1999: 62–3). The earliest evidence for the production of olive oil comes from a non-European site: Early Bronze Age Tel Yarmouth, Israel, in the Levant (Salavert 2008: 59–60).

Central and Northern Italy (South of the Alps)

In a former compilation of crops for Italy (Hopf 1991: 243–50), emmer was judged as being prevalent, and naked wheat as almost equally frequent. In the current compilation for the Early and Middle Bronze Age, emmer is still the dominant cereal. But barley is subdominant, together with free-threshing wheat and einkorn. However, this change may result mainly from new archaeobotanical research in the region carried out over the last 20 years, and the vastly increased amount of data provided by the research centres in Como, Modena, Florence, and Rome. The representativeness for cereal remains is, however, still low for the Early Bronze Age (RI = 14), moderate for the Middle Bronze Age (RI = 125), and low for the Late Bronze Age (RI = 62). The presence of broomcorn millet and foxtail millet (*Setaria italica*) is reported, and spelt is represented by the weakest count (RI = 1) for the region.

During the Late Bronze Age, the dominance of emmer persists, as well as the subdominance of barley. Einkorn decreases and free-threshing wheat is replaced mainly by broomcorn millet. Central and northern Italy (excluding the Alps and their foreland) was clearly a 'non-spelt' area, but rather an emmer region, following the main trend of increased millet cultivation in the Late Bronze Age observed in most other regions.

A few words need to be said about Sardinia, which is not included in our regional evaluation, and where a compilation by Bakels (2002) covers the Nuragic culture. Here it seems that the replacement of naked barley by hulled barley took place very late, during the Early Bronze Age, and from the Middle Bronze Age onwards only hulled barley is recorded. Emmer and free-threshing wheat are reported as well, the latter presumably a tetraploid wheat (such as durum wheat) as suggested by the identified rachis fragments (Bakels 2002: 5).

Table 19.2 RI Values of Non-Cereals in the Archaeobotanical Record of Central and Northern Italy (outside the Alps)

Plant species		EBA	MBA	LBA
Cicer arietinum	chickpea		1	1
Lathyrus sativus/cicera	grass pea			2
Lens culinaris	lentil		1	2
Pisum sativum	garden pea		2	6
Vicia ervilia	bitter vetch			4
Vicia faba	field bean		28	14
Vicia sativa	common vetch		2	1
Linum usitatissimum	flax		1	
Ficus carica	fig		1	
Juglans regia	walnut		2	
Olea europaea (undiff.)	olive	1	1	
Prunus domestica subsp. *insititia*	plum			1
Prunus dulcis	almond	1		
Sorbus domestica	service tree		2	
Vitis vinifera (undiff.)	grapevine	1	17	9

In the non-cereals, crop diversity is high in Italy, but only two species are well-represented: field bean and grape both in the Early/Middle Bronze Age and the Late Bronze Age. The beginning of grape cultivation for the regions of Tuscany and Emilia-Romagna during the Bronze Age has been discussed, but so far there is no confirmation for this hypothesis (Bellini *et al.* 2008: 108–9). Other pulses are recorded at low counts: garden pea, bitter vetch, lentil, grass pea, and chickpea. Bitter vetch, grass pea, and chickpea were found in the Late Bronze Age but are missing in the earlier periods. Linseed is only represented by two seeds (from Castellaro del Vhò: Rottoli 1997) from the Middle Bronze Age. Apart from grapes, fruit trees are weakly represented by olive, fig, and almond (*Prunus dulcis*) during the Early and Middle Bronze Age (Table 19.2). For the Late Bronze Age, plum (*Prunus domestica* subsp. *insititia*) is documented.

Southern France

Eleven sites in this region contribute to the evaluation of crop finds. Sites from the Early Bronze Age are absent, and the Middle Bronze Age is weakly documented (RI = 38). The Late Bronze Age again shows moderate representativeness (RI = 115). During the Middle Bronze Age, barley and free-threshing wheat are dominant at comparably high levels, and emmer and einkorn are subdominant. Other cereals are missing. In the Middle Bronze Age, the shift from naked barley to hulled barley is nearly complete in this region, with naked barley finds absent during the Late Bronze Age. In contrast to the continuously dominant hulled barley and subdominant emmer and einkorn during the Late Bronze Age, free-threshing wheat decreases from dominant to subdominant in this period. Spelt and oats as well as broomcorn

Table 19.3 RI Values of Non-Cereals in the Archaeobotanical Record of Southern France

Plant species		EBA	MBA	LBA
Lathyrus sativus/cicera	grass pea		1	11
Vicia ervilia	bitter vetch			2
Vicia faba	field bean		1	10
Linum usitatissimum	flax			2
Papaver somniferum s.l.	opium poppy			6
Olea europaea (undiff.)	olive		1	
Vitis vinifera (undiff.)	grapevine			1

millet and foxtail millet appear in the Late Bronze Age. Their high representativeness values are mainly based on two sites (Bouby, Fages, and Treffort 2005): one at Baume Layrou, Gard, was a storage find mainly consisting of hulled barley, spelt, and broomcorn millet, while Balme Gontran resulted in two nearly pure finds of stored spelt and broomcorn millet. For non-cereals the Middle Bronze Age sites were not productive; only single counts for the pulses field bean and grass pea and the fruit tree olive were noted.

During the Late Bronze Age, non-cereals are better represented both by grass pea and field bean, and in addition some bitter vetch (Table 19.3). Few counts of the oil seeds, poppy, and linseed, as well as grape are reported from Late Bronze Age contexts. General trends are pointed out by the available publications, but the data basis is still weak for this region.

Mediterranean Spain

The 15 sites that have entered our evaluation mainly cover the Middle Bronze Age (RI = 196) and the Late Bronze Age (RI = 106) with high and moderate representativeness indices, while the Early Bronze Age (RI = 36) is only weakly represented. Across the whole Bronze Age, barley remains the main cereal. A remarkable observation is that about half of the counts derive from naked barley and half from hulled barley. Consequently, the shift from naked to hulled barley, noticeable in most other regions, seems not to have taken place in Mediterranean Spain. In the Early and Middle Bronze Age, free-threshing wheat is subdominant whereas emmer, einkorn, broomcorn millet, and (most probably non-cultivated) oats appear with few or single counts. Indicated by few but well-preserved rachis fragments from Fuente Álamo (Stika 2001: 271–2), both tetraploid and hexaploid free-threshing wheats are documented for southern Spain.

Towards the Late Bronze Age, free-threshing wheat decreases while emmer increases; our study does not show any increase of millets as observed in most other regions. However, the site of Masada de Ratón (Fraga, Baix Cinca), situated inland in north-eastern Spain, must be mentioned before reaching conclusions. The site was not included in our evaluation because the relevant samples are ambiguously dated as Middle/Late Bronze Age (Alonso i Martínez 1999: 109–14). Yet in Masada de Ratón both foxtail millet and broomcorn millet are reported—foxtail millet with 485 finds (RI = 2) and broomcorn millet with 66 finds (RI = 1). So the evidence

Table 19.4 RI Values of Non-Cereals in the Archaeobotanical Record of Mediterranean Spain

Plant species		EBA	MBA	LBA
Lens culinaris	lentil		3	
Pisum sativum	garden pea		8	4
Vicia ervilia	bitter vetch	1		
Vicia faba	field bean	3	11	10
Linum usitatissimum	flax	4	8	5
Papaver somniferum s.l.	opium poppy	2		4
Castanea sativa	sweet chestnut			1
Ficus carica	fig	4	10	30
Olea europaea (undiff.)	olive	1	9	5
Phoenix dactylifera	date			1
Vitis vinifera (undiff.)	grapevine		8	6

seems to show a dramatically delayed spread of millets to the Iberian Peninsula in the Bronze Age by comparison with other regions in Europe (continental Greece and southern Bulgaria, the Pannonian Plains, Italy, the Alps, and western central Europe). Spelt arrived even later (several authors cited in Buxó i Capdevila 1997: 104).

The non-cereals from Mediterranean Spain (Table 19.4) display a high diversity. During the Early and Middle Bronze Age, field bean dominates the pulses, followed by garden pea, lentil, and bitter vetch. Oil plants are represented by finds of linseed and opium poppy, whereas among fruit trees fig, olive, and grape are recorded. Towards the Late Bronze Age, the pulse spectrum is reduced to field bean and pea. Again, linseed and poppy are found. Records of fig increase while olive and grape remain at the same level. For two sites in the province of Almería in Andalucía (Gatas and Fuente Álamo) there are unpublished data with further finds of grape pips (Stika 1996a; 2003), which are not included in the recent study. So the question when fruit-tree cultivation started in Spain is still unanswered. Rodríguez-Ariza and Montes Moya (2005) reviewed the origin and domestication of *Olea europaea* L. (olive) in Andalucía, Spain, by assessing charcoal and fruit data. For Mesomediterranean altitudes it seems to be clear that cultivation appeared no earlier than the Roman period. But at the Thermomediterranean level, where several sites included in our study are situated, the possible use of wild olive or even its cultivation during the Bronze Age still needs assessment.

Pannonian Basin

An earlier compilation (Wasylikowa et al. 1991: 214–17) covered the Pannonian Basin and gave a first impression about Bronze Age cereal cultivation, with einkorn, emmer, and hulled barley as the most important cereals in 25 analysed sites. For our new compilation, 46 sites were evaluated. Representativeness of archaeobotanical data is low for the Early Bronze Age (RI = 60), very high for the Middle Bronze Age (RI = 548), and high for the Late Bronze Age (RI = 264).

In accordance with the study by Wasylikowa et al. (1991: 215), the current data show that during the Early and Middle Bronze Age the three main cereals are hulled barley, einkorn, and emmer. Barley is also documented in its free-threshing (naked) variety, but to a low extent. Free-threshing wheat appears in some sites, more precisely identified as club wheat (*T. compactum*), and therefore subsumed in *Triticum aestivum* s.l. in the diagrams presented online, and spelt and broomcorn millet were recorded with few counts. The taxa rye (*Secale cereale*) and oats, most probably still non-domesticated, appeared with single counts. For the Late Bronze Age we recognize a change to four main cereals: broomcorn millet, hulled barley, emmer, and einkorn. While barley and einkorn decrease, broomcorn millet increases remarkably towards the Late Bronze Age. Spelt increases slightly, and free-threshing wheat keeps approximately the same proportion in the spectrum of cultivated crops. Foxtail millet was introduced to the area but was of low importance. For the Bronze Age Pannonian Basin, the 'new type' glume wheat is reported (Kohler-Schneider 2001: 116–25; Stika and Berzsényi forthcoming). No calculation of the importance of this taxon on the basis of grains can yet be given because identification criteria for the grains are still not available (and they have to remain unidentifiable for the moment)—in contrast to the glume bases/spikelet forks which are well-identifiable since the articles by Glynis Jones et al. (2000: 134–6) and Marianne Kohler-Schneider (2001: 116–25). For Stillfried an der March (Kohler-Schneider 2001: 180), it was possible to successfully identify rye brome (*Bromus secalinus*) grains as an important component in a porridge-like cereal preparation ('Hirsotto').

The diversity of pulses and oil plants is high in the region (Table 19.5). In the Early Bronze Age and Middle Bronze Age, lentil and pea are the main pulses, while subdominant ones are bitter vetch and field bean. Grass pea and common vetch (*Vicia sativa*) are recorded but are of less importance. Towards the Late Bronze Age conditions are similar, with slightly increased amounts of bitter vetch, but common vetch is now missing. In Early Bronze Age and Middle Bronze Age contexts, gold-of-pleasure, safflower, poppy, and linseed are documented, while

Table 19.5 RI Values of Non-Cereals in the Archaeobotanical Record of the Pannonian Basin

Plant species		EBA	MBA	LBA
Lathyrus sativus/cicera	grass pea		4	1
Lens culinaris	lentil	2	50	14
Pisum sativum	garden pea	2	40	12
Vicia ervilia	bitter vetch		20	14
Vicia faba	field bean	1	10	4
Vicia sativa	common vetch		1	
Camelina sativa	gold-of-pleasure	1	16	6
Carthamus tinctorius	safflower		11	
Linum usitatissimum	flax		14	
Papaver somniferum s.l.	opium poppy		5	4
Cucumis sativus	cucumber			1
Vitis vinifera (undiff.)	grapevine		2	7

the Late Bronze Age saw a reduction in gold-of-pleasure and poppy. Fruit trees are represented by finds of grape pips which might have been collected from the wild stands in the floodplains of the Danube.

Eastern Alps and their Foreland

This region is limited to the west by an imaginary line formed by the Alpine part of the River Rhine, the Splügen pass, and Lake Como. Twenty-seven sites are in our compilation, producing a well-balanced representativeness for the three main Bronze Age phases: Early Bronze Age (RI = 101), Middle Bronze Age (RI = 135), and Late Bronze Age (RI = 279). During the Early Bronze Age and Middle Bronze Age, barley was the dominant cereal mainly represented by its hulled variety, but free-threshing barley is recorded as well. Emmer and spelt are subdominant, followed by einkorn and free-threshing wheat. Broomcorn millet, rye, and oats are listed with only a few counts. Towards the Late Bronze Age, broomcorn millet increases remarkably while barley decreases. An earlier investigation (Küster 1991: 183) claimed that a complete change of the spectrum of cultural plants for this period could be detected. Our study, however, suggests otherwise: for the Late Bronze Age, barley, emmer, and broomcorn millet are recorded as the main cereals, with subdominant spelt and einkorn. On current data, the main changes refer to only two cereal taxa: parts of the barley production are replaced by broomcorn millet. A mixed find of mainly stored emmer and rye brome grains, along with low numbers of other weed finds, at the mountain site of Kulm, Trofaiach (Stika 2000: 165–7), suggests the cultivation of rye brome for its grains at higher elevations.

For the non-cereals (Table 19.6), pulses are important and are recorded with moderate representativeness especially for the Late Bronze Age (RI = 90), with low scores for the Early and Middle Bronze Age (RI = 44). In the Early/Middle Bronze Age, garden pea is dominant with few counts for field bean and lentil. Towards the Late Bronze Age, pulses become even more important with garden pea still being dominant, but now with a subdominance of field bean and lentil. Additionally, there are a few counts of bitter vetch. The oil plants poppy, gold-of-pleasure, and linseed are present with single counts, as is grape.

Table 19.6 RI Values of Non-Cereals in the Archaeobotanical Record of the Eastern Alps and their Foreland

Plant species		EBA	MBA	LBA
Lens culinaris	lentil		4	26
Pisum sativum	garden pea	12	24	33
Vicia ervilia	bitter vetch			6
Vicia faba	field bean	1	3	25
Camelina sativa	gold-of-pleasure			2
Linum usitatissimum	flax			1
Papaver somniferum s.l.	opium poppy	2	2	2
Vitis vinifera (undiff.)	grapevine	3		

Table 19.7 RI Values of Non-Cereals in the Archaeobotanical Record of the Western Alps and their Foreland

Plant species		EBA	MBA	LBA
Lathyrus sativus/cicera	grass pea			2
Lens culinaris	lentil			32
Pisum sativum	garden pea	4	1	15
Vicia faba	field bean	2	8	37
Camelina sativa	gold-of-pleasure			10
Linum usitatissimum	flax	5	2	24
Papaver somniferum s.l.	opium poppy	1		52
Castanea sativa	sweet chestnut			1
Vitis vinifera (undiff.)	grapevine			1

Western Alps and their Foreland

This region is extremely well represented for the Late Bronze Age, especially due to the well-investigated lakeside settlements with huge quantities of plant finds: Early Bronze Age (RI = 88), Middle Bronze Age (RI = 157), and Late Bronze Age (RI = 556). Twenty-four sites were evaluated in total. For the Early/Middle Bronze Age, three main cereals are reported: barley being dominant, emmer, and spelt subdominant. Free-threshing wheat and einkorn are frequently reported but of little importance. For broomcorn millet and oats only few counts and a single count for rye are given. In the Late Bronze Age, broomcorn millet increased and foxtail millet becomes important, arriving at its highest representativeness for all evaluated regions in this study. Barley and emmer decrease during the Late Bronze Age. Free-threshing wheat is still frequently represented, both tetraploid and hexaploid naked wheats being determined from rachis fragments (e.g. Jacomet and Karg 1996: 235). In Zug-Sumpf, spelt is quite important with 19 storage finds (a total of 68 storage finds from that site), but nevertheless hulled barley is the dominant cereal there (Jacomet and Karg 1996: 228–9). At the Late Bronze Age lakeside settlement of Hagnau-Burg on Lake Constance (Rösch 1996: Tab.le 1), three spikelets of oats were found and determined as common (i.e. cultivated) oats (*Avena sativa*).

For the Early/Middle Bronze Age the non-cereals (Table 19.7) are represented mainly by pulses, with a dominance of field bean and a subdominance of garden pea, and finds of linseed and opium poppy. Towards the Late Bronze Age, the representativeness rises considerably with field bean and lentil being dominant and garden pea being subdominant. Grass pea is represented with two counts only. The increased counts of oilseeds (RI = 86) during the Late Bronze Age are dominated by opium poppy with a subdominance of linseed and several counts for gold-of-pleasure. The latter is considered a weed in flax fields (Jacomet and Karg 1996: 249). The lakeside settlements, with both carbonized and waterlogged preservation conditions, reflect crop cultivation quite well, for both cereals and non-cereals.

West-Central Europe (Outside the Alps)

This region is quite diverse in terms of environmental setting. The sites are mainly located in Baden-Württemberg and Hesse in Germany, and Lorraine in France. The lower Rhine region,

Luxemburg, Bavaria as well as parts of northern Germany (but away from the North Sea) are included too, so we end up with quite a mixed group. Even allowing for that, the representativeness for the earlier phases is in general rather low: Early Bronze Age (RI = 65), Middle Bronze Age (RI = 35). The Late Bronze Age (RI = 284) is, however, well represented.

For the Early/Middle Bronze Age the dominance of barley is documented, mainly relying on its hulled variety. Emmer and spelt are subdominant. Einkorn and broomcorn millet are frequently reported but without any importance as far as the main crops are concerned. Free-threshing wheat, foxtail millet, and rye are reported with single counts. The Late Bronze Age results display an increase in broomcorn millet and a decrease in barley. In spite of an increase in scores of spelt in our evaluation, its percentage decreases towards the Late Bronze Age. A publication by Karl-Heinz Knörzer (1972: 399–401) reports several finds of grains of oats at the Urnfield site of Langweiler. In addition, spikelet bases were also found, both from common wild oats (*A. fatua*) and common (cultivated) oats. Langweiler, located on the Aldenhovener Platte in the westernmost part of North Rhine-Westphalia, thus hints at the presence of domesticated oats.

For non-cereals (Table 19.8), several taxa of pulses were found. In the Early/Middle Bronze Age, only a few counts were recorded of garden pea, field bean, lentil, and bitter vetch. Towards the Late Bronze Age, the representativeness of pulses rises (RI = 55): lentil and garden pea are dominant followed by some counts for field bean and single counts for bitter vetch and common vetch. The low counts of gold-of-pleasure in the Early/Middle Bronze Age are complemented by opium poppy and linseed in the Late Bronze Age.

For eastern central Europe we have not found enough data to arrive at an acceptable representativeness for the three phases of the Early, Middle, and Late Bronze Age. Research is ongoing at the well-known site of Bruszczewo in Poland. In the earlier period, barley and emmer are dominant. In the later period, there is a broad spectrum of cereals, with barley, emmer, spelt, free-threshing wheat, and broomcorn millet, as well as pulses with lentil, garden pea, bitter vetch, and field bean being present (pers. comm. H. Kroll). For the Czech Republic, a compilation was published very recently, containing valuable information that we were unable to include in this article (Kočár and Dreslerová 2010): 20 sites from the Early Bronze Age, 9 from the Middle Bronze Age, and 49 from the Late Bronze Age, indicating a clear dominance of emmer during the Early Bronze Age, with einkorn subdominant. Amounts of barley increase,

Table 19.8 RI Values of Non-Cereals in the Archaeobotanical Record of Western Central Europe (outside the Alps)

Plant species		EBA	MBA	LBA
Lens culinaris	lentil	2	1	24
Pisum sativum	garden pea	6		20
Vicia ervilia	bitter vetch		1	2
Vicia faba	field bean	2	1	8
Vicia sativa	common vetch			1
Camelina sativa	gold-of-pleasure	2	1	8
Linum usitatissimum	flax			3
Papaver somniferum s.l.	opium poppy			5
Vitis vinifera subsp. sylvestris	grapevine			1

Table 19.9 RI Values of Non-Cereals in the Archaeobotanical Record of Southern Scandinavia and the North Sea Coast

Plant species		EBA	MBA	LBA
Vicia faba	field bean			5
Camelina sativa	gold-of-pleasure			25
Linum usitatissimum	flax	1	1	22

and local flax cultivation begins. Millet cultivation is indicated from the Middle Bronze Age onwards. In the Late Bronze Age, the importance of einkorn decreases, leading to approximately equal proportions of four main cereals: emmer, barley, millet, and spelt. This is also the period when the cultivation of naked wheat begins in the region.

Southern Scandinavia and North Sea Coast

The data used for this region originate mainly from two recent compilations (Robinson 2003; Kučan 2007). The total of 26 sites, however, produced only weak representativeness for the Early Bronze Age (RI = 57) and Middle Bronze Age (RI = 27) and moderate values for the Late Bronze Age (RI = 177). Nevertheless, the data available for the North Sea coast and southern Scandinavia have greatly increased compared with what was available to previous researchers (Bakels 1991: 286–8; Jensen 1991: 337–8).

For cereals, the region is dominated by barley with a subdominance of emmer. Barley is represented with both its varieties, the free-threshing form and the hulled form. Spelt, free-threshing wheat, einkorn, and broomcorn millet are reported with few counts. In the Late Bronze Age site of Rodenkirchen in the marshlands of the River Weser (Kučan 2007: 40), aside from spikelets of wild oats, one grain within its spikelet and one spikelet basis were identified with certainty as common oats. There is no change detectable in the percentage of cereal counts towards the Late Bronze Age. Non-cereals are represented by linseed and gold-of-pleasure (Table 19.9).

On a coarse scale, not much change is visible during the Bronze Age. But when focusing on sub-regions, some changes seem to be detectable. In Thy, northern Jutland, from the Early to the Late Bronze Age barley and emmer persisted as the main crops (Stika and Henriksen 2010). No shift is visible from free-threshing to hulled barley as a main crop. In this region the change took place in the Iron Age around AD 100. In eastern Denmark and southern Sweden (Gustafsson 1998), the shift is observable one thousand years earlier in the Late Bronze Age.

Individual Cereals, Plants, and Trees

Barley

During the Early and Middle Bronze Age, barley is the dominant cereal in all regions of Europe evaluated in our analysis. In most regions the replacement of naked (free-threshing) barley by hulled barley took place already before the Bronze Age, in Greece and southern

Bulgaria, the Pannonian Basin, the eastern and western Alps, western central Europe, and southern France. Nevertheless, free-threshing barley is still recorded for these regions at low levels. In Mediterranean Spain as well as in southern Scandinavia and the North Sea coast, both for the Early/Middle Bronze Age and the Late Bronze Age, the record of free-threshing barley versus hulled barley remained balanced between both varieties. In some regions a slight decrease of barley is detectable from the Early/Middle Bronze Age towards the Late Bronze Age: Greece and southern Bulgaria, the Pannonian Basin, and in the eastern and western Alps. However, in all regions barley remains an important crop.

Wheat

The tetraploid hulled wheat species of emmer is among the main crops in all regions. In southern Spain its importance is somewhat less than in the other regions of Europe. The semi-arid south-west of Spain, from which the records for the Early/Middle Bronze Age in Mediterranean Spain are mainly derived, was probably too dry for emmer cultivation. In ecological terms, the Atlantic area of northern Spain, a region not included in our evaluation, is more suitable for emmer cultivation; emmer is still grown today in that region (Peña-Chocarro 1996: 131–3). In central and northern Italy (without the Alps and their foreland), emmer is the predominant cereal for the Early/Middle Bronze Age and Late Bronze Age. In a few regions, specifically Greece and southern Bulgaria, and in the western Alps, emmer slightly decreases towards the Late Bronze Age.

The diploid hulled wheat einkorn is an important cereal of Greece and southern Bulgaria, and in the Pannonian Basin, with slightly less dominance in central and northern Italy and southern France. In the other regions einkorn is listed frequently but with low counts. The Bronze Age finds, as well as recently cultivated einkorn in the Archaeological Park at Százhalombatta, have well developed grains, and cultivation seems to be productive in this region, as we can attest from our own experience. Generally there is a slight decrease in einkorn towards the Late Bronze Age in many regions.

The hexaploid hulled wheat species spelt tells another story. In contrast to einkorn and emmer, both deriving from wild ancestors in the Fertile Crescent and domesticated there (Zohary and Hopf 2000: 19–51), no wild-growing ancestor exists there for spelt; it evolved under cultivation. Apart from some 'Asian' spelt appearing early in Transcaucasia (see Zohary and Hopf 2000: 57), there seems to be a 'European' spelt of different origins, probably based on an introgression of a tetraploid hulled wheat (emmer) into free-threshing hexaploid wheat (bread wheat) as discussed by Örni Akeret (2005: 284 for discussion and further references). He dates the beginning of spelt cultivation in the northern Alpine foreland of Switzerland between 2400 and 2200 BC. There are even older hints of a 'European' spelt from south-western Germany and areas further north (cited in Körber-Grohne 1987: 72). One may conclude that the 'European' spelt possibly originated somewhere north of the Alps prior to the Bronze Age, and spread from there in the period transitional to the Early Bronze Age. This hypothesis is well displayed in our online diagrams: for the Early/Middle Bronze Age onwards, spelt is a dominant cereal in western central Europe, the western and the eastern Alps, and their respective forelands. From there it seems that spelt cultivation spread north to the North Sea coast and southern Scandinavia, south-west to southern France, and east and south-east to the Pannonian

Basin and Greece (with southern Bulgaria). The rise of spelt cultivation in Late Bronze Age Greece is remarkable. During the Bronze Age spelt was introduced neither to the Iberian Peninsula nor to Italy south of the Po.

Since Jones, Valamoti and Charles (2000) and Kohler-Schneider (2001: 116–25) have introduced the archaeobotanical community to a 'new' glume wheat, basing their belief on identifications from northern Greece and from eastern Austria ('emmer-like spelt wheat'), several researchers have found a new type of glume wheat which might be related to the tetraploid Timopheev's wheat (*Triticum timopheevi*). The identification can, however, only be carried out on well-preserved spikelet forks. In our experience the 'new type' glume wheat is present in archaeological samples from Turkey via the Balkans to Germany, and from the early Neolithic through to Early Iron Age layers. From the available literature, at the moment we cannot draw a reliable map of its distribution during the Bronze Age. In our evaluation we used the grain finds to describe the proportions of the different cereals in cultivation and use. The grains that might be connected to the spikelet forks of the 'new type' glume wheat can still not be identified with certainty, however, and the importance of this cereal is still largely unknown.

In free-threshing wheat, it is impossible to distinguish with certainty between tetraploid (*Triticum durum/turgidum*) and hexaploid (*T. aestivum* s.l.) species by grain morphology alone. There are quite globular grains that might be determined as hexaploid club wheat (*T. compactum*), a taxon mostly treated as a subspecies of *Triticum aestivum* s.l. (the wheat taxonomy in this paper follows the classification accepted by archaeobotanists, but which is not the latest nomenclature in systematic botany: see Jacomet 2006). Only if well-preserved rachis fragments are found in archaeobotanical samples can a more detailed classification be given. For Fuente Alamo in Spain (Stika 2001: 272) and Zug-Sumpf in Switzerland (Jacomet and Karg 1996: 235), both tetraploid and hexaploid free-threshing wheats are reported from the same sites and layers. Free-threshing wheat was dominant in Mediterranean Spain, in southern France, and central and northern Italy. In these three regions free-threshing wheat increased from the Early/Middle Bronze Age towards the Late Bronze Age. In all other evaluated regions free-threshing wheat is recorded but not of great importance in cultivation and use, either for the Early/Middle Bronze Age or the Late Bronze Age.

Due to identification problems with archaeobotanical finds, the reliability of the proportions within recorded finds of wheat species is far from satisfactory.

Millets

In prehistoric Europe, two species of millet (i.e. small-grained cereals) are cultivated: broomcorn millet and foxtail millet. Both species are first recorded from the seventh–sixth millennia BC in the Yellow River Valley and other regions in northern China. Broomcorn millet appeared almost synchronously in eastern Europe and the Caucasus, while the appearance of foxtail millet in Europe (fifth–fourth millennia BC) was delayed (Hunt et al. 2008: 5). Both millet species were widespread in the European Neolithic as well as the Early and Middle Bronze Age (Zohary and Hopf 2000: 83–8), though not grown as main crops. As our compilation clearly shows, the transformation of millets from minor to major (or even main) crops took place in the transition from Middle to Late Bronze Age in Europe. Broomcorn millet became important in many of the evaluated regions (Greece and southern Bulgaria, the Pannonian Basin,

the Alps and their foreland, western central Europe, and in Italy). In the Bronze Age of the Iberian Peninsula, southern France, the North Sea coast and southern Scandinavia, millets are reported but of minor importance. During the Late Bronze Age foxtail millet became an important crop only in the western Alps and its foreland. Later, especially in medieval times, broomcorn and foxtail millet became the main crops on sandy soils in several parts of Europe (Körber-Grohne 1987: 332–6).

Oats

In the pre-Roman Iron Age settlement of Rullstorf on the lower terrace of the Elbe Valley close to Lüneburg, the currently oldest storage find of oats was discovered, and determined as cultivated common oats by their well-preserved glume bases (Behre 1990: 148–50). In contrast, during the Bronze Age only single finds of common oats are reported. In the regions we have evaluated one grain within its spikelet and one separate spikelet basis of common oats were identified with certainty in the Early Bronze Age site of Rodenkirchen in the Weser marshlands (Kučan 2007: 40). Later, from the Urnfield site of Langweiler on the Aldenhovener Platte in the westernmost part of Germany, several finds of spikelet bases of common (cultivated) oats are reported (Knörzer 1972: 399–401). At both sites, apart from common oats, common wild oats are also reported. *A. fatua* is, together with *A. sterilis*, one of the probable wild progenitors of common (i.e. cultivated) oats (Zohary and Hopf 2000: 78–82). The three spikelets of common oats from the Late Bronze Age lakeside settlement of Hagnau-Burg on Lake Constance (Rösch 1996: Table 1) are reported with no finds of wild oats species. This might suggest that the domestication of common oats happened in the transition phase between the Bronze and Iron Age somewhere in northern Germany or neighbouring areas. The cultivation of common oats spread in the Roman Iron Age along the North Sea coast, and later on the species became a main crop especially in the northern European countries (Körber-Grohne 1987: 64–5).

Rye

In several evaluated regions we have records of rye grains (e.g. the Pannonian Basin, the Alps and their foreland, western central Europe, and the North Sea coast and southern Scandinavia). Rye migrated to Europe as a weed among other cereals, with single finds from the Neolithic and increasing numbers during the Bronze and Iron Ages (Behre 1992). The start of rye as a crop in its own right is estimated by Karl-Ernst Behre (1992) to have taken place independently by acculturation in different areas during the pre-Roman Iron Age and Roman period. The further spread of cultivated rye happened during the early Middle Ages. It is usual to assign the few Bronze Age finds of rye in Europe the status of a weed.

Legumes/Pulses

There are several species of legume of great importance in Bronze Age Europe. This is not only due to the use of their seeds in human nutrition, but additionally for their ability to fix atmospheric nitrogen in symbiosis with root-associated rhizobium bacteria (*Rhizobium* s.l.).

Crop rotation involving pulses following cereal cultivation can therefore help to maintain higher levels of soil fertility (Zohary and Hopf 2000: 92). In the Bronze Age the main legume crops are field bean, lentil, and garden pea. Of more regional importance are bitter vetch, grass pea, common vetch, and chickpea. Their wild ancestors are mainly distributed in the eastern Mediterranean basin and the Near East, or are of unknown origin, as in the case of field beans. In Bronze Age Europe the domestication process was over and the cultivation of pulses was already widespread. For Greece and southern Bulgaria, Italy, the Pannonian Basin, and the eastern Alps and their foreland, both diversity and representativeness of the pulses are high. There is a trend towards an increase in pulse cultivation during the Late Bronze Age in some regions, such as central western Europe, the Alps and their foreland, and Italy.

Oil Plants

In diversity and representativeness it is again the region of Greece and southern Bulgaria that display the highest values in this group. However, for all the other evaluated regions, the record of oil plants is low, or at best rather unbalanced. Oilseeds are generally under-represented in sites where only charred material is preserved; they are easily destroyed when they are in contact with fire. Where waterlogged preservation conditions exist, the representativeness of oil plants is therefore much higher, as seen in the western Alps and their foreland as well as the North Sea Coast and southern Scandinavia. In contrast, in Italy, Mediterranean Spain, and southern France values are low by comparison.

Linseed and opium poppy are old domesticates that spread throughout Europe from the Neolithic on. During the Bronze Age lallemantia and safflower are regionally limited to the south-eastern part of Europe in their use and distribution. Gold-of-pleasure is a secondary crop and was acculturated from its weed ancestor growing in linseed fields, and used in its cultivar form from the Bronze Age onwards (Zohary and Hopf 2000: 138–9). The Late Bronze Age pure storage find of gold-of-pleasure from Kastanas, filling a whole vessel, is proof of the intentional use of this oil plant (Kroll 1983: 58–9). Likewise, a large quantity (> 8 kg) of crop-processing by-product of gold-of-pleasure from the North Sea coast Late Bronze Age settlement of Rodenkirchen clearly demonstrates its cultivation and use in this region (Kučan 2007: 41–3). As gold-of-pleasure is a salt-tolerant plant, it is suitable for cultivation in these marshland areas sometimes affected by storm tides.

Fruit Trees (and Other Cultivated Fruit)

In our evaluation fruit trees are recorded with remarkable scores for three regions: Greece and Bulgaria, central and northern Italy, and Mediterranean Spain. For southern France only single scores are reported, which might relate to the weaker data basis of the region. Fig, olive, and grape are the species involved, but their domestication status during the Bronze Age is still a matter of debate. For the Pannonian Basin as well as the eastern Alps and their foreland, grape is reported, but located in the range of the natural distribution of wild grape. Additionally, there are reports from Italy of almond and plum, and from Greece of pomegranate and melon as a herbaceous cultivated fruit. The probable use of all these species is undoubted, in contrast to the status of their domestication. Perhaps agreement can be found that during the Bronze Age the Mediterranean area

was the starting point of European fruit- tree cultivation, and probably of the first stages of their domestication.

Conclusion

Before concluding, we need to decide how much the observed (or supposed) patterns of Bronze Age crop cultivation as evaluated in this study (see Tables 19.1–19.9) follow natural and social environmental conditions. Natural factors limiting crop cultivation influence marginal regions, like Mediterranean Iberia with its semi-arid conditions, or the North Sea coast and southern Scandinavia with their cold, wet, and frequently salt-influenced situation, or the Alps at higher altitudes (Primas 2009: 193–6). Consequently, these regions display some significant differences in their crop systems, such as the cultivation of salt-tolerant crops (field bean, gold-of-pleasure, and barley) in the North Sea coastal area.

In other regions the cultivation of cereals, pulses, and oil plants probably follows social factors that determined a preferred food system. Millets, for example, are completely different from large-grained cereals in their ecology and therefore their cultivation demands, their processing, and their consumption. How easily wheats can be used for baking bread, as another example, separates the wheat species from all other cereals cultivated during the Bronze Age. The influence on crop choices of bread-baking and other food preparation methods on the one hand, and their influence on crop representation in the archaeobotanical record on the other, is still a difficult issue, as demonstrated by recent research on porridge/bread remains (Hansson 1994; Heiss 2008: 26–30, 131–7; Valamoti et al. 2008), or on beer/malt (Stika 1996b). The beer topic is among many others discussed in Van Zeist (1991: 118–21), Kroll (1991b), and Procopiou and Treuil (2002).

At all events, the shift to millet, spelt, and hulled barley together with an increase in pulse cultivation that is observed in some regions towards the Late Bronze Age, reflects a change in subsistence strategies, and changes in the agrarian system in general. These may have happened because of the growth of local populations, the building of settlements in new landscapes with different natural conditions, or the acquisition of new techniques. Changes in the agrarian system, for example, are indicated in the Nordic Bronze Age by the switch from the two-aisled house to three-aisled farms with the byre included (most recently Fokkens 2009: 91), introducing the possibility of manuring with cattle dung, now readily available. There are hints at manuring described by Helmut Kroll (1987: 107–9) for the North Sea island of Sylt, which might explain the formation of 'Celtic field' systems (Fokkens 2009: 94). Numerous other indications of the beginning of manuring are given by Bakels (1997), De Hingh (2000: 159–62), Robinson (2003: 163), Brinkkemper and van Wijngaarden-Bakker (2005: 496), and in Stika and Henriksen (2010). As visible in the Nordic Bronze Age, the mixed-farming economy using cattle traction (see Chapter 18) for ploughing permanent fields with an ard (Fokkens 2009: 90) changed and intensified the agrarian system. Lists of ard finds and traces of ploughing, as well as field systems of Bronze Age date, are given by Tegtmeier (1993) and Fries (1995).

Another feature, much more difficult to grasp, is represented by the cultural aspects of plant cultivation, their processing and consumption—for instance, fostering esteem or disregard of certain crops, maybe even their tabooization. Field beans, for instance, were strongly

connected to death and the underworld in Hellenistic Greece (Hanelt 1972: 209; Ciarialdi 1999), and in Egypt, according to Herodotus, they were even considered unclean and taboo for certain social groups, such as priests (*Histories* II, 37; Macaulay 1890). Such beliefs may have seriously affected the choice or avoidance of certain crops (Hansson and Heiss forthcoming).

Even if this short chapter can only scratch the surface of what actually might have taken place during the centuries of the European Bronze Age, a few clear trends have been highlighted and discussed. Archaeobotany has already contributed significantly to the knowledge of prehistoric agricultural systems, and thanks to the ever-increasing data basis, we believe it will do so even more in the future.

Note

A longer version of this chapter with additional illustrative and tabular material is available online on the Oxford Handbooks website.

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CURRENT ARCHAEOBOTANICAL RESEARCH ON AGRICULTURE AND ENVIRONMENT OF LA TÈNE SETTLEMENTS IN LOWER AUSTRIA

ANDREAS G. HEISS · MARIANNE KOHLER-SCHNEIDER

Archaeological and archaeobiological analyses performed during the past twenty years have shown that the loess hills of the Weinviertel region in north-eastern Lower Austria (Fig. 1) have been continuously and intensively used for agrarian production since the arrival of the first Linear Pottery farmers 7,000 years ago. Numerous archaeobotanical data document these earliest phases of agrarian activities in Lower Austria up to the Late Neolithic[1]. Several sites from the Bronze Age have already been analysed as well[2].

Recently, a research focus on Late Iron Age sites in Lower Austria has been developing, involving work groups at the BOKU Vienna[3], the Prehistory Museum of Lower Austria[4] and the Museum of Natural History of Vienna (NHMW)[5]. Their joint objective is to gain insight into the agricultural practices of more complex societies, their economic basis and the dynamics between "urban" and rural settlements. Much of this research has been stimulated by work on the extraordinarily rich zoological and botanical material recovered from the large "Celtic city" near Roseldorf, a middle to late La Tène economic and religious centre, being excavated since 2001[6]. Parallel investigations on smaller villages raised questions about possible economic relationships between the Roseldorf agglomeration and its hinterland[7]. Since comprehensive archaeobotanical results are currenty available from only four exca-vation sites, no complete picture can be drawn as yet. The present article is rather intended to draw a first outline of the patterns of La Tène land use and subsistence in the Weinviertel region, and to provide a first glimpse of the coming analyses.

1 Kohler-Schneider 2007; Kohler-Schneider / Caneppele 2009; 2010.

2 Schneider / Raunjak 1994; Kohler-Schneider 2001; Wiesinger / Thanheiser 2009; Heiss / Thanheiser 2010.

3 Marianne Kohler-Schneider and Andreas G. Heiss.

4 Peter Trebsche and Ernst Lauermann.

5 Manfred Schmitzberger and Erich Pucher.

6 Kohler-Schneider / Caneppele / Heiss forthcoming; Holzer 2009; 2010.

7 Heiss / Kohler-Schneider forthcoming; Kohler-Schneider forthcoming; Kohler-Schneider / Heiss 2010.

THE REGION

As already mentioned, the Weinviertel represents the most important area of the fertile glaciogenic loess soils on Austrian territory, basically stretching from the crystalline Manhartsberg mountain range in the west to the Slovak border in the east and the river March. The Danube defines the limits of its area to the south, the river Thaya to the north, the latter forming the major part of the border to the Czech Republic (Fig. 1).

Local climate is of subcontinental character with hot summers and rather cold winters (although monthly mean temperatures hardly fall below 0°C). From a biogeographical point of view, the region belongs to the westernmost portion of the Eurasian steppe region, the Pannonian province, stretching from eastern Austria to the west of Romania, and from southern Moravia to northern Serbia. The natural vegetation in the lowlands of this province is a mosaic of deciduous forests (oak / hornbeam forests, thermophilous oak forests), forest steppes and steppe patches. The latter are mainly found on steep, south facing slopes and on stony, gravelly or sandy soils. Along the rivers and in flat valley bottoms, floodplain forests and other wetland vegetation play an important role[8]. Overall, the Pannonian biogeographical province is a transition area between the moderately humid deciduous forest climate of central Europe and the dry steppe climate of south-eastern Europe. At any rate, it has much in common with the forest-steppe belt of Ukraine and Southern Russia – including its suitability for a cereal-based agriculture. Especially on the fertile chernozem soils that have developed on glacial loess deposits, the former natural vegetation has been largely replaced by crop fields.

Annual precipitation is low by central European standards (Fig. 2), yet still highly suitable for agriculture. Due to the low precipitation rates, the sparseness of water bodies and the anthropogenic drainage of the formerly abundant wetlands in the 19th and 20th century[9], sources for off-site pol-

8 Niklfeld 1993.

9 Sauberer 1993.

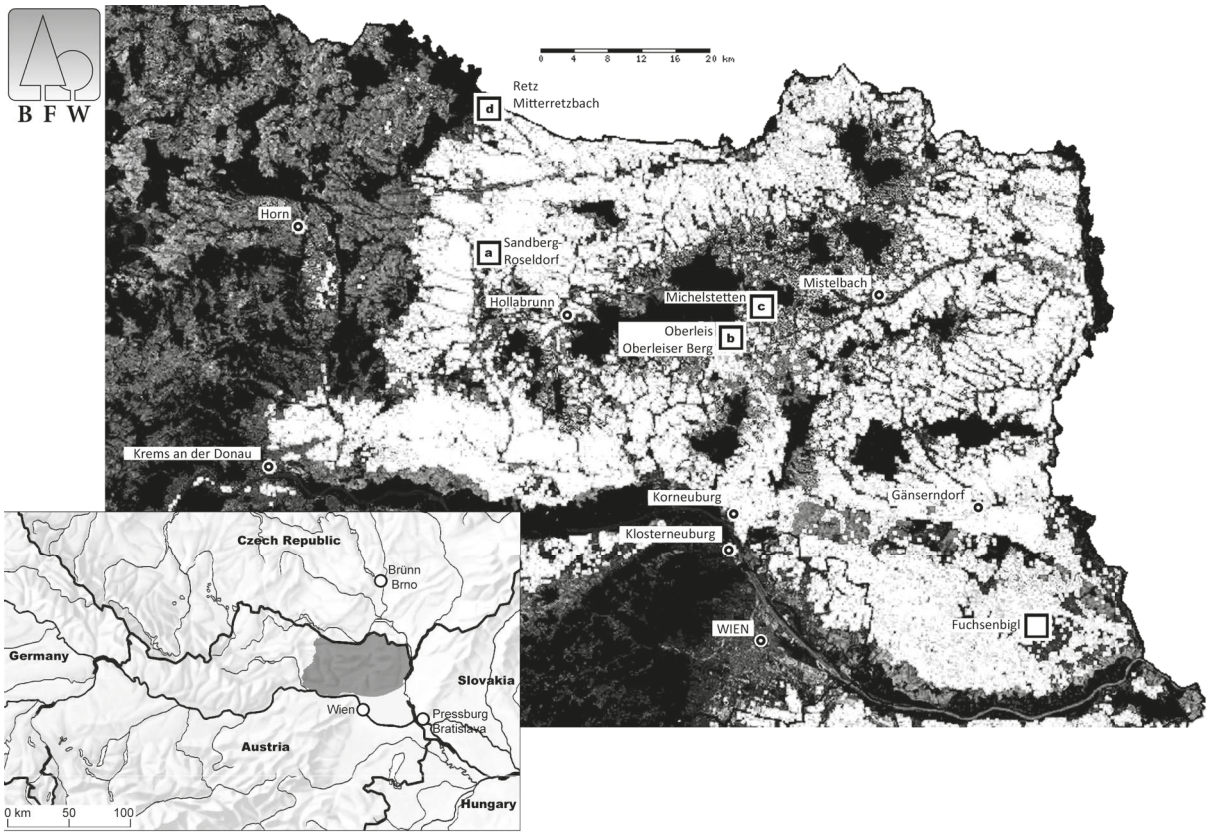


Fig. 1: Lower Austria and the loess hills of the Weinviertel (small map: shaded area) with the sites mentioned in the text marked by squares. a, b, c, d: sites with published archaeobotanical data available. Chernozem soils, their distribution mostly corresponding with the Weinviertel region, are indicated in bright shades in the large map. While mainly found on loess sediments, in the region south of Gänserndorf they are formed on alluvial sediments. Map sources: Spiess (2002) and BFW (2012).

len data such as bogs, fens, lake or oxbow sediments are very scarce, if lacking altogether. Data on ve-getation changes and land-use in the region must therefore be derived from on-site archaeological plant remains, which in the well-drained loess sediments are only preserved in charred state[10].

THE EXCAVATION SITES

So far, archaeobotanical data are available – and already partly published – from four sites (Fig. 1) and will briefly be discussed here[11]. In decreasing order of settlement size, these are:

a) Sandberg-Roseldorf (48°39'43"N, 15°57'29"E, 315 m a.s.l.), a large middle La Tène lowland settlement of almost urban character, covering at least 38 ha and obviously representing a centre of considerable economic and religious importance[12]. Approximately 27,000 plant remains have been analysed from Sandberg-Roseldorf up to now.

b) the late La Tène hillfort at Oberleiser Berg (48°33'30"N, 16°22'21"E, 492 m a.s.l.) covering an area of 7.35 ha[13]. A total of 3,451 plant macroremains have been analysed from La Tène contexts of this site.

c) the middle to late La Tène village of Michelstetten (48°35'07"N, 16°25'38"E, 309 m a.s.l.), exceeding 1 ha[14] in size, the samples yielding 1,526 plant remains.

d) the biphasic site of Mitterretzbach (48°47'14"N, 15°58'15"E, 256 m a.s.l.) with an early and a middle La Tène hamlet, both extending to areas less than one hectar[15]. 3,475 plant remains have been analysed so far from Mitterretzbach.

10 See Jacomet / Kreuz 1999.

11 See also Trebsche, this volume.

12 Holzer 2008; 2009; 2010; Caneppele / Heiss / Kohler-Schneider 2010; Caneppele / Kohler-Schneider 2009a; 2009b.

13 Kern 1987; 1992; Schneider / Raunjak 1994.

14 Lauermann 2010; Kohler-Schneider / Heiss 2010.

15 Trebsche forthcoming; Heiss / Kohler-Schneider forthcoming.

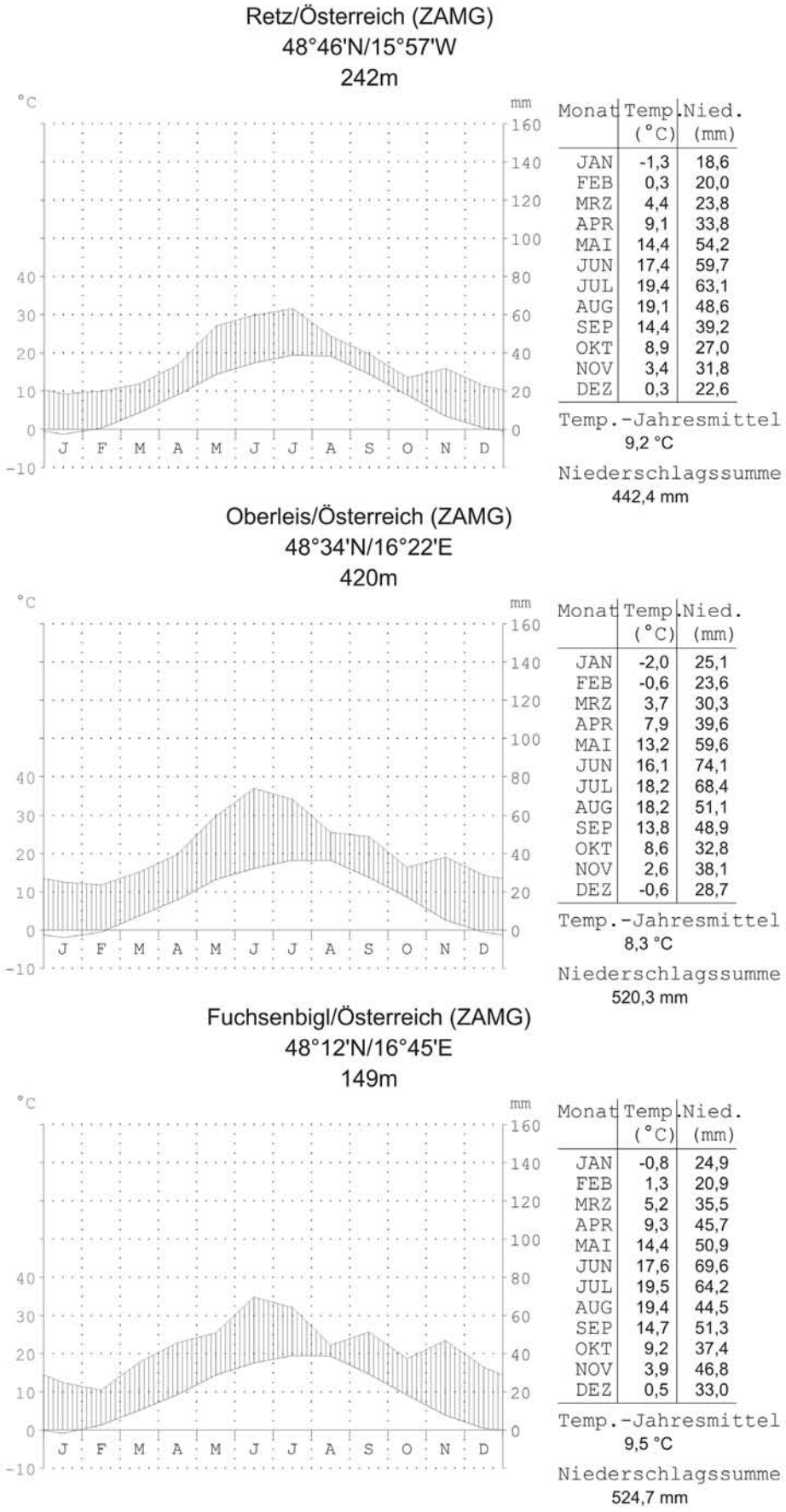


Fig. 2: Climate diagrams along a transect of the Weinviertel region. Data source ZAMG (2002), visualized with the software GeoKLIMA (Hanisch / Schulz 1998).

Sandberg-Roseldorf

This settlement of "urban" dimensions is situated in the centre of the loess plains of the western Weinviertel. The loess deposits reach a depth of up to 9 metres here, bearing a very fertile chernozem top-soil layer: intensive agriculture is still the main economic branch in the region.

The excavations yielded extraordinarily rich and well-preserved archaeobotanical material of which 20,000 plant remains have been analysed so far. Here we present results from three archaeological contexts: the ditch filling of a sanctuary (Sanctuary 1, "Heiligtum 1"), a supposed sacrificial pit, and an extraordinarily large storage find within a burnt granary, containing 204 litres of charred cereals. The remains identified from the filling of Sanctuary 1 seem to represent settlement waste from the very final phase of the temple's operation, or even from after its abandonment.

The analyses of the granary show a distinct dominance of hulled barley (*Hordeum vulgare*) in one of the two compartments of the building, and of the hulled wheat species einkorn (*Triticum monococcum*) and spelt (*T. spelta*) in the other. According to their weed spectra, both storage finds can be interpreted as deriving from spring-sown (barley) and autumn-sown fields (hulled wheat), respectively[16]. While the numerous chaff finds from the granary point to the storage of cereals within their glumes, glume remains and spikelet forks from outside this context represent the remains of cereal processing. Apart from these three main cereals, broomcorn millet (*Panicum miliaceum*) also must have played a major role in the settlement, as can be seen from the results from the temple area[17]. Additionally, naked wheat, rye and (possibly cultivated) oat were found. Pulses and oilseeds were represented by lentil (*Lens culinaris*), pea (*Pisum sativum*), gold-of-pleasure (*Camelina sativa*), opium poppy (*Papaver somniferum*), and flax (*Linum usitatissimum*). Also two plants deriving directly or indirectly from imported goods were identified: cultivated grapevine (*Vitis vinifera* ssp. *vinifera*) and dill (cf. *Anethum graveolens*). The find of cultivated grape might either relate to imported dried fruits or to an early local cultivation tradition (compare contemporary finds from eastern Austria and western Hungary[18]), based on vines brought from the Mediterranean region. Likewise, dill might have been cultivated locally from seeds imported from the Mediterranean, as already suggested for other sites, for example Basel-Gasfabrik[19] in Switzerland.

Seeds of segetal plants identified in Roseldorf allowed for a differentiation between spring-sown and autumn-sown crops in the granary stores. Likewise, the low height of some of the identified taxa (petty spurge *Euphorbia peplus*, field pennycress *Thlaspi arvense*, or roundleaf cancerwort cf. *Kickxia spuria*) together with scattered finds of straw fragments indicate that cereals were harvested close to the ground. Other wild plants originating from meadow-steppes relate to the traditional use of such areas as pastures. They also provide information on the size of the settlement's catchment area: among the numerous finds of grassland plants, many come from sites with calcareous soils (e. g. steep loess slopes and thus probably from the immediate vicinity of the settlement), while others clearly originate from stands on acidic substrates, like sheep fescue (cf. *Festuca ovina*), perennial knawel (*Scleranthus perennis*), and rabbitfoot clover (*Trifolium arvense*). They must have been transported to the Sandberg settlement from a distance of at least 10 km to the west or northwest, since it is only on the slopes of the Manhartsberg range that such soils are found. The seeds may have been transferred to the settlement by transhumance of cattle, goats or sheep, acting as vectors for the diaspores. Other wild plants such as rowan (*Sorbus aucuparia*), whose fruit may have played some role in ritual feasting in the temple district[20], are limited to acidic soils as well: the closest natural stands of rowan are found on the slopes of Manhartsberg, their occurrence in the Roseldorf site indicating transport as well. This fits well with isotope analyses on horse skeletons, which indicate trade between this region and Roseldorf[21]. Numerous charcoal finds of beech (*Fagus sylvatica*) and silver fir (*Abies alba*)[22] point to areas even farther away than the Manhartsberg, as these tree species thrive only in low to middle mountain regions and never in the warm Pannonian climate, to which the Manhartsberg is still exposed. Today,

16 Caneppele / Kohler-Schneider 2009a.

17 Kohler-Schneider / Caneppele / Heiss forthcoming.

18 Kohler-Schneider 2001.

19 Kühn et al. 2008.

20 Caneppele / Heiss / Kohler-Schneider 2010; Heiss / Kohler-Schneider 2011.

21 Theiner 2011.

22 Grabner 2003; Kohler-Schneider / Caneppele / Heiss forthcoming.

their closest stands are found in deep valleys and on exposed plateaus of the neighbouring Bohemian massif, more than 30 kilometres to the west of Roseldorf. All in all, given the extremely fertile surroundings, the "Celtic city" of Roseldorf seems to have met all requirements of a producer site[23], yet there are numerous hints on intensive exchange of goods over short and long distances.

Oberleiser Berg and Michelstetten

These two settlements were inhabited synchronously, and were located close to each other in the central Weinviertel, where the carbonaceous rock cliffs of the Waschberg zone penetrate the dominating loess cover. Aside from the highly fertile chernozem soils, the region also features patches of shallow and stony soils on calcareous hillslopes. The two middle to late La Tène sites – the lowland settlement of Michelstetten, and the hilltop fort at Oberleiser Berg – are separated by a distance of only 5 km.

The rich cereal spectrum recovered from pit houses and cultural layers at Oberleiser Berg was dominated by barley (*Hordeum vulgare*) and broomcorn millet (*Panicum miliaceum*)[24]. Additionally, there were einkorn (*Triticum monococcum*), emmer (*T. dicoccum*), spelt (*T. spelta*), naked wheat (*T. aestivum / durum / turgidum*) and foxtail millet (*Setaria italica*), as well as possibly rye (cf. *Secale cereale*), all in rather low quantities (Fig. 3). The presence of both summer and winter crop arable weeds documents both forms of cultivation. Millet fields must have been of some importance, judging from the ubiquity of millet grains in the samples and from the abundance of wild Paniceae diaspores. Gathered wild fruit are mainly represented by kernels of Cornelian cherry (*Cornus mas*).

Despite lower overall diaspore numbers, the analysis of six pit houses from Michelstetten also resulted in a diverse spectrum of cultivated and wild plants[25]: The array of cultivated crops is basically comparable to the other sites, and to Oberleis in particular. Broomcorn millet and barley are dominant while einkorn, spelt, naked wheat, and a slightly higher proportion of emmer account for the rest of the spectrum. Chaff finds indicate crop processing in the settlement. Although finds of straw are missing, low-growing weeds such as blue woodruff (cf. *Asperula arvensis*) and crabgrass (*Digitaria* sp.) seem to indicate cereal harvesting close to the ground. *Asperula arvensis* and also corn gromwell (*Buglossoides arvensis*) are of special interest as they grow on dry, stony and calcareous soils: it seems that despite the abundance of fertile chernozem sites in the region, the inhabitants of the settlement also shallow, nutrient poor soils on stony slopes. This raises the question of whether crop growing in these poorer fields was just a matter of practicality (the hill slopes being located in the immediate vicinity of the settlements), or whether this must be taken as a sign for a very dense human population and emerging social inequality among farmsteads. Of course, the prevailing use of these poorer soils must have been for grazing livestock, as is indicated by both the archaeozoological record of mainly sheep / goats[26] and the numerous archaeobotanical finds of dry grassland species[27].

Mitterretzbach

This small site is situated in the north-western periphery of the Weinviertel, on the slopes of the Manhartsberg range. The area is characterised by a sharp transition between calcareous loess soils and acidic soils on crystalline rock. Today, ample dry heathlands are found in the latter sites. From the two late Iron Age settlements, six pit houses were analysed, four dating to the early and two to the middle La Tène period.

The overall crop spectrum (Fig. 3) is dominated by hulled barley (*Hordeum vulgare*), with subdominant occurrence of broomcorn millet (*Panicum miliaceum*), emmer (*Triticum dicoccum*), spelt (*T. spelta*), foxtail millet (*Setaria italica*), and einkorn (*T. monococcum*). Other cereals such as naked wheat (*T. aestivum / durum / turgidum*), wild or cultivated oat (*Avena* sp.) and rye (*Secale cereale*) occur only in minor quantities, as do lentil (*Lens culinaris*), pea (*Pisum sativum*), and flax (cf. *Linum usitatissimum*).

When differentiating between the two settlement phases of Mitterretzbach, they reveal a remarkable shift in cultivated crops which is also mirrored by the arable weed spectrum[28]: while the early phase is

23 Heiss / Kohler-Schneider forthcoming.

24 Schneider / Raunjak 1994.

25 Kohler-Schneider / Heiss 2010.

26 Schmitzberger 2010.

27 Kohler-Schneider / Heiss 2010.

28 Heiss / Kohler-Schneider forthcoming.

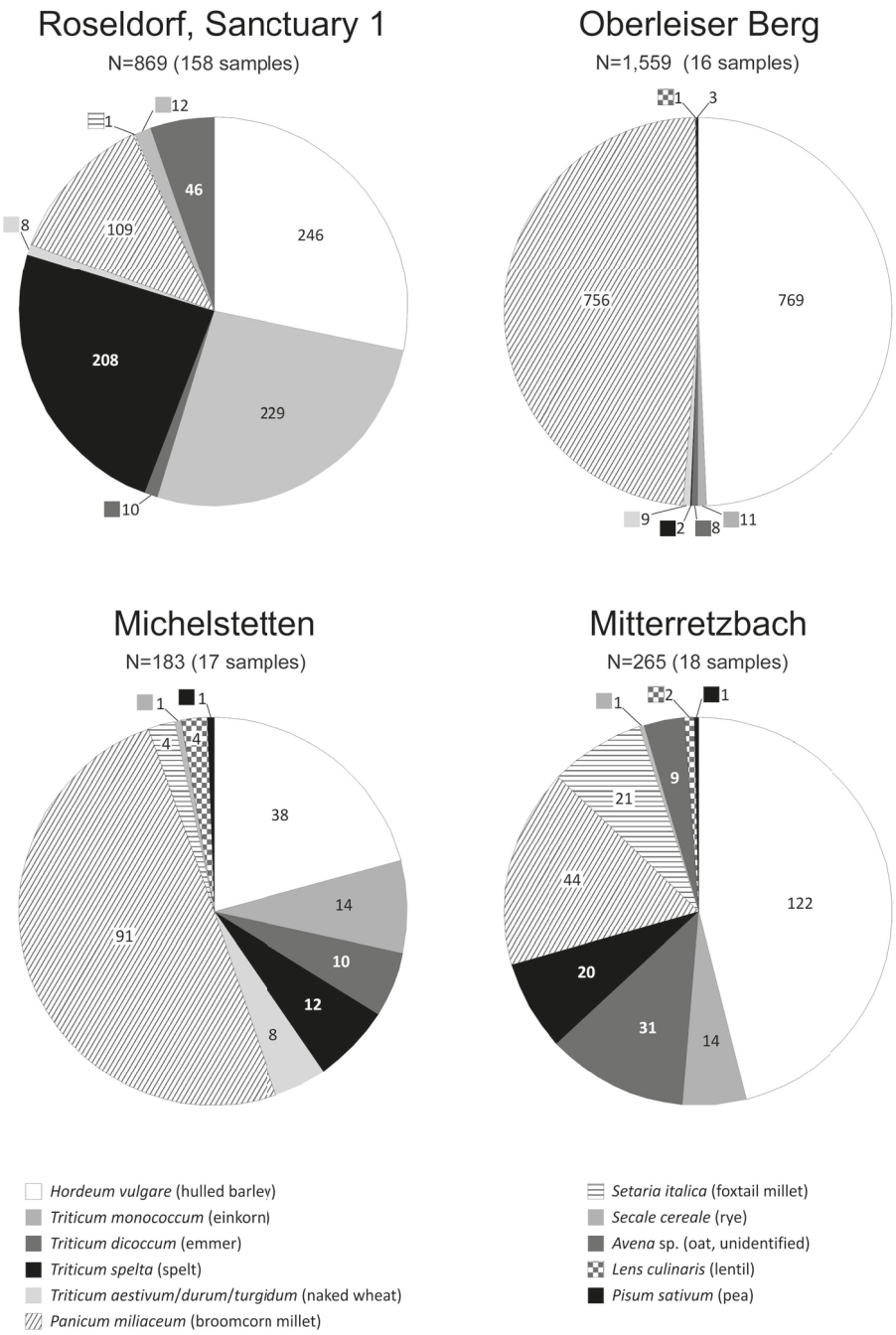


Fig. 3: Cultivated crops (cereals and pulses) from the La Tène settlements mentioned in the text. Only unambiguously identifiable grain finds were included, whereas chaff and uncertain identifications (intermediate groups and "cf." finds) were left out. Not mentioned in the diagrams are the rare finds of oilseeds, such as gold-of-pleasure (Camelina sativa, 41 grains from Roseldorf), flax (Linum usitatissimum, only two "cf." identifications from Roseldorf, and one from Mitterretzbach), and opium poppy (Papaver somniferum, 7 grains from Roseldorf).

characterised by a dominance of barley and millets, accompanied by arable weeds typical of spring-sown crops, the later phase displays a distinct shift towards hulled wheats and an increase of arable weeds typically found in autumn-sown crops. Millets almost disappear from the archaeobotanical record during this phase. The reasons for this marked change are unknown, but coincide with the quick rise of nearby Roseldorf, to which Mitterretzbach entertained close (trade?) contacts, as pointed out above. Given the low social reputation of millets and the generally higher status of cereals suitable for breadmaking found throughout European history[29], the change in the dominant cereals

29 See De Angelis 2006; Junkelmann 2006; and also Palmer / Van der Veen 2002, but mainly Heiss / Kohler-Schneider forthcoming.

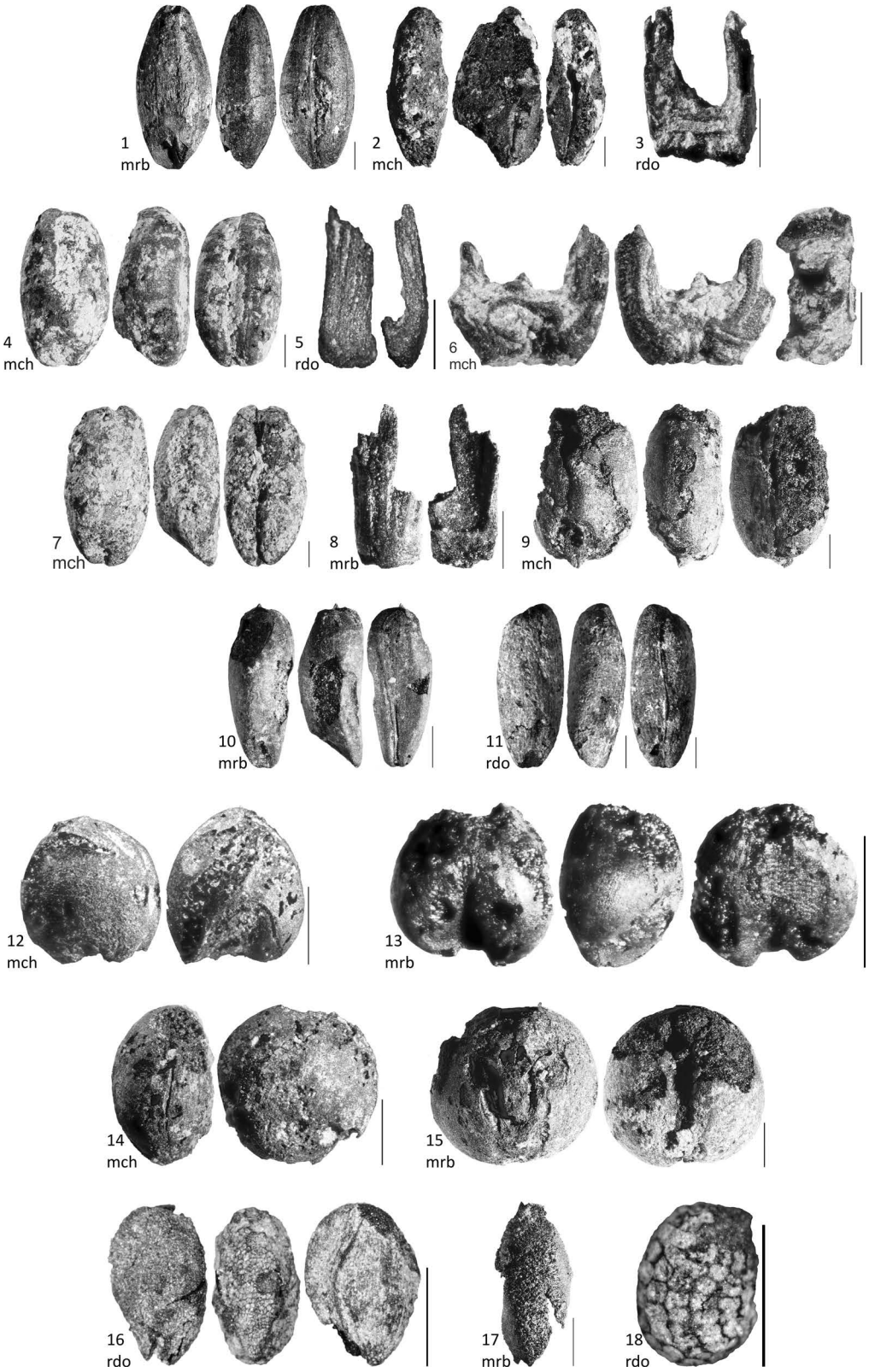


Fig. 4: Cultivated crops from the La Tène sites mentioned in the text. Site abbreviations: mch Michelstetten, mrb Mitterretzbach, rdo Roseldorf. 1 Hordeum vulgare (hulled barley) grain, 2 Triticum monococcum (einkorn) grain, 3 T. monococcum spikelet fork, 4 T. dicoccum (emmer) grain, 5 T. dicoccum glume base, 6 Triticum sp. "new" glume wheat spikelet fork, 7 T. spelta (spelt) grain, 8 T. spelta glume base, 9 T. aestivum / durum / turgidum (naked wheat) grain, 10 Secale cereale (rye) grain, 11 Avena sp. (cultivated / wild oat) grain, 12 Panicum miliaceum (broomcorn millet) grain, 13 Setaria italica (foxtail millet) grain, 14 Lens culinaris (lentil) seed, 15 Pisum sativum (pea) seed, 16 Camelina sativa (gold-of-pleasure) seed, 17 cf. Linum usitatissimum (cf. flax) seed, 18 Papaver somniferum (opium poppy) seed. Scale bar length: 1 mm. Images 5, 16, and 18 by A. Caneppele.

in Mitterretzbach may indicate a switch from local subsistence agriculture towards "export-oriented" production – or, in other words, from an emphasis on nutrition security towards the production of cash crops. This hypothesis will have of course to be tested with additional data, both from Roseldorf and Mitterretzbach, as well as from other settlements.

Quite comparable to the situation in Michelstetten, some of the arable weeds (corn gromwell *Buglossoides arvensis* and Austrian chamomile *Anthemis austriaca*) indicate crop cultivation on soils poor in nutrients. Considering the small numbers of inhabitants to be expected for the La Tène period settlements at Mitterretzbach, crop cultivation on shallow soils may have been a result of their proximity to the settlement rather than population pressure.

As in the other sites discussed, the results from Mitterretzbach bear evidence for a wide variety of gathered wild fruit, among them Cornelian cherry (*Cornus mas*), black elder (*Sambucus nigra*), sloe (*Prunus spinosa*), rowan (*Sorbus* cf. *aucuparia*), and bladder cherry (*Physalis alkekengi*), and thus a continuing exploitation of woodland resources for human nutrition. One particular find, an oak gall caused by the marble gall wasp (*Andricus kollari*), may relate to local tanning or dyeing crafts.

CONCLUSIONS AND OUTLOOK ON FUTURE RESEARCH

From a supra-regional perspective, the La Tène crop plant spectrum of Lower Austria fits well into the overall picture of eastern central Europe. Dálnoki and Jacomet (2002) recorded spelt and broomcorn millet as staple crops in a La Tène settlement in Budapest. And, as in the Weinviertel, einkorn and barley were also of major importance in Hungary. While in these eastern parts of central Europe einkorn and spelt still seem to have played a certain role, contemporary sites in the west (particularly towards the Alps) show a more pronounced dominance of barley and millet, and a clearly receding use of einkorn[30]. In contrast to this east-west pattern, rye remained a rare crop throughout the La Tène period in Europe[31]. A distinct feature of the Weinviertel settlements is the presence of foxtail-millet in all settlements investigated so far. The occurrence of the so-called "new glume wheat", a somewhat enigmatic hulled wheat[32] must be noted as well.

The recent archaeobotanical work on Roseldorf, Oberleis, Michelstetten and Mitterretzbach has certainly increased our basic knowledge of La Tène agriculture in one of the most fertile regions of central Europe. We now have an idea of the main crop species grown and there is an emerging pattern of a quite well-developed and varied land use, recalling arrangements in much later periods. Still, the picture is incomplete; it will need more investigations on additional sites and a special research focus on possible relations within and between settlements. The question is, whether the smaller and larger La Tène settlements were more or less self-sufficient units with respect to food production, or whether there was a local, regional or perhaps even supra-regional exchange of agricultural goods. Were such large agglomerations as Roseldorf pure consumer sites, depending on a steady food supply from neighbouring villages, or were they production centres in their own right – possibly ruling over additional farmsteads in the surroundings, to form a joint agricultural complex exporting food, for example to mining settlements in less favourable areas? To answer such questions, not only will data be needed from additional sites in the region, but also comprehensive analyses of several site catchments and their carrying capacity, as well as estimates of population density and an appraisal of the social structure of the settlements. Isotope analyses of cereal grains and animal bones might reveal local and regional transport processes, while data on agricultural techniques (like manuring, crop-rotation, harvesting methods, storage) might provide an idea of productivity and possible surplus management. A closer look at buildings in the settle-ment should inform us about their function and the economic activities of the inhabitants. In other words, there should be attempts to construct a palaeoeconomic model of an entire region. The results of such an endeavour should be cross-checked with comparable work from neighbouring areas in Moravia and Bohemia, where comparable clusters of La Tène settlements in highly fertile regions are currently being investigated.

30 Schmidl / Jacomet / Oeggl 2007.

31 Behre 1992; Wiethold 1996; Kroll 1997; Stika 1999; Dálnoki / Jacomet 2002.

32 Jones / Valamoti / Charles 2000; Kohler-Schneider 2003.

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ABSTRACT

Archaeobotanical research on four La Tène sites in the fertile loess region of the Weinviertel (Lower Austria) has revealed a broad spectrum of cultivated and wild plants species. On their well-tended and intensively managed fields, La Tène farmers grew einkorn (*Triticum monococcum*), spelt (*T. spelta*), hulled barley (*Hordeum vulgare*), and broomcorn millet (*Panicum miliaceum*) as the main crops, together with foxtail millet (*Setaria italica*), emmer (*T. dicoccum*), rye (*Secale cereale*), naked wheat (*T. aestivum / durum / turgidum*), and possibly also oat (*Avena* sp.). Lentil (*Lens culinaris*) and pea (*Pisum sativum*) were the main pulses, while poppy (*Papaver somniferum*), gold-of-pleasure (*Camelina sativa*), and flax (cf. *Linum usitatissimum*) served as oil plants. Crop husbandry was part of a well-developed and locally differentiated agricultural system, which included the herding of cattle, goat, sheep and horses on ample pastures in the nearer and farther surroundings of the settlement (judging from the numerous finds of plants growing on natural and semi-natural grassland). Some plants may even indicate haymaking for winter fodder. Transhumance across medium distances is documented by finds of plants at calcareous loess sites, but originating from places with acidic soil conditions. Likewise, finds of segetal plants growing on dry, stony calcareous soils point to the necessity of using less favourable field sites within the site catchments of some settlements, despite the availability of fertile chernozem soils. Shifts in local crop spectra may be interpreted in the context of local inter-settlement trade or exchange, while finds of luxury goods (grapevine and dill) suggest long distance contacts in the region and, directly or indirectly, even with the Mediterranean. Future research will focus on the question of whether the settlements of the region were independent, self-sustaining units with respect to food production or an integrated complex of smaller and larger production centres, acting in the framework of a supra-regional agrarian economy.

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A Fistful of Bladdernuts: The Shifting Uses of *Staphylea pinnata* L. as Documented by Archaeology, History, and Ethnology

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Research into the past cultural dimensions of plants is often restricted to plants with important uses, cultivated for millennia and ever sought after, and of fundamental meaning to human subsistence and economy. This is definitely true for the main cultivated crops of the Old World, and for plants regarded essential for other (e.g. medical) reasons. Bladdernut is definitely not one of these 'great' useful plants. Still, this shrub has had a curious past which seemed to us worth investigating, for the beliefs and meanings that still cling to it. As we will see, new beliefs are still developing.

Largely building upon the previous detailed work by the first author,[1] the current study pursues the goal of drawing as complete a picture as possible of the cultural relevance of bladdernut in past societies. This has been done by critically evaluating the extant literature on material evidence, written historical sources, and ethnographic studies on *Staphylea pinnata* across Europe, and trying to suggest new interpretations for this plant. Originally given as a conference paper by the first author listed, the following article has been considerably reworked and now includes substantially more research than previously.

KEYWORDS bladdernut, archaeobotany, historical botany, ethnobotany, ritual plant use, medicinal plants, food plants

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Introduction

Bladdernut botany

European bladdernut (*Staphylea pinnata* L.) is a small shrub in the Staphyleaceae family. It is the only species found in Europe, apart from its next relative, *Staphylea colchica*, which is limited to the Caucasus region. The plant is a deciduous, medium-sized shrub reaching a maximum height and width of about 4 to 5 m, bearing pinnate foliage, not unlike elder leaves, and contributing to the species epithet in its scientific name.[2] Usually during April and May, small white to slightly rose-tinted flowers emerge in hanging panicles (Figure 1). It was most probably this shape of the inflorescence which inspired Pliny the Elder to call this shrub 'staphylodendron' (grape-tree) in his *Naturalis Historia* (*Natural History*),[3] and which eventually led to the plant's modern genus name *Staphylea*. If pollinated, during summer the flowers develop into bi- to trilocular bloated capsules[4] of 3 to 5 cm in diameter (Figure 2), usually containing two to four seeds (rarely up to seven, see below). The seeds themselves (Figure 3) vary in size between 1 and 2 cm, and have a smooth and robust seed coat, usually nearly 1 mm thick. If shaken, the ripe seeds rattle inside the dried fruits. The shrub's bark bears a conspicuous pattern not unlike snakeskin.

Ecology and distribution

According to current vegetation surveys, the modern distribution of bladdernut extends mainly across south-eastern Europe[5] (a simplified range map is drawn in Figure 4). It covers a wide area extending from the most remote regions to eastern Moldova, Romania, and Bulgaria, reaching the Black Sea coasts to the middle Danubian basin (Croatia, Slovenia, Lower Austria) and the northern Alpine margin. Westwards, its range extends to the mountains of Jura, the Vosges and Ardennes (NE France and Belgium). Northwards, *Staphylea pinnata* reaches the Bohemian foothills (Czech Republic) and southern Poland.[6] The most southern records occur in Calabria, southern Italy. A singular (ephemeral?) population recorded from Greece is currently believed to be extinct.[7] Outside Europe, there are a number of sporadic occurrences in Turkey, in western Anatolia, and along the southern coast of the Black Sea, reaching the more restricted range of *Staphylea colchica* in the Colchis. In its natural range, bladdernut is most frequently found in thermophilous mixed lowland forests dominated by oak (*Quercus robur*, *Q. petraea*, and *Q. pubescens*) and hornbeam (*Carpinus betulus*), often as a companion of linden (*Tilia platyphyllos* and *T. cordata*), Scots elm (*Ulmus glabra*), and Norway maple (*Acer platanoides*).[8] In the Balkans, *Staphylea pinnata* is also found in beech (*Fagus sylvatica*) forests up to 700 m a.s.l., and often restricted to areas with cooler, wetter conditions protected from wind, such as the ravines and gorges of the Dinaric Alps.[9] The biogeographic interpretation of *Staphylea pinnata* has been widely discussed in the last century, and it still arouses interest in botanical and palaeobotanical research. Its dispersal by human activity in Central Europe remains an important question (see below). On the other hand, bladdernut is considered a Tertiary relic, and a representative element of the Submediterranean nemoral flora whose boundaries are controlled by climatic conditions.[10]



FIGURE 1 Flowering bladdernut shrub in April. Top: overview; bottom: detail of a flower panicle.
Images: (top) A. G. Heiss; (bottom) K. Wanninger



FIGURE 2 Left: ripening bladdernut fruits in June and right: in September.
Images: (left) A. G. Heiss); (right) K. Wanninger

A comprehensive distribution map,[11] and in particular the updated 1992 edition,[12] indicates a main continuous range where the species occurs in stable populations and, in addition, points out several isolated locations representing doubtful native stands, as well as a few localities (stated as synanthropic) where the species has definitely been naturalized by man (in gardens, yards, etc.). However, this cultivation is only well documented for very few areas. Such is the case in Britain and Ireland: the beginning of *Staphylea*'s history in England can be pinned to the late sixteenth/early seventeenth centuries,[13] its first written mention being John Gerarde's 'Herball' of 1597,[14] and bladdernut's first occurrence in the wild being dated to 1633.[15]

The situation is much more difficult in the rest of Europe, and several authors have addressed critical areas where *Staphylea pinnata* may have been introduced. For instance, the occurrence of the plant in southern Poland has been discussed widely and controversially by Gostyńska[16] and Środoń[17] on the one hand, and by Kornaś and Wróbel[18] on the other. While the first two authors favour the hypothesis of an anthropogenic origin of bladdernut populations in the region, the latter two suggest natural establishment during the current interglacial period. Parent[19] lists numerous stands of bladdernut at its western distribution limit (north-eastern France, Belgium, Luxembourg, and western Germany), pointing out that monastic communities may have introduced the species during the Middle Ages. Likewise, the secondary origin of *Staphylea pinnata* in Bohemia (Czech Republic) is asserted based on phytogeographical and historical evidence.[20] Finally, the distribution range of bladdernut is only vaguely defined for northern Italy,[21] thus also leaving unanswered questions about its exact locations there.



FIGURE 3 Modern bladdernut seeds, gathered in the Botanical Garden of Karlsruhe in 2006. *Image: A. G. Heiss*

Notes updating the distribution of bladdernut in northern Italy as well as several new palaeobotanical finds will be given in a forthcoming paper.[22] As already pointed out by Latałowa,[23] however, significant progress in the debate on the controversial present-day distribution of bladdernut will only be possible once palaeobotanical knowledge on this species is more extensively researched and published.

It is acknowledged here that research and discussion of this issue is still ongoing and that only further palynological evidence will allow the construction of an appropriate chronology of the spread of *Staphylea pinnata* across Europe.

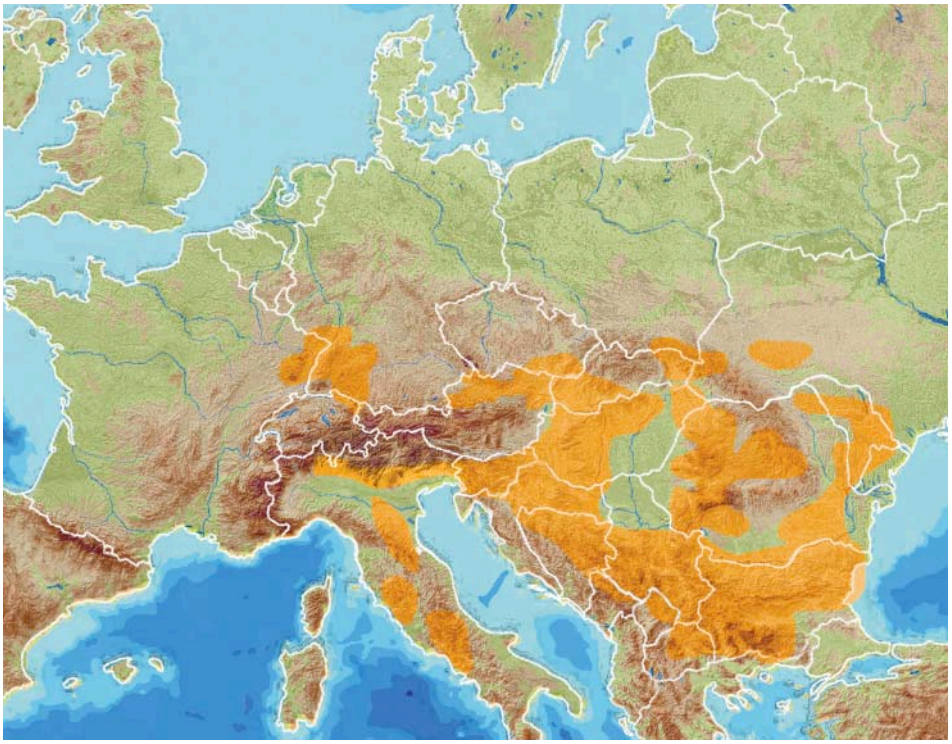


FIGURE 4 Modern distribution of *Staphylea pinnata* in Europe.
Image: G. Schramayr

Data sources and plant identification

Archaeology

Provided their identification is still possible due to favourable preservation conditions, the great advantage of archaeological plant remains is that they directly document the presence of a certain plant in a certain place and period. Former ways of plant utilization, however, including their reception by ancient societies, or their ritual/religious roles, cannot be assessed from botanical objects alone. A thoroughgoing interpretation of the finds is necessary, based on the plant's properties, the find's archaeological context, and extant information on various aspects of the particular society in question. For the purposes of this paper, the archaeobotanical bibliography was initially configured using the ample indices by H. Kroll,[24] as well as the work by M. Latałowa,[25] and subsequently by accumulating primary literature on archaeological finds. In addition, various collections and exhibition catalogues were consulted to finally build Table 1.

History and ethnography

Written historical sources and ethnographic research can help find analogues and build hypotheses of a plant's past role and perception.[26] However, written sources

TABLE 1

ARCHAEOLOGICAL FINDS OF BLADDERNUT REMAINS ACROSS EUROPE

Period	Country, Site	Context	Remain(s)	Ref.
'Prehistoric'				
n.a. (Neolithic till Iron Age)	BiH, Ripać near Bihać	culture layer	unknown number of seeds	170
n.a. ('Bronze Age')	I, Castione dei Marchesi	culture layer	unknown number of seeds	171
Early Bronze Age				
2030–1980 BCE	I, Lucone, Brescia	culture layer	12 punched seeds on a necklace together with 13 marble beads + 1 seed fragment	172
Late Bronze Age				
late 2nd/early 1st mill. BCE	I, Masseria Mammarella	culture layer	2 seeds	173
Early Iron Age				
n.a.	CZ, Těšetice	culture layer	2 wood fragments	174
eighth–sixth c. BCE	I, Guglionesi, Santa Margherita	culture layer	11 seeds	175
Roman Period				
end of second c. CE	PL, Pruszcz Gdański	grave	1 punched seed	176
third/fourth c. CE	PL, Pruszcz Gdański	grave	7 punched seeds on 2 metal strings	177
third/fourth c. CE	DK, Vindinge, Roskilde	grave	1 punched seed on bronze ring, together with 2 amber beads	178
n.a.	DK, Brænde	grave	1 seed + 2 seed fragments	179
n.a.	D, Bremen-Mahndorf	grave	1 seed	180
n.a. (Germanic)	SK, Očkov, Nitra	grave	wood	181

TABLE 1

CONTINUED

Period	Country, Site	Context	Remain(s)	Ref.
Early Middle Ages				
sixth c. CE	D, Trossingen-Stohrenhof	grave	1 seed + several seed fragments	182
end of 7th c. CE	D, Kirchheim am Ries	grave	5 punched seeds (3 on a bronze ring) + several fragments	183
680–880 CE	SLO, Resnikov prekop	culture layer	120 seeds + 7 seed fragments	184
eighth–tenth c. CE	CZ, Mikulčice	culture layer	7 seeds + 2 seed fragments	185
eighth–tenth c. CE	CZ, Lišeň	culture layer	3 wood fragments	186
High Middle Ages				
c. 1100 CE	CZ, Brno	culture layer	6 seeds	187
tenth–eleventh c. CE	PL, Kraków	culture layer	1 seed	188
tenth–twelfth c. CE	PL, Ostrówek (Opole)	culture layer	2 seeds	189
eleventh–thirteenth c. CE	PL, Wrocław	culture layer	unreported number of seeds	190
Late Middle Ages				
c. 1450 CE	D, Kelheim	well	1 seed	191
n.a.	I, Merano, Castel Tirolo	dead floor filling	3 seeds	192
end of fifteenth c. CE	H, Kerekí-Fehérkö vára	cesspit	unreported number of seeds	193
Early Modern Times				
beginning of sixteenth c. CE	B, Mechelen	cesspit	1 seed	194
seventeenth c. CE	D, Arnstadt, Ruine Neideck	cesspit	5 seeds	195
seventeenth/eighteenth c. CE	B, Kortrijk	refuse layer	1 punched seed on rosary	196

have their own pitfalls, the difficulty of the proper identification of a plant from a written description alone being the most important. This is mainly due to the vastly differing concepts of what is nowadays being considered a plant species, and how this was (and might have been) regarded in the past.[27] As we will see in the results, species identification could not be completely verified in some older written sources and remains inconclusive. Historical and contemporary texts containing possible mentions of bladdernut were consulted in a database of botanical literature from prior work by the first author,[28] compiled from extensive library searches, and based on information from other experts in the field. In prior publications, other authors have already assembled large amounts of ethnographic evidence for *Staphylea pinnata* use for southern Poland,[29] northern Moldavia,[30] and Bohemia,[31] which the current publication is building on. In cases where historical plant names in foreign languages are used, they are put in inverted commas, even when contrary to the common practice of using italics, with the aim of facilitating the discrimination between historical vernacular names and modern botanical (scientific) names conforming to the International Code of Botanical Nomenclature (ICBN).[32] However, in the Tables, no inverted commas were used in order to maintain legibility.

The data

Prehistory

Until a few years ago, finds of *Staphylea pinnata* from prehistorical periods were either hardly available, badly dated, or did not allow for clear interpretations of the plant's potential use based on the archaeological context. Among these finds are, for example, some charred seeds from the pile-dwelling settlement of Ripać in Bosnia[33] dating approximately from the Neolithic to Iron Age period. They were found among the remains of cultivated crops such as barley, peas, and lentils, and a multitude of gathered fruits. More *Staphylea* finds come from a similar context in the Bronze Age pile-dwelling settlement of Castione dei Marchesi in upper Italy.[34] However, as the bladdernut seeds from both sites have not been properly dated, and archaeobotanical methodology for identifying plant remains was far from fully developed at the end of the nineteenth century (when the above-mentioned finds were identified), as they stand, these objects cannot contribute much to our understanding of past uses of *Staphylea pinnata*. The situation at the early Bronze Age site of Masseria Mammarella in central Italy is quite different, however: as in the aforementioned cases, the seeds originated from a culture layer (well dated this time) containing numerous cultivated crops — barley, emmer, chickpea, and broad bean — as well as gathered fruits such as acorns, wild grapevine, and brambles.[35]

Different interpretations are suggested by the find's context at the site recently excavated in Lucone, close to Lago di Garda, Italy. The early Bronze Age culture layers at the pile-dwelling settlement revealed an intact necklace composed of marble beads and punched bladdernut seeds,[36] rendering this object the oldest existing evidence of the use of bladdernut seeds as 'botanical beads' (Figure 5), and currently the only find of its kind for this period.

Some finds from the early Iron Age are documented from Italian Guglionesi where eleven intact seeds were discovered in a culture layer.[37] Much further to the



FIGURE 5 One of the early Bronze Age *Staphylea pinnata* beads from Lucone, Italy.
Image: R. Perego

north-east, from roughly the same period, comes a find of several fragments of charred bladdernut wood in Těšetice, southern Moravia,[38] with unclear interpretation of the wood's purpose. However, there is ample evidence of ritual use of *Staphylea* wood in modern times (see below).

Currently, no pre-Roman finds from late Iron Age (La Tène culture) have been discovered.

Greek Antiquity: first written evidence?

Possibly the oldest written record for *Staphylea* may be found in Theophrastus' Enquiry into Plants from the third/fourth century BCE, where he describes a rather rare tree called κολυτέα (kolytea), bearing seeds in pods. Although this name is usually translated as bladder-senna (*Colutea arborescens*),[39] a shrub altogether unrelated to bladdernut, there have been authors who thought they recognized today's *Staphylea pinnata* in this text.[40] Yet, as the antique author provides no additional information on this plant, this source is of no real value to our topic.

A much later source is Pedanios Dioscorides *De Materia Medica* (on medical substances) from the first century CE, in which he writes about a Syrian tree with nuts like hazel, named πισταχίων (pistachion). Bearing the stated origin in mind, there is little doubt that this refers to what we know today as pistachio (*Pistacia vera*).[41] This reference is of great importance for bladdernut researchers: it seems that it laid the basis for some of the Italian, French, and Spanish names for our shrub in historical literature, where the plant is frequently called 'false pistachio' (Table 3), referring to this attributed but tenuous resemblance between bladdernut and pistachio foliage and their 'seeds' (fruit stones in pistachio), respectively. And as we will see later, some of the properties attributed both to pistachio and bladdernut seem to have shifted between the plants during their history of use.

Altogether, the lack of clear mentions of bladdernut in Greek antique literature is not necessarily surprising, as it seems that the plant did not occur frequently in Greece.[42] It may be for this reason that until now no archaeological finds of *Staphylea* seeds are known from Greece at present.

Bladdernut in the Roman world

The Roman author Pliny the Elder, in his *Naturalis Historia* (*Natural History*), probably gives the first written account of the plant 'staphylodendron' as mentioned

above,[43] describing a tree growing north of the Alps with wood resembling that of maple, and bearing pods containing seeds that tasted like hazelnuts. Although this description is still vague, it already exceeds accounts from Greek sources, and the combination of characteristics makes identification as bladdernut at least feasible.

From the Roman period, we know of several archaeological finds documenting what seems to have been the intentional deposition of *S. pinnata* as an item included in human burials: bladdernut seeds are documented as a component of Roman grave goods for a total of five sites across Europe (Table 1). In three cases the seeds were used as parts of pendants, or bracelets (Figure 6). The most remarkable fact about all these finds (in northern Poland,[44] northern Germany,[45] and Denmark[46]) is that they are located far outside the supposed modern area of natural distribution of bladdernut (see introduction). Obviously, the seeds of this plant were important enough to

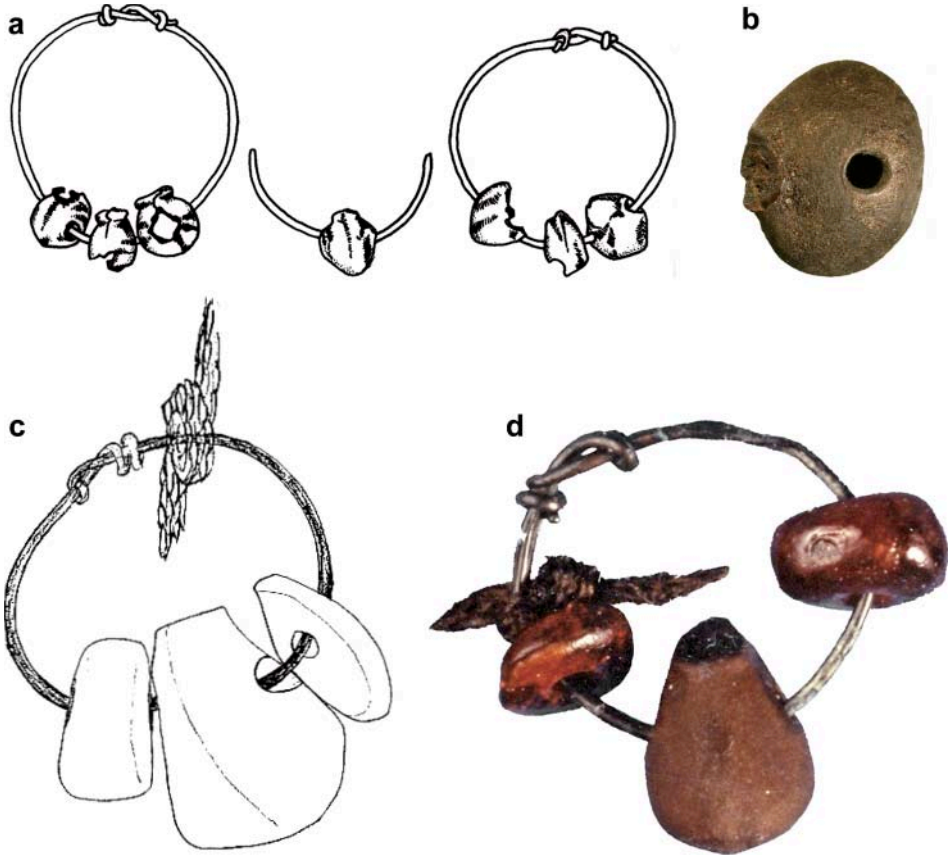


FIGURE 6 Roman bladdernut objects from northern Europe. (a) Seeds on metal strings from Pruszcz Gdański, northern Poland; (b) Photograph of one of the seeds; (c) Illustration of the bladdernut seed and two amber beads on the pendant from Vindinge, Denmark; (d) Photograph of the same object.

Images: (a) M. Pietrzak and M. Tuszynska;[166] *(b) M. Latałowa; (c) D. E. Robinson;*[167] *(d) National Museum of Denmark*

play a role in long-distance transport and trade and reach some of the most remote Roman provinces.

We know far less about the uses of bladdernut among peoples who were contemporary with the Romans. Although G. Hegi claimed that the Celts had planted *Staphylea pinnata* on their graves,[47] he did not provide any direct evidence or sources in support of this assertion. In fact, neither written sources (by the Romans) nor archaeological finds from the La Tène period (the 'Celtic' times) support this claim. Unfortunately, Hegi's statement has been reproduced uncritically in much of the literature on historical uses of bladdernut.[48] One author even states that the 'Celts used them to make various adornments',[49] ignoring the fact that up to now no archaeological or written evidence on bladdernut use during the La Tène period exists.

Some singular evidence for the use of *Staphylea* in Germanic funerary rites exists. For example, charred bladdernut wood was found in a grave close to Nitra in Slovakia,[50] although the exact significance of its presence remains unknown. As in the case of the early Iron Age bladdernut wood from Těšetice,[51] we should point to various kinds of folklore about bladdernut wood as recorded for modern times in Slovakia (see below). However, the long interval of more than 1500 years between these two sources provides a compelling caveat against simplistically equating any modern evidence with its earlier counterpart.

Early Middle Ages

The Roman tradition of using *Staphylea* adornments as grave goods seems to have been continued and also possibly ended during the early Middle Ages among the Alemannic population of south-western Germany (Baden-Württemberg): one intact seed and several fragments originate from a grave in Trossingen (sixth century CE),[52] though not worked into adornments. The youngest find from this period is again a pendant (or rattle? see below) composed of three bladdernut seeds on a bronze string (Figure 7) and two additional punched *Staphylea* seeds from a Christian noble's grave in Kirchheim am Ries (last quarter of the seventh century CE).[53] No later documentation of bladdernut as part of grave goods inventories is known up to now.

In contrast to what is documented for prehistoric periods, Madeja et al. (2009) suggest that, in the early Middle Ages, bladdernuts 'could have been used as food' for eastern Central Europe. This may very well be the case. More than a hundred bladdernut seeds were recovered from the culture layers of Resnikov prekop in Slovenia,[54] and a few seeds were unearthed in the settlement of Mikulčice[55] in the Czech Republic. The early medieval site of Brno-Líšeň, also in the Czech Republic, only resulted in three wood fragments from one culture layer.[56] As more detailed information on the context is lacking, no further interpretation of these wood remains can be given.

High and Late Middle Ages

One site from the Czech Republic (Brno[57]) and three sites from Poland (Kraków,[58] Opole,[59] Wrocław[60]), all dating to the tenth–thirteenth centuries CE, resulted in finds of bladdernut seeds, all from culture layers, and none worked into beads. These finds, and also the seeds discovered at castle Tirolo/Merano in northern Italy,[61] those from a well in Kelheim near Regensburg in Bavaria,[62] and those unearthed in a cesspit in



FIGURE 7 Bladdernut pendant from the early Middle Ages, Kirchheim am Ries, Baden-Württemberg, Germany.
Image from Neuffer-Müller (1983), image courtesy: Regierungspräsidium Stuttgart, Landesdenkmalamt

castle Fehérkö in Kerekí, south-western Hungary,[63] may very well point to the same direction as many previous finds: gathering of bladdernut seeds intended for nutritional purposes.

Written evidence on *Staphylea pinnata* is much more difficult to interpret in spite of an ample literary heritage from the High and Late Middle Ages. Most of the consulted works on plants either make no mention of bladdernut, or are obviously describing *Pistacia vera* (pistachio). Frequently, following the antique Dioscoridean tradition, they simply fail to make any noticeable differentiation between pistachio and the 'false pistachio' *Staphylea*,[64] thus making them rather unreliable sources of information on bladdernut use.[65]

Early modern times

Contrary to expectations, very little archaeological evidence of *Staphylea pinnata* is available from recent centuries. For this, we rely upon a single seed documented from

a cesspit in Mechelen in Belgium (sixteenth century CE),[66] and five seeds from a cesspit in Arnstadt, Thuringia (seventeenth century CE).[67] In contrast to the original interpretation,[68] the latter bladdernut assemblage may, nevertheless, derive from its use as food, considering that these seeds were found together with other food plants such as peach (*Prunus persica*), cherry (*Prunus avium*), plum (*Prunus domestica*), pumpkin (*Cucurbita pepo*), walnut (*Juglans regia*), and hazelnut (*Corylus avellana*). However, as both of these sites lie far outside the supposed natural area of *Staphylea* distribution, this interpretation must be treated with caution. Another find far outside the bladdernut's natural range was recorded in Kortrijk in Belgium and dates to the seventeenth/eighteenth century CE. This singular example comprises the fragment of a rosary, with a *Staphylea* seed as the centrepiece.[69]

As briefly alluded to above, a possible reason for the extremely scant written evidence on bladdernut prior to the Renaissance herbals may be that *Staphylea* had simply never been part of the 'great' medicinal books of antiquity. In addition to the tradition of translating and transcribing these ancient sources rather than conducting their own research, most authors seem to have simply ignored plants not contained in these works. During the Renaissance, with the emerging new ways of thinking, the famous herbalists sought new objects of interest instead of relying solely on the old traditions. The general situation for obtaining fresh insights into contemporary views on plants improves considerably in this period. Although some herbals, such as that compiled by Leonhart Fuchs, still do not mention *Staphylea*,[70] quite a few others include it in their lists (Table 2).

While Dodoens finds no use for bladdernut,[71] Lonitzer attributes a wide range of medicinal uses to the plant; however, making a common mistake, he equates it with pistachio.[72] A Bohemian manuscript mentioning a variety of magical (mostly apotropaic) properties of bladdernut, as well as medical and veterinary applications is the oldest source known to us.[73] A herbal from Poland mentions the use of the sweet-tasting nuts in rosaries, and the popular belief that they chase away demons.[74]

Modern times

Along with the rapid development of ethnography, ethnobotany arose as a scientific discipline in the second half of the nineteenth century.[75] The systematically gathered ethnobotanical data changed the knowledge of bladdernut utilization quite dramatically. Throughout Europe, and with a marked focus on central and eastern Europe, numerous records from these most recent periods were found. These related mainly to folk medicine, magical beliefs and nutritional uses, and to technical uses to a much lesser extent. They are listed in Table 2. Unfortunately, such sources tell little about the temporal dimension of a certain purpose unless combined with their historical and archaeological contexts. An attempt at interdisciplinary diachronical interpretations for each category of bladdernut utilization is presented in the following section.

Diachronical interpretations, old and new

Bladdernut as a food resource

The context of the find of *Staphylea pinnata* seeds among a wide assortment of cultivated and gathered food plants[76] at early Bronze Age Masseria Mammarella (see

TABLE 2

USES AS FOUND IN WRITTEN SOURCES ON BLADDERNUT ACROSS EUROPE

The dates or periods given are to be regarded as *termini ante quem*, as of course the actual ages of the listed uses cannot be determined. ABA: antibacterial, ado: antidote, APH: aphrodisiac, ARI: antirheumatic, antiinflammatory, ATR: apotropaic, CAL: carminative/laxative, CAN: cancer medicine, CRP: carpentry, DEC: decoration (either the whole plant or the seeds in adornments other than rosaries), DIU: diuretic, DOW: dowsing rod, DYE: dyeing, FUE: fuel, FUM: fumigant, HEM: hemostatic use, HEP: hepatical disorders, INS: insectifuge, MED: general medical purposes, MEL: melliferous flower, MEN: mental and nervous disorders, headaches, NUT: nutrition, PLA: against the plague, QUA: settles quarrels and misunderstandings, REL: other religious uses than in rosaries, RES: respiratory disorders, ROS: rosary beads, SKI: skin disorders, sym: sympathetic magic, TOX: warning against toxicity, TUR: turnery, VET: veterinary uses, WEA: weather magic

Date/period	Region	'Magical' uses	Other uses	Note	Ref.
Modern Times					
2012	Germany	ROS	-	-	[197]
2012	Notranjska (Slovenia)	-	DEC (seeds)	-	[198]
2012	Croatia	-	CRP, DEC (plant), TUR	-	[199]
2012	Vojvodina (Serbia/Croatia)	-	MEL	-	[200]
2010	Germany	CAL, RES	-	homeopathy	[201]
2009	W-/S-Poland	ATR, ATR (VET), DOW, REL, ROS, SYM	DEC (plant), VET	for making butter dashers, cigarette holders and pipes	[202]
2000–2009	Slovakia	-	ABA, ARI, CAN	-	[203]
2008	Bulgaria	-	MED	no particular use mentioned	[204]
2007	Poland	ROS	-	-	[205]
2006	Germany	-	CRP, TUR	-	[206]
1999	Bulgaria	QUA (flower decoction)	-	as herbal tea or bath	[207]
1996 onwards	S Germany	APH	-	-	[208]
1990s	E Bosnia		NUT (seeds as flour additive)		[209]
1986	W Balkans	-	NUT (spring shoots, seeds)	-	[210]
1960	Bulgaria	-	CAL, CRP, DEC (plant), MEL, NUT (seed oil), TUR	-	[211]
1957	Iuknov (Bohemia)	ROS	-	-	[212]
1948	Eifel region	ROS	-	-	[213]
1939	Bulgaria	QUA (flower decoction)	-	as herbal tea	[214]
1935/1936	Silesia	SYM	-	seeds from multi-seeded fruits as lucky charms	[215]

TABLE 2

CONTINUED

Date/period	Region	'Magical' uses	Other uses	Note	Ref.
1935/1936	Bohemia	ATR, REL	CAL	-	216
early twentieth century	central France	ROS	-	-	217
1908	Slovakia	MEN	-	someone who is unconscious is hit with bladdernut twigs to wake him/her up	218
1907	Austria	-	DEC (seeds)	excludes (!) use in rosaries	219
1903	northern Moldavia	ATR/SYM, ATR (VET), REL, WEA	DEC (seeds), HEM	-	220
1902	SE Hungary	ATR, SYM	-	-	221
1836–1900	Sweden	-	DEC (plant)	-	222
1879	Bohemia	ATR, ATR (VET)	INS	-	223
1857	Germany	-	DYE	-	224
1849	Belgium	-	DEC (plant), DYE	-	225
1846	France	-	DEC (plant)	'large grains resembling those in a rosary' (!)	226
1839	France	-	ARI, DEC (seeds and plant), NUT (seed oil)	-	227
1839	France	-	DEC (plant), NUT (seed oil), TOX (nausea)	-	228
1836	Vojvodina (Serbia/Croatia)	ROS	-	-	229
1827	Poland	-	DEC (seeds), FUE (seed oil), NUT (seeds), TOX (nausea, stomach ache)	-	230
1806	France	ROS	DEC (plant), NUT (seed oil)	-	231
1800	France	no uses mentioned		-	232
1799	Poland	ROS?	DEC (seeds), FUE (seed oil), MED (for children), NUT (seeds), TOX (nausea)	-	233
1791	Germany	ROS	TOX (nausea, headache)	-	234
Early Modern Times					
1721	Poland	ATR, ROS	(NUT)	-	235
1683	Scotland	-	DEC (plant)	-	236
1629	England	-	DEC (plant), DIU, HEP, NUT, (TOX)	medicinal uses are doubted in general	237

TABLE 2

CONTINUED

Date/period	Region	'Magical' uses	Other uses	Note	Ref.
1605	central Mediterranean	APH	CAL, DIU, NUT, TOX (nausea)	-	238
1597	England	APH	DEC (plant), TOX (nausea)	medicinal uses are doubted in general	239
1586	central/W Europe	-	TOX (nausea)	-	240
1581	central/W Europe	ROS	-	-	241
1586	central/W Europe	-	TOX (nausea)	-	242
1560	Moravia	ATR	FUM, PLA, NUT, SKI, VET	explicitly mentions that also eating many seeds does no harm	243
1557	central/W Europe	no uses mentioned		-	244
1557	central/W Europe	-	ADO, DIU, HEP, RES	treated as equal to *Pistacia vera*	245
Middle Ages					
1487–90	central/W Europe	APH	CAL, RES, TOX ('man sol yr nit zu vil essen')	most probably referring to *Pistacia vera*	246
Antiquity					
first c. CE	central/E Medit.	-	NUT?	-	247
first c. CE	central/E Medit.	-	ADO, CAL	most probably referring to *Pistacia vera* (pistachio)	248
fourth/third c. BCE	E Medit.	no uses mentioned		maybe referring to *Colutea arborescens* (bladder senna)	249

Table 1) can safely be regarded as the oldest evidence of the plant as a food resource in southern Europe. The early Iron Age finds from Guglionesi[77] can be interpreted in the same way. Of course, the finds from Ripać[78] and Castione dei Marchesi[79] may point to similar uses, but due to the absence of exact dating methods, and the current lack of precise identification as bladdernut, these remain of limited value.

Subsequent to the Guglionesi find, we observe a large temporal and spatial gap in the evidence on human consumption of bladdernut seeds. The hiatus ends with a series of bladdernut seeds found in cesspits and all kinds of other culture layers across European sites. Such widely dispersed examples hail from Slovenia,[80] to northern Italy[81] and from to Belgium[82] to Poland[83] spanning the periods from the seventh[84] to the seventeenth/eighteenth[85] centuries. The contextualized provenance of these seeds, found either as part of the refuse in cesspits, or amongst other food plants, suggests their use as a foodstuff highly likely in these periods and regions.

Written sources remain rather silent on this kind of *Staphylea* use. While Pliny may be the earliest author implying bladdernut consumption,[86] later sources from medieval until early modern times do explicitly mention the possibility of eating bladdernuts (mainly for medical reasons). Usually, these add warnings of side-effects of the seeds' consumption such as impending nausea or churning guts (Table 2) due to their alleged toxicity. Such caveats were, however, completely unfounded as the plant is by no means considered toxic nowadays.[87]

In general, the knowledge of the palatability of bladdernut (seeds, shoots, and flowers) seems to be most rooted and best preserved in eastern-central and eastern Europe: the only two 'old' historical sources we could find which explicitly state that even excess consumption is regarded harmless come from Renaissance Moravia[88] and from Late Baroque southern Poland,[89] respectively. Modern evidence for the consumption of bladdernut is still abundant in these regions: in the western Balkans, the pickled spring shoots eaten as a side-dish, and the roasted seeds mainly used as a sweet flour-like additive to bread and cakes continued into the twentieth century.[90] In particular, the use of roasted and ground bladdernut seeds as a basis for porridge and as a bread additive is reported from eastern Bosnia during Yugoslavian Wars of the 1990s.[91] Consumption of pickled blossoms is also reported from present-day eastern Georgia and northern Armenia, although the consulted sources do not clearly differentiate between *Staphylea pinnata* and *S. colchica*.[92]

Medicinal uses

Due to the nearly impossible task of differentiating medical uses from consumption based on the archaeological evidence alone, sensible discussion of this issue is only possible for periods for which written sources exist. And as mentioned above, plant identification in written sources often makes it difficult to discern between the species treated in a particular text. In the case of bladdernut, it is mainly the confusion or amalgamation of *Staphylea pinnata* and *Pistacia vera* that is observed in the literature. In general, it is mainly the carminative or laxative effects which are expected, often in connection with warnings of the seeds' alleged but unfounded toxicity (see above). Applications as antidote or against skin and respiratory disorders are also found (Table 2). The use of bladdernut as an aphrodisiac, listed among the 'magical' properties, is discussed in a separate section. In general, the bladdernut's role in folk medicine seems to have completely ended by the end of the eighteenth century, giving way to mainly magico-religious and technical uses. The boundary between the medicine and magic is not, however, always clear.

Surprising for some, perhaps, the very recent utilization of bladdernut in homeopathy is listed among the 'magical' rather than the 'medicinal' uses in Table 2. This is due to the lack of any homeopathic effects beyond placebo as observed in major studies and meta studies,[93] and some serious clashes with well-known mechanisms in physics and chemistry,[94] placing homeopathy in esotericism rather than in medical science. With roots in both the doctrine of signatures and the idea of *similia similibus curantur*, the bloated fruits of bladdernut are believed to be an ailment against meteorism and pulmonary disorders,[95] the latter perhaps also influenced by the tradition of certain late medieval[96] and early Modern texts,[97] as already mentioned above.

Current research in medicinal uses of bladdernut aims to investigate the potential of certain secondary metabolites (polyphenols, flavonoids, and hydroxycinnamic derivatives) for their possible antibacterial, antiproliferative, and antioxidant activities.[98]

Technical purposes

Few records have been found on technical uses of bladdernut. In the nineteenth-century literature on dyeing, the leaves and fruits of bladdernut are mentioned as a source for red dye.[99] Carpentry and turnery are also mentioned,[100] with bladdernut wood being used to produce small items like cigarette holders and pipes.[101] The use of the seeds as a source of oil is mentioned in several sources (Table 2). The purpose of this oil is not usually clearly stated, although mention of lamp oil exists from Poland.[102]

Staphylea *seeds as natural beads*

Evidence of bladdernut seeds used as 'botanical beads' is temporally and spatially scattered. But in taking into account the early Bronze Age finds from northern Italy, the Roman and early medieval finds in central and northern Europe (Table 1), a certain tradition of using *Staphylea pinnata* seeds as raw material for bead production can be affirmed, but without proof of unbroken transmission. For modern times, various text sources mention the custom of rosaries made of bladdernut seed (see below), but some also document sheer decorative purposes. For the beginning of the twentieth century, for example, M. Kautsch[103] reports the use of *Staphylea* beads in bracelets in Upper Austria, a phenomenon also reported for southern Slovenia,[104] and the existence of bladdernut beads for Poland.[105] In northern Moldavia at about the same time, wearing necklaces made of bladdernut seeds is documented,[106] although most (but not all) of the cited informants mention magical uses of the plant, its seeds, and the adornments made from them (Table 2).

Bladdernut: a death symbol?

The exact meaning of the *Staphylea* seeds found as grave goods in the Roman period sites in Denmark, northern Germany, and northern Poland (Table 1) cannot be adequately addressed: Roman literature tells us absolutely nothing about the purpose of bladdernut in the funerary rites. Undoubtedly, the long-term prehistoric tradition of using the seeds as natural beads may have played a significant role. Two additional aspects shall be considered here for discussion:

1. In Roman graves, finds of rattles are not uncommon.[107] It is argued that these idiophones (metal bracelets, vibrating bells, and the like) bearing apotropaic properties[108] may have served their purpose in the graves: either averting evil spirits from the deceased, or protecting the living from the dead. Cases in which rattles were not exposed to the fire in incineration graves (as were the corpse itself and the 'regular' grave goods), but were interred separately, may accentuate their particular roles.[109] Bladdernut seeds represent natural rattles inside their ripe fruits. We therefore hypothesize that the *Staphylea* pendants may not have been just adornments, but may have represented an artefactual translation of their noise-making into an apotropaic idiophone (i.e. a strung rattle or stick rattle[110]).

2. The particular shape of the seeds may have played a role in the use of bladdernut in Roman funerary rites: the seeds bear resemblance to little heads with their noses cut off, or little skulls (Figure 3). This resemblance is reflected in some modern French and German local names, such as 'nez coupé' (cut nose), 'Todtenköpfli' (small skull),[111] or 'Todtenkopfbaum' (skull tree)[112] and also made its way into a legend recorded in Steyr, Austria (see below).[113] Whether the Romans also saw this resemblance and whether this sufficed for an association with death and to the underworld, we cannot know without further evidence.

The latter issue may, however, have some general relevance to the use of bladdernuts as beads: all archaeological finds of *Staphylea* — from early Bronze Age northern Italy[114] to early medieval south-western Germany[115] — which had been transformed into beads (see Table 1) have the holes drilled through the lateral faces of the seeds at the right angle to the longitudinal axis (Figures 5–8). This is quite difficult to achieve, and the easier way would be drilling through the soft attachment scar. It may very well be that this method of manufacture was deliberately chosen during prehistory and early history in order to preserve the view of 'cut noses'.

Apotropaic and sympathetic magic

As mentioned above, some apotropaic properties may have been assigned to bladdernut in Roman times, although no written evidence is available on this topic. In general, most written documents on magical properties attributed to *Staphylea pinnata* concern apotropaic magic: from Poland, the Czech Republic, and northern Moldavia, numerous reports are available on the use of bladdernut as a protection for people, cattle, and houses against witches, the devil, demons, and all sorts of bad luck or diseases (Table 2). In some rarer cases these apotropaic beliefs are focused on food, such as the protection of butter or beer against witchcraft.[116] Also, cases of using bladdernut for weather magic are documented: girthing oneself with a bladdernut twig in northern Moldavia averts showers of sleet, and wielding a bladdernut rod at the same time sends them in the desired direction.[117] An unusual application vaguely linked to apotropaic effects is known for early twentieth-century Bulgaria: a decoction of the scented bladdernut flowers (either drunk as herbal tea, or used for taking a bath) is regarded an appropriate means to settle quarrels in the family.

As reported for Moravia, for northern Moldavia, and western and southern Poland, apotropaic properties (involving blessing) of bladdernut wood or branches were often embedded into Catholic festivities, mainly Easter,[118] the Sacred Heart,[119] and the Assumption of Virgin Mary.[120]

Sympathetic uses — such as bladdernut as a lucky charm — are not reported as frequently as apotropaic ones, but the two are not always easy to distinguish. For example, a *Staphylea* necklace worn by a northern Moldavian woman in order not to get lost in the woods[121] may be regarded as apotropaic (= it wards off bad luck) or as sympathetic (= it attracts good luck). Similar is the use reported from Békešská Čaba in 1902: the bridegroom wears bladdernuts sewed onto his garments as a lucky charm, but also to ward off witches.[122] A less ambiguous record comes from early twentieth-century Silesia: as noted in the introduction, bladdernut fruits usually



FIGURE 8 Rosary fragment from the seventeenth/eighteenth century, discovered in Kortrijk, Belgium.[168] Mind that the holes of the remaining bladdernut seed were drilled avoiding the seed's attachment scar (the 'cut nose').
Image: B. Cooremans

contain two to four seeds. However, in rare cases the seed number per fruit may go up as high as seven (Figure 9). These were regarded as 'lucky seeds' ('Glücksnüßchen') in Silesia and carried in the purse as a warrant for good luck and wealth.[123]

The numerous rhymes (most probably spells) involving bladdernut, as they are documented from early twentieth-century northern Moldavia, are difficult to evaluate. Most of them refer to sick youths, either ending with their death or their healing. One example from Mahala[124] shall be given here:

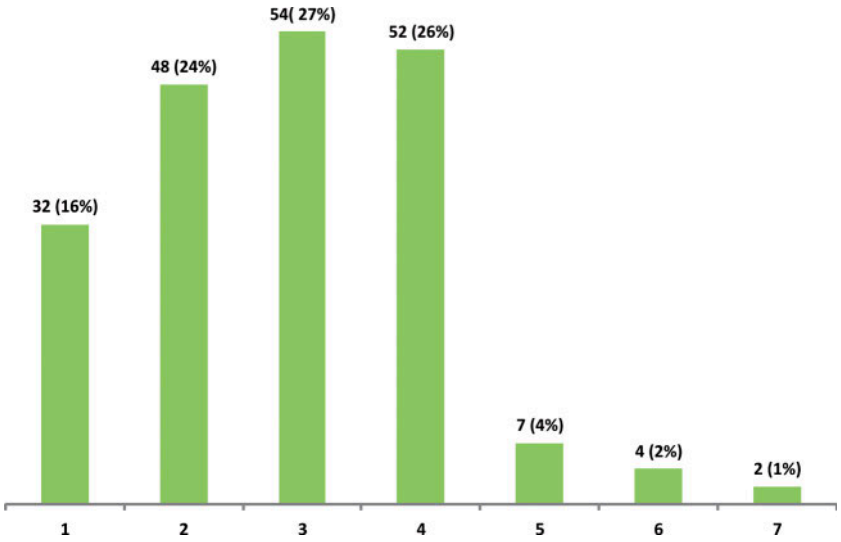


FIGURE 9 Histogram of seed counts per fruit as observed in 199 bladdernut fruits from twenty stands in Lower Austria. X axis: seed count per fruit, Y axis: frequency of seed count: 93% of the observed fruits did not bear more than four seeds.
Diagram: K. Wanninger

Frunză verde clocotici
Plin îi codrul de voinici,
La tot fagul cîte cinci.
Da la fagul din carare
Zace-un voinic de lungoare.
– Or zaci, bade, or te scoală,
Or dă-mi şi mie o boală.
– Eu ţie boală cum ţ-oi da,
Cînd singur nu mă pot scula?

Green leaf bladdernut
The wood is full of younglings,
Under each beech five
Close to the beech at the path,
Lies a youngling fallen ill.
'Either stay lying ill, or recover,
or give me a disease as well'.
'How might I give you a disease,
If I can't get up by myself?'
(translation: G. Ruß-Popa)

Bladdernut in rosaries

The rosary, being basically a prayer mnemonic,[125] unites in itself aspects of an adornment and also of apotropaic properties (see above). This particular aspect of the use of bladdernut seeds shall be treated in a separate section.

Motivated by the archaeological find of a *Staphylea* rosary fragment from Belgian Kortrijk,[126] and by the ample written sources mentioning the use of *Staphylea* seeds as rosary beads beginning with the late sixteenth century (Table 2), the authors tried to find more factual evidence for this kind of use. However, intensive research in the collections of several large European museums focusing on religious objects, each containing dozens to hundreds of rosaries,[127] did not result in any leads on actual objects made of *Staphylea* seeds. Other fruit and seed beads were frequently found in these collections, however, such as cherry (*Prunus avium*) and apricot (*Prunus*

armeniaca) stones,[128] water chestnut (*Trapa natans*),[129] eucalyptus (*Eucalyptus* spp.) cupules,[130] or Job's Tear (*Coix lacryma-iobi*) fruits.

As the city of Vienna is situated in the actual area of natural distribution of *Staphylea pinnata* (see Introduction), an attempt was made to investigate the rosaries discovered up to now in Vienna's recently excavated cemeteries. But none of the rosary beads recovered from *c.* 300 graves from two cemeteries in Vienna's seventeenth district (Middle Ages to nineteenth century),[131] resulted in any positive evidence of *Staphylea* seeds, although numerous beads made of wood as well as of Job's Tears fruits (*Coix lacryma-iobi*) could be identified.

Of course, the authors were not able to conduct research on rosaries in every European country, so there may be more examples of bladdernut rosaries from historical times yet to be discovered. All in all, however, the lack of evidence does not support a hypothesis of bladdernut seeds having been a very popular raw material for rosaries in the past, especially when compared to other kinds of seeds used for this purpose. The question has to be raised whether this is caused by actual rarity of use at the time, or by social bias affecting the collections (bladdernut rosaries might have been regarded as 'too cheap' to be acquired by collections or museums). B. Cooremans has suggested that this may indeed account for the dearth of artefactual evidence, with bladdernut seeds perhaps used only by those who could not afford rosaries made of other, more highly valued materials.[132]

On the other hand, contemporary rosaries made of bladdernut seeds seem to be widely available across Europe: one specimen from central France dating to the beginning of the twentieth century is displayed in A.-M. Stampfler's book.[133] Another one from Poland, made in 2008, is depicted in a recent journal article.[134] Both objects are shown in Figure 10. A flourishing business with *Staphylea* rosaries is reported for the Vatican,[135] and online searches result in various extant manufacturers of bladdernut-based rosaries.[136] From the German/Belgian Eifel region, J. Schröder reports that the last rosary-maker using bladdernut seeds died in 1948.[137] Gostyńska even writes of bladdernut plantations dedicated to rosary bead production in south-eastern Poland.[138]

But there is also a conspicuous observation that excludes *Staphylea pinnata* as a potential raw material for rosary beads: the early twentieth-century Austrian ethnologist Marianne Kautsch writes in her observations on *S. pinnata* seeds: 'Man trug sie einstens als Handschmuck, niemals sah ich dieselben zu einem Rosenkranz verwendet, vermutlich weil die Nüsse sehr hart zu bohren sind' ('They were once worn as bracelets, never did I see them used in a rosary, presumably because the nuts are hard to drill').[139]

When comparing contemporary *Staphylea* (rosary) beads with any of the archaeological bladdernut beads, one significant difference in the method of their production can be observed: 'modern' rosary beads are usually produced by drilling a longitudinal hole through the attachment scar (i.e. right through the 'cut nose') as this is the softest spot of the very hard seed[140] (Figure 10). But the only archaeological rosary found, the seventeenth-/eighteenth-century Kortrijk fragment (Figure 8), displays the 'ancient' way of production as mentioned above — just as it is found in the archaeological bladdernut beads from the Bronze Age, the Roman period, and the early Middle Ages (Figure 7). Why this way of punching the seeds was chosen in the past might again be explained by the desired 'cut nose' (suggestively skull-like) look of the seeds,



FIGURE 10 Modern bladdernut rosaries. (Top) object from central France (made in the first half of twentieth century CE) with polished *Staphylea* seeds; (bottom) object from southern Poland (kept in the Botanical Garden Museum of the Jagiellonian University, Kraków. Specimen number: 44/47, inventory number: O/2008/1962), manufactured in 2008 in the Michalici monastery of Miejsce Piastowe.[169] Both objects show holes drilled through the attachment scars. *Images: (top) A.-M. Stampfler; (bottom) Sikora-Majewska*

which would have been preserved in this way. For rosaries which often feature skulls as a kind of *memento mori*[141] this would seem a plausible strategy. However, since up to now the Kortrijk fragment represents the only known archaeological bladdernut rosary, we cannot argue that this manufacturing method was once deliberately used for rosaries.

The bladdernut's career as a sex drug

Since 1994, a Bavarian nursery has been cultivating bladdernuts, selling liquor and schnapps produced from the roasted seeds.[142] The producers claim that the

'aphrodisiac use of bladdernut dates back to the Roman period'[143] and that 'according to a Roman legend, the shrub was nearly eradicated due to its virility-boosting properties'.[144] Alas, no ancient Roman author mentions anything of the like, and only a very few later authors do so: the earliest explicit mentions of the bladdernuts' use as an aphrodisiac come from the late sixteenth/early seventeenth century,[145] but neither bear any reference to the 'Roman legend'.

The reasons for and origins of this apparently recent tradition of using *Staphylea* seeds are still unclear. To the authors, there seem to be three possible and rather plausible explanations why the plant is now being perceived (i.e. bought and sold) by some as a source of love potions. One reason might stem from the doctrine of signatures passed down since antiquity, which interprets nature in a most anthropocentric way: an organism's characteristics — shape, colour, and the like — signal its medicinal properties for humans.[146] In the case of bladdernut, the inflated capsules do have a striking resemblance to body parts such as the scrotum, reflected in folk names such as 'klootzakkenboom' in Flemish Brabant,[147] or 'kochi madi' (= ram testicles) in Bulgaria.[148] Likewise, analogies to 'breasts or buttocks'[149] have been drawn in the literature, and the Bulgarian folk name 'skutlik' (= womb)[150] ought also to be mentioned in this context. All these similarities may have served as an inspiration to Renaissance and modern-day quacks.[151] A second possible explanation is that, beginning with the earliest probable references from Ancient Greek sources, bladdernut has often been confused or equated with, pistachio (*Pistacia vera*), the seeds of which have been regarded as an aphrodisiac since that period. Bladdernut might thus have acquired properties associated with true pistachio in the literature. The third possibility is only plausible for the German-speaking parts of Europe, as it may be rooted in a misconception of the onomatopoetic word 'pimpern' (also see below). In modern southern German dialects, including most Austrian ones, 'pimpern' is a slang expression for sexual intercourse,[152] not unlike the English 'to shag'. All three reasons may have influenced modern recommendations of bladdernut as an aphrodisiac.

Bladdernut legends

A few legends deal with bladdernut, two of which shall be mentioned here:

> Austrian ethnologist M. Kautsch[153] recounts a narrative possibly related to the 'cut nose' of the bladdernut seeds, and possibly referring to the Napoleonic wars around 1805.[154] During an invasion by the enemy who were about to enter an (unnamed) convent, the nuns cut off the tips of their noses to protect themselves from being molested. Later, so the legend continues, a bladdernut shrub sprouted from the very same place where the nuns had buried their cut-off noses. Rhinotomy, or amputation of the nose, has long associations as a punishment for adultery and other legends also relate that nuns used the practice in the hopes of avoiding rape.[155]

The second legend deals with the *Galgen- und Hühnerwunder* (the 'gallows and chicken miracle'), documented in numerous altar pieces across Switzerland, the oldest ones dating to the early seventeenth century. The son of a family on their pilgrimage from Switzerland to Santiago de Compostela is tricked by a landlord, then wrongly accused of theft, and hanged. The parents, shocked and distraught, continue with their pilgrimage, but then hear a voice telling them their son was still alive. When

they return to the place of execution, they discover that their son has been supported and kept alive on the gallows by none other than the patron of the pilgrimage, St James himself. They report this to the judge (or, alternatively, the bishop), accusing the landlord of deceitful behaviour. At that moment, as a divine proof, three roast chickens on a spit become alive and whole again, and fly away, which subsequently leads to the condemnation and execution of the landlord. The father cuts a staff from a bladdernut (it is not said whether he does this in Spain or back in Switzerland), plants it, and the staff sprouts into a tree.[156]

Staphylea's names: rattles and bladders, grapes and pistachios . . . and body parts

Although the vernacular names of *Staphylea pinnata* collected in Table 3 were actually the starting points for basic identification of the plant in the literature, they shall be treated among the outcomes, as the Table does constitute a part of the results on its own.

Generally speaking, the vast majority of eponyms we found derive from onomatopoetic verbs referring to the rattling noise the ripe seeds produce in their capsules: 'klokoti' and the like in Slavic languages, and 'pimpern' in German, partially reaching out to adjacent Germanic languages such as Flemish, Dutch, Danish, and Swedish.

A second large group may more or less derive from the Dioscoridean reference to a plant, 'pistachion', most probably referring to true pistachio (*Pistacia vera*). The majority of French, Italian, and Spanish (and Latin) vernacular names for bladdernut denote this alleged similarity between the two plants, and isolated evidence for such a connection is also found in English and German. More exclusively limited to the Romance languages are the adaptations of Pliny's Greek term 'staphylodendron', describing the habit of the blossoms as grape-like. Schramayr[157] suggests that these kinds of bladdernut names — directly deriving from antique names — do not tell much about the thoughts attributed to the plant but may rather indicate the lack of local folklore surrounding it, due to the plant not being native to a region. For this reason, these names were completely omitted from Table 3. However, the concept of creating plant eponyms that allude to an existing taxon also exists in areas at the centre of autochthonous bladdernut distribution. Good examples are Bulgarian folk names such as 'div margarit' (= wild chrysanthemum), 'mekishovina' (= similar to *Acer tataricum*, Tatar maple), or 'zaichi leshnitsi' (= rabbit hazelnuts).

One group of bladdernut names of particular interest are those that relate the seeds and fruits to human or animal body parts, mainly alluding to more intimate body regions, such as 'skutlik' (= womb) or 'kochi madi' (= ram testicles) in Bulgaria, or 'klootzakkenboom' (= scrotum tree) in Flemish Brabant, which have already been discussed above. The 'cut nose' eponyms also belong to this group, like the French 'nez coupé' (= cut nose) and German 'Todtenkopfbaum' (= skull tree).

Factual or alleged uses of the bladdernut seeds as natural beads (and in rosaries) are given in denominations such as 'paternosterbollekesboom', 'Perlenbaum', 'Rosenkranzbaum', 'patenôtrier', and the like.

A note on toponyms

In Slavic-speaking countries, numerous toponyms which at first sight derive from bladdernut names are known. An extensive list covering Slovakia, the Czech

TABLE 3

VERNACULAR NAMES OF BLADDERNUT IN VARIOUS EUROPEAN LANGUAGES, SORTED BY THEIR EPONYMS

For reasons of simplification, the modern genus-species composita (based on botanical binomenclature) are shortened to genus names. For the same reason, all historical names deriving from Pliny's 'Staphylodendron' (such as Staphylodendros, Staphylier, Stafilea, and the like) are omitted

Similarity to pistachio	Flowers	Fruit shape	Fruit rattling	Seed shape	Use in rosaries and adornments	Others	Ref.
SLAVIC LANGUAGES							
Bulgarian							
	див маргарит (div margarit = wild chrysanthemum), мекишовина (mekishovina = similar to *Acer tataricum*, Tatar maple)	кочи мъди (kochi madi = ram testicles), скутлик (skutlik = womb)	кълкоч (kalkoch), кликоч (klikoch), клочина (klochina), клокоч (klokoch), клокочина (klokochina), клокочка (klokochka), куркотик (kurkotik), скокотица (skokotitsa)	Зайчи лешници (zaichi leshnitsi = rabbit hazelnuts)	висулка (visulka = pendant)	Горчовица (Gorchovitsa = wife of a man called Gorcho)	[250]
Romanian*							
-	-	-	clocotici, clocoticiul, clocotişul	-	-	-	[251]
Serbian							
-	-	-	клокоч (klokoč), клокочиковина (klokočikovina), клокочевина (klokočevina), клокочика (klokočika), клокочина (klokočina)	-	-	-	[252]
Croatian							
-	-	-	kloček, klokoč, klokoča, klokočika	-	-	-	[253]
Slovenian							
-	tozhiza/ točica (catkin)[254]	-	klazhki, kloček, kločkovk, klozhki	divji leshniki (= wild hazelnuts)	-	-	[255]
Slovak							
-	-	-	klokoč, klokočka	-	-	-	[256]

TABLE 3

CONTINUED

Similarity to pistachio	Flowers	Fruit shape	Fruit rattling	Seed shape	Use in rosaries and adornments	Others	Ref.
Czech							
-	-	-	klokoč, klokoczka, klokočové, klokoczynky	-	-	sicomorna, sycomorus	[257]
Polish							
-	-	-	kłokoćina, kłokoczka, kokoczka, kokocyna, krokosz, krokoczym, krokoczyna	-	-	-	[258]
Sorbian							
-	-	-	klukoćina	-	-	-	[259]
FINNO-UGRIC LANGUAGES							
Hungarian							
-	-	hólyagfa	-	-	-	-	[260]
GERMANIC LANGUAGES							
German							
wilde Pistacien	-	Blasenbaum (= bladdertree), Blasennuß (= bladdernut)	Klappernuß, Pemmanissl, Pimpernoeßle, Pimpernüßlein, Pimpernuss, Pumpernuß, пимпернуса (pimpernusa)**	Todtenkopfbaum (= skull tree), Todtenköpfli (=small skull)	Perlenbaum (= bead tree), Rosenkranzbaum (= rosary tree)	Zirbelnüsse (referring to *Pinus cembra* seeds)	[261]
Dutch							
-	-	-	pimpernoten	-	-	Sint Antuenis nootkens (= St. Anthony nuts)	[262]

TABLE 3

CONTINUED

Similarity to pistachio	Flowers	Fruit shape	Fruit rattling	Seed shape	Use in rosaries and adornments	Others	Ref.
Flemish							
-	-	klootzakkenboom (= scrotum tree)	pimpernoot	-	paternosterbolle-kesboom (= rosary bead tree)	-	263
Danish							
-	-	Blærenød (= bladdernut)	Pimpernød	-	-	Bennød (= bone nut), Jobs Taarer (= Job's tear)	264
Swedish							
-	-	-	pimpernöd	-	-	-	265
English							
wilde Pistacia	-	bladdernut	-	-	-	S. Antonies nuts	266
ROMANIC LANGUAGES							
French							
faux pistachier, pistache bâtarde, pistache sauvage	-	-	-	nez coupé (= cut nose)	baguenaudes à patrenostres (= rosary beads), patenotier, patenôtrier		267
Italian							
pistachio salvatico, pistacchio falso	-	bossolo (= 0can, or box)	-	-	-	lacrime di Giobbe (= Job's tear)	268

TABLE 3

CONTINUED

Similarity to pistachio	Flowers	Fruit shape	Fruit rattling	Seed shape	Use in rosaries and adornments	Others	Ref.
Latin							
fistici, pistacia agrestia, pistacia germanica, pistacea sylvestris, pistacia silvestris	-	follicularis, nux vesicaria, vesicaria	-	-	-	-	269
GREEK							
-	staphylodendron (latinized)	-	-	-	-	-	270
πισταχίων (pistachion)		-	-	-	-	-	271
-	-	κολυτέα (kolytea)	-	-	-	-	272

* Although of course not being a Slavic language, Romanian is mentioned in this group, as the vernacular Romanian name for *staphylea* is a Slavic loan word. Besides, due to the characteristics of rattling fruit, *staphylea pinnata* in Romanian shares the same name with *rhinanthus* (rattleweed) species, requiring some caution in identifying the plant in literature.
** Likewise, the Bulgarian 'pimpernusa' is a German loan word, thus not listed among Bulgarian vernacular names, but rather among German eponyms.

Republic, Croatia, and Bulgaria has been compiled by R. Hendrych.[158] In addition, the settlements of Клокотиш (Klokotish) near Годеч (Godech) in western Bulgaria[159] may be named here, likewise Клокочевац (Klokočevac) in the Бор (Bor) district in Serbia,[160] Klokoča in Vukovarsko-srijemska županija (županija = county) and the town of Klokoč in Karlovačka županija in Croatia,[161] the Klokoč hill in Bosnia and Herzegovina, and Clucucica near Cernăuți in Romania.[162]

Some authors derive the 'klokoč' toponyms directly from the rattling of the ripe bladdernut fruits,[163] but others see those names rather as originating from a different Slavic root ('klokotati' and the like) meaning 'to bubble' or 'to gush', related to bodies of flowing water, particularly springs.[164] Also in Romanian, the verb 'clocoti' actually translates the same way. A full evaluation of one or other interpretation is beyond the scope of this paper. It should, however, be noted that 'bladdernut toponyms' are not clearly related to *Staphylea pinnata* after all, and may as well, or instead, refer to places simply named after nearby springs.

Conclusions

The data compared here provides a surprisingly diverse picture of views and uses of the rare shrub *Staphylea pinnata*. The richest historical and ethnographical evidence comes from eastern Europe, although archaeological evidence clearly demonstrates that the shrub was also significant in central and northern Europe, as far back as prehistoric times. The following interim conclusions are suggested.

Consumption of bladdernut seeds is fairly well documented for the early Bronze Age, for the early Iron Age, and then continuously from the seventh century CE until today. However, the record contains millennium-wide gaps between these three periods, and, since their provenance spans an area from southern Italy to central to southeastern Europe, it robustly challenges claims for any alleged 'continuum'. However, the existing evidence is not unimportant for a plant of such rare occurrence, and it is quite reasonable to suggest a general habit of people eating *Staphylea* (mainly the seeds, but also other parts) where available throughout Europe. It is to be expected that further archaeological clues on the past role of bladdernut in human nutrition will become available in the future.

Until the Renaissance, written evidence on bladdernut in medicinal use is very rare, and such evidence as there is hardly differentiates it from pistachio (*Pistacia vera*). And even in later periods, indications of pistachio seem to have played a role for medicinal views on bladdernut. A question that could not be answered concerns the unfounded 'toxicity myth' occurring now and then in written sources from western and central Europe.

Ritual uses are best documented for modern times due to methodological reasons. Some of the diverse traditions recorded in the nineteenth and twentieth centuries date back as early as the late Middle Ages/early Modern Times, and many may indeed be based in some distant past not covered by written sources, although this hypothesis is of course difficult to prove. One particular ritual use, the habit of using bladdernut seeds (as well as adornments made thereof) as grave goods is currently only documented for a rather short spell: evidence for this exists from the second until the

fourth centuries CE, as for the sixth and seventh centuries. All known find contexts either lie at the very limit of the supposed natural *Staphylea* distribution (south-western Germany), or far beyond it (northern Germany, Denmark, northern Poland), raising the question of what made these seeds a merchandise worth transporting hundreds of kilometres. Apart from decorative reasons, apotropaic attributions are also suggested.

The data on its use in rosaries is indeed scanty, but can at least be precisely dated from the sixteenth century onwards, which is about the period when the rosary emerged in its modern shape — long preceded, however, by earlier forms of prayer beads since at least the twelfth century.[165] Given its very rare appearance and a strong concentration of the evidence only from the twentieth (!) century onwards, the widely accepted hypothesis that bladdernut provided raw material for rosaries during history cannot be said to have been fully refuted, but it is very probable that *Staphylea* was never the 'first choice' for this purpose.

Abstract

An interdisciplinary approach combining archaeological, historical, and ethnological data is used in the attempt to draw a general image of the role of bladdernut (*Staphylea pinnata*) in past societies. The purposes encountered in this literature study extend from nutritional and medicinal uses to particular ritual/religious aspects, incorporating apotropaic and sympathetic magic, the use in grave goods, and the role of bladdernut in rosaries. In the two latter purposes, the 'cut nose' aspect of the seeds is suggested to be an important symbolic factor.

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ORIGINAL ARTICLE

Land use, economy and cult in late Iron Age ritual centres: an archaeobotanical study of the La Tène site at Sandberg-Roseldorf, Lower Austria

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Abstract Sandberg-Roseldorf—one of the largest known lowland La Tène settlements in central Europe—is located in a very fertile area favouring cereal cultivation. The site is remarkable for its temple districts and its possible religious significance. A total of 27,252 charred plant remains have been analysed from Temple District 1 and a section of the settlement area, including a burnt granary. Altogether 14 crop plant species have been identified, some of them pointing to contacts with the Mediterranean. The 136 recorded wild plant taxa originate from major habitat types around the settlement, including arable fields, ruderal sites, steppe grassland on loess, dry grassland on acidic soils, mesic grassland on moist valley bottoms, as well as woods and forest steppe complexes. Land use seems to have been quite intensive around Roseldorf. Palaeoeconomic calculations show that the exceptionally rich agrarian environment could have easily supported a sizeable human population, only parts of which had to devote themselves to food production. Ritual contexts yielded rich and some exceptional plant material.

Keywords Charred plant remains · Granary · Sanctuary · Landscape reconstruction · Consumer/producer-site · Palaeoeconomic model · Lower Austria

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Introduction

Excavations of late Iron Age sites in central Europe have rarely yielded rich plant spectra (Dálnoki and Jacomet 2002; Kreuz 2004; Kreuz and Wiethold 2010) and only in exceptional cases has it been possible to analyse settlement structures and sanctuaries at the same place, as at Mont Beuvray, France (Wiethold 1996, 2011). The site of Sandberg-Roseldorf in eastern Austria is such an exceptional case (Fig. 1). This lowland La Tène settlement of almost urban dimensions was excavated from 2001 onwards, in the framework of the research project "Fürstensitz Keltenstadt Sandberg-Roseldorf", under the leadership of Veronika Holzer from the Prehistory Department of the Vienna Natural History Museum. The regional context is provided by archaeobotanical studies of several neighbouring sites: so far, two hillfort sites, Oberleiserberg (Schneider and Raunjak 1994) and Gars/Thunau (Popovtschak and Zwiauer 2003) have been analysed, as well as two smaller rural settlements, Michelstetten (Kohler-Schneider and Heiss 2010) and Mitterretzbach (Heiss and Kohler-Schneider, in press; Kohler-Schneider, in press). On this basis, it is possible to draw a sketch of late Iron Age land-use and agriculture in a region that belongs to the most fertile areas in central Europe.

The main goal of this paper is to reconstruct landscape and vegetation patterns around Roseldorf based on the remarkably rich archaeobotanical material. In addition, we aim to address questions of land use and food procurement for this large Iron Age settlement and also discuss the question whether this site could have been self-sufficient. We will have a look on the unique position of Roseldorf in a regional and supraregional context. Although our database is not as large as the ones in British studies for example (Van der Veen 1992; Van der Veen and Jones

2006), we will venture to address questions about a possible food surplus production in the late Iron Age settlements of eastern Austria.

The site and its environment

The La Tène settlement of Sandberg-Roseldorf (48°39′N, 15°58′E) is located in Niederösterreich, northeastern Austria, in a gently rolling hill country, at an elevation of 330 m.a.s.l. (Fig. 1). The site was a lowland settlement of remarkable dimensions. According to geomagnetic surveys it covered an area of at least 25 ha, but might possibly extend to 40 ha (Holzer 2009a; Trebsche 2012). Finds of brooches, glass bracelets and coins (Holzer and Karwowski 2008; Dembski 2009) point to the middle La Tène (LT C2) as the main occupation period. This is largely confirmed by AMS ^{14}C data, for instance from the granary, dated to 230–160 cal BC (Stadler 2009). It appears that the settlement had no precursors and was never built upon after its demise.

Judging from the rich finds of local and foreign coins, Sandberg-Roseldorf was an economic centre with its own mint and far-reaching trade relations (Holzer 2009a, 2010a; Dembski 2009). There was some glass production and a metal foundry (Holzer and Karwowski 2008) and it seems that the settlement had been a major ritual centre: so far, seven so-called "Temple Districts" have been located. These districts are aggregations of pits and square shaped structures, delimited by ditches. At least one of these structures, located in Temple District 1, closely resembles sanctuaries excavated in France, as in Gournay-sur-Aronde (Bruneaux 1995; Holzer 2009a) and has therefore been labelled as Sanctuary 1. It is 25 m square, with a central pit (Fig. 2). The fillings of the ditch contained fragmented animal and human bones (Bruckner-Höbling and Pucher 2008; Teschler-Nicola et al. 2009) as well as many metal objects, like swords, shields, and parts of harnesses and chariots. Since many objects showed signs of intentional destruction, they probably represent ritual offerings (Holzer 2009b, 2010a). The distribution of these offerings was rather uneven, but spectacular finds were made in various sections of the ditch, among them an iron ceremonial (?) piece of headwear, a deer antler which might have been part of a statue, a seven starred amulet, fragments of a coat of mail etc., (Holzer 2009a). Temple District 1 harboured another two sanctuaries (12 and 13 in Holzer 2009a), which were only half the size of Sanctuary 1 and poorer in artefacts. Among the pits of the Temple District, Sacrificial Pit 14 was of considerable dimensions (10 × 7 m). In one corner there was a narrow, square shaped shaft of 1.3 m wide, reaching down to 4 m below the surface. Parts of the shaft had remnants of a wooden lining (Holzer 2010b). Obviously, the pit had been dug around the mouth of a well. Both well and pit were extremely rich in artefacts, among them spears, shields, swords and sheaths, metal fittings from harnesses and war-chariots, a bone dice, silver coins and many human and animal bones (many from horses). Pit complexes 15 and 16 as well as Pits 17–27 were only shallow with less numerous artefacts.

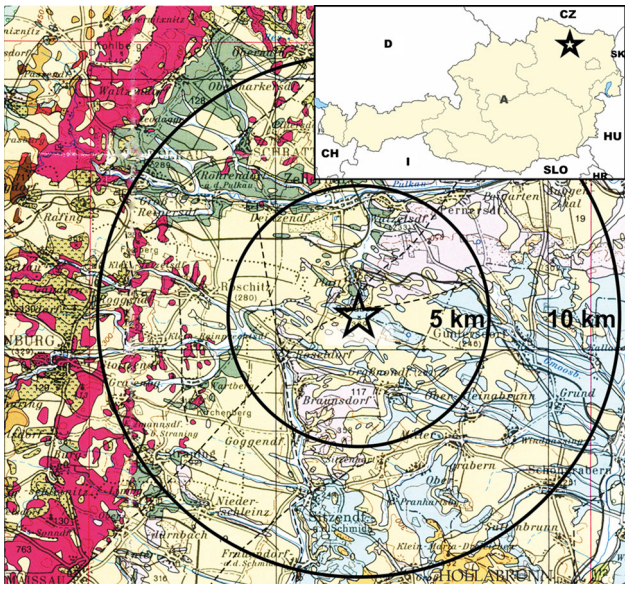


Fig. 1 Location of Sandberg-Roseldorf, site catchment and geology. *Yellow* loess; *blue* and *light purple* marl and sandstone; *green* clay; *red* granite. Geologische Bundesanstalt Wien, modified

Since Sandberg-Roseldorf is a dry mineral soil site, plant macroremains have survived only in a charred state. Archaeobotanical investigations have mainly focused on Temple District 1. So far, only few other features have been analysed, collectively referred to as "settlement objects": amidst a densely built up area, three houses destroyed by fire were excavated. House 1 was a granary, with an exceptional store of charred cereal grains (Holzer 2009a). It was a rectangular building (6 × 5 m), constructed of massive logs of oak-wood (Grabner 2003; Fig. 3), partly preserved in situ in charred condition. In contrast to the adjacent houses, the granary was only slightly dug into the ground and probably had an upper floor. The interior of the building was subdivided into several wooden compartments, two of which contained the grain stores. In the south-eastern corner of the building, an intact pot was found, standing in its original position (Fig. 3). Adjoining the granary, Houses 2 and 3 (Holzer 2009a) were of roughly the same dimensions, but with walls of wattle and daub.

Geologically, the flat hilltop of Sandberg consists of calcareous marl and sandstone, deposited during the late Tertiary by the receding Paratethys sea. During the

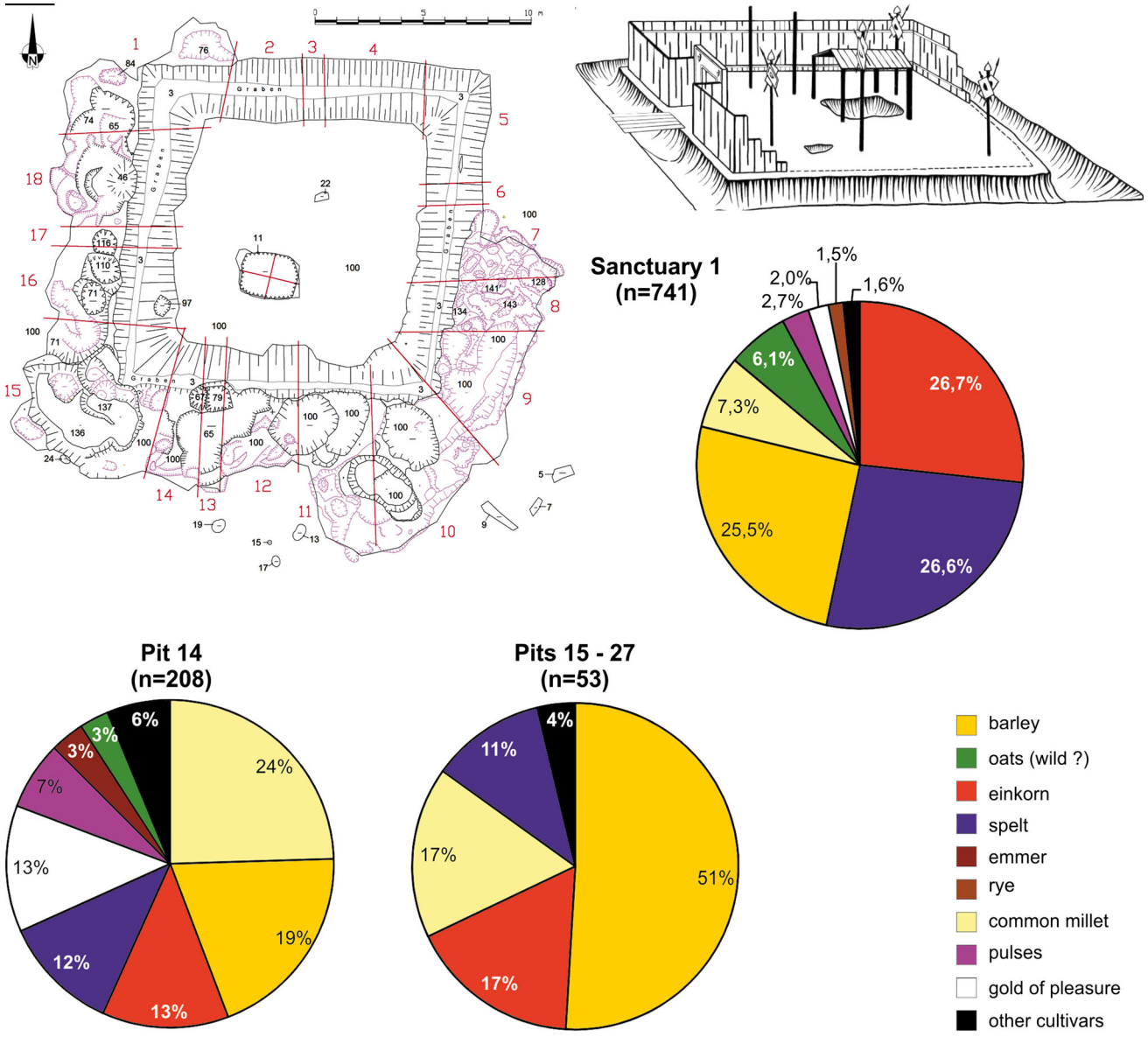


Fig. 2 Cultivated plant spectra from Temple District 1 (figures based on number of grains, no chaff remains included). *Top left*, plan of Sanctuary 1, Natural History Museum Vienna. *Top right*, reconstruction of Sanctuary 1, line drawing by authentic-experience/V. Holzer

Pleistocene, these marine sediments were covered by thick layers of loess, upon which very fertile chernozem soils developed later on. At a distance of 10–15 km north and west of Roseldorf, the cover of Tertiary and Quaternary sediments is broken by the first outcrops of granite bedrock belonging to the neighbouring Bohemian Massif. In sharp contrast to the calcareous soils on loess, marl and sandstone, acidic and nutrient poor soil types prevail around the granite outcrops (Digital soil map of Austria, Schnabel 2002). The climate of the region is of marked subcontinental character, with dry and warm summers and relatively cold winters. Average annual temperature amounts to 9.2 °C, while annual precipitation reaches only 442 mm, which places the region on top of the list of the driest spots in Austria (ZAMG 2002). The potential natural vegetation of the region would be a mosaic of thermophilous oak woods, oak-lime woods, oak-hornbeam woods and meadow steppes, with dry loess steppes on steep slopes and acidic dry grassland around the granite outcrops according to the vegetation map (Wagner 1985). The flat and poorly drained valley bottoms would be covered with fens, reedbeds and willow thickets, while wet gallery woods would have lined the meandering small rivers and brooks. Due to the dry climate, even patches of salt steppe may be expected in sites with permanently high ground water table. The modern vegetation differs strongly from this picture, as millennia of land use with vine and cereal growing, grazing, wetland drainage and almost total loss of woodland

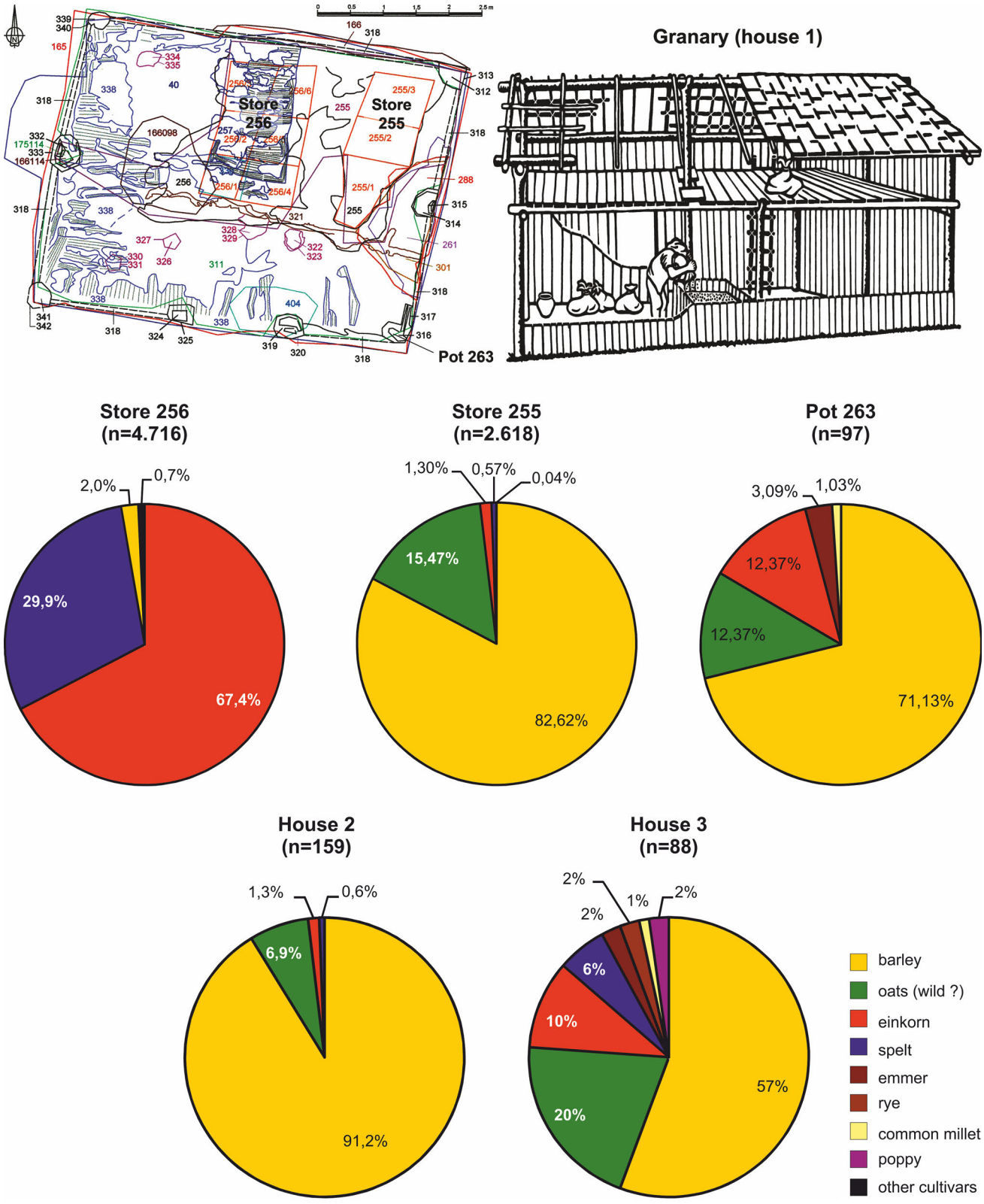


Fig. 3 Cultivated plant spectra from the granary and Houses 2 and 3 (figures based on number of grains, no chaff remains included). *Top left*, plan of the granary, Natural History Museum Vienna. *Top right*, reconstruction of the granary, line drawing by authentic-experience/V. Holzer

have changed the landscape; still, there are small remnants of natural plant communities in the most extreme sites such as steep loess slopes, granite outcrops, wetland patches and salt steppe remnants; the region is renowned for the occurrence of botanical rarities like *Kraschenninnikovia ceratoides, Bassia prostrata* and *Astragalus exscapus*, considered as relics of Pleistocene and early Holocene steppes (Wiesbauer 2008), which testify to the unbroken continuity of naturally treeless habitats in the region. Almost nothing remains of woodlands, the few scattered woodland patches obviously being of secondary character and there are plantations of *Robinia pseudacacia, Pinus sylvestris* and *Quercus robur* on former grazing land. Within the site catchment of Roseldorf there is a single larger remnant of semi-natural woodland on a steep north-facing slope. It is currently managed as a coppice with standards, where *Quercus petraea*, *Q. robur* (oaks) form the upper layer, while *Carpinus betulus* (hornbeam), *Corylus avellana* (hazel) and a large proportion of *Tilia cordata* and *T. platyphyllos* (limes) constitute the lower layer. The rich undergrowth of ancient woodland species such as *Convallaria majalis, Asarum europaeum, Polygonatum odoratum* and *Buglossoides purpurocaerulea* points to a less artificial character of that woodland patch.

Materials and methods

A total of 323 soil samples (7,221 l) has provided the database for the present analysis (Table 1). In the Temple District sampling was done in a systematic way, with sampling plots being distributed evenly across stratigraphic units, while subjective sampling was used in the settlement, focussing on conspicuous features within the floor layers of the three excavated houses. The large samples from the cereal stores of the granary (200 l of almost pure grain) had to be divided into subsamples for closer analysis, using the grid sampling method (Jacomet and Kreuz 1999). Apart from this pure grain assemblage, all other soil samples were processed by flotation, using sieves with mesh sizes of 1 and 0.5 mm. Hand sorting under the stereomicroscope resulted in a total of 26,832 items (Table 1). For identification, the author's seed reference collections, the herbarium of the Institute of Botany and the relevant literature (Jacomet 2006a; Anderberg 1994; Berggren 1969, 1981; Cappers et al. 2006) were used. When counting chaff remains, single glume bases and rachis internodes were treated as one item, while spikelet forks (with the two glume bases still fused together) were counted as two. Botanical nomenclature follows Fischer et al. (2008).

A first set of charcoal analyses was made during dendrochronological investigations on the granary's construction timber (Grabner 2003). In addition, charcoal from Temple District 1 was analysed under a reflected light microscope, totalling 420 identified specimens. For wood identification, charred reference material as well as the usual literature (Schweingruber 1990; Heiss 2009) were used. Charcoal amounts were recorded both by number and weight.

The recorded wild plant taxa were assigned to ecological groups, based on actualistic assumptions. We are fully aware of the problems arising from direct comparisons

Table 1 Sample statistics (overview) Sandberg-Roseldorf

	Temple District 1								Settlement objects					
	Sanctuary			Pits					Granary			House		
	1	12	13	14	15	16	17-27	Total	Store 256	Store 255	Pot 263	2	3	Total
Σ of soil samples	158	4	17	72	24	21	15	311	6	3	1	1	1	12
Volume (l)	4,707	120	510	1,070	356	230	180	7,173	0.48	0.24	1.4	21	25	48.12
Σ of plant remains (diaspores)	7,108	24	90	4,717	545	183	41	12,708	8,892	3,286	457	566	923	14,124
Cultivated plants	4,680	2	6	1,417	461	81	33	6,680	8,245	3,197	448	465	558	12,913
Wild plants	2,428	22	84	3,300	84	102	8	6,028	647	89	9	101	365	1,211
Macroremains indet.	604	17	82	936	37	12	2	1,690	12	11		18	60	101
Plant remains/l	1.51	0.20	0.18	4.41	1.53	0.80	0.23	1.77	18,525	13,691.66	326.43	26.95	36.92	293.52
Cultivated plants/l	0.99	0.02	0.01	1.32	1.29	0.35	0.18	0.93	17,177.08	13,320.83	320	22.14	22.32	268.35
Wild plants/l	0.52	0.18	0.16	3.08	0.24	0.44	0.04	0.84	1,347.91	370.8	6.43	4.81	14.60	25.17
Σ of cultivated species	13-16	1	0-1	10-14	5-6	5	1	14-17	6-8	4-5	4-6	3-4	7-9	8-10
Σ of wild plants ecol. grouped	87	4	2	62	11	8	2	112	12	11	3	22	34	51
Wood charcoals identified	244			121				365						55

between archaeobotanical assemblages and modern vegetational groupings. These problems have been stressed many times (Behre and Jacomet 1991; Hillman 1991), especially with regard to synanthropic communities, which may have changed considerably over time with changes in human land use practices and techniques. Still, our habitat types represent such broad categories that we do not feel the necessity of being over-cautious with regard to the "actualistic trap". In those cases where we venture into a finer subdivision of habitat types as with the distinction between dry grasslands on calcareous loess soils and those on acidic soil, this is based on very fundamental ecological traits of the species in question. In no instance do we intend to suggest that modern, syntaxonomic units were present in the past in exactly the same composition as today.

Results

General overview

A total of 26,832 charred plant remains (wood charcoals excluded) have been recovered from the various archaeological objects in Roseldorf (Table 1). Most of them, 19,593 items, were classified as cultivated plants and 5,448 as wild plant remains. Find density was rather uneven among the samples, with an average of 1.77 remains/l in the Temple District (range: 0.2–4.4) and an exceptional 293.5 remains/l in the settlement (range: 26.9–18,525). Due to a very different amount of analysed (sampled) soil volume, the total number of plant remains retrieved from the Temple District and from the settlement (12,708 vs. 14,127) is quite comparable.

Cultivated plants

Due to the excellent preservation state of most cultivated plant remains, 14,079 items were identifiable to species level (Fig. 4; Tables 2, 3). This resulted in a total of at least 14 species, plus another two (*Linum usitatissimum* and *Anethum graveolens*) which were only classifiable as *cf.* In a third taxon, *Avena* sp., it was not possible to decide whether the remarkable amount of grains found belonged to *Avena sativa* (cultivated oats), or to *A. fatua* (wild oats). Although the presence of the latter was confirmed by numerous floret bases, domestic oats might have been involved as well – the oat grains being part of a cereal store that had otherwise been carefully cleaned of weed admixtures (see below). Should all grains indeed belong to wild oats, it must be assumed that this edible taxon was tolerated, if not purposefully sown, among other cereals. Either way, a treatment of *Avena* sp. under the heading of "cultivated plants" would seem justified.

Regarding the importance of different crop plants (in terms of proportions and ubiquities), it can be seen from Figs. 2, 3, 5 and from Tables 2, 3 that *Hordeum vulgare* (barley), *Triticum monococcum* (einkorn), *T. spelta* (spelt), *Avena* sp. (oats) and *Panicum miliaceum* (common millet) were the dominant crops; *Lens culinaris* (lentil), *Pisum sativum* (pea), *Secale cereale* (rye) and *Camelina sativa* (gold of pleasure) were frequent as well, while *Triticum dicoccum* (emmer) and *T. aestivum/durum/turgidum* (naked wheat) clearly played a less important role. As always in dry soil excavations, *Papaver somniferum* (poppy) is probably underrepresented on account of its low preservation chances in a charred state. Of *Setaria italica* (foxtail millet) and *Vitis vinifera* (grapevine) there were only single finds. Presence of the so called "new glume wheat" was proved by finds of the characteristic spikelet forks (Fig. 4, compare Kohler-Schneider 2003). Identification of naked wheat was also made through chaff remains, although a finer distinction between tetra- and hexaploid forms was not possible. Most chaff remains, however, came from the dominant cereals.

Because of their special character, three archaeological contexts have to be treated in more detail: the granary, Sanctuary 1 and Sacrificial Pit 14.

The granary contained an almost pure assemblage of very well preserved charred cereals (11,442 remains, Table 2). Eventually, 6–8 taxa were recorded within this material, of which einkorn, spelt and barley were the most common. The cereal assemblage consisted of two distinct units, which had been stored in separate, wooden compartments of the building (Fig. 3; Holzer 2009a). The first store was a mixture of einkorn (67 %) and spelt (30 %), while the other contained mostly hulled barley (83 %), together with a substantial amount of oats (15 %). Many of the hulled cereals were preserved as spikelets, the grains still within their glumes; additionally, there were large amounts of corresponding chaff. Weeds were strikingly rare within the assemblage. Rye occurred as an admixture to both the barley-oats and the einkorn-spelt assemblages. Single grains of naked wheat, millet and oats were found only in the latter.

The intensively sampled square shaped enclosure ditch of Sanctuary 1 yielded a rich spectrum of cultivated plants. 4,680 remains could be assigned to 13–16 taxa (Tables 1, 3; Fig. 2). Most of these remains came from the upper and intermediate layers of the ditch. Except for *S. italica*, all domesticates recorded so far from Sandberg-Roseldorf were present in the different stratigraphic layers of the sacrificial ditch. In addition to the dominant taxa in the granary and in Houses 2 and 3—*Triticum monococcum*, *T. spelta* and *Hordeum* (each 26 %, many chaff remains)—there were also ample records of *P. miliaceum*. Grains and awn fragments of *Avena* sp. were numerous, too. *Secale*



Fig. 4 Cultivated plants from Sandberg-Roseldorf. **a, b** *Triticum spelta* (whole spikelet, caryopsis); **c, d** *Triticum monococcum* (spikelet forks fused together, caryopsis); **e** *Triticum* sp. "new" glume wheat (chaff remain); **f** *Triticum aestivum/durum/turgidum* (caryopsis); **g, h** *Avena* sp. (awn fragments, caryopsis); **i,** *Panicum miliaceum* (caryopsis); **j** *Hordeum vulgare* (caryopsis); **k, l, m** *Secale cereale* (3 caryopses); **n** cereal food residue (porridge or bread); **o** *Lens culinaris* (seed); **p** *Camelina sativa* (seed); **q** cf. *Anethum graveolens* (fruit); **r** *Vitis vinifera* (pip). *Scale bars* 1 mm; photo credits: **a–i**, **l**, **m**, **p**, **q** A. Caneppele; **j**, **r** M. Kohler-Schneider; **k**, **n**, **o** A.G. Heiss; arrangement and digital remastering A.G. Heiss)

and cultivated legumes (*Lens* and *Pisum*) played a less important role, and the remaining cereals were rare. Of greater importance must have been the oilseeds *C. sativa,* (Fig. 4) and *P. somniferum*, whereas of *Linum* only 1 cf. seed was recorded. A special discovery was a charred pip of *V. vinifera* (Fig. 4), showing features of the cultivated form with an elongated shape and long stalk (Caneppele and Kohler-Schneider 2009).

The highest find density of the entire Temple District was observed in Sacrificial Pit 14 (Table 1). This is due to a large proportion of wild plant remains, whereas cultivated plants were less than half as numerous (1,417 in total). At the same time, the broad spectrum of domesticates (10–14 taxa) is very similar to that of Sanctuary 1 (Table 3). An obvious difference is that in Pit 14 *P. miliaceum* is the most important cereal, judging from the number of remains. Many finds of *Camelina* as well as of *Papaver* again point to the importance of these oil crops. Cultivated legumes, emmer, oats, naked wheat, rye and new glume wheat were present as well. Unique features of Pit 14 were 39 pieces of amorphous charred objects (AOV sensu Jacomet et al. 2006). Closer inspection with SEM revealed traces of bran remains, an indication of cereal food residues from porridge, gruel or bread (Fig. 4; Hansson 1994; Samuel 2000;

Table 2 Cultivated plants from the settlement area; 13 samples, 48.12 l sediment

		Granary			House		Total
		Store 256	Store 255	Pot 263	2	3	
Cereals							
Avena sp. (det./cf.)	Grains	20/2	405	12/4	11	18	466/6
	Chaff, awn frag.		403	15		10	428
Hordeum vulgare	Grains	94	2,163	69/8	145/155	49	2,520/163
	Chaff	4/1	124	1	4	2	135/1
Secale cereale	Grains	10/4	1			2	13/4
Triticum dicoccum	Grains	/12		3		2	5/12
	Chaff			/2		/3	/5
T. monococcum	Grains	3,179	34	12	2	9	3,236
	Chaff	2,592	10	3	11	27	2,643
T. spelta	Grains	1,409	15	/1	1	5	1,430/1
	Chaff	619/1	1/2			7	627/3
T. aest./dur./turg.	Grains	2					2
	Chaff	2					2
Triticum sp. (hulled)	Grains	128	3	7	1	9	148
	Chaff	139		1		68	208
Panicum miliaceum	Grains	2		1		1	4
Cerealia indet.	Grains	3	9	309	135	341	797
	Chaff	22	27				49
Pulses							
Lens culinaris	Seeds					/3	/3
Oilseeds							
Papaver somniferum s.l.	Seeds					2	2
Total (det./cf.)		8,225/20	3,195/2	433/15	310/155	552/6	12,715/198

Heiss 2014). In contrast to Sanctuary 1, the distribution pattern of plant remains across the sampled layers of Pit 14 was relatively even, and only a few samples were barren. Finally, we have to mention the find of a flesh-fly puparium (Fig. 6)—the hardened exoskeleton of the last larval instar of a member of the dipteran family Sarcophagidae (identification: B. Janeček, in litt.).

Wild plants

The 5,448 identifiable wild plant remains were ascribed to 136 taxa (Tables 1, 4). Of these, 119 taxa were assigned to four habitat types based on actualistic principles (Table 4, Fig. 7; Grabherr et al. 1993; Fischer et al. 2008, own observations in the region). The majority of wild plant taxa belong to arable fields and ruderal sites (43.3 %), a large proportion to grassland (35.8 %), a smaller one to woodland (18.5 %) and only 3.4 % to wetland sites.

Ruderal and segetal species have been placed in one category, since many species are difficult to assign exclusively to one or the other group, even at present. Some species of the ruderal/segetal group might act as indicators of the prevailing crop regime. *Agrostemma githago, Bromus secalinus, Centaurea cyanus* and *Lamium amplexicaule* are frequently associated with autumn-sown crops, while *Avena fatua, Bromus arvensis, Digitaria sanguinalis, Echinochloa crus-galli, Persicaria maculosa, Setaria viridis/verticillata* and *Stachys annua* are typically seen as summer crop weeds (Fig. 8). In the granary, the above mentioned winter crop weeds dominated in Store 256 (within the einkorn/spelt mixture), while Store 255 had mainly summer crop weeds (within barley/oats). A striking feature of the arable weeds/ruderals group is the considerable number of thermophilous species like *Adonis aestivalis, Bupleurum rotundifolium, E. crus-galli, Glaucium corniculatum, Kickxia spuria, Nigella arvensis* and *Valerianella rimosa*. Most of these are typical components of the modern Caucalidion alliance, a group of thermophilous segetal plant communities growing in cereal fields of the warm loess regions in eastern Austria. In addition to thermophilous plants, there are some indicators of a high degree of continentality like *A. aestivalis, Camelina*

Table 3 Cultivated plants from the Temple District 1; 312 samples, 7,173 l sediment

		Sanctuary			Pits				Total
		1	12	13	14	15	16	17-27	
Cereals									
Avena sp. (det./cf.)	Grains	45/12			6				51/12
	Awn frag.	14/2							14/2
Hordeum vulgare	Grains	189/8			41/8	21/4	6		257/20
	Chaff	17			5	12	1		35
Secale cereale	Grains	11/17			3/3	/1	1		15/21
	Chaff	4/1							4/1
Triticum aest./dur./turg.	Grains	4/14			5/1				9/15
T. dicoccum	Grains	5/4			7/5				12/9
	Chaff	2/1			4/1				6/2
T. monococcum	Grains	198/8	1		26/1	4	4	1	234/9
	Chaff	203			7	2			212
T. spelta	Grains	197/1			24/5	5	1		227/6
	Chaff	81/1		/1	12	3			96/2
Triticum sp. "new type"	Chaff	2			2				4
Triticum sp. (hulled)	Grains	232			72	3			307
	Chaff	128			3				131
Triticum sp.	Grains				13			2	15
Panicum miliaceum	Grains	54/2			51	8/1	1		114/3
Setaria italica	Grains					1			1
Cerealia indet.	Grains	3,159	1	4	1,010	396	67	30	4,667
	Chaff	1							1
Amorphous charred objects	Porr brd			1	39				40
Pulses									
Lens culinaris	Seeds	6/20			3/12				9/32
Pisum sativum	Seeds	3			1/2				4/2
Lens/Pisum	Seeds	11							11
Fabaceae cultivated	Seeds				10				10
Oilseeds									
Camelina sativa	Seeds	15			26/2				41/2
Linum usitatissimum	Seeds	/1			/2				/3
Papaver somniferum s.l.	Seeds	2/2			5				7/2
Other cultivars									
Anethum graveolens	Fruits	/2							/2
Vitis vinifera ssp. *vinifera*	Seeds	1							1
Total (det./cf.)		4,584/96	2	5/1	1,375/42	455/6	81	33	6,535/145

microcarpa, and *Chenopodium hybridum.* The prevalence of calcareous soils around the settlement is indicated by calciphiles like *A. aestivalis, B. arvensis, B. rotundifolium, Camelina microcarpa, C. hybridum, Galium spurium, G. corniculatum, Lepidium campestre, Neslia paniculata, Nigella arvensis, Picris hieracioides* and *Stachys annua* (Fig. 8). There are no taxa which grow on acidic soils. Not surprisingly, a high nitrogen content of the soil is indicated by species which would be considered as typical ruderals by modern standards. However, there are only few such indicators among possible arable weeds (*E. crus-galli, Stellaria media*), although none of the typical segetal plants points to a real lack of nitrogen. The arable weeds/ruderals group is clearly dominated by annuals.

A considerable number of wild plants (42 taxa) originate from grassland-like formations (Table 4). *Stipa pennata* (present in the archaeobotanical material with numerous awn fragments), *Salvia nemorosa, Teucrium chamaedrys, Asperula cynanchica, Hypericum perforatum, Acinos arvensis* and *Thymus* sp. may be mentioned as typical representatives of dry grassland communities on calcareous soils. The high ubiquity of *Acinos* diaspores was especially striking (Fig. 8). This species grows in hot and dry places, with only a thin vegetation cover and hardly any humus

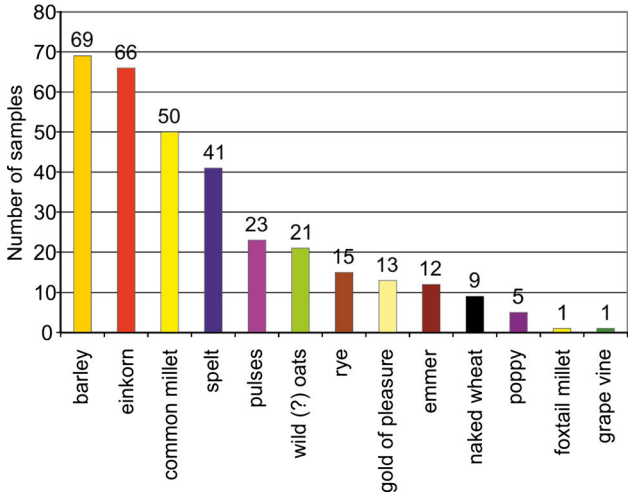


Fig. 5 Ubiquity of cultivated plants (total number of samples = 323, figure based on number of grains, no chaff remains included)

layer, often on loess soils. A second, smaller group of dry grassland species is clearly associated with acidic soils: *Trifolium arvense, Scleranthus perennis, Armeria elongata* and *Festuca ovina* (Fig. 8). Another set of species like *Ajuga reptans*, *Phleum pratense*, *Plantago lanceolata*, *Poa pratensis/trivialis*, *Lolium perenne*, *Medicago lupulina, Trifolium pratense* and *Trifolium repens* (Fig. 8) probably originates from comparatively mesic grassland communities, that would also be suitable for hay making.

There are only few plant records which might be ascribed to *wetlands*. Species like *Dipsacus fullonum* and *Persicaria lapathifolia* certainly grow in wet places and might come from half-open floodplain and gallery woods along the small brooks in the valley.

Among the *woodland* taxa (22 in total), some species might in fact originate from floodplain woodland communities: *Humulus lupulus, Physalis alkekengi, Sambucus nigra* and *Galium aparine* grow in moist sites with a rich nutrient supply, which would either qualify them as floodplain species or as inhabitants of ruderal shrubbery. However, a far greater proportion of woodland species belongs to woodland on dry soil or woodland margins and clearings. Most notable among these are species of thermophilous oak woods and their fringes, like *B.*



Fig. 6 **a** Reconstruction of Sanctuary 1, open air museum Asparn/Zaya; **b**, **f** *Vitis vinifera* (charred pip, modern grape); **c**, **g** *Sorbus aucuparia* (charred seeds, modern fruits); **d**, **h** *Crataegus laevigata* (charred stone, modern flowers); **e**, **i** Sarcophagidae (charred puparium, modern imago). Photo credits: **a**, **b**, **f**, **g**, **h** M. Kohler-Schneider; **c**, **d** A. Caneppele; **e** A.G. Heiss, **i** T. Hudson@wikimedia.org

Table 4 Wild plants from Sandberg-Roseldorf (only taxa attributable to habitat types included); 323 samples, 7,221 l sediment; granary: Store 256, 255 and Pot 263

	Temple District 1							Settlement objects				
	Sanctuary			Pits				Store		Pot	House	
	1	12	13	14	15	16	17-27	256	255	263	2	3
Wetlands												
Atriplex hastata (det./cf.)				/1								
Chenopodium ficifolium				/1								
Dipsacus fullonum	5/1											
Persicaria lapathifolia	7/1			1/1								6
Woodland, wood edges and clearings												
Astragalus glycyphyllos	/1			/1								
Buglossoides purpurocaer.	1											
Carex muricata-type	1											
Carpinus betulus	1											
Clematis recta	/1											
Clinopodium vulgare	/1											
Cornus mas				3		5						
Corylus avellana				1								1
Crataegus laevigata	1											
Fragaria vesca	3/1											
Galium aparine	10/2											3
Humulus lupulus	1											
Lamium maculatum				/1								
Physalis alkekengi				2								
Prunus spinosa				3								
Rubus fruticosus agg.				1								
Sambucus nigra	2/1			1	1	2					1	
Sambucus sp.											/1	
Silene alba	7/8										2	/2
Silene dioica	4/4			1				1				
Sorbus aucuparia	2											
Thalictrum minus	71/1			15		1					1	8
Grassland												
Acinos arvensis	139			11							1	12
Ajuga reptans	2			3								
Alchemilla sp.				2								
Armeria elongata				10								
Asperula cynanchica	2											
Carex sp.				1								
Centaurea jacea s.l.				1								
Centaurea sp.				3								
Cyperaceae				/2					2			
Festuca ovina	/1											
Genista sp.	1											
Hypericum perforatum	1			1								
Lolium perenne	1/1											1
Lotus corniculatus	/5			1								
Lotus sp.	/2											
Medicago lupulina	25/34										/2	2
Medicago sp.	/9											
Medicago/Trifolium				3								
Mentha sp.	4	/1										
Phleum pratense	3/4											1/1
Plantago lanceolata	20	1		40						1	1	1
Plantago lanceolata/media				15								
Plantago sp.	4											
Poa annua											1/1	
Poa pratensis/trivialis	5			1							1	
Poa sp.	2											/1
Poaceae	226		1	207/1	14	7		6		1		11
Potentilla sp.	2/2											
Rumex sp.	1/1			1				2				
Salvia nemorosa									1			
Scleranthus perennis	1											
Securigera varia				4/1								1
Silene vulgaris	1/3								1			/1
Stipa pennata agg.	12/2			2/2							1	
Teucrium chamaedrys	8			7/2								
Thymus sp.	1											
Trifolium arvense	4/6			2							/1	
Trifolium pratense	3/1			/3								
Trifolium repens	6/3										/1	
Trifolium sp.				3								
Verbascum sp.	5			1								
Veronica chamaedrys				2								

Table 4 continued

	Temple District 1							Settlement objects				
	Sanctuary			Pits				Store		Pot	House	
	1	12	13	14	15	16	17-27	256	255	263	2	3
Arable weeds and ruderals												
Adonis aestivalis	1											
Agrostemma githago	16			48/1		2		206/2	2		1	5
Arctium minus	/1											
Artemisia vulgaris	/2											
Atriplex sp.	42		1	7	/1						2	8
Avena fatua (floret bases)									45	7		
Brassica sp.	1											
Bromus arvensis	2							8/8				
Bromus secalinus	1							24/7	/1			/1
Bromus sp.	13			15				93	1			11
Bupleurum rotundifolium	/1											
Camelina microcarpa	/1											
Camelina sp.	1			1								
Centaurea cyanus	/3											
Chelidonium majus	/1											
Chenopodium album agg.	230			55	3	5		39/2			7	20
Ch. hybridum	48			71	5	51	4				6	17
Ch. murale				5								
Ch. polyspermum				/2								
Chenopodium sp.	386	2		1,670	6	16	1	186	3		43	86
Digitaria sanguinalis												/1
Echinochloa crus-galli	2/1			2	1				1/1		1	1
Euphorbia peplus					1							
Fallopia convolvulus	76	1		43	8			21				10
Galeopsis tetrahit	/2											
Galium spurium	17/3			1	2							3
Glaucium corniculatum				1								
Hyoscyamus niger	1			4								/1
Kickxia spuria	/15											/3
Lamium amplexicaule	1											
Lapsana communis											1	
Lepidium campestre				9								
Malva neglecta	5			3	1							
Malva sp.	3			1								
Melilotus sp.	/1											
Microrrhinum minus	/1											
Neslia paniculata				2/1								
Nigella arvensis	8/1											1
Panicoideae	7			7					1			
Persicaria maculosa	39/1			/1								57
Picris hieracioides	2											1
Polygonum aviculare s.l.	16			3/2								
Polygonum sp. s.l.	46			7	2	1		26				12
Setaria verticillata/viridis	1/2			1					1		2	1
Sisymbrium sp.								/1				
Solanum nigrum agg.	1			2							3	1
Stachys annua	1			1								/1
Stellaria media agg.	1											
Thlaspi arvense	2										1	
Valerianella rimosa	/1											
Viola arvensis/tricolor	4/1											
Additional taxa												
Apiaceae				4					/1			1
Asteraceae	3/1			/6			1		10			
Astragalus sp.				1					/1			
Brassicaceae	5			10	/1							2
Caryophyllaceae	2							3				
Dipsacus sp.	1/1											
Fabaceae	53			5/1	1						1	1
Galium sp.	10											4
Lamiaceae	6			1					3/1			
Lamium sp.	3											
Lathyrus/Pisum/Vicia				1								
Rosaceae				1								
Rubiaceae	1								/1			
Silene sp.	27			3					1			4
Solanaceae	1											
Teucrium sp.	1											
Viola sp.	6											
Total(det./cf.)	1,688/136	4/1	2	2,334/30	45/2	90	6	615/20	72/6	9	77/6	293/12

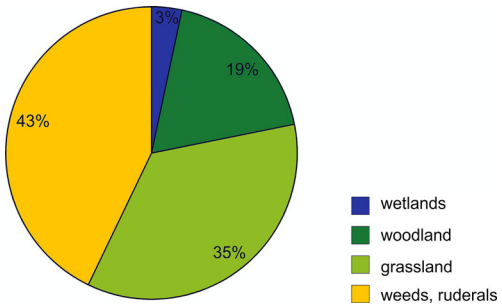


Fig. 7 Wild plant taxa grouped according to habitat types (n = 119)

purpurocaerulea, Clematis recta, Clinopodium vulgare, Cornus mas and *Thalictrum minus*. The dominant tree taxon of the region—*Quercus*—was only recorded among wood charcoals, where the majority (80–96 %) of the investigated charcoals came from oak (Table 5). A nutlet of *C. betulus* (along with charcoals of that species) is worth mentioning. A very remarkable find is *Sorbus aucuparia* from Sanctuary 1. As this tree is restricted to acidic soils in the region, its fruits must have been brought to the settlement from some distance, most probably from the granite outcrops to the west of the site (Figs. 1, 6).

Plant remains from "ritual" and "non-ritual" contexts

Archaeozoological analysis of the ditch filling layers of the enclosure of Sanctuary 1 has resulted in a distinction between deposits with ritual character on the one hand, and simple domestic waste on the other hand (Abd El Karem 2011). The latter is characterized by a mixture of fragmented bones of cattle, sheep, pig, dog and horse with marks of butchering, food processing and consumption. It seems that these uppermost filling layers (especially SE 103) have been relocated from the surrounding settlement to the ditch, after the sanctuary had lost its function. By contrast, the layers on the bottom of the ditch (SE 37, 43, 47, 57, 59, 60, 70, 107, 109, 117) were unusually rich in cattle and horse remains and mixed with numerous human bones, as well as with intentionally destroyed weapons and other metal objects. As similar find assemblages are characteristic of Gallic sanctuaries, a ritual deposition of that layer seems likely. The animal bones might well be remnants of ritual feasting (Abd El Karem 2011). Some stratigraphic layers (SE 2, 40, 51) have an intermediate position, however. They are located in the upper portion of the ditch and contain domestic bone refuse, along with some human bones, distorted weapons and other objects of possible cult significance.

These different kinds of deposits can also be distinguished from an archaeobotanical point of view. In the bottom layer, plant remains are strikingly scarce, while in the upper fillings—especially SE 103—plant species diversity is high and closely mirrors the composition of "normal settlement waste" like single cereal grains, chaff and some weed seeds, as found for example within the investigated houses (Table 3). The intermediate layers have both elements from settlement waste and from possible ritual contexts: the botanical "exotics" grapevine and dill, which might have served as valuable offerings, have been found here, as well as the seeds of *Sorbus aucuparia* (rowan) and *Crataegus laevigata* (hawthorn) (Fig. 6).

Further remarkable features of Sacrificial Pit 14 were the comparatively large amount of common millet grains and the numerous finds of *Camelina* and *Papaver* seeds. In addition, almost all cereal food residues recovered from Sandberg-Roseldorf came from Sacrificial Pit 14, as well as the flesh-fly puparium (Fig. 6) and the find of a rare Mediterranean weed, *Glaucium corniculatum* (Fig. 8). When considered in isolation, none of these finds would necessarily point to a ritual use. But their striking concentration in one very special context (and their almost total absence from others) might be more than just a product of chance.

Discussion

Crop plants

From a regional perspective, the crop plant spectrum of Roseldorf shows some similarities to other investigated La Tène sites in eastern Austria, mentioned in the introduction, but also some differences. Among cereals, *Hordeum* is of greatest importance in all other sites, followed (or even surpassed, as in the rural site of Michelstetten) by *P. miliaceum*. In Roseldorf, *Panicum* only comes third after *Hordeum* and *T. monococcum* when all samples are considered together; however there are exceptions like Sacrificial Pit 14. Roseldorf is also special on account of its large share of *T. spelta*, while in the other sites, spelt was of secondary importance. When classified as a crop plant, the large proportion of oats can also be considered a special feature of Roseldorf. Emmer was present in some numbers at all sites, while rye, naked wheat, new glume wheat and foxtail millet had either the status of admixtures, or they were totally absent. Judging from its ubiquity in Roseldorf, rye could have been on the threshold of regular cultivation. But since in central Europe, conscious use of rye is postulated for the Iron Age at the earliest (Behre 1992), and since there is no evidence for it from other Austrian La Tène sites, the status of rye in Roseldorf must be treated with caution. It might still have been a welcome, but inadvertent admixture to other cereals.

The find of a burnt granary shows that hulled cereals (still within their glumes) were stored in large amounts in

the settlement. As weeds were strikingly rare within the assemblages, we assume that both stores represent material for sowing that had been carefully cleaned, possibly by hand sorting. Stores intended for consumption might not have required the same amount of cleaning.

Legumes were represented at all sites by *Pisum* and *Lens*, while *Vicia faba* (celtic bean) was lacking, except perhaps at the rural settlement of Michelstetten, where a *cf.* fragment has been found. Whether this is due to the notoriously low preservation chances of legumes in dry soil situations, or to a truly subordinate status of the species, remains an open question. A regional record of *V. faba* comes from late Bronze Age Stillfried (Kohler-Schneider 2001a), so the crop was known regionally from an early date onwards.

Even lower preservation chances in dry land sites also hamper the status assessment for oil seeds. Records of *Papaver*, *Camelina* and possibly *Linum* confirm that they were used in Roseldorf, but they were absent from the rural settlement of Michelstetten and the hillfort at Oberleiserberg. From the rural settlement at Mitterretzbach too, there is only an uncertain find of *Linum*. It is hard to imagine that these extremely useful crops—with an important double use in the case of linseed/flax—should largely have been disregarded by the La Tène people. Rather, their scarcity must be attributed to the instability of the seeds in the face of heat and fire and to the high probability of being destroyed during the recovery process.

The special status of Roseldorf as a large central agglomeration with social stratification is best illustrated by the find of *V. vinifera* in the ditch of Sanctuary 1. There is a minor possibility that it represents an aberrant pip of *V.v. sylvestris* (wild grapevine). But today, the occurrence of wild grapes in Austria is limited to the large and dynamic floodplain woods of the rivers Danube and March (Wotzi 2013; Arnold et al. 1998). This was so even in the 19th century (Reissek 1856), before the species became rare because of river regulation, changes in forestry practices and the advent of introduced diseases and competing lianas from North America. Whether the narrow gallery woods along the small rivulets and brooks near Sandberg-Roseldorf could ever have harboured wild grape is questionable. At least in lowland situations, the species prefers extensive hardwood floodplain woods, where recurrent and intensive disturbance events (flooding, sediment deposition, uprooting of trees) create spots of open soil and maintain woodland edge habitats (clearings, gaps, fringes) (Wotzi 2013; Arnold 2002). We therefore consider it much more likely that the Roseldorf pip really derives from cultivated grapes. Based on this assumption, grapevine has to be seen as an influence of Mediterranean traditions. Consumption of (imported) wine became a status symbol in central European cultures at least from the Hallstatt period onwards, and it is well known that this also holds for the La Tène period (Olmer 2012). Whether the high esteem for wine had also led to the first experiments with local wine growing (on the basis of imported vines), is still a matter of debate. According to conventional views, large scale cultivation of grapevines has been brought to central Europe only by the Romans. But scattered archaeobotanical finds of cultivated grape pips from western Hungary and eastern Austria point to a possible, much earlier start in the Pannonian region, which has a very favourable climate for viticulture (review in Kohler-Schneider 2001a). Similar hints, based on palynological data, are also known from the Valais (Switzerland), an inner alpine valley with a long-standing tradition of viticulture (Wick 2010). Of course, the pip in Roseldorf could also have come from dried raisins, brought from the Mediterranean as luxury goods. Such an exchange might also be indicated by the possible record of a spice of southern origin, cf. *Anethum graveolens* (dill). This species has rarely been found in pre-Roman central Europe, for example in Swiss late Neolithic lake-shore settlements (Jacomet 2006b, 2007, 2009), but also in a few Iron Age sites (Rösch et al. 2008; Stika 2009). All in all, cf. *A. graveolens,* and the grapes might either represent an import of luxury goods from the Mediterranean (as raisins, or as single pips in an imported wine amphora), or they were already cultivated locally (Fig. 5).

From a supraregional perspective, the La Tène crop plant spectrum of Lower Austria fits well into the overall picture of eastern central Europe. Dálnoki and Jacomet (2002) recorded *T. spelta* and *P. miliaceum* as staple crops in a La Tène settlement in Budapest. As in the region around Roseldorf, *T. monococcum* and *Hordeum* were also of major importance in Hungary, along with cultivated (!) *Avena* spp. While in these eastern parts of central Europe *T.*

Fig. 8 Wild plants from Sandberg-Roseldorf. **1a–g** Dry grassland on ▶ calcareous soils; **1a** *Acinos arvensis*; **1b** *Asperula cynanchica*; **1c** *Centaurea jacea*; **1d** *Hypericum perforatum*; **1e** *Salvia nemorosa*; **1f** *Stipa pennata* agg.; **1g** *Teucrium chamaedrys*. **1h–j**: Dry grassland on acidic soils; **1h** *Armeria elongata*; **1i** *Scleranthus perennis*; **1j** *Trifolium arvense*. **1k–o**: Mesic grassland; **k** *Ajuga reptans*; **l** *Lolium perenne*; **m** *Phleum pratense*; **n** *Plantago lanceolata*; **o** *Silene vulgaris*; **2a–s**: Arable weeds and ruderals; **2a** *Adonis aestivalis*; **2b** cf. *Bupleurum rotundifolium*; **2c** *Glaucium corniculatum*; **2d** *Nigella arvensis*; **2e** *Agrostemma githago*; **2f** *Avena fatua*; **2 g** *Bromus secalinus*; **2h** *Digitaria sanguinalis*; **2i** *Galium spurium*; **2j** *Lapsana communis*; **2k** *Stachys annua*; **2l** *Thlaspi arvense*; **2m** *Viola arvensis/tricolor*; **2n** *Euphorbia peplus*; **2o** *Lepidium campestre*; **2p** *Malva neglecta*; **2q** *Neslia paniculata*; **2r** *Picris hieracioides*; **2s** *Solanum nigrum* agg. **3a–j** Woodland, wood margins and clearings; **3a** *Carpinus betulus*; **3b** *Cornus mas*; **3c** *Crataegus laevigata*; **3d** *Fragaria vesca*; **3e** *Prunus spinosa*; **3f** *Rubus fruticosus* agg.; **3g** *Silene alba*; **3h** *Silene dioica*; **3i** *Sorbus aucuparia*; **3j** *Thalictrum minus*. *Scale bars* 1 mm; photo credits: **1a**, **1b**, **1d–1g**, **1i–1o**, **2a**, **2b**, **2d**, **2f–2m**, **2p**, **2r**, **2s**, **3a**, **3c**, **3d**, **3g–3j** A. Caneppele; **2c**, **2e**, **3f** M. Kohler-Schneider; **1c**, **1h**, **2n**, **2o**, **2q**, **3b**, **3e** A.G. Heiss; arrangement and digital remastering A.G. Heiss



monococcum and *T. spelta* still seem to have played a certain role (Hajnalová 1989), contemporary sites in the west (particularly towards the Alps) show a more pronounced dominance of *Hordeum* and *Panicum* (Schmidl et al. 2007; Kreuz and Schäfer 2008). *Secale* remained a rare crop throughout the La Tène period in most parts of Europe (Behre 1992; Wiethold 1996; Stika 1999; Kroll 1997; Dálnoki and Jacomet 2002). The scarce, but constant

Table 5 Wood charcoal from Sandberg-Roseldorf; * Grabner (2003)

	Granary*	Sanctuary 1		Pit 14		Total
No of samples analysed	52	42 (224 l)		12 (60 l)		106
Taxa	*n*	*n*	weight [g]	*n*	weight [g]	*n*
Abies	1					1
Acer	2					2
Alnus glutinosa/incana		1	0.78			1
Betula pendula/pubescens		1	0.68			1
Carpinus betulus		7	0.51	4	0.34	11
Corylus avellana		2	0.01			2
Fagus sylvatica	2	36	1.63	2	0.16	40
Quercus deciduous	48	195	28.6	115	8.79	358
Indeterminata	2	2	0.36			4
Total	55	244	32.57	121	9.29	420

occurrence of *S. italica* is also a distinct feature in all La Tène sites of Lower Austria. Our knowledge of the European distribution pattern of new glume wheat is still evolving, but its presence in Roseldorf and Michelstetten should be noted however, as it matches earlier regional records (Kohler-Schneider 2001a, 2003; Kohler-Schneider and Caneppele 2009).

Land use and landscape around Roseldorf

On the basis of archaeobotanical finds and present day analyses of the site catchment of Roseldorf, the following picture of land use and landscape around the La Tène settlement may be drawn:

Arable fields, fallow land Since there was a tendency in early agrarian societies to minimize travelling time from homesteads to fields/gardens (Posluschny 2010), we can expect that the gentle and fertile loess slopes surrounding the agglomeration were entirely devoted to agriculture (Fig. 1). The staple cereals *Hordeum*, *Panicum*, *Triticum spelta* and *T. monococcum* were most probably grown on large tracts of land. To minimize the risk of crop failures, some of these cereals may have been cultivated as maslins (Jones and Halstead 1995). The peculiar mixture of cereals encountered in the burnt granary might be a result of this practice: it is striking that in the first store, the *T. monococcum-spelta* proportions were highly constant among all subsamples taken from the wooden compartments where the grain had been stored. Such a regular pattern would not occur if separate cereal stores had become mixed when the granary collapsed in the fire. A combined cultivation of *T. monococcum* and *T. spelta* produces good results, as experiments with land races of both species in the Botanical Garden of the University of Natural Resources and Life Sciences at Vienna have shown (Kohler-Schneider and Zimmerhackl unpublished). In contrast to this, the *Hordeum-Avena* mixture could have simply resulted from a heavy infestation of *Hordeum* fields with wild oats. Because of their nutritional value, wild oats might have been tolerated and harvested together with the principal barley crop.

In some fields, *Secale* was a regular and welcome companion to *T. monococcum* and *T. spelta*. Perhaps it already enjoyed increasing attention from the La Tène farmers. By contrast, naked wheat and new glume wheat occurred only as minor admixtures to other cereals, and might not even have been noticed. The same probably applies to *S. italica*, which made its appearance here and there in *P. miliaceum* fields, together with wild Panicoideae. Legumes and oil seeds were most probably grown on smaller, maybe garden-like fields in the immediate vicinity of the settlement, on account of their labour intensive cultivation. *Pisum* and *Lens* were the main pulses, while the growing of *V. faba* was perhaps not as important in the very warm and benign climate of the area as it would have been in cooler and wetter regions. *Papaver, Camelina* and *Linum* provided indispensable vegetable oils. *Linum* may also have been grown for textile production. If there was already some grapevine growing, it probably happened in vineyard-like enclosures.

The rich spectrum of available cultivars would have allowed for another risk-minimizing strategy with regard to crop failures: differential sowing times. Sowing times can be inferred from the weed spectra in the granary stores. Although weed seeds were rather rare, there were striking differences between the two stores: the *T. monococcum-spelta* mixture contained typical autumn-sown crop weeds like *Agrostemma githago* and *B. secalinus*, whereas the

Hordeum store held some frost-susceptible summer crop weeds, like *E. crus-galli*, *S. verticillata/viridis* and Panicoideae in general. Thus, the *T. monococcum-spelta* mixture was probably a result of autumn-sown crops, whereas the *Hordeum* store was the result of a spring-sown crop. *Panicum* must also have been cultivated as a summer crop.

Judging from the dominance of annuals in the weed flora, the fields must have been worked and tended quite intensively. The weed spectrum also provides some information on soil fertility and possible measures to maintain it. Not surprisingly, a high nitrogen content of the soil is indicated by those plants which would be considered as typical ruderals by modern standards. However, among possible arable weeds from Sandberg-Roseldorf there are only a few indicators of high nitrogen values, like *E. crus-galli* and *Stellaria media*. On the other hand, none of the typical segetal plants points to a real lack of this nutrient. Thus, soil fertility must still have been fair, either because the depletion of the naturally fertile chernozem soils was not too advanced yet, or because land fertility was actively maintained by practices like manuring, dung being readily available from the ample livestock husbandry (see below). Another way to secure a sufficient nitrogen supply to fields is crop rotation with legumes; this however is hard to prove. We believe that such a rotation might have been limited to fields next to the settlement, as the cultivation of legumes is demanding in terms of time and workforce. For large and more distant expanses of arable land, fallowing is the easier way to prevent soil exhaustion and to restore nutrient levels in the soil. The best results are obtained when fallow fields are subject to a moderate grazing regime. Such a treatment would further enhance the grassland character of these sites. Some of the recorded mesic grassland species like *A. reptans*, *Phleum pratense*, *Plantago lanceolata*, *Poa pratensis/trivialis*, *Lolium perenne*, *Medicago lupulina, Trifolium pratense* and *T. repens* might in fact have grown on grazed fallow land (Fischer et al. 2010).

Grazing land According to archaeozoological results (Bruckner-Höbling and Pucher 2008; Abd El Karem 2011) livestock was an important element in the agrarian economy of Roseldorf and its possible tributary villages. Even in the gentle loess country, there were enough tracts of land unsuitable for ploughing, such as the dry grasslands on steep loess slopes, the remnants of oak woods and forest steppe complexes and the wet valley bottoms with their alluvial meadows, fens and gallery woods. All of these vegetation units are represented in our exceptionally rich wild plant spectrum (Table 4). They may well have sustained the numerous sheep, goats, pigs, cattle and horses recorded in the settlement. Additional grazing would have been available on the temporary fallow fields of arable land and on the dry meadows around the granite outcrops, at some distance from the settlement (Fig. 1). We also can expect a certain degree of spatial segregation according to livestock type and use. Animals kept for milk production (cows, goats and some sheep) were most probably kept close at hand, in pastures nearest to the settlement, as were all draught animals (oxen, horses). Suitable grazing for horses might have been located especially in the wetlands of the valley bottoms. The remaining patches of oak woodland must have been prime pastures for pigs, while sheep and goats were better suited to the dry shrubby lands and steppe grasslands. The large livestock herds moving on a regular basis between pastures and settlement would have greatly contributed to the high plant diversity in the archaeobotanical record, diaspores being transported in the fur, the hooves and the guts of grazing animals as well as with hay gathered as winter fodder. Accordingly, the majority of grassland taxa originate from dry grassland on calcareous soils, habitats which were part of the natural vegetation mosaic around the settlement. The large numbers and ubiquity of *Acinos* diaspores were especially striking (Table 4, Fig. 8). This species grows in hot and dry places, with only a thin vegetation cover and hardly any humus layer, often on loess soils. It could have occurred in overgrazed portions of the pastures. A second, smaller group of dry grassland species is clearly associated with acidic soils: *T. arvense, S. perennis, A. elongata* and *F. ovina* (Table 4, Fig. 7). Their occurrence at the excavation site proves that the inhabitants of Sandberg-Roseldorf were also making use of the acidic grasslands 10 km to the west of the settlement, along the slopes of the Manhartsberg range, where acidic soil types prevail. These widely scattered patches of siliceous grassland may have been used by sheep flocks—perhaps even in a system of local transhumance. As with crop production, a certain amount of livestock husbandry centred on the agglomeration would not preclude livestock exchange and trade with neighbouring villages. Archaeozoological records strongly hint that such an exchange actually existed (Theiner 2011; Schmitzberger, in press). It remains to be tested within the framework of a comprehensive palaeoeconomic model, how much of the livestock consumption within Roseldorf was based on domestic products and how much depended on local imports.

Hay meadows and wetlands Remains of plants which would have grown on mesic grassland have an important share in the archaeobotanical material (Table 4). Thus, it is conceivable that winter fodder for livestock was at least partly obtained by hay-making. The find of a short scythe (Holzer, unpublished)—a tool supposedly used for harvesting grass or wetland plants (Bernigaud 2013; Nillesse and Buchsenschutz 2009; Motyková and Čtverák 2006)—points in the same direction. Suitable sites for hay-making might have been provided by alluvial meadows on the

valley bottoms next to the settlement. Another part of the winter fodder might have come from coppiced woods in the vicinity of the settlement, although it is unlikely that there was enough woodland left to support large numbers of livestock entirely with leaf fodder. The paucity of wetland species in the wild plant record is surprising, as these habitats must have played a certain role in livestock husbandry.

Woodlands Woodlands around Roseldorf must have been heavily affected by human use. Due to climatic constraints, natural woodland cover of the region would never have been dense anyway and large scale woodland clearance has occurred from the Neolithic onwards (Svobodová 1997; Kohler-Schneider, in press). Due to the overall dryness of the region and the recent drainage of most wetlands, there are no pollen-bearing sediments left for a proper reconstruction of the regional woodland history. But a pollen study from a 40 km distant site in southern Moravia stresses that "… the pollen spectrum clearly shows that a secondary steppe had developed in the region because of the dense population during the La Tène and Roman periods …" (Svobodová 1997).

Around the sizeable settlement of Sandberg-Roseldorf with its large livestock herds, grazing alone would have been sufficient to transform any woodland into a semi-open parkland-like mosaic of grassland, thorny shrubs, isolated trees and small copses. If leaf and twig harvesting occurred on a larger scale, stunted trees and bushes must have been a regular sight. Wood cutting for domestic fuel, for building and all kind of woodwork would have led to a further opening and depletion of the woods. If we add the fuel needs for local glass production, pottery and a metal foundry—for which there is clear archaeological evidence (Holzer 2009a; Holzer and Karwowski 2008)—it is conceivable that much of the woodland within the site catchment of Roseldorf was in fact in a highly degraded state, if not largely destroyed. Archaeobotanical finds provide some support to this view, as woodland species in the Roseldorf material mostly consist of plants of wood fringes, clearings and forest steppe complexes (Table 4). Such woods were part of the natural vegetation mosaic on sunny slopes and hilltops of the region; in addition, human exploitation of woodlands probably promoted the spread of forest steppe species even into more mesic woodland patches. Of course, the numerous finds of oak charcoals, the oaken planks of the granary and the find of a *C. betulus* nutlet (along with hornbeam charcoal, Table 5) point to some remaining woodland—but other evidence clearly suggest that wood as a resource was already in short supply: the surprising charcoal finds of *Fagus sylvatica* (beech) and *Abies alba* (silver fir) (Table 5). These trees do not grow in the region, so their timber must have been brought to Roseldorf from a considerable distance away. Today, the closest natural stands of *Fagus* are located in the Bohemian Massif, at several tens of kilometres from Roseldorf (Chytrý and Vicherek 1995; Kohler-Schneider, in press). For *Abies*, the distance might even be greater; it cannot be assessed however, as natural stands *Abies* are totally lacking in the wider surroundings due to modern forestry and game management practices. The regional climate would have been unsuitable for an occurrence of both species within 20 km of Roseldorf, even during the slightly wetter La Tène period, as *Abies alba* needs a minimum annual precipitation of 800 mm, while *Fagus* is normally not found in areas with rainfall below 600 mm and both species are very sensitive to prolonged spells of drought during the vegetation period (Mayer 1984; Bucher 1999; Felbermeier and Mosandl 2002). Where available, *A. alba* was often used for construction, whereas *Fagus* wood has excellent energy properties and produces high quality charcoal for metal working and glass making (Felbermeier and Mosandl 2002). If *Fagus* and *Abies* timber was ever transported to Roseldorf in large amounts, it must have been a tedious affair, as there is no large river nearby for drifting wood (*Fagus* wood being unsuitable for drifting anyway, on account of its specific weight). In historic times, it was a widespread practice in Austria to produce *Fagus* charcoal on the very spot where the trees had been felled and to transport the charcoal by boat, on horseback or by human porters to often distant metal processing sites (Johann 1994; Wopfner 1997; Hasitschka 2005). Whether this was already done during the La Tène period, is an open question.

Altogether, the La Tène landscape around Roseldorf must be pictured as a very open one, dominated by arable fields, fallow land, extensive pastures, some meadows around wetlands and scattered patches of more or less degraded woodland.

Could Roseldorf have been self-sufficient?

A question frequently arising with regard to large prehistoric settlements is whether such agglomerations really were self-sufficient in terms of food production, or whether they were dependent on a constant stream of supplies from neighbouring smaller villages or individual farmsteads (consumer vs. producer sites, van der Veen and Jones 2006; Stevens 2003; Kreuz and Schäfer 2008). From geomagnetic surveys, it is estimated that the La Tène settlement of Roseldorf consisted of at least 500 pit houses. If all these houses were occupied at the same time and if we assume that the average size of a household was five people, this would amount to a minimum of 2,500 inhabitants. Could all these people have been fed from the available land within an hour's walking distance from the settlement? A 5 km radius is normally taken as the maximum space

within which daily agrarian activities can take place, without spending too much time on going between the settlement and the fields or pastures (Higgs 1975; Vita-Finzi and Higgs 1970; Bintliff 1999). The answer to the above question depends upon many factors, ranging from soil fertility and the amount of land suitable for ploughing and grazing, to achievable yields, diet, food requirements and the crop plant spectrum. Another important determinant is the work force available at critical times in the agrarian cycle, especially during harvest time. At present, data from Roseldorf may not be sufficient to derive a comprehensive palaeoeconomic model, but we may venture to make a first attempt in that direction, based on the assumptions made for comparable cases (Pals 1987; Jacomet and Karg 1996; Kohler-Schneider 2001b; Kreuz and Friedrich 2007; Fischer et al. 2010).

Concerning achievable yields, we assume that under the agrarian conditions of the Iron Age, cereal yields of 1,000 kg/ha were possible. This value was used in the calculations of Fischer et al. (2010) and must be considered as rather conservative with regard to Roseldorf, as it refers to soils of medium quality. Subtraction of sowing material (200 kg/ha) results in a net yield of 800 kg/ha left for consumption, storage and (possibly) trade. The average annual energy requirement of a modern adult human can be set at 3.07 Mio kJ, corresponding to 2,000 kcal/day, but compare U.S. Food and Nutrition Board (2002/2005) and Stephan et al. (2010). Most of this had to come from crop plants, as recent ethnographic and historical studies have shown that 90 % of the energy needs in self-sustaining agrarian communities are usually covered by the consumption of crop plants, even if livestock keeping is of great importance in the agrarian system (Ebersbach 2002) and notwithstanding a certain contribution of collected wild plants to the diet. This value is higher than the 65 % commonly used in older palaeoeconomic models (Pals 1987; Jacomet and Karg 1996; Kohler-Schneider 2001b) but fits well with recent modelling results for late Hallstatt and early La Tène settlements (Stephan et al. 2010). Thus, we assume that crop plants had to deliver 2.76 Mio kJ/year and person. Setting the energy content of large seeded cereals at 13,000 kJ/kg (which neglects the higher values of millets and pulses), 212 kg of cereals would be needed to sustain one person for a year. Given the above values for net yields, 0.26 ha of land are necessary to produce this amount of grain. A household of five persons would need 1.33 ha, accordingly. For the long-term sustainability of yields, it is necessary to allow for soil regeneration. If fallowing is the principal method used to restore the nutrient potential of soils and if the ratio between cultivated and fallow land is 1:1, a total of 2.66 ha per household would be needed. If the ratio is 1:2, the amount of land needed increases to 3.99 and to 5.32 ha, if it is 1:3. The latter case is improbable for Roseldorf however, considering the abundance of extremely fertile chernozem soils. Fischer et al. (2010) have pointed out that with very fertile soils, the ratio between cultivated and fallow land should approach 1:1. Under a 1:1 fallowing regime, the supposed 500 homesteads of Roseldorf would need a total of 1,330 ha to supply themselves with the energy share derived from cereals. With a 1:2 ratio, 1,995 ha would be needed and with 1:3, the amount of necessary land would rise to 2,660 ha. It must be stressed that these values would be lower if manuring with livestock dung or crop rotation with legumes were practised, which was very probably the case, at least on land close to the settlement. Also, the above calculations do not take into consideration differences in yields between different crop plants, the share of different plants in the diet and the possibly lower energy requirements of the inhabitants, for example those resulting from the demographic structure of the population, a smaller average body size and from a varying proportion of hard-working persons. In any case, the amount of arable land needed for self-sufficiency is easily available around Roseldorf. A 5 km radius corresponds to 7,850 ha. The modern soil map (digital soil map of Austria) shows that at least 75 % (=5,887 ha) of the area is made up of very fertile chernozem soils, the rest being mostly gley soils on wet valley bottoms. Besides wetlands, there are few other terrain features like steep slopes around the settlement that would make ploughing difficult. Even if we assume that only half of the available chernozem soil was actually under cultivation, the rest being either pasture or woodland, the resulting 2,944 ha of arable/temporary fallow land would still exceed the needs of the inhabitants, even under the most unfavourable fallowing regime (1:3). By the way, such a land use pattern would also leave plenty of room for an ample livestock production, even if we assume very low stocking densities of 0.3 Large Cattle Units/ha (Stephan et al. 2010; Schibler et al. 1997).

Thus, the land around Roseldorf may have offered good opportunities for a considerable surplus production. To determine the possible extent of that surplus, a full palaeoeconomic model combining archaeobotanical, archaeozoological and archaeological results would be needed. From a purely agrarian point of view, it should be remembered that one of the most influential factors regarding surplus production is the available work force during harvest time. Normally, harvest must be completed within a week after the grains are ripe, to avoid major losses through shedding or predation by wild animals. With Iron Age technology, one adult person can harvest between 1.26 and 1.99 ha/week (Kreuz and Friedrich 2007), which would be 5–7 times the area needed to sustain a person under the assumptions of the present model. This means that one worker could feed the corresponding amount of

additional people. To supply 2,500 inhabitants with their annual needs in cereals, 360–500 people would need to work in the fields. If more hands could devote themselves temporarily to agriculture, a significant surplus would be achievable, which might either be traded or stored for times of dearth. Of course, these simple calculations do not take into account time constraints from various competing activities, both within and outside the agrarian system and they neglect the complex interactions between livestock keeping and plant production. These factors will have to be considered in a full model. But even our rough calculations already point to the possibility that in agrarian terms, Roseldorf was a very wealthy settlement. Cereal and livestock production could have been important pillars of its economy, even on a greater than regional scale.

Some remarkable aspects of the Temple District

The two Mediterranean elements, *Vitis* and *Anethum*, have an interesting counterpart within the arable weeds spectrum, the record of *Glaucium corniculatum* in Sacrificial Pit 14 (Table 4; Fig. 8). Nowadays, this species occurs only sporadically in our region and is considered a straggler from southern Europe and southwestern Asia. Prehistoric finds of *Glaucium* are very rare and have been reported for instance from Bronze Age Hungary (Hartyányi and Nováki 1975). Later records come from medieval contexts in Hungary (Hartyányi and Nováki 1975, Poland (Woch et al. 2008) and Austria (Heiss and Thanheiser 2013). Of course, no ritual significance can be attributed to this rather inconspicuous plant, but its occurrence underlines the possibly far-reaching relations of Sandberg-Roseldorf.

A ritual connection might be suspected for two other plants found in Sanctuary 1, *S. aucuparia* and *C. laevigata*. The *Sorbus* fruits must have been brought to the settlement on purpose and from some distance, as the tree grows only on acidic soils. The closest suitable sites are located on the already mentioned granite outcrops to the west of Sandberg-Roseldorf (Figs. 1, 6). *Sorbus* and *Crataegus* fruits have been believed to ward off evil spirits, demons and witches in the folklore of many European countries (Schell 1912; Marzell 1926; Lucas 1963; Lindow 2001; Merceron 2003; Allen and Hatfield 2004). *Sorbus* especially figures prominently in the folklore and mythology of Ireland and other Celtic speaking countries (Mac Coitir 2003). A generally accepted hypothesis relates the magical properties of *Sorbus* and *Crataegus* to the contrast between their red fruits resembling blood or fire as symbols of life, and their white blossoms exuding a stench of death and decay (trimethylamine). Against this background, the occurrence of both species in a ditch filling together with many intentionally destroyed metal offerings and with human and animal bones might not be a coincidence. Considering the difficulties in ritual interpretations in general (Brück 1999; Hansson and Heiss 2014), the two plants may also have served a purely decorative function, or just as ingredients for the feasting.

While the sinister connections of *Sorbus* and *Crataegus* remain speculative, the find of the flesh-fly puparium (Sarcophagidae) is clearly related to death and decay (Fig. 6). The larvae of these flies live on decaying organic material and carrion. Since some species are part of a characteristic succession of decomposers colonizing corpses, Sarcophagid flies are often used in forensic entomology to reconstruct the timing of a crime. In archaeology, they may help to elucidate the special circumstances of a burial or ritual offering (Stegmaier 2009; Scharrer-Liška and Grassberger 2005). Occurrence of these carrion eating flies is of course to be expected among the plentiful deposits of human and animal bodies in the Roseldorf temple district. What is remarkable is their preservation in a charred state. A future systematic search for such remains could help to shed additional light on taphonomic issues.

Conclusions

From the above, it appears that the almost urban-like La Tène lowland settlement of Sandberg-Roseldorf made full use of its advantageous location in a highly productive agrarian environment. It could rely on a broad spectrum of cultivated plants, on very fertile soils, in a warm climate and with ample opportunities for grazing livestock. Even if considered in isolation and despite its considerable size, the settlement could have acted as a producer site, allowing parts of the population to devote themselves to other activities and pursuits than food production. Still, nothing is known to date about the relations between this central site and possible surrounding smaller settlements. Efficiency of food production, labour division and social stratification could have been enhanced further, if there had been a similar degree of interaction with tributary villages as in the hillforts of southwestern Germany (Fischer et al. 2010). A focus on these relationships and the development of a comprehensive palaeoeconomic model for the entire region will be one of the future challenges for the research activities into Sandberg-Roseldorf.

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Human impact on Holocene sediment dynamics in the Eastern Mediterranean – the example of the Roman harbour of Ephesus

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: During the past millennia, many erosion and accumulation processes have been modified by anthropogenic impact. This holds especially true for the environs of ancient settlements and their harbours along the Mediterranean coasts. Our multi-proxy investigations in the Roman harbour and the harbour canal of Ephesus (western Turkey) reveals that humans have significantly triggered soil erosion during the last three millennia. Since the eighth century BC, and especially since the Hellenistic period, a high sedimentation rate indicates fast alluviation and delta progradation of the Küçük Menderes. Deforestation, agriculture (especially ploughing) and grazing (especially goats) were the main reasons for erosion of the river catchment area. One consequence was significant siltation of the Hellenistic/Roman harbour basin. This sediment trap archives the human impact, which was strongly enhanced from Hellenistic/Roman to Byzantine times (second/first centuries BC to the sixth/seventh centuries AD), evidenced by high sedimentation rates, raised values of heavy metal contaminations [lead (Pb), copper (Cu)], the occurrence of fruit tree pollen and of intestinal parasites. From the middle to the end of the first millennium AD, the influence of Ephesus declined, which resulted in a decrease of human impact. Studies of several ancient settlements around the Mediterranean Sea tell a comparable story. They also confirm that during their most flourishing periods the human impact totally overprinted the climatic one. To detect the latter, geo-bio-archives of relatively pristine areas have to be investigated in detail. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: geochemistry; human impact; sediment dynamics; eastern Mediterranean; harbour geoarchaeology

Introduction

Anthropogenic impacts upon sediment processes have been occurring for several millennia. Especially with the beginning of a sedentary lifestyle and the practise of agriculture, sediment processes were directly affected by humans through soil erosion and floodplain deposition (Broothaerts *et al.*, 2014; Lewin and Macklin, 2014). This period of strong and global human impacts on the environment especially since the Industrial Revolution has been called 'the Anthropocene' (Crutzen and Stoermer, 2000; Crutzen, 2002; Steffen *et al.*, 2007). Humans have become a geological factor. Their impact can be studied in many geo-bio-archives (e.g. floodplains, colluvial deposits, lakes, deltas, soils, ice caps; Dusar *et al.*, 2011). However, there are many discussions about the processes, the stratigraphy, the onset, the spatial scales of recorded impacts and hence its precise definition (Ehlers, 2008; Zalasiewicz *et al.*, 2008, 2015; Brown *et al.*, 2013a, 2013b; Lewin and Macklin, 2014). We follow those authors who take the term 'Anthropocene' in the widest possible sense: the period of strong human–environment interactions.

The impact of humans was already proven during the Neolithic period when small farming communities started to practise agriculture (Ruddiman and Thomson, 2001; Ruddiman *et al.*, 2008; Ruddiman and Ellis, 2009; Derin, 2012; Lichter and Meriç, 2012; Foley *et al.*, 2013; Anthony *et al.*, 2014; Stock *et al.*, 2015). However, by then, only some examples are known where extensive deforestation took place (Marriner *et al.*, 2012; Kaniewski *et al.*, 2013). Enhanced soil erosion has been observed

since the Bronze age with a larger population and agricultural activities (Zolitschka *et al.*, 2003; Zalasiewicz *et al.*, 2010; Dusar *et al.*, 2011; Broothaerts *et al.*, 2014; Lewin and Macklin, 2014; Wilkinson *et al.*, 2014). Especially with a higher population density during the Hellenistic and Roman periods, land-use changes and deforestation led to intensified erosion processes (Casana, 2008; Dusar *et al.*, 2011; Broothaerts *et al.*, 2014).

In the Mediterranean coastal areas, human–environment interactions have been studied intensively in the environs of ancient settlement sites and their harbours through a wide range of approaches. The investigations focused on landscape and coastline changes during the Holocene, often correlated to shoreline migration due to the advance of river deltas or the evolution of coastal barriers (e.g. Kraft *et al.*, 2000; Brückner *et al.*, 2002, 2006; Goiran *et al.*, 2011; Bini *et al.*, 2012; Flaux *et al.*, 2013). Recently, ancient harbours have been investigated in detail with sedimentological, geochemical, macrofaunal and microfaunal analyses since they serve as sediment traps in an anthropogenic context (e.g. Frenzel and Boomer, 2005; Marriner and Morhange, 2006a, 2007; Bernasconi *et al.*, 2010). Study sites include Alexandria (Bernasconi *et al.*, 2006; Véron *et al.*, 2006), Elaia (Seeliger *et al.*, 2013; Pint *et al.*, 2014), Ephesus (Kraft *et al.*, 2000, 2007, 2011; Brückner, 2005; Brückner *et al.*, 2008; Stock *et al.*, 2013, 2014), Magdala (Sarti *et al.*, 2013), Marseille (Morhange *et al.*, 2003; Le Roux *et al.*, 2005), Miletus (Brückner *et al.*, 2006, 2014, 2015), Luna (Bini *et al.*, 2012), Portus (Mazzini *et al.*, 2011; Salomon *et al.*, 2012; Delile *et al.*, 2014a, 2014b, 2014c), Sidon (Marriner *et al.*, 2006), Troy (Kraft *et al.*, 2003), Tyre (Marriner and Morhange, 2006b), Utica (Delile *et al.*, 2015a), and İstanbul/Yenıkapı (Algan *et al.*, 2011). For this paper, we used a multi-proxy approach by applying sedimentological, geochemical, palynological, parasitological, microfaunal and macrofaunal as well as archaeobotanical tools for deciphering the intensity of the human impact recorded in the harbour archive, and thus test the concept of the Anthropocene *sensu lato* for the Küçük Menderes graben and the Roman harbour of Ephesus.

Study Area

The study area is located on the Aegean coast of Turkey in the east–west (E–W) striking Küçük Menderes graben. The still active graben has formed within the pre-Miocene basement during the Neogene, and contains a Miocene-Quaternary sediment fill (Rojay *et al.*, 2005). The Küçük Menderes follows the graben structure. Nowadays it debouches into the Aegean Sea 6 km to the west of Ephesus (Figure 1). The river was

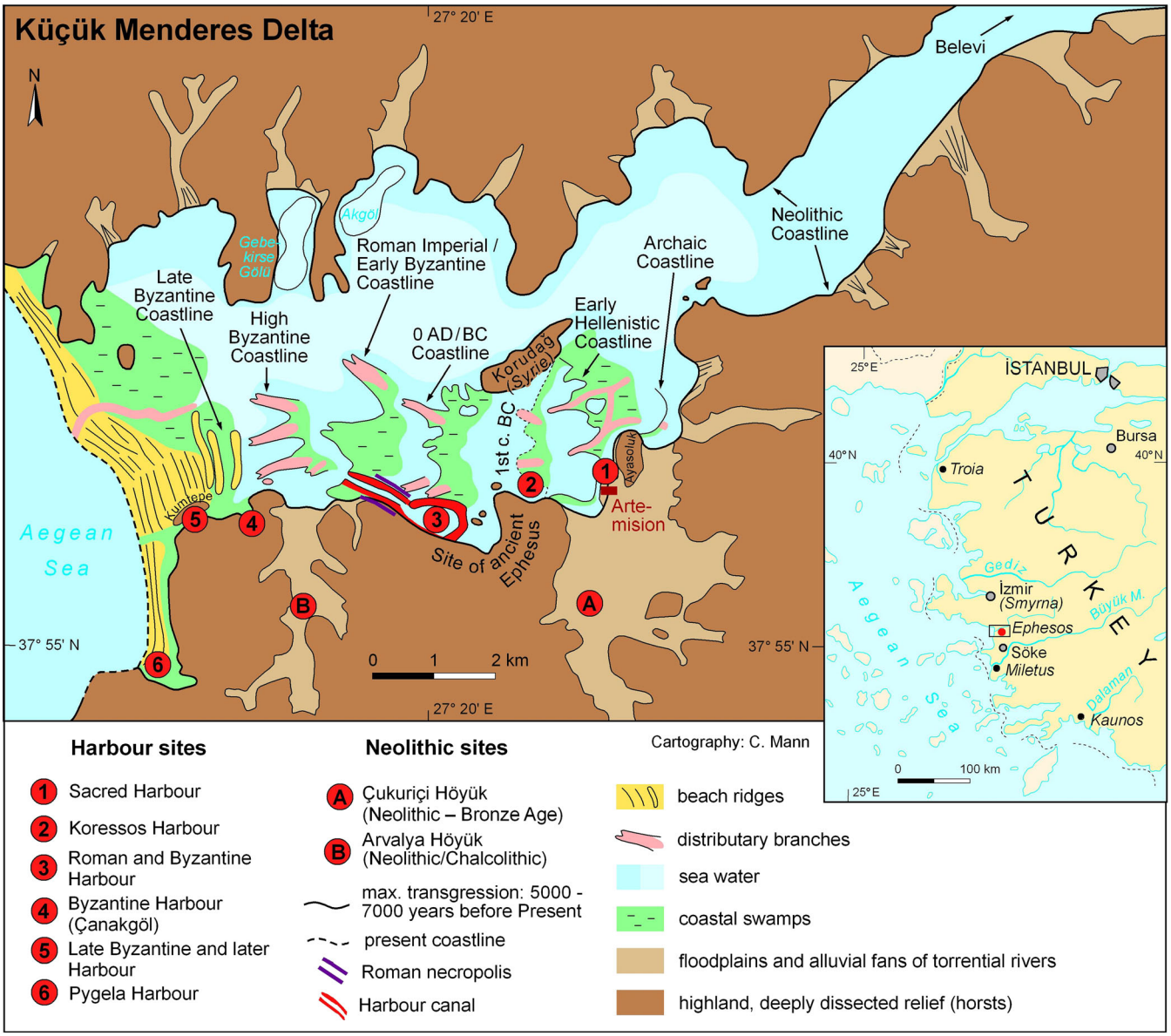


Figure 1. Scenario of the progradation of the Küçük Menderes (Cayster) delta since Neolithic times (after Brückner, 2005, modified).

characterized by the highest denudation rates in Turkey with 660 m^3/m^2 (Eggeling, 1973) until it was regulated during the twentieth and twenty-first centuries AD (Güldali, 1979; Figure 1). The drainage basin of the Küçük Menderes River (100 km) as well as the mountain ranges to the south and east of the study area mostly consist of erosion-prone mica schist, quartzite schist, gneiss and marl (Vetters, 1989; Brückner, 1997; Çakmakoğlu, 2007; Rantitsch and Prochaska, 2011) whereas the mountains to the north of the Küçük Menderes graben (marble, partly dolomitic) are more resistant to weathering processes.

During the maximum ingression of the sea, a marine embayment had extended for about 20 km inland (Brückner, 2005). Since 6000–5000 BC, an alluvial plain has formed due to the progradation of the deltas of the Küçük Menderes River and its tributaries, which has led to a continued regression of the shoreline towards the west (Kraft *et al.*, 2000; Brückner, 2005). Many decametres of sediment have been deposited on top of the pre-Holocene strata (Kraft *et al.*, 2005). Evidence of the former embayment are two remaining lakes at the northern side of the graben, and the fact that Korudağ had formerly been the island of Syrie (Figure 1).

The ancient Hellenistic–Roman city of Ephesus is located on the southern flank of the graben. It is surrounded by the mountain ranges of Bülbüldağ to the south (356 m) and Panayırdağ to the east (157 m) which form the southern hanging wall of the graben and mostly consist of dolomitic marble, limestone, and phyllite (Figure 2a; Vetters, 1989; Çakmakoğlu, 2007; Rantitsch and Prochaska, 2011). The Roman harbour is nowadays located 5 km east of the present coastline. During the summer it almost dries out (Figure 2b).

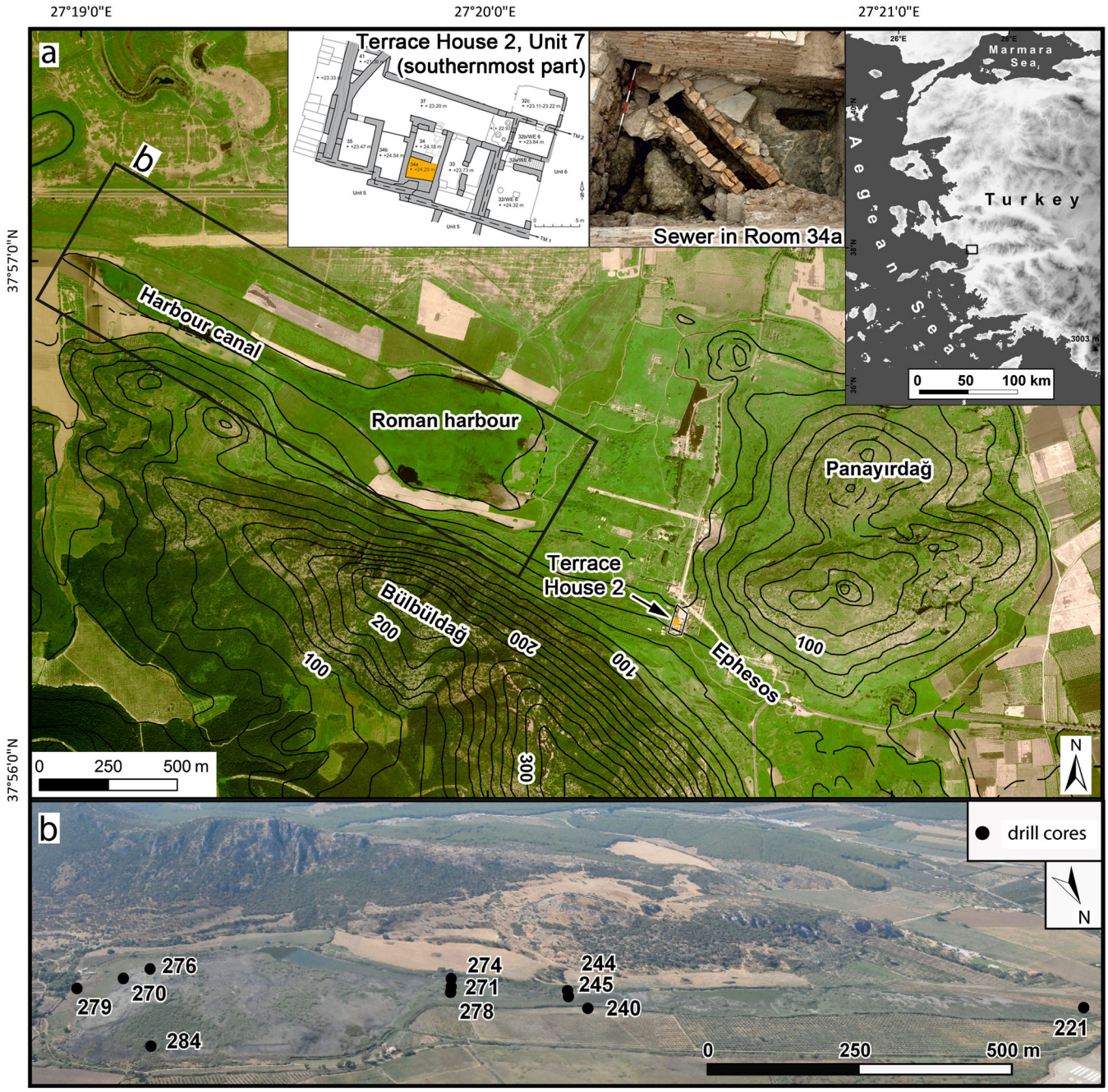


Figure 2. (a) Study area within the city of Ephesus with the surrounding mountains of Bülbüldağ and Panayırdağ. The sewer is from Room 34a of Terrace House 2, a Roman agglomeration (*insula*) (stratigraphical units SE 1014 and 1024). Conversion of the aerial image from miscolour to natural colour. Sources: Austrian Archaeological Institute, University Vienna Institute of Photogrammetry and Remote Sensing, İstanbul Technical University Department of Photogrammetry, 1997, modified. (b) Location of drill cores in the Roman harbour basin and the harbour canal. View during summer time.

Methodology

Nine sediment cores up to a depth of 12 m and with diameters of 6 and 5 cm were retrieved from geo-bio-archives of the harbour basin and the canal using the percussion coring device Cobra pro of Atlas Copco. Coring positions and elevations were levelled with a Topcon HiPer pro GPS (global positioning system with a precision of 2 cm); they refer to the present mean sea level. The focus was set on two master cores from the basin and the canal (Eph 276 and 244) which were analysed in detail.

In the laboratory, magnetic susceptibility (MS) was measured with a Bartington MS2B sensor. Elemental analyses were conducted in 2 mm resolution using an energy-dispersive X-ray fluorescence (XRF) Itrax Core Scanner (Cox Analytical Systems, Sweden; Croudace *et al.*, 2006) equipped with a 1.9 kW chromium (Cr) X-ray tube set to a voltage and current of 30 kV and 30 mA, and an exposure time of 20 seconds. For grain size analysis (111 samples from Eph 276, 39 samples from Eph 244), the fractions < 2 mm were measured with a laser diffraction particle sizer (LS 13320, Beckman Coulter Ltd.); the results were statistically processed with GRADISTAT (Blott and Pye, 2001). Loss-on-ignition (LOI) was measured for both cores in a muffle furnace (*c.* 5 g of sediment heated for 12 hours at 105 °C, and 4 hours at 550 °C), calcium carbonate ($CaCO_3$) (Eph 244) was determined with the Scheibler apparatus [0.5 g of sediment reacted with hydrochloric acid (HCl) (10%)].

Thin sections were carried out on samples from characteristic layers of Eph 276. The micromorphological interpretation is according to van der Meer and Menzies (2011).

A detailed microfaunal investigation was carried out for drill core Eph 276 (98 samples). About 4 cm^3 of sediment were sieved with 100 µm mesh size, and determined following Meisch (2000) and Handl *et al.* (1999) for ostracods and Meriç *et al.* (2004) for foraminifers.

For pollen analysis, samples from Eph 244 (25 samples; 2–4 cm^3) were treated as described in Eisele *et al.* (1994) and cleaned by ultrasonic sieving with a 7 µm mesh. For pollen and spore identification, the collection of recent pollen and spores at the Institute of Botany, University of Hohenheim (Stuttgart, Germany) was used together with Beug (2004); Moore *et al.* (1991) and Reille (1992). Calculation of the results and plotting of the pollen diagram were done using the software FAGUS (University of Innsbruck, Austria).

Ancient parasite analysis (nine samples of Eph 244) was performed at the University of Cambridge, UK. Following disaggregation, 1 g samples were passed through sequential microsieves (300, 160 and 20 µm) (Anastasiou and Mitchell, 2013a). Due to their size, intestinal parasite eggs are trapped on the 20 µm mesh; they were determined according to their shape, colour, dimensions and other characteristics (Garcia, 2009).

On-site macro-charcoal of Terrace House 2 was recovered from archaeobotanical flotation samples, dated by pottery and numismatic typologies. Samples were processed from Dwelling Unit 1 (Popovtschak, 2010), Dwelling Unit 2 (Thanheiser, 2010), and from the Rooms 32c (one sample, 18.6 l from a secondary chalk pit filling, second quarter of the first century AD; Ployer, in press), and 34a in Dwelling Unit 7 (three samples, 45 l, from the stratified filling of a sewer, second century BC–third century AD; Ployer, in press). Due to their precise numismatic dating the sewer layers in particular allowed a high-resolution interpretation of the data. The material was floated and searched for plant macro-remains and charcoal (Heiss and Thanheiser, in press); this was carried out on a minimum of 50 randomly picked charcoal fragments per sample. Its identification is based on standard literature (Schweingruber, 1990; Heiss, 2000–2009; Heiss and Marinova, 2009).

In total, 23 accelerator mass spectrometry radiocarbon (AMS-^{14}C) age estimates of organic material and enriched pollen plus fragments of diagnostic ceramics constrain the chronostratigraphy (Table I).

Table I. Radiocarbon data set

Sample code	Laboratory code	Unit	Material	Depth (cm) b.s.	Depth (cm) b.s.l.	$\delta^{13}C$ (‰)	^{14}C age	Age cal BC/ cal AD (2σ)
Eph 270/12H	UGAMS 11910	3a	wood	3.77	-4.41	-26.5	1520±20	cal AD 432–600
Eph 270/14 Sg	UGAMS 13571	3a	echinoid spins	4.88	-5.52	1	2100±25	cal AD 173–363
Eph 276/186/113P	Lyon-9957 37622	6a	plant fragment	1.86	-2.32	-26.6	665±30	cal AD 1276–1391
Eph 276 362H	Lyon-9959 37624	4a	wood	3.62	-4.08	-30.8	1455±30	cal AD558–649
Eph 276 460	Lyon-9960 37625	3a	seeds	4.6	-5.06	-31.3	2020±30	104 BC– cal AD 57
Eph 276 680-690	UGAMS 17652	2a	enriched pollen	6.85	-7.31	-27.8	2000±40	111 BC– cal AD 83
Eph 276 1080-1090	UGAMS 17352	1a	seeds	10.85	-11.31	-25.9	1990±25	43 BC– cal AD 62
Eph 276 1189pl.	Lyon-9962 37627	1a	plant fragment	11.89	-12.35	-31.9	2040±30	162 BC– cal AD 47
Eph 284/13H	UGAMS 11913	2a	plant fragment	4.6	-5.21	-28.9	2090±25	179–45 cal BC
Eph 284/21P	UGAMS 11912	2a	olive stone	9.4	-10.01	-26.3	1980±25	40 BC– cal AD 68
Eph 278/285	Lyon-9955 37620	8a	plant fragment	2.85	-3.52	-33.1	475±30	cal AD 1409–1453
Eph 278/660	Lyon-9958 37623	2a	shell fragment	10.5	-11.17	-6.2	3195±30	1159–930 cal BC
Eph 271/7	UGAMS 11909	1a	charcoal	0.9	-1.77	-24.5	390±20	cal AD 1445–1617
Eph 271/79Pf	UGAMS 11908	2a	plant fragment	9.87	-10.74	-22.9	2270±25	399–212 cal BC
Eph 271/95H	UGAMS 11906	2a	plant fragment	11.68	-12.55	-29.8	2020±25	91 BC– cal AD 52
Eph 244 B1 137-138	UGAMS 8222	2b	plant fragment	1.37	-2.11	-29.0	650±35	cal AD 1279–1396
Eph 244 B5S 377	UGAMS 8223	5b	seeds	3.77	-4.51	-22.5	1700±25	cal AD 256–402
Eph 244 B8 575-577	UGAMS 8224	4b	plant fragment	5.76	-6.5	-27.3	2120±25	334–53 cal BC
Eph 244 B12 859-860	UGAMS 8225	2b	plant fragment	8.59	-9.33	-13.8	2520±25	792–545 cal BC
Eph 245 B4 77-78	UGAMS 8226	7b	plant fragment	1.27	-2.02	-29.5	1490±25	cal AD 539–637
Eph 245 B4 77-78	UGAMS 8227	4b	charcoal	7.88	-8.63	-25.9	2270±25	399–212 cal BC
Eph 221/8H	UGAMS 13072	8b	wood	2.51	-27.4	-19.9	240±20	cal AD 1642–1950
Eph 221/16Cg	UGAMS 13071	2a	shell fragment	5.52	-0.8	-21.8	2360±25	129 BC– cal AD 57

Note: Samples were calibrated with Calib 7.1 (Reimer *et al.*, 2009). Marine samples were corrected using the reservoir age for the Eastern Mediterranean region, i.e. 390 ± 85 years (Siani *et al.*, 2000). b.s. below surface, b.s.l. below sea level. Radiocarbon age estimates with two sigma (2σ) standard deviation (95.5% probability). The six radiocarbon ages from drill core Eph 276 have already been published in Delile *et al.* (2015b).

Results

The study is based on nine drill cores from the harbour basin and the harbour canal (Figure 3). Eph 276 represents the typical stratigraphy of the harbour basin, Eph 244 the one of the harbour canal, wherefore they are described in detail. The archived time span reaches from the end of the second millennium BC to the twentieth century AD. We used the multi-proxy approach by applying sedimentological, geochemical, palynological, parasitological, microfaunal and macrofaunal as well as archaeobotanical tools for a detailed knowledge about (i) the stratigraphy and evolution since pre-Hellenistic times; (ii) the landscape changes; and (iii) the intensity and dynamic of the human impact.

Overview of the stratigraphy in the harbour and the harbour canal

In the harbour basin, Eph 276 reveals laminations of clayey silts at the base (unit 1a in Figure 4a). The drill cores from the harbour basin and the transition to the canal (Eph 279, 270, 276, 284, 278, 271) are characterized by silts with intercalations of fine sand from the base to *c.* 5 m b.s.l. (metre below present sea level), dating from the end of the second millennium BC to the first century AD (Figure 3, unit 2a). Different ages occur at the same level (e.g. 1172–932 cal BC and 43 cal BC–62 cal AD at 11 m b.s.l.). This may be due to the fact that the harbour basin had once been dredged (Kraft *et al.*, 2000, 2011; Kirbihler, 2013).

Unit 3a of core Eph 276 is a stratified silty layer of pale yellow to brown colour; it yielded ages between the first century BC to the sixth/seventh centuries AD. The overlying greyish silts (units 4–5a) seem to have been deposited after the seventh century AD. Eph 271 and 279 are dominated by a brown layer rich in organic matter with angular stones, mortar and ceramic fragments spanning from Roman Imperial times to Late Antiquity.

All drill cores reveal a silty to sandy pale yellow layer (unit 6a), deposited until the fourteenth century AD. Peat occurs after the fourteenth century AD (units 7–8a). Brown silts (unit 9a) with ceramic sherds (Late Antiquity) dominate Eph 279, 270 and 276 to the top.

In the harbour canal (Eph 244, 245, 221), the base of Eph 244 and 245 is formed of sandy silts and overlain by mica-rich sands, deposited before the eighth–sixth centuries BC (units 1–2b) and between the fourth and the first centuries BC (units 3–4b) (also Eph 221). A sharp contact separates the mica-rich sands from silts (unit 5b), dated between the first centuries BC/AD until at least the fifth century AD. Units 6b and 7b reveal the same silty to sandy pale yellow layer as units 5–7a, poorly dated with a ^{14}C age estimates of the sixth/seventh centuries AD (Eph 245). On top follow peat (unit 8b, thirteenth–twentieth centuries AD), and in Eph 221 brown silts rich in ceramic fragments and edged stones.

Chronology and stratigraphy of the harbour basin

Master core Eph 276 (E 27°19′59.32″, N 37°56′32.89″) from the harbour basin can be differentiated into nine lithostratigraphical units (Figures 2, 4a and 5).

Unit 1a (12.46–11.26 m b.s.l.) is composed of clayey silt with laminations of greyish and dark greyish brown colour (cf. thin section in Figure 4a); it shows low LOI values (3–9%), variations of titanium (Ti) and relatively high strontium/calcium (Sr/Ca) ratios. In the upper part few specimens of ostracods (especially *Cyprideis torosa*, *Darwinula stevensoni* and *Limnocythere*

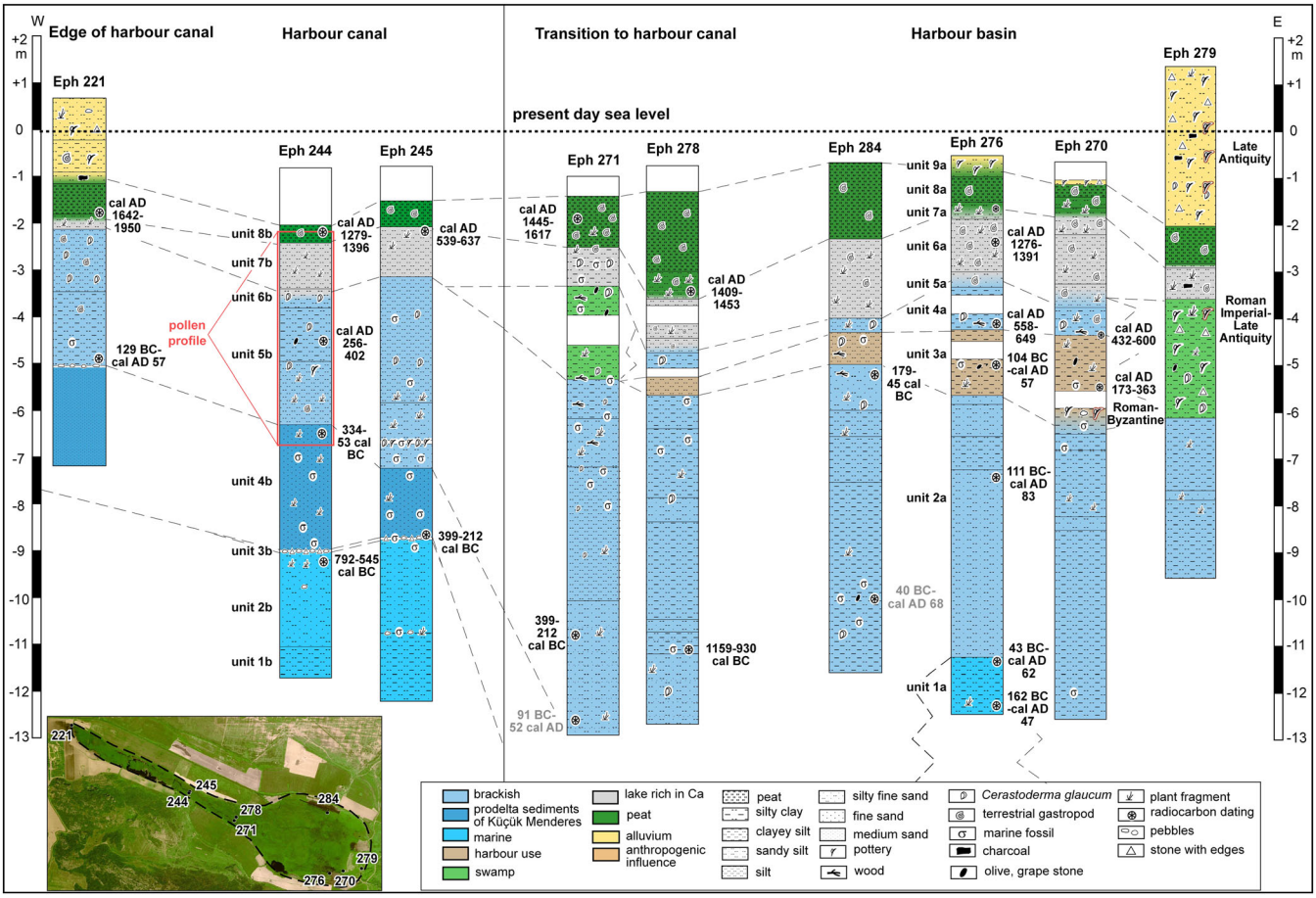


Figure 3. Geological profiles and cross-sections from the harbour basin to the edge of the harbour canal (see Figure 2b for core positions). Please note that Eph 271 and 284 reveal an age inversion. The improbable ages are shown in grey colour.

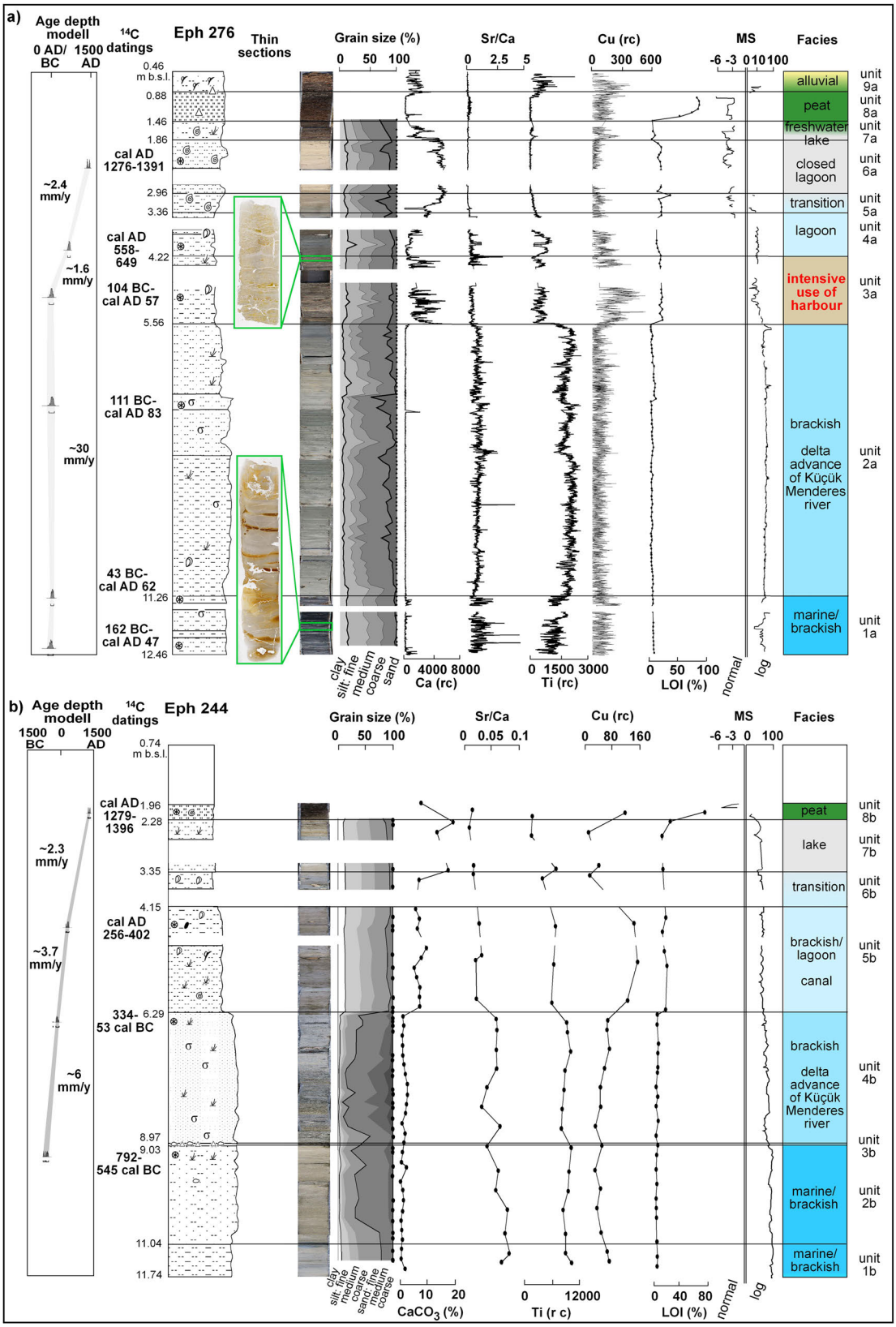


Figure 4. Stratigraphy of vibracores Eph 276 in the Roman harbour basin (a), and Eph 244 in the harbour canal (b), together with age/depth model, ^{14}C ages, granulometry (except for peat), geochemical data (Ca and $CaCO_3$, respectively, Sr/Ca, Ti, Cu), LOI, magnetic susceptibility (MS), and facies interpretation. Position of cores in Figure 2b, legend for the granulometry and fauna content in Figure 3. Photographs of thin sections reveal the detailed stratification at two important sections of the core. rw = raw counts, magnetic susceptibility in normal and logarithmic scales. Magnetic susceptibility, grain size and ^{14}C ages for core Eph 276 are already published in Delile *et al.* (2015b).

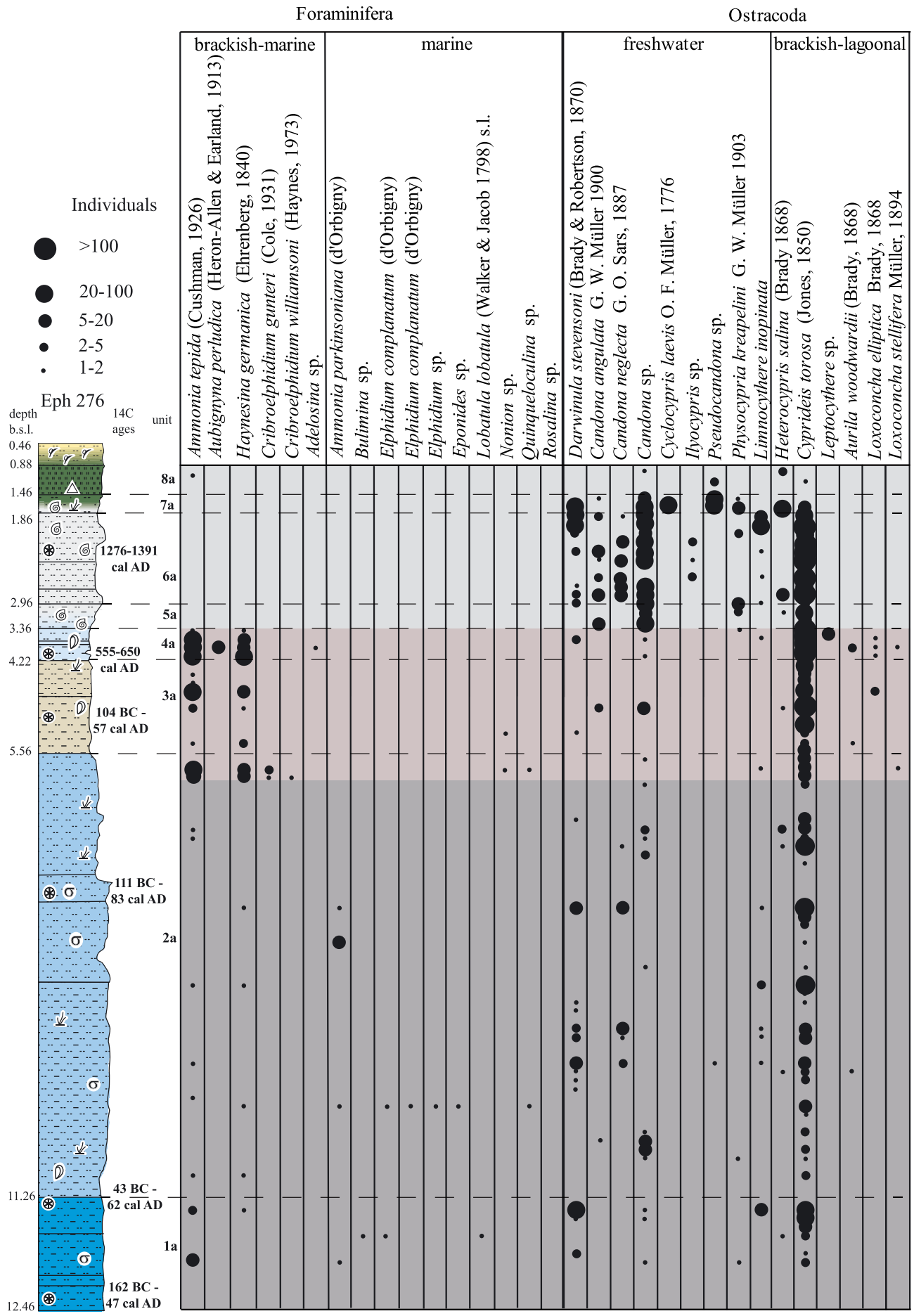


Figure 5. Microfossil analysis of foraminifera and ostracoda (with frequencies) of drill core Eph 276 from the Roman harbour basin, with stratigraphic units and depositional environments. Four different habitats were detected which may overlap to some degree: marine, brackish-marine, brackish-lagoonal, and freshwater. The dashed lines represent the boundaries between lithological units 1a–8a.

inopinata) and foraminifers (especially *Ammonia tepida*) are present. Unit 1a was deposited between 162 cal BC and 62 cal AD.

Slightly coarser sediments build up unit 2a (11.26–5.56 m b.s.l.), which consists of homogeneous, grey to dark greyish silts (up to 75%). Subsections rich in fine sand and void of microfossils show an increased MS. High Ti and low Ca values, low Sr/Ca ratios, frequent *Pinus* pollen and *Isoetes* spores (at 9.31 m b.s.l.) occur. In this unit, the ostracods *Cyprideis torosa*, *Darwinula stevensoni*, and *Candona* sp. dominate whereas towards the top the foraminifer species *Ammonia tepida* and *Haynesina germanica* appear. Units 1a and 2a both reveal similar ages and were deposited with a high sedimentation rate of ~30 mm/yr from the end of the second century BC to the first century AD.

Unit 3a (5.56–4.22 m b.s.l.) is characterized by alternations of greyish brown silts and pale yellow silts with a lower amount of sand and increased values of Ca. The facies change is demonstrated by raised values of organic matter (up to 25%), declined Sr/Ca ratios, low Ti values, and the highest copper (Cu) peaks in the core. Ostracod *Cyprideis torosa* as well as foraminifers *Ammonia tepida* and *Haynesina germanica* are frequent. The age of this unit is sandwiched between 104 cal BC–57 cal AD and 555–650 cal AD.

Unit 4a (4.22–3.36 m b.s.l.) consists of homogeneous, very dark greyish clayey silts. Geochemical values are similar to those of unit 2a. The layer contains shell fragments of the bivalve *Cerastoderma glaucum*, abundant specimens of the foraminifers *Ammonia tepida* and *Haynesina germanica* as well as the ostracod *Cyprideis torosa*. The sedimentation rate significantly decreases to 1.6 mm/yr from the first to the seventh centuries AD (555–650 cal AD).

Unit 5a (3.36–2.96 m b.s.l.) is composed of sandy silts, with an elevated amount of sand, lower Cu values and Sr/Ca ratios, and Ti values decreasing upwards. No foraminifers are present anymore, however a rich ostracod fauna.

Unit 6a (2.96–1.86 m b.s.l.), a silty layer of very pale brown colour, contains laminae rich in sand towards the top of the unit, plant remains (LOI up to 25%), and the highest Ca values of the core. The gastropods *Gyraulus* sp. and *Radix* sp., as well as ostracods such as *Cyprideis torosa*, *Candona* sp. and *Darwinula stevensoni* are present. The sedimentation rate rises to 2.4 mm/yr.

Unit 7a (1.86–1.46 m b.s.l.) is characterized by dark brown silts, low Ca content, the dominance of *Gyraulus* sp. and the same ostracods as in unit 6a. Moreover, *Pseudocandona* sp. and *Cyclocypris laevis* occur.

Unit 8a (1.46–0.88 m b.s.l.) consists of peat (LOI rises up to 87%) that is marked by a strong decrease of microfossils. The stratigraphy is terminated by unit 9a (0.88–0.46 m b.s.l.), brown sandy silts with ceramic fragments.

Chronology and stratigraphy of the harbour canal

Master core Eph 244 (E 27° 19′29.372″, N 37° 56′47.795″) from the harbour canal comprises eight units (Figures 2 and 4b). Unit 1b (11.74–11.04 m b.s.l.). It is dominated by olive to dark olive grey sandy silts with intercalations of sandy laminae of up to 1 cm thickness. The sedimentary unit is void of plant remains and shell fragments. LOI and $CaCO_3$ show low, Sr/Ca, Ti and MS high values.

Unit 2b (11.04–9.03 m b.s.l.), a homogeneous sand-dominated deposit, contains a few remains of plants and mollusc shells. While MS exhibits the highest values of the entire core, the values of other geochemical parameters are low. Seagrass (*Posidonia* sp.) at a depth of 9.34 m b.s.l. dates to 775–556 cal BC.

Unit 3b is a 6 cm layer of stones (quartz and mica schist, mostly angular), sandwiched with sharp contrast between units 2b and 4b.

Unit 4b (8.97–6.29 m b.s.l.) is mostly composed of olive grey fine and medium mica-rich sands, with seagrass, fragments of mollusc shells and barnacles. The geochemistry shows minor changes, with low Sr/Ca ratios and Ti values. The MS peaks correlate with horizons of increased grain size. This unit was deposited between the eighth/sixth and the fourth/first centuries BC.

The boundary to unit 5b is marked by a sharp contact at 6.29 m b.s.l. Up to 4.15 m b.s.l. the sediments consist of silts with many mollusc shell fragments (including *Cerastoderma glaucum*) and a pottery sherd. The geochemistry reveals an environmental change, with raised values of $CaCO_3$ and LOI, highest Cu contents of the core, and decreased values of Ti, MS and Sr/Ca. A grape seed at 4.51 m b.s.l. dates to 257–410 cal AD.

A transition stratum (unit 6b, 4.15–3.35 m b.s.l.) consists of similar sediments as before, with *Cerastoderma glaucum* and declined Cu values. The overlying unit 7b (3.35–2.28 m b.s.l.) is composed of homogeneous dark olive grey silts with intercalations of organic-rich layers, high $CaCO_3$ values and low Sr/Ca ratios; it was deposited after the third/fifth centuries AD. The top part is enriched in organic matter (up to 25%). Towards the uppermost sediment of the core (unit 8b) consists of peat (organic matter up to 80%). Macrofossils are represented by the freshwater gastropod *Gyraulus* sp. One date of the compacted unit dates to the thirteenth/fourteenth centuries AD.

Palynological and parasitological studies of drill core Eph 244

In total, five pollen assemblage zones (PAZs) were differentiated (Figure 6a, see Figures 3 and 4b for depths in Eph 244). PAZ 1, 6.71–6.35 m b.s.l., contains a high level of indeterminate pollen, *Isoetes* spores and burnt plant remains. The quantity of deciduous oak (*Quercus*) remains low and declines towards the top of the unit, while *Olea* pollen increases. Cerealia-type, *Plantago lanceolata*-type, *Cannabis* and a high amount of Fabaceae are present.

PAZ 2, 6.29–5.32 m b.s.l., is characterized by a sudden change in the pollen spectrum: discontinuation of *Isoetes* spores and a rapid decline of indeterminates. Typical of this unit are high amounts of *Sarcopoterium*-type and Brassicaceae (crucifers) partly occurring in clusters and anthers. A further differentiation between Brassicaceae in wild plants or crops is not possible. *Sarcopoterium*-type pollen appears as thorny burnet (*Sarcopoterium spinosum*) and/or small burnet (*Sanguisorba minor*), which cannot be distinguished accurately. Characteristic for PAZ 2 are pollen grains of fruit trees (*Olea*, *Juglans*, *Castanea*, *Vitis*), Cerealia-type, *Cannabis*, Fabaceae, eggs of the intestinal parasites whipworm (*Trichuris* sp.; cf. Figure 6b) and roundworm (*Ascaris* sp.), as well as *Cucumis melo* (muskmelon) (cf. Beug, 2004) towards the top.

PAZ 3, 5.22–4.21 m b.s.l., still reveals *Cucumis melo*, *Trichuris* sp. and *Ascaris* sp. parasite eggs and *Papaver rhoeas*-type pollen (poppy) during the third–fifth centuries AD. Whipworm eggs were much more common than roundworm in all of the analysed samples. The distinction between opium poppy and wild species is not possible. More burnt plant remains occur towards the top.

In PAZ 4, 3.72–3.50 m b.s.l., the amount of *Pinus* pollen increases, *Olea* decreases while *Quercus ilex*-type and *Pistacia* rise. Eggs of *Trichuris* sp. and *Ascaris* sp. are lacking in this zone while more aquatic algae occur. Flax pollen (*Linum*

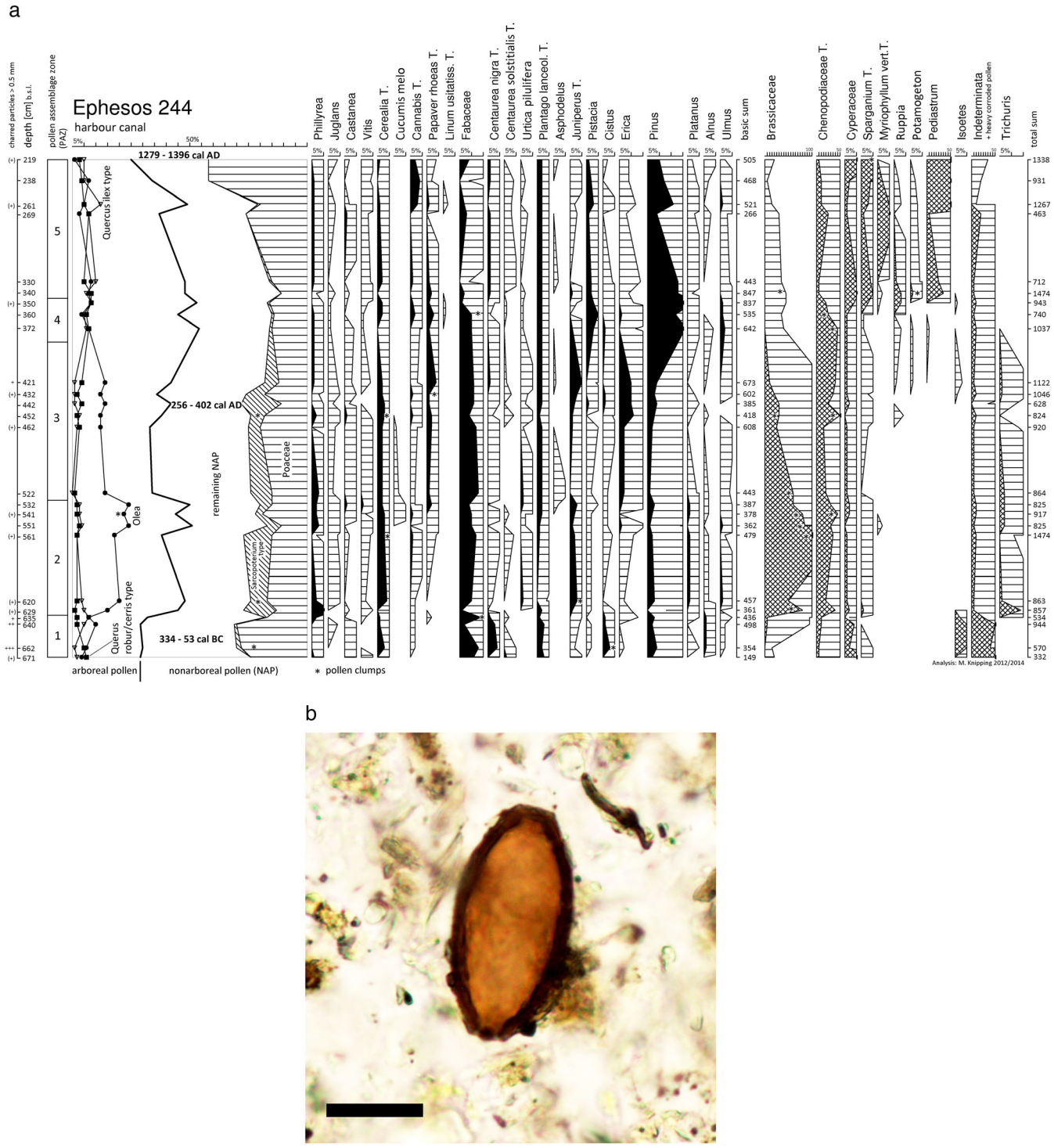


Figure 6. (a) Pollen diagram of sediment core Eph 244 from the harbour canal. The input of pollen in the sediment derives from different sources. Therefore, the preservation of pollen grains is extremely variable, which was accounted for by clustering them into different preservation groups during counting. All terrestrial taxa are included in the basic sum, whereas *Brassicaceae* and *Chenopodiaceae* (as possibly overrepresented elements), pollen clumps and anther remains, wetland plants (Cyperaceae, *Sparganium*-type, *Typha latifolia*-type, *Lythrum*), indeterminable and heavily corroded grains as well as spores and algae are excluded. The scale is always 5% with a magnification of 10. Only the most frequent taxa are shown in the pollen diagram. In total, 22 468 palynomorphs and algae were counted from 25 samples of drill core Eph 244. (b) Egg of the intestinal parasite *Trichuris* sp. (scale bar: 20 μm).

usitatissimum-type) is still present. PAZ 5, 3.40–2.19 m b.s.l., is characterized by abundant aquatic and swamp plants during the thirteenth–fourteenth centuries.

Finds of plant macro-remains in terrace house 2

Several of the pollen grains and especially the intestinal parasite eggs seems to originate from the city area; they were washed into the Roman harbour and the canal. Therefore, it is interesting to study the source area of these sediments. In the following section, the plant macro-remains in Terrace House 2, a Roman agglomeration (*insula*) built upon Hellenistic structures, and spanning the first until the third centuries AD, are described (Figure 7, Table II).

The mineralized finds are dominated by *c.* 20 000 fig pips (*Ficus carica*) and nine muskmelon seeds in the canal (SE 1016) of Dwelling Unit 7; they are dated to the third century AD (Figure 2). Grapevine (*Vitis vinifera* ssp. *vinifera*), one of the most significant cultivated woody plants in antiquity (also

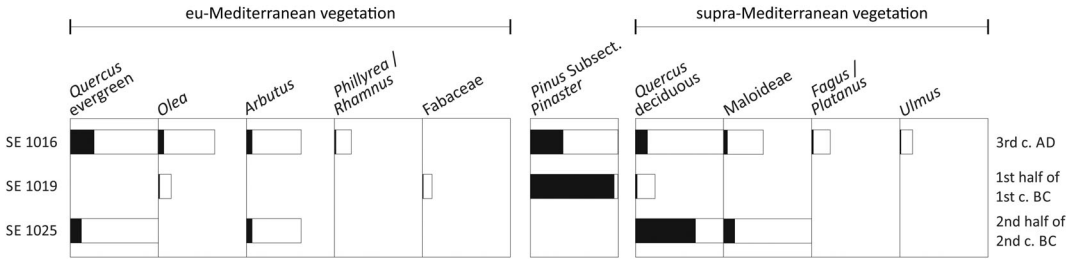


Figure 7. Charcoal percentages by weight from the sewer in Room 34a (cf. Figure 2a).

documented in the pollen profile), is present in mineralized form throughout the sewage layers from the first century BC to the third century AD. The presence and use of olive (*Olea europaea*) is proven by charred olive stones in all previously analysed Dwelling Units (Popovtschak, 2010; Thanheiser, 2010; Heiss and Thanheiser, in press). The charcoal spectrum is dominated by oak (*Quercus*, mainly deciduous taxa) and some species from the cluster pine group (*Pinus* subsect. *Pinaster*), to varying extents. Woody plants representative of a maquis shrubland, and high-altitude woodland from elevated altitudes are found in minor quantities.

Discussion

Interpretation of the stratigraphy of the harbour basin

The base of Eph 276 (unit 1a), a distinct lamination, probably in the form of varves (see thin section). The preservation of the laminated texture implies the sediments to be deposited in a non-bioturbated embayment at a water depth of *c.* 10 m from the second century BC to the first century AD (Figure 4a). Ostracods represent changing environments: brackish-lagoonal (*Cyprideis torosa*), freshwater to a slightly salinity (*Darwinula stevensoni* and *Limnocythere inopinata*), and brackish-marine (*Ammonia tepida*) ones. While variations of Ti may be linked to the beginning of detrital input from catchment erosion due to fluvial activity (Haug *et al.*, 2001; Yancheva *et al.*, 2007; Panizzo *et al.*, 2008), the increased Sr/Ca ratio may indicate a strong salinity (Wünnemann *et al.*, 2006). We interprete the basal sediments to be deposited in a very low-energy environment, probably under marine-brackish conditions with seasonal input of freshwater from the direct environs.

Unit 2a, also encountered in Eph 279, 270, 284, 271 and 278 (Figure 3), seems to reflect a very fast sedimentation of silts (~30 mm/yr), with some thin sand intercalations, from the second century BC to the first century AD; these are probably harbour muds (Marriner and Morhange, 2006a) deposited after the construction of a mole on the northern side of the harbour (159–138 BC). It was built in order to maintain the harbour's function for trade and communication and as a protection against the deposition of river sediments (Kraft *et al.*, 2000, 2001; Zabehlicky, 1995, 1999; Steskal, 2015; Strabo, 2007; 14.1.24). It may also reflect a dredging dump site; from ancient literature we know that the harbour and canal had been cleaned and dredged several times between the first to the third centuries AD (Zabehlicky, 1995; Kraft *et al.*, 2000, 2011). Despite the very high sedimentation rate, a natural deposition is likely since the sediments at the base reveal stratifications under natural conditions. In Eph 278 and 271, the silts were deposited earlier, between 1172–932 cal BC and 397–211 cal BC. Obviously, they represent the natural deposition prior to the harbour and canal construction. The age inversions in Eph 284 and 271 may derive from dredging activities close to the assumed quay on the northern and southern side of the basin/canal. The presence of *Isoetes* spores in the lower part of unit 2b is typical of fluvial transport, as proven in the Büyük Menderes graben (Knipping *et al.*, 2008). Moreover, it is supported by the brackish-lagoonal ostracod *Cyprideis torosa*, and few freshwater ostracods (*Darwinula stevensoni*, *Candona* sp.). Low Sr/Ca ratios are characteristic for a brackish water environment with low salinity probably due to the regular freshwater inputs (Delile *et al.*, 2015b). High MS values in the sandy intercalation reflect the terrigenous flux derived from fluvial input (Dearing, 1999), as proven in Portus, the harbour of Ostia (Salomon *et al.*, 2012). On top of the unit, the occurrence of the brackish-marine foraminifer species *Ammonia tepida* and *Haynesina germanica* indicate a facies change to a brackish-lagoonal milieu.

A sharp contact separates unit 2a from unit 3a, also encountered in Eph 270, 284 and 278 (Figure 3). The 0.40–2 m thick alternations of greyish brown and pale yellow silts may have been caused by seasonal variations in the hydrological conditions in a protected harbour basin (as for similar examples see Marriner *et al.*, 2006, 2010; Algan *et al.*, 2011; Salomon *et al.*, 2012; Sarti *et al.*, 2013): the pale yellow layer may result from epilimnic calcification during summer, with terrestrial clastic input occurring during the rainy winter season. In this section Cu attains the highest values in the core, most probably due to human impact (Sakan *et al.*, 2013). A significantly decreasing sedimentation rate to 1.6 mm/yr may indicate a decreased fluvial input, but also dredging operations explaining the sharp contact to the underlying unit. Microfossils suggest once more a lagoonal environment with brackish ostracod *Cyprideis torosa* and brackish-marine foraminifers *Ammonia tepida* and *Haynesina germanica*. In core Eph 279 unit 2a is overlain by swampy material deposited during Roman Imperial times which suggests siltation in the eastern part of the basin. Eph 271 reveals a similar environment on the southern side.

Unit 4a (Eph 276, 270, 284, 278) reveals a decreasing grain size, similar to unit 1a. The layer was deposited in a low-energy environment with declining human impact in a lagoon-like environment with abundant brackish-marine foraminifers *Ammonia tepida* and *Haynesina germanica* and the brackish-lagoonal ostracod *Cyprideis torosa*. The change in sedimentation may have been caused by dredging activities of the harbour or a subsidence caused by an earthquake. It was deposited from the sixth/seventh centuries AD onwards; the top is poorly dated. Decreasing Ti values towards the top of the core indicate the recession of fluvial and marine input (unit 5a). High Ca values and lower Sr/Ca ratios in units 5a and 6a (Eph 279, 270, 276, 284, 278, 271) can be explained by a higher biogenic calcite production during the thirteenth/fourteenth centuries AD (Bayon *et al.*, 2007) related to the decrease of the harbour water depth (Delile *et al.*, 2014c, 2015b). While brackish-marine foraminifers disappear, abundant freshwater gastropods (*Gyraulus* sp. and *Radix* sp.), brackish and freshwater ostracods (brackish: *Cyprideis torosa*; freshwater: *Candona* sp., *Darwinula stevensoni*) indicate the ecology of a permanent

Table II. Anthracological data from Terrace House 2, unit 7 (cf. Figure 2a)

Context	Room 34a, sewage canal layers						Room 32c, chalk pit filling	
Layer/sample	SE 1025		SE 1019		SE 1016		99/640	
Period	Second half of second century BC		First half of first century BC		Third century AD		Mid-first century AD	
Volume (l)	10		10		15		18.6	
Total charcoal content (g)	6.22		10.53		37.16		17.6	
Identified charcoal	68%		53%		42%		26%	
	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)
eu-Mediterranean vegetation								
Arbutus sp.	2	0.26	—	—	3	0.90	—	—
Fabaceae	—	—	1	0.05	—	—	—	—
Olea europaea s.l.	—	—	1	0.09	3	0.40	—	—
cf. *Olea europaea* s.l.	—	—	—	—	1	0.60	—	—
Phillyrea sp./*Rhamnus* sp.	—	—	—	—	2	0.30	—	—
Quercus sp. evergreen	8	0.54	—	—	14	4.20	3	0.23
anthropogenic woodland								
Pinus subsect. *Pinaster*	—	—	31	5.31	17	5.80	15	1.71
supra-Mediterranean vegetation								
Fagus sp. / *Platanus* sp.	—	—	—	—	1	0.30	—	—
Fraxinus sp.	—	—	—	—	—	—	9	0.67
Maloideae	4	0.54	—	—	2	0.70	—	—
Quercus sp. deciduous	16	2.87	2	0.10	6	2.10	4	0.37
Ulmus minor	—	—	—	—	1	0.20	—	—
traded timber								
Abies sp./*Cedrus* sp.	—	—	—	—	—	—	14	1.33
Tilia sp.	—	—	—	—	—	—	5	0.22
Total	30	4.21	35	5.55	50	15.50	50	4.53

lacustrine system, which was likely fed by karstic springs (Somay *et al.*, 2008; Somay and Gemici, 2009; Delile *et al.*, 2015b).

The organic rich layer in all drill cores (units 7a and 8a) with a thickness of 0.50 to 2.50 m together with low Ca contents and the dominance of freshwater fauna (gastropod: *Gyraulus* sp.; ostracods: *Pseudocandona* sp., *Candona* sp.) indicate a swampy environment and the gradually siltation of the area. Radiocarbon age estimates prove the peat development after the fourteenth century. The uppermost part of Eph 276 and 279 represent the final siltation of the area (unit 9a).

Interpretation of the stratigraphy of the harbour canal

Facies interpretation

In contrast to Eph 276, the base of Eph 244 and 245 (units 1b and 2b) is dominated by high-energy conditions in a marine environment until the eighth–sixth centuries BC, probably even until the fourth–third centuries BC (^{14}C age at the base of unit 4b, Eph 245) with detrital input from the environs.

The overlying layer of stones (unit 3b) may derive from slope debris or have been dumped there intentionally after dredging activities of up to 6 m (see also Bony *et al.*, 2011). The mica-rich sand (3–4 m thick) with peaks in MS correspond to a coarse-grained fluvial material and point to a prograding advancing river delta from the fourth to the first centuries BC, in Eph 221 until the first century AD (unit 4b in Eph 244, 245, 221).

A sudden change to a low-energy environment with silts in all three drill cores represents sediments of the canal (unit 5b); its time of operation is dated from the first century BC onwards. In this unit, Cu shows the highest amounts of the drill core; it declines after the fifth century AD (unit 6b). It indicates human influence in the sediments as it is not linked to a changing grain size. The uppermost units also represent the development of a lake and its siltation from the thirteenth century AD onwards.

Interpretation of palynological and parasitological analyses

At the base (PAZ 1), the pollen diagram reveals many indeterminate pollen grains which show signs of decay during transport and *Isoetes* spores from the hinterland, probably transported by the Küçük Menderes River in Hellenistic times. This zone is characterized by a strong anthropogenic influence (*Olea*, Cerealia-type, *Plantago lanceolata*-type, *Cannabis*, high amount of Fabaceae). From Late Hellenistic to the Early Byzantine period, PAZ 2 and PAZ 3 represent the canal sediments with a discontinuation of *Isoetes* spores and a rapid decline of indeterminates. *Sarcopoterium spinosum* hints at a higher grazing pressure whereas *Sanguisorba minor* is more likely to have been used as lettuce. With the appearance of eggs of the intestinal parasites whipworm (*Trichuris* sp.) and roundworm (*Ascaris* sp.), *Cucumis melo*, and pollen grains of fruit trees, the anthropogenic impact rises. *Papaver rhoeas*-type pollen as a predictor of poppy use is abundant. The high amounts of Brassicaceae during this period also point to the use of some species of this family as vegetable like cabbage or radish (Russo Ermolli *et al.*, 2014). Between the third and the fifth centuries AD, the amount of eggs of the intestinal parasite *Trichuris* sp. decreases. In the overlying PAZ 4, the increasing amount of *Pinus* indicates fallow land with pines as pioneer trees. The decreasing indicators for human impact (less *Olea*, discontinuation of intestinal parasites) may reflect the declining population in Ephesus after the seventh century AD. However, settlement activities still continue (e.g. flax pollen *Linum usitatissimum*-type). It also persists during the thirteenth–fourteenth centuries AD (PAZ 5). Abundant aquatic and swamp plants indicate the beginning of the siltation of the canal.

Palaeoenvironmental changes and their consequences

Development from the end of the second millennium BC to the second century BC

The results presented here clearly reveal the siltation of Ephesus' harbour and its environs in response to the advance of the Küçük Menderes delta. Until the first millennium BC, a dynamic marine embayment with detrital input from the adjacent drainage area was in existence. From the fourth–third centuries BC onwards, the influence of the Küçük Menderes became dominant. The high sedimentation rate of ~6 mm/yr in comparison to earlier low values (i.e. 1 mm/yr from the sixth to the first millennia BC; Stock *et al.*, 2013) can be explained by an increase in erosion in the drainage basin, triggering a faster advance of the Küçük Menderes delta. This phenomenon was probably linked to the rise of several settlements (Stock *et al.*, 2013). A fast delta progradation was described for the Küçük Menderes delta by Eisma (1978); Erinç (1978); Meriç (1985); Hess (1989); Brückner (2005) and other Mediterranean rivers (Grove and Rackham, 2001; Vella *et al.*, 2005; Kaniewski *et al.*, 2013). All of them start their advance during the mid-Holocene when sea level stabilized following its rapid rise after the Last Glacial Maximum (LGM) (Stanley and Warne, 1994; Kraft *et al.*, 1999). For the first millennium BC, human influence is evidenced in the vegetation association by the presence of Fabaceae, *Cannabis*, Cerealia-type and *Plantago lanceolata*-type pollen present; this is confirmed by other pollen records from the Mediterranean (e.g. Casana, 2008; Bellotti *et al.*, 2011; Broothaerts *et al.*, 2014).

Strong human influence from the second century BC to the seventh century AD

After the second century BC, laminated silts at the base of the harbour basin are overlain by homogeneous silts of the open harbour with a particularly high sedimentation rate of 30 mm/yr. A similar high value was determined for the protected harbour of Marseille (22 mm/yr; Marriner and Morhange, 2006b). Besides the human impact the high value was caused by the proximity of the delta front. The deposition of laminae between the second/first centuries BC and the sixth/seventh centuries AD in the harbour of Ephesus suggests seasonal deposition. The changing geochemistry (e.g. elevated Cu values) points to the construction of a protected harbour basin and its intensive use. This corresponds to the most prosperous phase of the city. Similar laminites composed of mineral-rich and biogenic sediments, deposited during winter and summer seasons, have been described, e.g. for the Santa Barbara Basin, California (Schimmelmann *et al.*, 2006). The same is also visible in core Eph 244: a sudden change to low-energy conditions indicates the man-made development of a canal around the end of the first century BC to the beginning of the first century AD. Eggs of intestinal parasites, typical for latrines (Mitchell *et al.*, 2008; Anastasiou and Mitchell, 2013b), muskmelon, macroremains in a dwelling of Ephesus as also found in Portus (Pepe *et al.*, 2013; Sadori *et al.*, 2014), and *Cannabis*, and fruit tree pollen in combination with raised lead (Pb) (Delile *et al*, 2015b) and Cu concentrations confirm the strong human influence (Sarti *et al.*, 2013).

Evidence for the footprint of human impact is also seen from the on-site charcoal record from the city area. The role of

cluster pines (dominant from the 1st century BC onwards) may be an anthropogenic indicator: only two species from the group are likely to have occurred in the region during antiquity, and both are fostered by anthropogenic action – either through the degradation of natural forests as in the case of *Pinus brutia* (Axelrod, 1975; Knipping *et al.*, 2008) or by planting as for *P. pinea* (Kislev, 1988). High quantities of *Pinus* in the charcoal record during the Roman period may result from the overuse of woodland resources in the vicinity (Heiss and Thanheiser, 2014). In a synopsis of all data from the Roman period (Table II), it becomes apparent that throughout there is a noticeable presence of plants from woodland in the Ephesian hinterland: *Fraxinus* (ash), *Ulmus* (elm), and *Fagus*/*Platanus* (beech/plane) point to a considerable amount of wood gathering – be it for fuel, tool-making or construction timber. *Olea* appears from the beginning of the first century BC, which indicates that this species was also used for its wood, not only its fruits (see for instance older evidence of this kind from Sicily: Stika *et al.*, 2008; Mercuri *et al.*, 2013; Sadori *et al.*, 2013).

Taking all these data into account they clearly provide many indications for a fast delta advance during the Roman and Byzantine periods (so called 'man-made deltas'; Maselli and Trincardi, 2013). This is in line with evidence from other deltas around the Mediterranean: the Büyük Menderes (Brückner *et al.*, 2002), the Po (Simeone and Corbau, 2009), the Tiber (Bellotti *et al.*, 2011) and the Rhône (Arnaud-Fassetta, 2002) – just to mention a few examples. Human impacts also occur during the Hellenistic/Roman to Byzantine periods, as e.g. in Tyre and Alexandria (Marriner *et al.*, 2008a). These results prove once more that humans had a strong impact on the environment.

There has been an ongoing debate about climate forcing (Vita-Finzi, 1969; Grove and Rackham, 2001) *versus* human forcing (Zolitschka *et al.*, 2003; Broothaerts *et al.*, 2014). Climate changes may have played a role, but the changes along the deltas of the Mediterranean seem to correlate with population dynamics, especially during the last millennia. Moreover, most of the studied geo-bio-archives are dominated by human impact, therefore it is very difficult to trace evidence of the climate. Especially from the end of the first millennium BC, the faster delta advance correlates with a higher population density. The landscape changed with a degradation of the hillslopes due to deforestation (for agriculture, fuel, construction of houses and ships) and grazing (Williams, 2000). Kaplan *et al.* (2009) calculated a significant decrease in forests on usable land between 500 BC and the turn of the era. As a consequence of a decreased forest cover, torrential rains during the winter season led to increased slope erosion and associated deposition in the floodplain and delta areas (Dusar *et al.*, 2011). Thus, it seems that the anthropogenic signal clearly overprinted the climatic one.

Development since the seventh century AD

From the sixth/seventh centuries AD onwards, greyish silts were deposited in the harbour basin, probably in a lagoon-like environment. Both in the port and in the canal, a Ca-rich layer, dominated by freshwater ostracods and also characterized by a lack of foraminifera, overlies the brackish water indicating sediments. Its deposition took place between the seventh and the thirteenth centuries AD. Detrital input from the environs is missing, maybe as a result of reduced cultivation on surrounding slopes or the distal delta-mouth location. Human impact decreases considerably, most probably due to a decline of the city and a less intensive use of the harbour and the surroundings after the mid-seventh century AD. The increase in *Quercus ilex*-type and *Pistacia* points to the increased importance of pasture farming on abandoned land; higher values of pine tree pollen support this hypothesis. According to palynological results marine/brackish algae disappear; they were progressively replaced by aquatic and amphibious plants, indicating a reduced inflow of marine water due to a siltation of the canal. Settlement activities, however, are still confirmed by archaeological and historical evidence.

The decline of harbours and their cities after the Roman period is a common phenomenon in the Mediterranean (e.g. Brückner, 1986; Pranzini, 2001; Marriner *et al.*, 2008a, 2008b). Along with a shrinking population, agricultural activities were diminished and the hillslopes started to recover (Pranzini, 2001). More recently and especially during the last centuries, the opposite has occurred, with dam and barrage construction serving as sediment traps, resulting in erosion along the coasts in the outer deltas (Hoffmann *et al.*, 2010; Anthony *et al.*, 2014). This clearly demonstrates that population dynamics strongly influences land-use changes and erosion processes.

Conclusion

Multi-proxy analyses of sediment cores from Ephesus have revealed the development of the Roman harbour and its canal since the end of the second millennium BC. The study proved that harbours are excellent geo-bio-archives for recording human impact during the last millennia and for underlining the fact that growing cities and societies in the Mediterranean had severe effects on sediment dynamics. This is especially true for the Hellenistic to Byzantine periods, thus confirming the concept of the Anthropocene *sensu lato* from this period on. From the first millennium BC on, with a peak during the Hellenistic and Roman periods, a high sedimentation rate indicates fast delta progradation which has also been proven for other Mediterranean deltas. A stratified layer attests to the development of a protected harbour basin and the construction of the canal during the first century BC/AD. The results prove strong human impacts for the period between the first century BC to the seventh century AD with elevated Cu values, high amounts of pollen from cultivated plants, and the discovery of eggs of two species of intestinal parasites. The data show that a larger population, especially during the Roman period, deforested the direct environs of the settlements as well as the hinterland, leading to increased erosion from the adjacent hillslopes. In consequence, more sediment was transported by the rivers causing a faster delta progradation. From the seventh century AD onwards, human impact diminishes. This goes along with a decrease in population and the decline of the harbour. The demise of the cities directly affected land-use changes and resulted in a decreased sediment supply due to recovered hills.

It is noteworthy that most of the research in the Mediterranean took place in the environs of settlements. For a better differentiation between climate change and human impact, geo-bio-archives relatively untouched by humans should be studied more intensively. The swamps and lake of Belevi *c.* 20 km east of the present shoreline in the Küçük Menderes graben are such an example.

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UPLC-MS metabolome based classification of *Lupinus* and *Lens* seeds: A prospect for phyto-equivalency of its different accessions

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ABSTRACT

Fabaceae is well-known for its seed nutritious and bioactive composition as exemplified by *Lupinus* and *Lens*. Developing efficient analytical approaches for profiling their bioactive matrix is a prerequisite to provide proof for their health benefits or nutritive traits. Eight *Lupinus* and *Lens* seed accessions were subjected to liquid chromatography-mass spectrometry (UPLC-MS)-based metabolomic study, which identified 66 metabolites, *viz.* flavonoids, alkaloids, saponins, phenolics, fatty acids and sphingolipids. Chemometric tools were explored to assess heterogeneity across the two genera leading to elucidation of the species-most enriched and differential metabolites. The two dark-colored lentil cultivars are identified as the richest source of functional foods with presumed therapeutic benefits; however, *Lupinus hispanicus* was proved to be the most nutritive accession. To our knowledge, this study provides the first UPLC-MS-based comparative metabolite profiling of *Lupinus* and *Lens* seeds. This platform was also able to discern metabolites diversity at the intraspecific level among *Lupinus* species and *Lens* cultivars.

1. Introduction

With a global demand for functional plant-based foods and much more concern towards reliable characterization of their chemical makeup for which many therapeutic and nutritional attributes are claimed, development of analytical methodology should now follow. Information on the phytochemical composition and confirmed health benefits of many plant-based functional foods is scarce in the literature or at least under-exploited which necessitates employing large-scale screening analytical tools to better evaluate their claimed health effects and nutrigenomic data. Appropriate analytical platforms ought to be selected that can capture metabolites variabilities from different classes and generate high-quality food composition data (Scalbert et al., 2011).

One of the promising sources of functional food is pulses (plant family: Fabaceae) as being enriched with a myriad of nutritious and bioactive components. Since the dawn of the Neolithic in the Fertile Crescent, it has been mainly species from the tribus Fabeae which have been playing key roles for millennia in human nutrition in the Old World, the most prominent being pea, lentil, faba bean, and bitter vetch (Weiss & Zohary, 2011). Phylogenetically lentil species are nested within vetches (*Vicia* L.) (Schaefer et al., 2012). Likewise of importance, yet from different tribus, are taxa such as chickpea from Cicereae, and lupin from Genisteae (Butler, 1998). Today, the pulses most commonly used for human consumption are lentil, lupin, pea, bambara bean, faba bean, chickpea, cowpea, groundnut, *Phaseolus* spp., pigeon pea, and soybean (FAO, 2018).

During the past years, pulse crops have been receiving increasing attention against the background of climate change. Legumes represent a highly efficient way of supplying excellent source of protein for human consumption while affecting environment far less than livestock (Foyer et al., 2016). Considering the dominance of soybean as both food and fodder on worldwide markets, also other promising pulse crops have recently been suggested as alternatives, such as lupins (Lucas et al., 2015). Although not phylogenetically close relatives, lupins

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Table 1
Origin of *Lupinus* and *Lens* seed accessions used for metabolites analyses. All accessions are permanently stored at the Department of Bioarchaeology at the Austrian Archaeological Institute (ÖAI), and are accessible on request. Seed providers: Botanischer Garten der Universität Basel, Switzerland (BAS), Jardim Botânico da Universidade de Coimbra, Portugal (COI), Hohenheimer Gärten, Germany (HOH), Alpengarten Patscherkofel und Botanischer Garten Innsbruck, Austria (IB), MARAP HandelsgesmbH, Vienna, Austria (MRP), and Vollkraft Naturnahrung Handels und Produktions GmbH, Grimmenstein, Austria (VKR).

Sample code	Species and cultivar	Provider	Country origin	ÖAI accession number
LU_PO	*Lupinus polyphyllus* Lindl. 'Russell'	HOH	Germany	510
LU_A	*Lupinus angustifolius* L. 'Boltensia'	IB	Austria	649
LU_L	*Lupinus luteus* L.	IB	Austria	1325
LU_H	*Lupinus hispanicus* Boiss. & Reutt.	COI	Portugal	2872
LCB	*Lens culinaris* Medik. subsp. *culinaris* 'verte du Puy' (brown colored seed)	VKR	Austria	2827
LCO	*Lens culinaris* Medik. subsp. *culinaris* 'Petite Rouge d'Egypte'	MRP	Austria	2376
LCY	*Lens culinaris* Medik. subsp. *culinaris* (yellow colored seed)	BAS	Switzerland	555
LCBK	*Lens culinaris* Medik. subsp. *culinaris* 'Black Beluga'	MRP	Austria	2375

(*Lupinus* L. spp.) together with lentil (*Lens culinaris* Medik.), are two of the most nutritionally-valuable dietary components which are traditionally consumed worldwide, and particularly in Mediterranean cuisines. They are well reported to provide a balanced source of nutritive components *viz.* essential amino acids, fibers, minerals and vitamins. Legume seeds exhibit several health promoting effects such as antioxidant, hypoglycemic, hypocholesterolaemic, protection against cardiovascular diseases, and in cancer prevention (Campos-Vega, Loarca-Piña, & Oomah, 2010; Rochfort & Panozzo, 2007).

Several hundreds of non-nutritive phytochemicals, like phenolic compounds (flavonoids, phenolic acids, and condensed tannins), phytosterols, and quinolizidine alkaloids have also been identified in leguminous seeds, the latter being important markers in chemotaxonomy, such as in the delimitation of tribus Genisteae including *Lupinus* (Cardoso et al., 2012; Salatino & Gottlieb, 1981). Some of these secondary metabolites might contribute to explain the health benefits mediated upon their consumption (López-Amorós, Hernández, & Estrella, 2006; Rochfort & Panozzo, 2007). Such bioactive metabolites are recognized as functional ingredients in human diet and nutraceuticals (Campos-Vega et al., 2010), and are (more) likely to show natural variation within the different species (Farag, Weigend, Luebert, Brokamp, & Wessjohann, 2013). The food value of *Lupinus* and *Lens* depends on the relative content of both nutritive and anti-nutritive phytochemicals, while the latter class might have a negative impact on seeds digestibility and bioavailability of minerals and proteins. For instance, *Lupinus* seeds contain variable amounts of bitter-tasting quinolizidine alkaloids (range: 0–4% of the seed, *w*/w) which offer the plants protection against insects and pests; however, they may result in acute anticholinergic toxicity in humans and require extra processing for their removal, such as leaching (Yeheyis, Kijora, Wink, & Peters, 2011). The seeds phenolic content also varies within respective species, subspecies or cultivars depending on the degree of ripeness and germination stages (López-Amorós et al., 2006).

Metabolomics studies are being recently employed as a global profiling approach to characterize food metabolomes and to assess the heterogeneity in the overall bioactive matrix of functional foods (Farag, Elsebai, & Khattab, 2018). Such knowledge on the bioactive composition of food is essential in building-up phytochemical databases that help in unveiling the complex relationships linking chemical diversity of food-based bioactives, and their nutritive and therapeutic effects. Therefore, sensitive mass spectrometry (MS) techniques hyphenated to gas or liquid chromatography have been extensively applied in metabolomics studies. One such valuable tool is UPLC coupled with high resolution Q-TOF-MS that offers high sensitivity in compounds detection compared to conventional low resolution LC-MS (Farag, Gad, Heiss, & Wessjohann, 2014). The generated MS-derived datasets are then mostly explored for heterogeneity among specimens *via* different chemometric tools such as unsupervised methods *viz.* principal component analysis (PCA) or hierarchical clustering analysis (HCA). Whereas, metabolic differences between predefined sample classes are disclosed using supervised methods *viz.* partial least square discriminate analysis (PLS-DA) (Manach, Hubert, Llorach, & Scalbert, 2009). Such metabolite profiling approach combined with chemometrics has been developed to unravel variabilities across different plant genera as well as closely-related species and taxa (Farag, Sharaf Eldin, Kassem, & Abou El Fetouh, 2013; Farag, Weigend, et al., 2013; Wojakowska et al., 2013; Wojakowska et al., 2013).

Only scarce information on the phytochemical diversity existing among and within taxa of *Lupinus* and *Lens* seeds has been reported up to now. In continuation to our previous GC–MS report on *Lupinus* and *Lens* seeds (Farag et al., 2018) primary metabolites, we extend herein by performing a complementary UPLC-MS-based metabolite profiling to scrutinize the secondary metabolome fingerprint of *Lupinus* and *Lens* seed accessions.

2. Materials and methods

2.1. Plant material

The studied *Lupinus* and *Lens culinaris* seed accessions were procured from four Botanical Gardens (BAS, HOH, IB, COI) and two Austrian organic food vendors as depicted with more details in Table 1.

2.2. Chemicals

LC-MS grade solvents purchased from J. T. Baker (The Netherlands) were used. Umbelliferone was purchased from ChromaDex (LGC Standards, Wesel, Germany). All other chemicals and standards were procured from Sigma Aldrich (St. Louis, MO, USA).

2.3. Extraction procedure and sample preparation for UPLC-MS analysis

Air dried seeds were ground using pestle and mortar under liquid nitrogen. 30 mg of the obtained powder was then homogenized with 2.5 mL 100% MeOH containing 5 µg/mL umbelliferone (an internal standard for relative quantification) using a Turrax mixer operated at 11.000 rpm for 20 s for 5 periods, with a recession time of 1 min between each mixing period to avoid generation of excessive heat during mixing. The extracts were vortexed vigorously and centrifuged at 3000 *g* for 30 min to get rid of plant debris. For solid phase extraction, 500 µL of the methanol extracts was loaded on a 500 mg C18 SPE cartridge which was preconditioned with a mixture of methanol and water. About 3 mL 70% MeOH and 3 mL 100% MeOH was used as eluting solvent, then the eluents were evaporated till dryness using a gentle stream of nitrogen. The obtained dry residue was re-suspended in 500 µL MeOH to be used for subsequent UPLC-MS analysis.

2.4. High resolution UPLC-TOF MS analysis

The analytical conditions for high resolution UPLC-MS were employed as previously described in (Farag, Rasheed, Kropf, & Heiss, 2016). Chromatographic separation was performed on an ACQUITY UPLC system (Waters, Milford, MA) equipped with a HSS T3 column (100 × 1.0 mm, particle size 1.8 µm; Waters). The analysis was carried out using a binary gradient elution system at a flow rate of 150 µL min^{-1}: 0 to 1 min, isocratic 95% A (water/formic acid, 99.9/0.1 [v/v]), 5% B (acetonitrile/formic acid, 99.9/0.1 [v/v]); 1 to 16 min, linear from 5 to 95% B; 16 to 18 min then isocratic 95% B; 18 to 20 min, and finally, isocratic 5% B. Full loop injection volume (3.1 µL) was used. The eluted compounds were detected in mass range from *m/z* 100 to 1000 mainly in negative ion mode, the following instrumental settings were used: nebulizer gas, nitrogen, 1.6 bar; dry gas, nitrogen, 6 l min^{-1}, 190 °C; capillary, −5500 V; in-source CID energy, 0 V; hexapole RF, 100 Vpp; quadrupole ion energy, 5 eV; collision gas, argon; collision energy, 10 eV; collision RF 200/400 Vpp (timing 50/50); transfer time, 70 µs; prepulse storage, 5 µs; pulser frequency, 10 kHz; spectra rate, 3 Hz. Internal mass calibration was performed by infusion of 20 µL 10 mM lithium formate in isopropanol: water, 1:1 (v/v), at a gradient time of 18 min using a diverter valve.

2.5. UPLC-CID-MS/MS analysis

High resolution mass spectrometry experiments were performed using a MicrOTOF-Q orthogonal-accelerated TOF mass spectrometer (Bruker Daltonics). Precursor ions were selected in Q1 with an isolation width of ± 2 D and dissociated at collision energies of 10–30 eV using argon as a collision gas. Product ions detection was carried out using the following instrument settings: collision RF 150/400 Vpp (timing 50/50); transfer time, 70 µs; pre-pulse storage, 5 µs; pulser frequency, 10 kHz; spectra rate, 1.5 Hz. For pseudo-MS^3 analysis, in-source CID energy was increased from 0 to 100 V.

2.6. Identification and quantification of metabolites via UPLC-PDA-ESI–qTOF-MS

Identification of the seeds metabolites was accomplished by their UV–VIS spectra (220–600 nm), retention times relative to external standards, mass spectra and comparison to phytochemical dictionary of natural products database (CRC) and reference literature.

2.7. MS data processing for multivariate analysis: PCA and OPLS

Relative quantification and comparative analysis of *Lupinus* and *Lens* metabolic profiles after UPLC-MS was conducted using XCMS data analysis software under R 2.9.2 environment, which is freely downloadable as an R package from the accessible metabolite database "Metlin" (http://137.131.20.83/download/). Several MS data processing tools were employed including peak alignment, matching and comparison to produce a final peak list. The ion features were then normalized to the total integrated area (1000) per sample using the Microsoft Excel software (Microsoft, Redmond, WA) and imported into the R 2.9.2 software package for principal component analysis (PCA). Autoscaling the absolute peak area values (the mean area value of each feature across all samples was subtracted from each individual feature area and the result divided by the standard deviation) was also performed prior to PCA. This procedure was carried out to ensure that all variables have attained similar weights.

2.8. Multivariate data analysis

Principal component analysis (PCA) and orthogonal partial least squares-discriminate analysis (OPLS-DA) were performed on the MS scaled data using SIMCA-P Version 13.0 (Umetrics, Umeå, Sweden). The PCA, an exploratory tool, was run for visualizing a general outlook through scores plot for the existing sample groupings, trends and/or outliers among the studied seed accessions. OPLS-DA, a supervised pattern recognition tool, was employed to model the differences in the metabolite composition among species in order to identify species-specific biomarkers. Outliers were recognized by testing the samples distance to the model (DModX). OPLS-DA model performance was assessed by monitoring R^2 and Q^2 values, where $R^2$is used to measure the goodness of model fit, whereas Q^2 is indicative of the degree of the model predictability. An iterative permutation test was further done to omit the non-randomness of between groups separation.

3. Results & discussion

3.1. Characterization of phytochemical composition of Lupinus & Lens seeds via UPLC-PDA-ESI–qTOF-MS

The heterogeneity in *Lupinus* and *Lens* secondary metabolomes was explored using non-targeted UPLC-MS metabolite profiling of their seeds coupled with different chemometric tools. Methanol extracts of seed accessions were analyzed using a high resolution UPLC–PDA–(−) ESI–qTOF–MS, following a gradient elution of mobile phase composed of acetonitrile with aqueous formic acid that allowed for the comprehensive elution of the seed metabolites within 19 min compared to the 60 min analysis time previously reported (Stobiecki et al., 2010).

Seed accessions were initially analyzed in both negative and positive electrospray ionization (ESI) modes, as changing the ESI polarity attenuates competitive ionization and helps to provide better detection of a wide range of metabolites. However, identification of polar phenolic acids and glycosidic metabolites was dependent on negative-ion MS spectra as a higher sensitivity and more observable MS peaks with lower signal to noise ratio has to be achieved (Farag et al., 2016).

The simultaneously acquired UPLC–MS total ion chromatograms of the studied seeds are depicted in Fig. 1. Metabolite assignments were made by comparing retention times, UV/Vis spectra and MS/MS data (accurate mass, isotopic distribution and fragmentation pattern in both positive and negative ion modes) of the compounds reported for *Lupinus* and *Lens* in literature and phytochemical dictionary of natural product database, see experimental section 2.6. The identification was further confirmed using standard compounds whenever available in-house. The identities, relative retention times, UV characteristics, and observed molecular and fragment ions for the annotated metabolites are provided in Table 2 and structures of the metabolites discussed throughout the manuscript are illustrated in Fig. 2.

A total of 94 chromatographic peaks were detected belonging to different metabolite classes *viz.* phenolic acids, alkaloids, flavonoids, terpenoids, sphingolipids and fatty acids, with flavonoids being the most abundant class (Table 2). The abundance of such subclass is also visible in the base peak chromatogram (BPC) that is extremely rich in the elution region (rt 100–300 s), as depicted in Fig. 1 and the relative quantities of the identified metabolites are presented in Table S1. Metabolites were eluted in order of decreasing polarity, whereby phenolics and flavonoid glycosides appeared first in the chromatograms followed by aglycones, terpenoids, and lastly fatty acids.

3.1.1. Macronutrients

3.1.1.1. Saccharides. Two polysaccharides were common in both *Lupinus* and *Lens* seeds identified as gallactotriose (2) with a $(M-H)^-$ at *m/z* 503.1614 ($C_{18}H_{31}O_{16}^-$), along with its hexoside derivative, stachyose (1) exceeding it by 162 amu with a molecular ion at *m/z* 665.2145 ($C_{24}H_{41}O_{21}^-$) previously reported from *Lupinus luteus* and *Lens* (Gorecki, Piotrowicz-Cieslak, & Obendorf, 1997). Galacto-oligosaccharides are known to exert prebiotic activity despite its tendency to cause flatulence (Campos-Vega et al., 2010). Beyond its prebiotic and nutritive significance, galactose free sugar is reported to cause a pronounced improvement in case of cognitive deficits

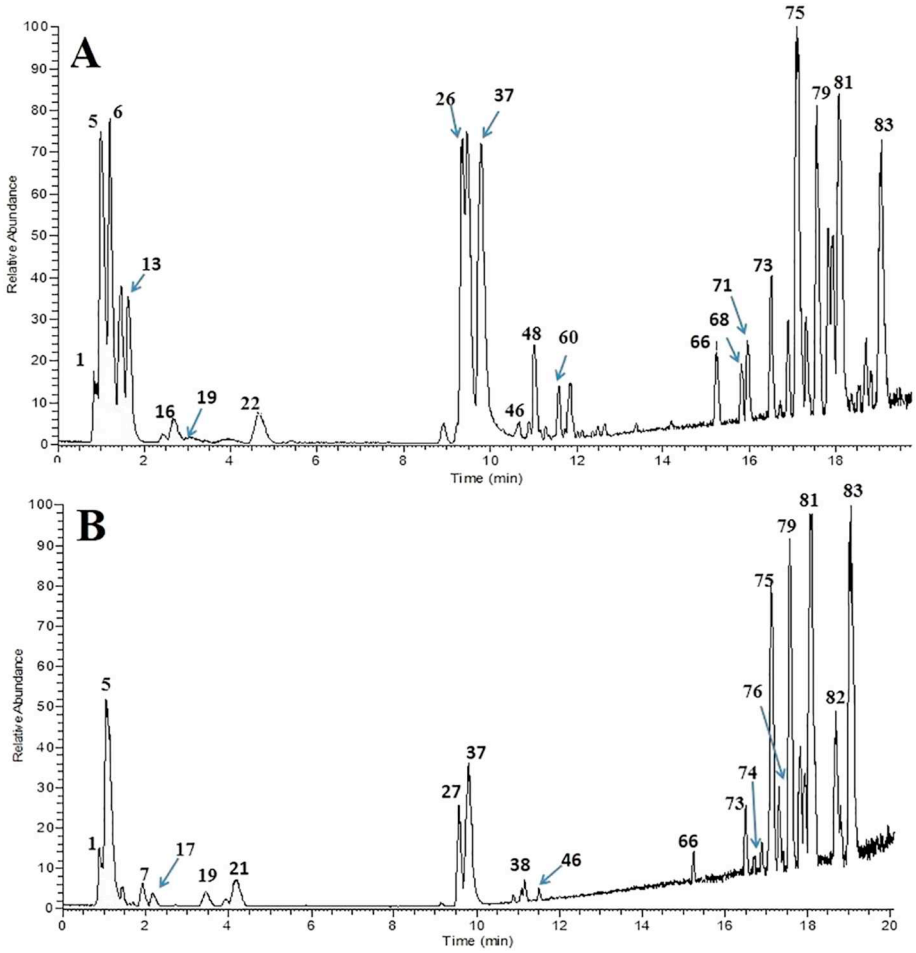


Fig. 1. Representative UPLC- -MS trace chromatogram of metabolite peaks detected in *Lupinus* and *Lens* seeds (A) & (B). The corresponding names for peaks follow that listed in Table 2.

associated with glucose hypometabolism in Alzheimer's disease (Salkovic-Petrisic et al., 2014). Also galactose supplementation in diets of patients suffering from phosphoglucomutase-1 deficiency, a congenital disorder of glycosylation, has led to pronounced clinical improvement in glycosylation indexes (Tegtmeyer et al., 2014).

3.1.1.2. Fatty acids and sphingolipids. Only few studies were concerned with the lipophilic metabolite profile of pulses (Caprioli et al., 2016) predominated by poly unsaturated fatty acids. Fatty acids as phenolic and organic acids were better detected in negative ionization owing to their freely ionized carboxylate group. The negative ion MS spectrum of the unsaturated fatty acid "linoleic acid" (89), found in *Lupinus* seeds, was identified at *m/z* 279.2337 ($C_{18}H_{31}O_2^-$). Another fatty acid (87) appeared at *m/z* 277.2178 ($C_{18}H_{29}O_2^-$), with 2 amu mass difference from (89) indicative of an extra double bond in its structure and assigned as linolenic acid. Essential fatty acids, *i.e.* alpha-linolenic (omega-3) are well-acknowledged to play a role in managing inflammation in human bodies by providing the building blocks for prostaglandins (Leventhal, Boyce, & Zurier, 1993).

Palmitic acid (92) was also detected in both seeds at *m/z* 255.2343 ($C_{16}H_{31}O_2^-$) while its hydroxylated form (86) (*m/z* 271.2287, $C_{16}H_{31}O_3^-$), with a mass difference of 16 amu from (92), was found only in *Lupinus* seeds. Mono-unsaturated octadecenoic acid (oleic acid) and the saturated octadecanoic acid (stearic acid) were assigned in peaks 93 & 94. The former was found in both seeds at *m/z* 281.250 ($C_{18}H_{33}O_2^-$) having an extra double bond than (94) with a mass difference of 2 amu at *m/z* 283.264 ($C_{18}H_{35}O_2^-$) and present only in *Lupinus* seeds. Fatty acids of pulses are reported to possess several health beneficial effects on cardiovascular system such as improving blood lipid profile (Keys & Parlin, 1966) and insulin sensitivity (Lovejoy, 1999) in addition to lowering type 2 diabetes incidence (Salmerón et al., 2001).

Furthermore, several hydroxylated fatty acids (oxylipids) were detected as major peaks in both *Lupinus* and *Lens* species *i.e.* peaks 85, 90 & 91 with respective exact masses of *m/z* 295.2277 ($C_{18}H_{31}O_3^-$), 297.2442 ($C_{18}H_{33}O_3^-$) and 299.2604 ($C_{18}H_{35}O_3^-$) identified as hydroxyoctadecadienoic acid, hydroxyoctadecenoic and hydroxyoctadecanoic acids, respectively. Both genera were found to contain dihydroxylated fatty acids, *viz.* dihydroxy-octadecanoic (78) at *m/z* 315.2549 ($C_{18}H_{35}O_4^-$), dihydroxyoctadecenoic (74) at *m/z* 313.2549 ($C_{18}H_{33}O_4^-$) and dihydroxyoctadecadienoic acids (71) at *m/z* 311.2239 ($C_{18}H_{31}O_4^-$).

It should be noted that trihydroxy-oxylipids were found only in *Lupinus* species *viz.* tri-hydroxyoctadecadienoic (62) and tri-hydroxyoctadecenoic acids (64) with exact masses of *m/z* 327.2169 ($C_{18}H_{31}O_5^-$) and 329.2335 ($C_{18}H_{33}O_5^-$), respectively. There is an increasing interest in oxylipids for their reported biological activities as being of anti-inflammatory, antimicrobial and cytotoxic activity (Abou-Elwafa, Shaaban, Shaaban, El-Naggar, & Laatsch, 2009) and whether they characterize the seed accessions examined has yet to be determined.

Several lipid peaks (76, 77, 80, 81 & 82) were detected in both genera with an even mass weights of 562.3148 ($C_{27}H_{49}O_9NP^-$), 476.2788 ($C_{23}H_{43}O_7NP^-$), 564.3305 ($C_{27}H_{51}O_9NP^-$), 540.3314 ($C_{25}H_{51}O_9NP^-$) and 566.3457 ($C_{27}H_{53}O_9NP^-$) tentatively assigned for sphingolipids with characteristic loss of 285 amu indicative for

Table 2
Metabolites identified in methanol extracts of *Lupinus* and *Lens* seed accessions using UPLC–PDA-MS

Peak	RRt	UV (nm)	Mol. ion m/z (±)	Molecular formula	Error (ppm)	Metabolites	MS/MS	Class	Lupinus	Lens	Ref.
1	0.085	ND	665.2145	$C_{24}H_{41}O_{21}^-$	0.8	Stachyose	647	Saccharide	+	+	(Gorecki et al., 1997)
2	0.089	ND	503.1614	$C_{18}H_{31}O_{16}^-$	1.5	Gallactotriose	152, 272	Saccharide	+	_	(Gorecki et al., 1997)
3	0.10	ND	517.1766	$C_{19}H_{33}O_{16}^-$	1.6	Unknown trisaccharide	272	Saccharide	_	+	
4	0.11	ND	341.1083	$C_{12}H_2O_{11}^-$	2.3	Sucrose	179, 161, 143	Saccharide	+	+	(Farag, Gad, et al., 2014, Farag, Mohsen, Heinke, & Wessjohann, 2014)
5	0.12	262	191.0205	$C_6H_7O_7^-$	−3.6	Citric/isocitric acid	173, 129, 111	Organic acid	+	+	(Farag et al., 2016)
6	0.17	260	191.0208	$C_6H_7O_7^-$	−4.8	Citric/isocitric acid	111	Organic acid	+	+	
7	0.19	278	447.1130	$C_{18}H_{23}O_{13}^-$	2.2	Hydroxysalicylic acid pentosylhexoside	315, 297, 271, 153,135	Phenolic acid	+	+	(Farag et al., 2016)
8	0.22	259	265.1913	$C_{15}H_{25}N_2O_2^+$	0.5	3-Hydroxy lupanine (Lupanoline)	170	Alkaloid	+		
9	0.22	273	873.2729	$C_{38}H_{49}O_{23}^-$	−1.2	Naringenin-*O*-dihexosyl-rhamnosyl-pentoside	711,549, 271	Flavanone glycoside	+	+	
10	0.22	255, 322	711.2186	$C_{32}H_{39}O_{18}^-$	−5.4	Naringenin- *O*-hexosyl-rhamnosyl- pentoside	549	Flavanone glycoside	+	+	
11	0.28	256	711.2191	$C_{25}H_{43}O_{23}^-$	2.5	Unknown	665, 549, 162,439, 387, 195	–	+	_	
12	0.35	261	129.0199	$C_5H_5O_4^-$	4.4	Methylidenesuccinic acid (Itaconic acid)	85	Organic acid	_	+	(Gorecki et al., 1997)
13	0.45	272	255.0509	$C_{11}H_{11}O_7^-$	0.3	*p*-hydroxybenzyltartaric acid (Piscidic acid)	193, 179, 175, 165, 149	Phenolic acid	+	_	
14	0.49	263	249.1966	$C_{15}H_{25}N_2O^+$	−1.2	Lupanine	170	Alkaloid	+		
15	0.60	276	205.0980	$C_{11}H_{13}N_2O_2^+$	−4.3	Tryptophan	188	Amino acid	+		(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
16	0.65	275	323.1347	$C_{13}H_{23}O_9^-$	1.6	Unknown disaccharide	271, 203, 112	Saccharide	+	_	
17	0.70	ND	451.1231	$C_{21}H_{23}O_{11}^-$	2.3	(Epi) Catechin-hexoside	289, 271, 137	Flavan glycoside	_	+	(Dueñas et al., 2003)
18	0.71	278,	577.1339	$C_{30}H_{25}O_{12}^-$	−0.2	Procyanidin dimer	425, 152, 407, 289	Anthocyanin	_	+	(Dueñas et al., 2003)
19	0.72	271, 274, 286	443.1921	$C_{21}H_{31}O_{10}^-$	0.8	Dihydrophaseic acid hexoside	281	Organic acid	+	+	(del Refugio Ramos et al., 2004)
20	0.72	270	245.1292	$C_{14}H_{17}N_2O_2^-$	1.7	3-(1*H*-Indol-3-yl)-2-propenoic acid	–	Organic acid	_	+	(Hofinger et al., 1970)
21	0.73	272	417.1040	$C_{17}H_{21}O_{12}^-$	0	Gentisic acid-di-*O*-pentoside	285,153, 135	Phenolic acid	_	+	(Beelders, De Beer, Stander, & Joubert, 2014)
22	0.75	277, 337	743.2045	$C_{32}H_{39}O_{20}^-$	2	Hydroxy-dihydrogenistein-*C*, *O*-dihexosylpentoside	725, 653, 623, 581,533, 461, 401	Isoflavonoid glycoside	+	_	
23	0.80	308	278.0665	$C_{13}H_{12}NO_6^-$	1.5	*N*-*p*-coumaroylaspartic acid.	174, 112	Amino acid	_	+	
24	0.81	268	527.1975	$C_{21}H_{35}O_{15}^-$	0.9	Unknown	–	–	–	+	
25	0.82	264	901.2596	$C_{39}H_{49}O_{24}^-$	6.9	Apigenin-*C*-dihexosyl-*O*-pentosyl-hexouronide	883, 781, 811, 769, 725, 635, 605,383, 352	Flavone glycoside	+	_	
26	0.83	268, 321, 337	725.1910	$C_{32}H_{37}O_{19}^-$	2.1	Apigenin-*C*-dihexosyl-*O*-pentoside	707, 635, 605, 593, 383, 352	Flavone glycoside	+	_	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
27	0.84	267, 347	901.2567	$C_{39}H_{49}O_{24}^-$	6	Kaempferol-di-*O*-rutinoside	755, 593, 285	Flavonol glycoside	_	+	(Aguilera et al., 2010)
28	0.85	ND	548.1164	$C_{28}H_{22}O_{11}N^-$	9.5	Unknown	–	–	_	+	
29	0.88	264	517.2263	$C_{24}H_{37}O_{12}^-$	−3.4	Unknown	–	Terpene glycoside	_	+	
30	0.91	269, 343	755.2021	$C_{33}H_{39}O_{20}^-$	2.7	Chrysoeriol-*C*, *O*-di-hexosylpentoside	741, 725, 695,665, 635, 593	Flavone glycoside	+	_	(Wojakowska, Muth, et al., 2013, Wojakowska, Piasecka, et al., 2013)
31	0.91	265, 344	755.1997	$C_{33}H_{39}O_{20}^-$	5.4	Kaempferol-3-*O*-rutinoside 7-*O*-hexoside.	609, 593, 575, 285	Flavonol glycoside	_	+	(Aguilera et al., 2010)
32	0.92	265, 335	679.1520	$C_{30}H_{31}O_{18}^-$	−1.5	Genistein-*O*-di-hexosyl malonate	635, 593, 431, 269	Isoflavonoid glycoside	+	_	(Pawlak-Sprada et al., 2011)
33	0.94	266, 351	443.1190	$C_{19}H_{23}O_{12}^-$	1.1	Unknown	–	Phenolic acid	_	+	
34	0.96	308.3	603.2282	$C_{27}H_{39}O_{15}^-$	2.1	Unknown	–	–	_	+	
35	0.97	316	491.1771	$C_{21}H_{31}O_{13}^-$	0.2	Unknown	–	Flavonoid glycoside	+	_	
36	0.99	323	401.1806	$C_{19}H_{29}O_9^-$	0.2	Trihydroxy-megastigmadien-one hexoside	239, 221, 177	Saponin	_	+	(Tsopmo & Muir, 2010)
37	1.00	214, 323	161.0257	$C_9H_5O_3^-$	−6.9	Umbelliferone (internal standard)		Coumarin	+	+	
38	1.02	323	545.1875	$C_{24}H_{33}O_{14}^-$	0.6	Unknown	503, 483, 443, 401, 383, 269	Flavonoid glycoside	–	+	

(*continued on next page*)

Table 2 (*continued*)

Peak	RRt	UV (nm)	Mol. ion m/z (±)	Molecular formula	Error (ppm)	Metabolites	MS/MS	Class	Lupinus	Lens	Ref.
39	1.05	262, 328	461.1072	$C_{22}H_{21}O_{11}^-$	6.4	Chrysoeriol-*O*-hexoside	299	Flavone glycoside	+	-	(Wojakowska, Muth, et al., 2013, Wojakowska, Piasecka, et al., 2013)
40	1.08	269, 325	447.0935	$C_{21}H_{19}O_{11}^-$	0.1	Luteolin-*O*-hexoside	285	Flavone glycoside	+	-	(Wojakowska, Muth, et al., 2013, Wojakowska, Piasecka, et al., 2013)
41	1.11	315	589.2503	$C_{27}H_{41}O_{14}^-$	−0.3	Unknown	545, 463	–	-	+	
42	1.11	323,	555.2437	$C_{27}H_{39}O_{12}^-$	1	Unknown	447	–	+		
43	1.12	267, 330	871.2300	$C_{34}H_{47}O_{26}^-$	−5	Apigenin-*C*-dihexosyl-*O*-rhamnosylpentoside	781, 751, 739, 725, 649, 635, 619, 605, 383, 352	Flavone glycoside	+	-	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
44	1.123	265	373.1874	$C_{18}H_{29}O_8^-$	3	Unknown	193, 179, 143, 113	Terpene hexoside	+	-	
45	1.13	260, 330	901.2386	$C_{42}H_{45}O_{22}^-$	2.1	Apigenin-*O*-dihexosyl-feruloyl-pentoside	769, 739, 607, 563, 431	Flavone glycoside	+	-	
46	1.16	270, 330	563.1411	$C_{26}H_{27}O_{14}^-$	−1.1	Apigenin-*O*-pentosylhexoside	431, 269	Flavone glycoside	+	-	(Wojakowska, Muth, et al., 2013; Wojakowska, Piasecka, et al., 2013)
47	1.17	–	447.0932	$C_{21}H_{19}O_{11}^-$	2.3	Kaempferol-*O*-hexoside	285	Flavonol glycoside	-	+	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013), (Ibrahim et al., 2015)
48	1.18	260, 322	431.0982	$C_{21}H_{19}O_{10}^-$	1.4	Apigenin-*O*-hexoside	269	Flavone glycoside	+	-	
49	1.19	ND	463.0882	$C_{21}H_{19}O_{12}^-$	−0.1	Quercetin-*O*-hexoside	301	Flavonol glycoside	-	+	(Ibrahim et al., 2015)
50	1.20	ND	575.2697	$C_{27}H_{43}O_{13}^-$	2.1	Unknown	507, 415, 343	–	+	-	
51	1.20	ND	301.0359	$C_{15}H_9O_7^-$	5.5	Quercetin	191, 151	Flavonol	-	+	(Ibrahim et al., 2015), (Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
52	1.22	267, 322	517.0978	$C_{24}H_{21}O_{13}^-$	1.2	Apigenin-*O*-hexosyl malonate	269, 431, 473	Flavone glycoside	+	-	(Wojakowska, Muth, et al., 2013, Wojakowska, Piasecka, et al., 2013)
53	1.23	312	473.1089	$C_{23}H_{21}O_{11}^-$	0	Unknown	–	–	+	-	
54	1.25	ND	431.0988	$C_{21}H_{19}O_{10}^-$	−0.8	Luteolin-*O*-rhamnoside	285	Flavone glycoside	+	+	(Kabran et al., 2014)
55	1.27	272, 338	285.0411	$C_{15}H_9O_6^-$	−2.3	Luteolin	–	Flavone	+	-	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
56	1.28	320, 354	285.0410	$C_{15}H_9O_6^-$	6	Kaempferol	175, 151	Flavonol	-	+	(Ibrahim et al., 2015)
57	1.33	–	647.2713	$C_{33}H_{43}O_{13}^-$	−0.6	Unknown	–	–	+	-	
58	1.36	–	245.0451	$C_{13}H_9O_5^-$	2	Unknown	–	–	+	-	
59	1.37	–	607.2750	$C_{31}H_{43}O_{12}^-$	2.3	Unknown	555, 245	Terpene glycoside	-	+	
60	1.37	ND	269.0458	$C_{15}H_9O_5^-$	−1.5	Apigenin	–	Flavone	+	-	(Wojakowska, Muth, et al., 2013, Wojakowska, Piasecka, et al., 2013)
61	1.40	–	957.4989	$C_{48}H_{77}O_{19}^-$	1.4	Oleanene-tetrol-*O*-hexosyl rhamnosylhexouronide	–	Saponin	+	-	(Sarwar Alam et al., 2008)
62	1.42	–	327.2169	$C_{18}H_{31}O_5^-$	−0.1	Trihydroxyoctadecadienoic acid	–	Fatty acid	+	-	
63	1.44	ND	369.0977	$C_{20}H_{17}O_7^-$	0.7	Lupin isoflavone D	–	Isoflavonoid	+	-	(Hashidoko et al., 1986)
64	1.46	–	329.2335	$C_{18}H_{33}O_5^-$	−0.3	Trihydroxyoctadecenoic acid	311, 229, 211, 171	Fatty acid	+	-	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
65	1.51	–	609.2673	$C_{34}H_{41}O_{10}^-$	3.6	Unknown	373, 287	–	+	-	
66	1.60	–	941.5084	$C_{48}H_{77}O_{18}^-$	3.9	Dihydrooleanolic acid-*O*-hexosylrhamnosylglucuronoide	779, 633, 457	Saponin	+	+	Oleanolic acid glucuronoide ID: 56940675
67	1.62	–	307.1907	$C_{18}H_{27}O_4^-$	3.1	Unknown	–	Fatty acid	+	-	
68	1.70	–	939.4902	$C_{48}H_{75}O_{18}^-$	6.5	Oleanolic acid-*O*-hexosylrhamnosyl-glucuronoide	777, 631, 455	Saponin	+	-	
69	1.73	–	293.1756	$C_{17}H_{25}O_4^-$	1	Unknown	–	Fatty acid	+	-	
70	1.75	296	309.2067	$C_{18}H_{29}O_4^-$	9.1	Epoxy-hydroxy-octadecadienoic acid	–	Fatty acid (oxylipid)	+	-	Hydroxyoctadecadienoic acid Pubchem ID:6443013
71	1.78	–	311.2239	$C_{18}H_{31}O_4^-$	−2.8	Dihydroxyoctadecadienoic acid	293, 275	Fatty acid	+	+	Hydroxyoctadecadienoic acid Pubchem ID:6443013
72	1.81	–	675.3373	$C_{36}H_{51}O_{12}^-$	1.5	Triterpene glycoside	381	Saponin	+	+	
73	1.85	–	593.2923	$C_{34}H_{41}O_9^-$	−3.9	Unknown	413, 315, 277	Saponin	-	+	(Farag et al., 2016)
74	1.82	–	313.2382	$C_{18}H_{33}O_4^-$	1.4	Dihydroxyoctadecenoic acid	295, 277	Fatty acid (oxylipid)	+	+	Chisholm & Hopkins, 1957).

(*continued on next page*)

Table 2 (*continued*)

Peak	RRt	UV (nm)	Mol. ion m/z (±)	Molecular formula	Error (ppm)	Metabolites	MS/MS	Class	Lupinus	Lens	Ref.
75	2.10	–	595.2882	$C_{34}H_{43}O_9^-$	−4.5	Unknown	313	Saponin	+	+	(Farag et al., 2016)
76	1.89	–	562.3148	$C_{27}H_{49}O_9NP^-$	0.4	Sphingolipid	502, 277	Sphingolipid	_	+	
77	1.98	–	476.2788	$C_{23}H_{43}O_7NP^-$	−1.9	Sphingolipid conjugate I	279	Sphingolipid	+	+	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
78	2.01	–	315.2549	$C_{18}H_{35}O_4^-$	−1.8	Dihydroxyoctadecanoic acid	297, 279	Fatty acid (oxylipid)	+	+	Pubchen ID: 89377
79	2.04	–	571.2887	$C_{39}H_{39}O_4^-$	−6.2	Unknown	391, 315, 255	Terpene glycoside	+	+	
80	2.11	–	564.3305	$C_{27}H_{51}O_9NP^-$	0.3	Sphingolipid conjugate II	279	Sphingolipid	+	+	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
81	2.13	–	540.3314	$C_{25}H_{51}O_9NP^-$	3.4	Sphingolipid	281	Sphingolipid		+	
82	2.19	–	566.3457	$C_{27}H_{53}O_9NP^-$		Sphingolipid conjugate III	281	Sphingolipid	+	+	(Farag, Gad, et al., 2014, Farag, Mohsen, et al., 2014)
83	2.34	–	599.3187	$C_{34}H_{47}O_9^-$	6.8–1.9	Unknown	566, 564, 409, 509, 295, 363, 315, 283	Saponin	+	_	(Farag et al., 2016)
84	2.34	–	483.2731	$C_{29}H_{39}O_6^-$	4.3	Unknown	255	Terpene	_	+	
85	2.38	–	295.2277	$C_{18}H_{31}O_3^-$	1	Hydroxyoctadecadienoic acid	–	Fatty acid (oxylipid)	+	+	(Farag et al., 2016)
86	2.54	–	271.2287	$C_{16}H_{31}O_3^-$	−2.4	Hydroxyhexadecanoic acid	–	Fatty acid (oxylipid)	+	_	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
87	2.54	–	277.2178	$C_{18}H_{29}O_2^-$	−1.9	Octadecatrienoic acid (linolenic)	211	Fatty acid	+	+	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
88	2.67	–	285.2435	$C_{17}H_{33}O_3^-$	0.9	Hydroxyheptadecanoic acid	267	Fatty acid (oxylipid)	+	_	
89	2.71	–	279.2337	$C_{18}H_{31}O_2^-$	−2.7	Octadecadienoic acid (linoleic)	211	Fatty acid	+	_	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
90	2.79	–	297.2442	$C_{18}H_{33}O_3^-$	−3.1	Hydroxyoctadecenoic acid	–	Fatty acid (oxylipid)	+	_	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
91	2.80	–	299.2604	$C_{18}H_{35}O_3^-$	−2.8	Hydroxyoctadecanoic acid	–	Fatty acid (oxylipid)	+	_	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
92	2.83	–	255.2343	$C_{16}H_{31}O_2^-$	−4.1	Hexadecanoic (palmitic)	–	Fatty acid	+	+	(Farag et al., 2016)
93	2.87	–	281.2494	$C_{18}H_{33}O_2^-$	−3.6	Octadecenoic acid (oleic)	–	Fatty acid	+	+	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)
94	4.05	–	283.2640	$C_{18}H_{35}O_2^-$	1.4	Octadecanoic acid (stearic)	182	Fatty acid	+	_	(Farag, Sharaf Eldin, et al., 2013, Farag, Weigend, et al., 2013)

ND = not identified.; RRT = relative retention time to spiked umbelliferone internal standard.

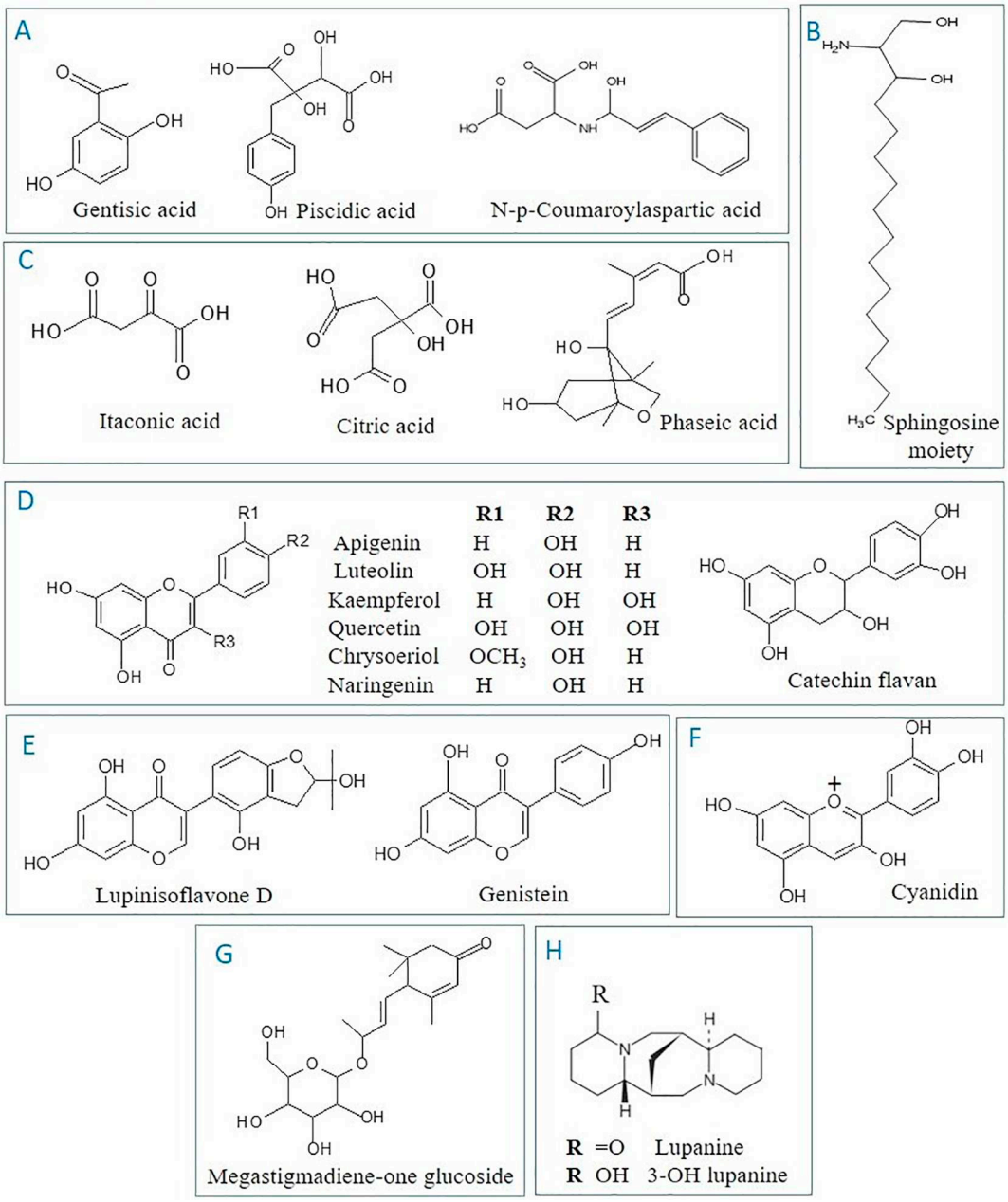


Fig. 2. Major classes of phytochemicals: phenolic acids (A), sphingosine moiety (B), organic acids (C), flavonoids (D), isoflavones (E), anthocyanin (F), terpene glycoside (G) and alkaloids (H) detected in *Lupinus* and *Lens* seeds with selected compounds discussed in the manuscript.

sphingosine moiety. Sphingolipids are lipid compounds with sphingosine moiety (an organic aliphatic amino alcohol), *i.e.* ceramides, which are widely distributed in plants and animal and well-characterized for their role in cell growth regulation, differentiation and metabolism. The health benefits of plant sphingolipids in the human diet has not been documented yet, however, some plant sphingoid bases prepared from wheat cerebrosides were reported to exhibit a cytotoxic effect (Zhu, Soroka, & Sang, 2013).

3.1.1.3. Organic acids. Several organic acids were recorded among which citric acid and/or its isomer (5 & 6) identified in both *Lupinus* and *Lens* specimens from its $(M\text{-}H)^-$ at *m/z* 191.0205 ($C_6H_7O_7^-$) and are likely to conjugate alkaloids in *Lupinus* serving for its solubilization. Peak 12 in *Lens* seeds was identified as methylidenesuccinic acid (*m/z* 129.0199, $C_5H_5O_4^-$), known as itaconic acid showing fragment ion at *m/z* 85 $(M\text{-}COO\text{-}H)^-$ reported from *Lens culinaris* L. seed coat (Tsopmo & Muir, 2010). Other organic acids *viz.,* 3-(3-indolyl) acrylic acid (20) (*m/z* 245.1292, $C_{14}H_{17}N_2O_2^-$) previously identified in *Lens culinaris* roots (Hofinger, Gaspar, & Darimont, 1970) and dihydrophaseic acid hexoside (19) (*m/z* 443.1921, $C_{21}H_{31}O_{10}^-$) found in both genera and showing MS^n ion for dihydrophaseic acid aglycone at *m/z* 281 $(M\text{-hexose-}H)^-$. Phaseic acid is a terpenoid catabolite of abscisic acid which are both plant hormones regulating important physiological functions in growth, photosynthesis, abscission and arrest, as well as in responses to biotic and abiotic stress conditions such as cold, drought, heat exposure, salinity (Sharkey & Raschke, 1980). A myriad of health effects of dihydrophaseic acid was reported such as antioxidant, lipid peroxidation inhibition, antidiabetic and chemoprevention effects (Lin et al., 2014; Uzor & Osadebe, 2016).

3.1.2. Non-nutritive phytochemicals

3.1.2.1. Flavonoids. UV spectra (200–500 nm) were recorded and provided the basis for the differentiation of various flavonoid subclasses including 13 flavones, 5 flavonols, 3 isoflavones, one anthocyanin in addition to one flavan and one flavanone. Flavone glycosidic conjugates appeared as the major subclass herein as evidenced by their characteristic UV max (Table 2). For MS/MS glycosidic conjugates structural elucidation, there is a striking difference in the fragmentation pattern of *O*-glycosyl and *C*-glycosyl flavonoids that enabled discrimination among them. The identified flavonoids were mostly *O*-type glycosides showing neutral loss of their sugar units, that are either hexose (glucose or galactose), deoxyhexose, pentose or hexouronic acid with their respective losses of 162, 146, 132 or 176 amu (Simirgiotis, Schmeda-Hirschmann, Bórquez, & Kennelly, 2013). In contrast, *C*-glycosyl flavonoids fragmentation pathway exhibits non-homogenous fragments which are characterized by daughter ions resulting from dehydration with its respective loss of 18 amu, in addition to 0,2 and 0,3 cross-ring cleavages of the sugar moiety in *C*-hexosides leading to losses of 120 & 90 amu, while *C*-pentosides resulting in losses of 90 & 60 amu (Davis & Brodbelt, 2004). The identification of mono-and di-*C*-glycosides can be further confirmed by the detected fragment ions (aglycone +41, 71)$^-$ and (aglycone +83, 113)$^-$, respectively, which are found corresponding to the aglycone plus its remained linked sugar residues (Ferreres, Gil-Izquierdo, Andrade, Valentão, & Tomás-Barberán, 2007).

MS/MS spectral data in our study led to the detection of several flavone derivatives *i.e.* luteolin (*m/z* 285, $C_{15}H_9O_6^-$) in peaks 39, 54 & 55, and apigenin (*m/z* 269, $C_{15}H_9O_5^-$) in peaks 25, 26, 43, 45, 46, 48 & 52, along with the methylated analogue *i.e.* chrysoeriol signals (*m/z* 299, $C_{16}H_{11}O_6^-$) in peaks 30 & 39. Most of the identified flavone conjugates were found more abundant in *Lupinus* seeds, in contrary, *Lens* seeds appeared to be more enriched in flavonol conjugates *i.e.* quercetin (*m/z* 301, $C_{15}H_9O_7^-$) in peaks 49 & 51 and kaempferol (*m/z* 285, $C_{15}H_9O_6^-$) in peaks 27, 31, 47 & 56.

Two methoxylated luteolin glycosides were identified *viz.,* chrysoeriol-*O*-hexoside (39) (*m/z* 461.1072, $C_{22}H_{21}O_{11}^-$), reported previously in leaves and roots of *Lupinus* species (Wojakowska, Muth, et al., 2013; Wojakowska, Piasecka, et al., 2013) in addition to chrysoeriol-*C*, *O*-di-hexosyl-*C*-pentoside (30) detected in *Lupinus* seeds at *m/z* 755.2021 (M-H)$^-$ with MS^n ions at *m/z* 725 (M-OCH_3-H)$^-$, 593 (M-162) indicative for an *O*-glycoside linkage and *m/z* 741 corresponding to the characteristic loss of methyl group from its methoxy. Other sugar moieties were confirmed from fragment ions at *m/z* 695, 665 & 635 due to the losses of 120, 90 & 60 amu, respectively, with characteristic fragmentation behavior of *C*-hexosyl pentosyl glycosides. It is worth noting that methoxylated flavonoids are known to exert a strong anticancer activity than their hydroxylated counterparts which can be ascribed to their lypophilic nature (Bernini, Crisante, & Ginnasi, 2011).

Apigenin-*O*-dihexosyl-feruloyl-pentoside (45) was annotated with a high resolution mass of 901.2386 for $C_{42}H_{45}O_{22}^-$ and MS^n at *m/z* 739 (M-hexose-H)$^-$, 607 (M-hexose-pentose-H)$^-$ and 563 (M-hexose-ferulic acid-H)$^-$. While peak 46 was identified as apigenin-*O*-pentosyl hexoside (*m/z* 563.1411, $C_{26}H_{27}O_{14}^-$) showing typical fragmentation pattern of mono-*O*-hexosyl flavones, with sequential loss of terminal pentose, at *m/z* 431 (M-pentose-H)$^-$ and 269 (M-pentose-hexose-H)$^-$ for apigenin aglycone.

Peaks 25 & 26 were identified as apigenin-*C*-dihexosyl-*O*-pentosyl-hexouronide (*m/z* 901.2596, $C_{39}H_{49}O_{24}^-$) and apigenin-*C*-dihexosyl-*O*-pentoside (*m/z* 725.191, $C_{32}H_{37}O_{19}^-$). They both showed fragmentation pattern of flavone- *C/O* glycosides as evidenced from the fragments ions at *m/z* 883 & 707 (M-18)$^-$, 811 & 635 (M-90)$^-$, 781 & 605 (M-120)$^-$ and 769 & 593 (M-132)$^-$ for (25) & (26), respectively; while fragment ion at *m/z* 725 (M-176)$^-$ due to the loss of hexouronide moiety was detected in tandem MS/MS spectrum of (25).

An acylated glycoside was identified in peak 52 (*m/z* 517.0978, $C_{24}H_{21}O_{13}^-$) assigned as apigenin-*O*-hexosyl malonate with a loss of malonyl moiety at *m/z* 431 (M-86)$^-$ & 473 for (M-44)$^-$. The latter is indicative for CO_2 (44 amu) cleaved from the malonic acid moiety (Wojakowska, Muth, et al., 2013; Wojakowska, Piasecka, et al., 2013). Notably, malonated glycosides were not identified in luteolin peaks suggestive for the presence of an acylating enzyme with low substrate specificity towards luteolin.

The identified flavonoid conjugates in our study are referred to as being hexosides or pentosides unless they were previously reported from *Lens* or *Lupins* species, such as kaempferol-3-*O*-rutinoside-7-*O*-glucoside (*m/z* 755.1997, $C_{33}H_{39}O_{20}^-$) (31) previously reported in *Lens esculenta* (Aguilera et al., 2010) and also detected in *Lens* seed accessions from its product ions at *m/z* 593 (M-glucose-H)$^-$, 609 (M-rhamnose-H) and 285 (kaempeferol, $C_{15}H_9O_6^-$). The hypsochromic shift in λ_{max} = 265 & 344 nm, compared to its free aglycone, indicated that multiple hydroxyl groups are occupied. Peaks 27 & 47 exhibited exact molecular masses of 901.2567 ($C_{39}H_{49}O_{24}^-$) and 447.09323 ($C_{21}H_{19}O_{11}^-$), respectively, and their MS/MS fragmentation pattern was in agreement with that of kaempferol-*O*-dirutinoside and kaempferol-*O*-hexoside, respectively, previously reported in lentil seeds (Aguilera et al., 2010).

Members of Fabaceae plant family are well known to biosynthesize isoflavones like phytoalexins in response to pathogenic attacks or for symbiosis with soil nitrogen-fixing bacteria. They exhibit estrogenic, antioxidant, chemoprevention of osteoporosis and anticancer activities (Dixon & Ferreira, 2002). In our study, hydroxyl- dihydrogenistein dihexosyl pentoside (22) was identified in *Lupinus* seeds from its (M-H)$^-$ at *m/z* 743.2045 ($C_{32}H_{39}O_{20}^-$) and product ion at *m/z* 725.1933 (M-H_2O-H)$^-$. MS/MS data suggested for C/O linked sugars as revealed from MS^n ions at *m/z* 581 (M-hexose-H)$^-$ indicative for *O*-hexose moiety *versus m/z* 623 (M-120) & 653 (M-90) for the loss of a *C*-linkage hexose moiety.

Peak 32 was assigned as genistein-*O*-di hexosyl malonate, previously reported in *Lupinus luteus* (Pawlak-Sprada, Stobiecki, & Deckert, 2011) from its (M-H)$^-$ at *m/z* 679.152 ($C_{30}H_{31}O_{18}^-$) and MS^n ions at *m/z* 593 for the loss of malonyl group (86 amu) and *m/z* 431 (M-malonyl-hexose-H)$^-$. Gensitein conjugates were found enriched in sprouted hypocotyls of *Lupinus albus* suggestive that they play a role in cell wall lignification (Ros Barcelo, Muñoz, & Sabater, 1989).

Lupinus genus-specific isoflavones, namely lupin isoflavones (Hashidoko, Tahara, & Mizutani, 1986) showed fungitoxic activity (Tahara, Ingham, Nakahara, Mizutani, & Harborne, 1984) of which lupin isoflavone-D (63) was identified with (M-H)$^-$ at *m/z* 369.0977 for $C_{20}H_{17}O_7^-$ (Tahara, Ingham, & Mizutani, 1985).

A procyanidin dimer (18), previously reported in *Lens culinaris* species, was identified in the studied *Lens* accessions at *m/z* 577.1339 (M-H)$^-$ $C_{30}H_{25}O_{12}^-$ (Dueñas, Sun, Hernández, Estrella, & Spranger, 2003). The (−) ESI-MS/MS spectra of (18) gave fragment ions at *m/z* 425 (M-H-152)$^-$ from Retro-Diels-Alder (RDA) rearrangement of the heterocyclic ring, *m/z* 407 (M-H-170)$^-$ and *m/z* 289 (M-H-289)$^-$ due to loss of H_2O resulting in cleavage of the interflavanic bond (Sun & Miller, 2003). These phenolic compounds in seed coat of lentils could be of interest in food and pharmaceutical industries owing to its potent antioxidant activity.

Catechins are also well-known to serve as building blocks for *Lens* seed coat formation in addition to imparting bitterness and astringency to lentil sprouts (Troszyńska et al., 2011). A (*epi*)catechin hexoside was identified in *Lens* seeds in peak 17 (*m/z* 451.1231, $C_{21}H_{23}O_{11}^-$) from its MS^n fragment ion at *m/z* 289 corresponding to a monomer of flavan-3-ol post sugar moiety cleavage (Dueñas et al., 2003).

3.1.2.2. Phenolic acids. Peak 13 was identified in *Lupinus* seeds as *p*-hydroxybenzyltartaric acid (*m/z* 255.0509, $C_{11}H_{11}O_7^-$) known as piscidic acid reported for the first time herein. Two gentisic acid glycosides were identified, *i.e.* hydroxysalicylic acid pentosylhexoside (7) and gentisic acid dipentoside (21) from their respective molecular ions (*m/z* 447.113, $C_{18}H_{23}O_{13}^-$) and (*m/z* 417.104, $C_{17}H_{21}O_{12}^-$). The

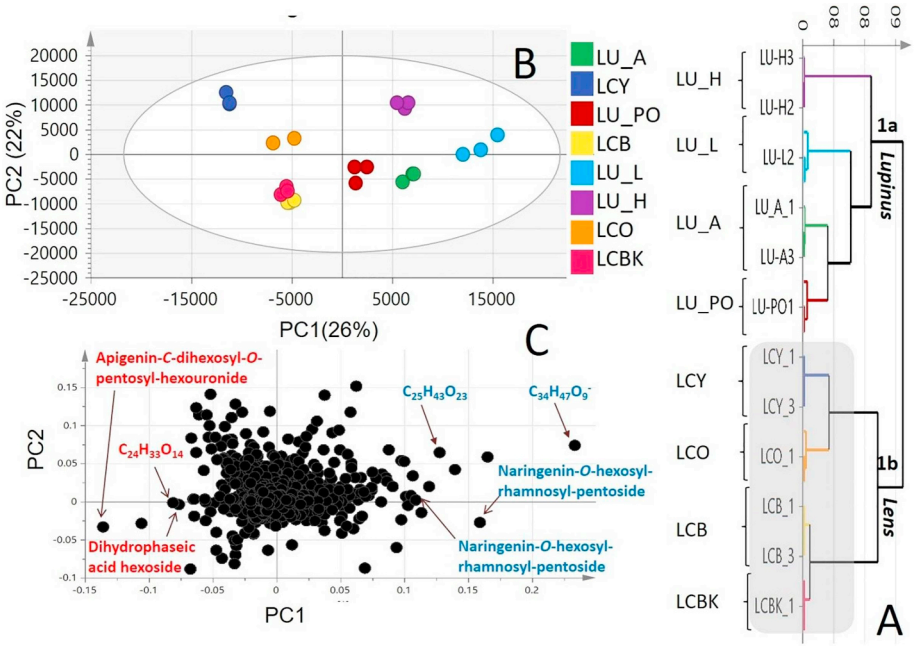


Fig. 3. UPLC/MS-based unsupervised hierarchical clustering and principal component analyses (PCA) of metabolites analyzed in *Lupinus* and *Lens* seeds. (A) HCA plot (B) PCA score plot of PC1 *vs.* PC2 scores. (C) Loading plot for PC1 & PC2 contributing metabolites and their assignments. The metabolome clusters are located at the distinct positions in two-dimensional space described by two vectors of principal component 1 (PC1) = 26% and PC2 = 22%.

former was identified in the two genera studied from its product ions at *m/z* 315 (M-pentose-H)$^-$, 297 (M-pentose-H_2O-H)$^-$, 153 (M-pentose-hexose-H)$^-$ and 135 (M-pentose-hexose-H_2O-H)$^-$ with the latter fragment corresponding to that of salicylic acid aglycone ($C_7H_3O_3^-$). In contrast, peak 21 was solely detected in *Lens* seeds showing fragment ions corresponding to the sequential loss of two pentosyl moieties at *m/z* 285 & 153 with the latter fragment corresponding to gentisic acid ($C_7H_5O_4^-$).

In general, pulses polyphenolics are reported to reduce seeds nutritional traits owing to its ability to bind protein and minerals, hence reducing their bioavailability. They also influence both seed taste and color (Oomah, Tiger, Olson, & Balasubramanian, 2006) in addition to playing a major role in protecting against both cellular and molecular damages caused by reactive oxygen species (Xu & Chang, 2007).

3.1.2.3. Quinolizidine alkaloids. Two alkaloids, widely distributed in certain Fabaceae genera, particularly *Lupinus*, were detected with higher responses in positive ionization mode and identified as lupanine (14) and its hydroxy derivative lupanoline (8) with molecular ions at *m/z* 249.1966 ($C_{15}H_{25}N_2O^+$) and 265.19 ($C_{15}H_{25}N_2O_2^+$), respectively. These alkaloids exhibit a strong hypoglycemic activity; however, their level is considered a limiting factor for human consumption of *Lupinus* seeds as they impart a bitter taste and have toxic actions in levels of *ca.* 2–4% contained in bitter *Lupinus* varieties (Wink, Meißner, & Witte, 1995).

This made modern agricultural techniques develop genetically engineered "sweet" lupins with low-alkaloid level of about 0.001% (Boschin, Annicchiarico, Resta, D'Agostina, & Arnoldi, 2008).

3.1.2.4. Saponins. Saponins are common secondary metabolites in many edible pulses including lupins and lentils and are regarded as antinutrients due to their haemolytic properties (Campos-Vega et al., 2010). However, they also exhibit an immune-stimulatory, anti-carcinogenic and hypocholesterolemic activities in addition to a reduction of heart diseases risk (Chang, Yu, Lin, Wang, & Tsai, 2006). In our current study, pentacyclic triterpene glycosides of oleanene skeleton were detected, of which peak 66 was the major form present in both *Lupinus* and *Lens* seeds and assigned to dihydro-oleanolic acid-*O*-hexosylrhamnosyl glucuronoide (*m/z* 941.5084, C_{48} H_{77} O_{18}^-). In contrast, peak 68 was found exclusively in *Lupinus* specimens identified as oleanolic acid-*O*-hexosylrhamnosyl glucuronoide (*m/z* 939.4902$^-$, C_{48} H_{75} O_{18}^-). The structures of both saponins were confirmed from their respective fragment ions at *m/z* 779, 633 & 457 and 777, 631 & 455 resulting from sequential loss of sugar moieties (M-hexose-H)$^-$, (M-hexose-rhamnose-H)$^-$ and (M-hexose-rhamnose-hexuronic acid-H)$^-$ and ultimately yielding its C_{30} triterpene aglycone fragment ions at *m/z* 457 & 455, respectively. Another triterpenoid saponin (61) found only in *Lupinus* seed extracts was identified as oleanene-tetrol-*O*-hexosylrhamnosylhexouronide (*m/z* 957.4989, $C_{48}H_{77}O_{19}^-$), its aglycone was previously isolated from *Lupinus angustifolius* and showed moderate anticandidal activity (Woldemichael & Wink, 2002). Enrichment of the saponins in lupin seeds poses them as ideal carbohydrate source for diabetic patients due to their ability to potentiate glucose-induced insulin release (Pereira et al., 2001).

Another terpene glycoside was detected in peak 36 present in all *Lens* species assigned as trihydroxy-megastigmadien-one hexoside (*m/z* 401.1806, $C_{19}H_{29}O_9^-$) for its MS^n ions at *m/z* 239 (M-hexose-H)$^-$, 221 (M-hexose-H_2O-H)$^-$ and 177 (M-hexose-H_2O-COO-H)$^-$ previously reported in *Lens culinaris* seed coat with antibacterial activity against *Helicopacter pylori* (Tsopmo & Muir, 2010).

3.2. Multivariate data analysis of UPLC–MS metabolome of Lupinus & Lens seeds

The heterogeneity of the UPLC–MS metabolomics dataset of the examined *Lupinus* and *Lens* seed accessions was initially explored using two unsupervised pattern recognition methods, namely, principal component analysis (PCA) and hierarchical cluster analysis (HCA).

3.2.1. Unsupervised PCA and HCA analyses

The UPLC–MS data matrix-driven hierarchical clustering dendrogram (Fig. 3A) exhibited two distinctively-separated clusters "1a & 1b" corresponding to the two unrelated genera, *Lupinus* and *Lens*, respectively. Within each genus the different taxa studied were well-defined, showing in *Lens* samples representing the two seeds with dark-colored testa "*Lens culinaris subsp. culinaris* "verte du Puy" brown colored (LCB) and *L. culinaris* subsp. *culinaris* "Black Beluga" (LCBK) together in one subgroup within cluster "1b"; *i.e.* being suggestive for their comparable bioactive makeup. Within *Lupinus,* the more closely related Old World taxa, *i.e. L. angustifolius*, *L. hispanicus*, and *L. luteus* (*cf.* Drummond, Eastwood, Miotto, & Hughes, 2012; Gladstones, 1998; Kass & Wink,

1997) were clustered together with *L. angustifolius* showing a more similar metabolomic profile compared to the New World *L. polyphyllus*.

A PCA model was then established to differentiate among different seed accessions and to reveal for the most discriminatory metabolite variables. PC1 and PC2 accounted for 48% of the total seed metabolome variability, and basically PC1 (26%) separated the two genera *Lens* and *Lupinus*. Biological replicates from the same seed accession were tightly grouped indicating the high reproducibility attained in sample measurements. Metabolomic similarity of *Lens culinaris* seed accessions with dark colored testa was clearly evident from their close segregation at the left side of PC1 (negative PC1 & PC2 score values) in the respective score plot (Fig. 3B). A clear discrimination between most of the studied seed accessions was achieved using this PCA model and opposite from that previously observed in GC/MS-derived PCA (Farag, Elsebai, & Khattab, 2018; Farag, Khattab, et al., 2018), suggestive that here the captured metabolome reflects more accessions relationships.

PCA loading plot (Fig. 3C) revealed that MS signals assigned for flavonoid glycosides, *i.e.* apigenin-*C*-dihexosyl-*O*-pentosyl-hexouronide (peak 25), unidentified flavonoid glycoside $C_{24}H_{33}O_{14}^-$ (peak 38) and terpenoid glycoside, *i.e.* dihydrophaseic acid hexoside (peak 19) that contributed mostly negatively to PC1, and were found more abundant in both *Lens* seeds characterized by a dark testa. Hence, these metabolites can be regarded as discriminatory markers for both *Lens* seeds with dark testa from the other two closely related cultivars of *Lens culinaris, i.e. L. culinaris* subsp. *culinaris* “Petite Rouge d'Egypte” (LCO) and L. *culinaris* subsp. *culinaris* yellow colored seed (LCY)”. Based on these findings along with those extrapolated from our previous GC/MS metabolomics study (Farag et al., 2018), which highlighted these two dark-colored lentil cultivars as the peptide- and “α-amyrin” triterpene-richest accessions and lacking any alkaloids. They can now be emphasized, among the eight seed accessions studied, as being richest source of functional foods with presumed high antioxidant, anti-inflammatory and antidiabetic effects. However, these therapeutic assumptions need to be further validated by clinical studies.

For *Lupinus* seed accessions which were distantly allocated from other *Lens* specimens in the right side of the score plot (Fig. 3B), MS signals corresponding to flavanone glycosides, *i.e.* naringenin-*O*-dihexosyl-rhamnosyl-pentoside and naringenin-*O*-hexosyl-rhamnosyl-pentoside (peaks 9 & 10), and an unknown saponin (peak 83) accounted for their distinctiveness.

In comparison to GC–MS based analysis of same seed specimens pointing out to melibiose sugar as the most discriminatory primary metabolite among examined accessions (Farag et al., 2018), UPLC-MS based PCA model has provided more insight on secondary metabolome variability which is more likely to account for seeds health beneficial effects, *i.e.* saponins and flavonoid content. However, both techniques failed to discriminate between two of the closely related cultivars of *Lens culinaris*, and implied that phylogenetic analyses might provide a more appropriate tool for their systematic classification (Gupta et al., 2012).

3.2.2. Supervised OPLS-DA analysis

A classification model (Fig. 4) was further built using OPLS-DA by modelling *Lupinus* seed accessions in one class against *Lens* in order to identify unique taxonomic markers for each genus. The performance of the developed model was validated by the computed parameters “R^2 (0.9856)” and “Q^2 (0.9577)”, indicating its covered variance and good prediction power, respectively. The observed segregation in the derived S-score plot (Fig. 4A) was ascribed to glycoside peaks, *i.e.* naringenin-*O*-hexosyl-rhamnosyl-pentoside (peak 10) and an unknown saponin (peak 82) enriched in *Lens versus* the abundance of apigenin-*C*-dihexosyl-*O*-pentosyl-hexouronide (peak 25) and dihydrophaseic acid hexoside (peak 19) in *Lupinus* species (Fig. 4B). Apigenin-*C*-dihexosyl-*O*-pentosyl-hexouronide is solely found in *Lupinus* seed accessions and thus can be considered as potential chemotaxonomic marker for the studied *Lupinus* seed accessions compared to closely allied taxa. Another potential marker revealed from GC–MS based OPLS-DA model is lupinine alkaloid found exclusively in *Lupinus* genus (Farag et al., 2018).

In general, it appeared that *Lens* accessions accumulated more flavanone conjugates *viz.,* naringenin *versus* enrichment of flavones *viz.,* apigenin flavonoids in *Lupinus*, suggesting differential activation of each flavonoid subclass in different Fabaceae genera.

To further identify interspecific variation within individual *Lupinus* genotype accessions, another UPLC–MS based PCA model was performed by modelling the four *Lupinus* seed accessions separately (Fig. S1). On the far right side of the score plot (Fig.S1-A), *L. hispanicus* specimens were allocated most distantly from the other three *Lupinus* species, being positioned to the left side of the plot (negative PC1 scores). MS signals assigned for hydroxylated fatty acids, *viz.* dihydroxyoctadecadienoic acid (peak 71), dihydroxyoctadecenoic acid (peak 74), hydroxyoctadecadienoic acid (peak 85) and octadecatrienoic acid (linolenic) (peak 87) as revealed from PCA loading plot (Fig.S1-B), contributed the most to separate *L. hispanicus* from the other three *Lupinus* species as being most enriched with these hydroxylated fatty acids. However, this clear metabolomic separation is not reflecting phylogenetic relationships among the studied *Lupinus* species (*cf.* Drummond et al., 2012; Kass & Wink, 1997), because *L. polyphyllus* as the only New World species under study might have been expected to be more distinct. Nevertheless, *L. hispanicus* was also recommended to be prioritized for future breeding, in our previous GC–MS metabolomics study of the same accessions (Farag et al., 2018), due to its enriched phytochemical profile with organic and amino acids, inorganic phosphates and anti-inflammatory nitrogenous compounds *viz.* indole-3-acetamide. Hence, it was corroborated that L. *hispanicus* can be regarded as being the most nutritive seed accession among the four examined seed accessions.

This is the first report for *Lupinus* species classification using supervised pattern recognition analysis of LC-MS data. Previous chemotaxonomic study by Coïsson et al. (2011) employed merely alkaloids as targeted metabolites in two *Lupinus* species, *i.e. L. albus* and *L. angustifolius* (Coïsson et al., 2011). Our study, not only encompass more genotypes but as well a more comprehensive untargeted metabolite profiling approach and through which several unique chemotaxonomic markers were unexpectedly revealed *viz.,* hydroxylated fatty acids for *L. hispanicus*.

Concurrent with our GC–MS-derived model (Farag et al., 2018), UPLC-MS also failed to clearly differentiate the New World lupin species *L. polyphyllus* from the other three closely related Old World members of the *Lupinus* genus arising the hypothesis that the metabolic differences inferred from geographical distribution are rather obscured due to the recent domestication and/or cultivation practices.

4. Conclusion

With an increasing interest in functional foods and/or nutraceuticals analysis associated with better health status in humans, untargeted techniques for food metabolomics studies now follow for its characterization and standardization. An untargeted approach based on UPLC–PDA/ESI–qTOF-MS coupled to chemometric tools was employed herein for the first time to reveal for metabolites heterogeneity within *Lupinus* and a set of cultivars of *Lens culinaris*.

The adopted UPLC-MS methodology allowed for the detection of 94 bioactive metabolites mostly belonging to flavonoids, alkaloids, saponins, organic, phenolic and fatty acids in addition to sphingolipids. Species-specific biomarkers were also revealed as being saponin and flavone glycosides for *Lens* seed accessions. Whereas flavanone glycosides were found as being more abundant in *Lupinus* seeds. The compositional differences in the secondary metabolome of the closely related *Lens culinaris* cultivars were discerned except for the two seeds with dark colored testa. Hence, a more conclusive metabolome characterization of the intraspecific diversity in *Lens culinaris* should be considered by including a wide variety of representatives of *Lens*

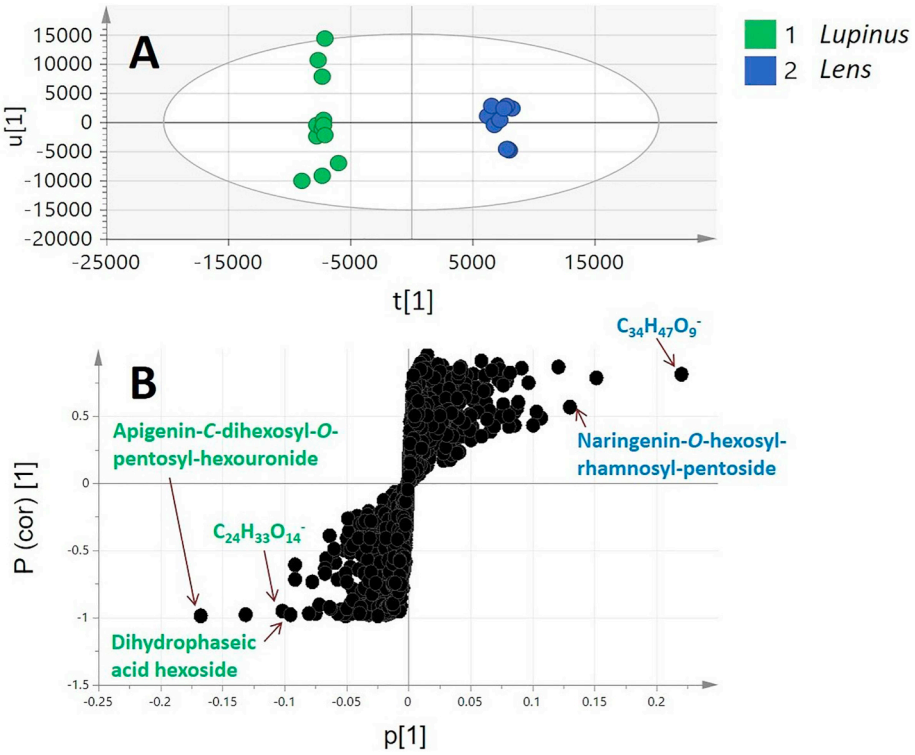


Fig. 4. UPLC/MS based OPLS-DA score plot derived from modelling *Lupins* seeds against *Lens* seeds (A). The S-plot (B) shows the covariance p[1] against the correlation p(cor)[1] of the variables of the discriminating component of the OPLS-DA model. Cut-off values of $P < .05$ were used; selected variables are highlighted in the S-plot and identifications are discussed in text.

culinaris subspecies and cultivars.

Further, within *Lupinus* species discrimination was successfully revealed for richness of *L. hispanicus* in hydroxylated fatty acids which poses this species as a promising source for these phytochemicals. Despite covering only a small population of *Lupinus* and *Lens* seeds, the adopted methodology can provide a rapid and efficient tool for analyzing further samples to disclose the impact of different industrial processing methods *viz.* thermal or sprouting and/or storage conditions on seeds metabolite composition. The current study, enlightened by our previous GC/MS-based primary metabolomics analysis of the same seed accessions, was able to prioritize two *Lens* taxa, *i.e. L. culinaris* subsp. *culinaris* 'verte du Puy' (brown colored seed) and *L. culinaris* subsp. *culinaris* 'Black Beluga', for future breeding as being the richest accessions with phytochemicals having promising therapeutic effects. Regarding the most nutritive seed accessions, it was concluded to be that of *Lupinus hispanicus* based on its enriched phytochemical make up with many nutrients *viz.* organic, amino and hydroxylated fatty acids in addition to nitrogenous compounds and inorganic phosphates.

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Conflict of interest

Authors declare no actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2018.11.003.

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