Prehistoric Fermentation, Delayed-Return Economies, and the Adoption of Pottery Technology

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Pottery production, like fermentation, is a highly skilled technology that requires the careful selection and transformation of raw ingredients under controlled conditions. Although the precise drivers for the invention and dispersal of ceramic containers are uncertain, it is clear that even the earliest pottery had a culinary role for processing foods. We now know from organic residue analysis that early pottery was used to process only a relatively limited range of the foodstuffs available, with biases, for example, toward fish among some hunter-gatherers or dairy products by early farmers. One reason for such selection might have been that pottery is well suited for the transformation of perishable fresh produce, such as milk and fish, to long(er)-life products that could be stored, exchanged, or accumulated. Such fermented products would be particularly useful for maximizing the return from seasonally abundant foods, thereby facilitating sedentism and greater investment in pottery production. Notwithstanding the fact that direct chemical evidence for fermentation is difficult to obtain, here it is proposed that the early uses of pottery and fermentation and the accumulation of storable surpluses are interrelated technologies that emerged in early sedentary or semi-sedentary societies during the final Pleistocene and start of the Holocene.

Physiological adaptations observed in humans and some other primates make it likely that the consumption of ethanol and lacto-fermented foods gained dietary significance by a common ancestor living some 10 million years ago (Amato et al. 2021; Carrigan et al. 2015; Peters et al. 2019). Beyond that, virtually nothing is known about the prehistory of fermentation or how practices developed. Most sources of evidence proposed for intentional fermentation are, at best, indirect. Organic residue analysis of artifacts associated with the purposeful production of fermented foods and beverages may offer our clearest hope for directly identifying this practice in the past. The identification of dairy fats or fruit-derived organic acids on prehistoric artifacts may suggest that milk and grape juice were fermented to storable and often more valuable commodities, but even these are not conclusive. In the absence of such evidence, we may still infer that fermentation was inevitably encountered, if not perfected, in prehistory, or even that the practice was widespread, considering the advantages that it brought for removing toxins, improving food digestibility—particularly of starchy foods—and for dealing with surpluses following harvests of cereals or seasonal fruits. Such arguments are often made to lay the origins of fermentation squarely at the door of early farming communities (e.g., Kuijt 2009). However, if we are to follow this line of argument, then the history of intentional fermentation must have even greater antiquity, as surpluses were also produced, and therefore had to be dealt with, by hunter-gatherers long before farming.

One aspect of material culture that appears closely associated with both surplus-producing agriculturalists and hunter-gatherers is pottery. Ceramic technology is often seen as a culinary innovation, where foodstuffs could be easily boiled or steamed to render them more palatable or combined to create new tastes (Arnold 1988).[1] Similarly, pottery is well suited for fermentation, either as a container to initially boil foods and beverages prior to fermentation or as the fermentation vessel itself. Porous ceramic vessels might retain the microorganisms needed for fermentation to proceed and would be essential for controlling and manipulating liquid ferments. While grain could be transformed to bread with grinding technologies before pottery, beer would require a container (Fuller and Rowlands 2011). Most histories and ethnographies of dairying also commence with boiling raw milk prior to fermentation into low-lactose products. For hunter-gatherers, fermentation of fish, wild starchy tubers, and berries could easily be envisaged. These also have direct historic and ethnographic analogues, particularly from populations living at high latitudes (de Laguna 2011:132; Heizer 1956:30). Many of these resources would have arrived in seasonal gluts that required scheduling in preparation for mass harvesting and storage.

This essay aims to examine the evidence in the archaeological record for the use of pottery for fermentation. More broadly, it

1. Various other "boiling" and "steaming" technologies have been proposed, and these may well have existed prior to pottery, e.g., hot rock boiling. The introduction of ceramic cooking "pots," however, probably provided a more efficient and effective way to prepare foods in this way.

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is proposed that early pottery production, fermentation, and the accumulation of storable surpluses are interrelated technologies that allowed prehistoric populations to thrive by buffering risks and promoting sedentism. If so, this techno-culinary revolution may have had far-reaching effects on health, population densities, and social inequality long before farming.

A Potted History

Pottery is a technology fundamental to the manipulation and processing of natural products. Ceramic vessels came to be produced by most societies around the world and were superseded only relatively recently by metal and plastic containers. The earliest evidence for pottery production dates to the Late Pleistocene of southern China as early as 20,000 years ago (Wu et al. 2012). Other Late Pleistocene pots are recorded in other parts of China (Boaretto et al. 2009), the Russian Far East, and also Japan (Keally, Taniguchi, and Kuzmin 2003). In all cases, the environmental context for the emergence of pottery was during near-glacial conditions. Late Pleistocene pottery production is best studied in Japan, where so-called Incipient Jomon pots (ca. 16,000 to 11,000 BP) were produced by disparate groups of mobile hunter-gatherers. Produced in low numbers and with relatively small volumes, the earliest pottery vessels were unlikely to have had an economic or utilitarian role. Often described as an experimental phase of production (Kaner 2009), pottery at this time may have had a greater social and symbolic value reserved for special ceremonial events, perhaps involving feasting (Craig et al. 2013; Hayden 1995).

It is not until the very final phases of the Pleistocene period and the early Holocene (ca. 11,000 BP) when pottery begins to flourish (Taniguchi 2011; Wang and Sebillaud 2019). This boom in production corresponds to the establishment of warmer temperate boreal conditions in Northern Eurasia and new opportunities for the exploitation of forest products, such as deer and nut-bearing trees, although the extent of production was likely to be dependent on local environmental conditions (Morisaki 2020). With increased production during the early Holocene, pottery most likely became a "practical" technology incorporated in everyday culinary practices (Jordan and Zvelebil 2009:73). At this point, it has been suggested that pottery dispersed westward into central Asia and then, more tentatively, to the forest-steppe of Eastern Europe by around 8000 BP (Gibbs and Jordan 2013; Jordan et al. 2016). From there, pottery was most likely acquired by hunter-gatherers of the eastern Baltic and southern Scandinavia in the following millennium.

Also during the early Holocene, pottery appears in North Africa among semipermanent foragers as a separate innovation, at sites spanning sub-Saharan Africa to the Nile Valley, perhaps associated with the reestablishment of tropical grasslands (Garcea 2006; Huysecom et al. 2015). Some of the earliest pottery in East Africa is found in lakeshore settings with intensive fishing and shellfish gathering by semi-sedentary groups (Ashley and Grillo 2015). From an origin in Africa, it is argued that pottery spread along a Mediterranean corridor to the Near East, whereby at ca. 9000 cal BP it was widely produced by sedentary early farming communities of the Levant (Gibbs 2015; Jordan et al. 2016) and subsequently northward and westward to Europe, with agriculture and pastoralism, as part of the so-called Neolithic package. The independent innovation of pottery by hunter-gatherers living in other boreal/aquatic productive ecotones are also well known, including in Northeastern America at ca. 3000 BP (Taché and Hart 2017) and the Amazon Basin at ca. 8000 BP (Roosevelt et al. 1991).

Although the origin and dispersal of pottery is relatively well documented as an easily recognizable phenomenon appearing in archaeological strata, the motivations that led to its invention and widespread dispersal are far less clear. There is no single explanation for the emergence of pottery globally, yet some broad bounds regarding the social and environmental contexts for it can be proposed. First, in Eurasia and Africa, there is a step change in pottery production at the start of the Holocene corresponding to climate amelioration and, in many cases, reduced sedentism. Second, globally, hunter-gatherer pottery often emerges in highly productive ecological niches, such as boreal/aquatic ecotones and coastlines and environments conducive to the development of affluent, surplus producing and socially complex groups, again with reduced mobility. Third, in Central, Southern, and Western Europe, pottery also appears with the earliest evidence for farming also linked to surplus production and sedentism.

Within this general scheme, it is important to point out that pottery did not inevitably rise from all surplus-producing Late Pleistocene and Holocene societies; indeed many never produced pottery, including those who undoubtedly encountered it (Elliott et al. 2020). Nor is it likely that increased sedentism was a prerequisite for pottery production. Although pots may have been too cumbersome to have been of use to many highly mobile hunter-gatherers (Arnold 1988), there is evidence that some mobile groups used pottery at stations strategically located in the landscape (Eerkens 2003), and the transportation of even large vessels, particularly by boat or sleigh, cannot be ruled out. Rather, it is proposed that pottery emerged in societies that created surplus and practiced storage as a risk-buffering mechanism, and it is these practices that facilitated increased sedentism (Hayden 2018; Jordan and Zvelebil 2009; Rowley-Conwy and Zvelebil 1989).

The precise role of pottery proposed in these theoretical models is more difficult to ascertain. Pottery may have been practically implicated in resource specialization, food processing, and storage, including fermentation. Alternatively, or even additionally, it may have had a noneconomic role, for example, as a prestige technology used to denote power or success by political aggrandizers that also characterize surplus-producing societies (Hayden 1995, 1998). Evidence of pottery use through chemical and molecular analysis offers an approach to directly address these questions and has been widely applied to both agricultural and Holocene hunter-gatherers from Europe and Northern Asia. Based on the results of such analysis, here I examine the case for fermentation as a possible driver for the uptake of pottery by Holocene food-producing and hunter-gathering societies.

Northern Hunter-Gatherers, Fermented Fish, and Pottery

Drying and fermenting aquatic foods has a long tradition in East Asian, Northern European, and Inuit societies (Stopp 2002) producing such delicacies as Alaskan fermented seal flipper, fermented herring (Surströmming), and dried bonito (Katsuobushi), an important ingredient in Japanese cuisine. Many of these food preservation techniques do not require pottery and may have been an adaptive strategy that predates sedentism (Stopp 2002). Indeed, Speth argues that putrefied meat and fish were likely to have been an important component of Northern Eurasian hunter-gatherer diets since the Middle Paleolithic, allowing long-term storage, enhancing nutritional content, and serving as an alternative to cooking for predigesting proteins and fats (Speth 2017). While those uses seem entirely plausible, the evidence is less forthcoming. Recent amino acid analysis shows that high nitrogen stable isotope values ($\delta^{15}N$) measured in Neanderthals are explained by the consumption of high trophic level foods (Jaouen et al. 2019) rather than consumption of putrefied foods, as suggested by Speth.[2] Other paleolithic evidence for the subaquatic deposition of animal carcasses (Speth 2017) and storage of bone marrow (Blasco et al. 2019) may both indicate delayed consumption, but neither unequivocally points to fermentation.

The most conclusive and earliest evidence for prehistoric fermentation is of fish from an Early Mesolithic "gutter" pit feature in southern Scandinavia that was packed with cyprinid bones (Boethius 2016). Although this example dates several thousand years before hunter-gatherers began producing pottery in this region, it is argued that such Holocene semi-sedentary hunter-fisher-gatherers may have had a greater need for storage and food preservation due to the amount of surplus they generated (Boethius 2016). Similar fish fermentation pits have also been proposed in East Asia (Nakajima et al. 2012), also linked to highly productive fisheries, and there are numerous cases of pits, often clay lined, being used for such purposes, particular by high-latitude hunter-gatherers (Heizer 1956; Birket-Smith and de Laguna 1938). Compared to pits, skins, and intestinal containers, pottery offered an alternative technological approach for dealing with such an aquatic surplus. As discussed below, ceramic vessels may be more efficient at controlling fermentation, which is likely to be important in more temperate climates. With the advent of new research on the chemical analysis of early hunter-gatherer pottery, it is worth examining the evidence for its use in more detail.

The Japanese archipelago has the longest, richest, and most intensely studied hunter-gatherer ceramic sequence anywhere in the world. Jomon (cord-marked) pottery extends from the late Pleistocene (Incipient Jomon) through the early Holocene (Initial and Early Jomon) until the arrival of agriculture (rice and millet) around 3000 BP. Analysis of over 800 samples from Late Pleistocene and early Holocene in Japan contexts has shown that the vast majority of vessels during this period were used for processing fish (Craig et al. 2013; Lucquin et al. 2018) regardless of the environmental or geographical setting. This study used a range of complementary approaches, but notably the thermal transformation products (ω-(o-alkylphenyl) alkanoic acids) of polyunsaturated fatty acids present in aquatic oils were readily identified in many cases. The presence of these compounds also shows that the aquatic oils were thermally processed, presumably through boiling. The resolution of the approach generally precludes the distinction of different aquatic species such as fish, shellfish, or aquatic mammals, although isotopic characterization of associated lipids can be used to distinguish freshwater, marine, and, to some degree, anadromous species such as salmon (Lucquin et al. 2018).

Extensive residue analysis has also shown that the use of Jomon pottery does not fundamentally change with climate amelioration in the Holocene, a period corresponding to increased pottery production and sedentism (Lucquin et al. 2016, 2018). Second, although wild game, chestnuts, and acorns were certainly exploited by Jomon Holocene hunter-gatherers, they do not seem to have used pottery for processing these foods. Rather it is suggested that from the Holocene, pottery assumes a greater utilitarian function and was used to process a wider spectrum of aquatic foods, including shellfish, freshwater fish, and a greater range of marine species (Lucquin et al. 2018). Fishing may have intensified at this time corresponding to the appearance of shell middens along Japan's coastlines and lakeshores (Habu et al. 2011). Here I argue that pottery was produced in large quantities in anticipation of this seasonal resource creating aggregations of hunter-gatherers in semipermanent settlements at these productive aquatic ecotones.

A similar argument is made following the identification of aquatic oils as the main identifiable residue on pottery used by other boreal hunter-gatherers in North America (Taché and Craig 2015), Kodiak Island (Admiraal et al. 2020), Sakhalin (Gibbs et al. 2017), the Korean peninsula, and the eastern Baltic (Oras et al. 2017). This close association between early pottery and aquatic resource exploitation is argued to constitute a trajectory analogous to the "agricultural" Neolithic (Gibbs 2015). As with the agricultural Neolithic, the "aquatic Neolithic" sees pottery production developing in the wake of affluent, sedentary societies with delayed-return economies that are conducive to the production of surpluses, albeit from seas, lakes, and rivers rather than from the land.

2. Consumption of putrefied foods would be expected to lead to relatively enriched $\delta^{15}N$ lysine values in collagen. Lysine is the main precursor to putrescine and cadaverine formed during putrefaction, which would be expected to be depleted in ^{15}N, thus enriching the remaining dietary lysine that is directly incorporated in collagen. Although $\delta^{15}N$ lysine values are not reported in Neanderthal collagen, this hypothesis is inconsistent with the observed ^{15}N-enriched glutamic acid values that are explained through consumption of high trophic level foods.

Although the use of pottery is often directly implicated in the aquatic economy, its precise role is less clear. The antiquity of fishing demonstrably predates pottery in almost all cases. The "aquatic Neolithic" hypothesis therefore requires pottery to have driven (or developed in response to) a step change in fishing intensity augmented perhaps by other technologies for the mass capture, such as nets, traps, or weirs. Admittedly, the evidence for such artifacts is less forthcoming, and in certain cases, as with the Scandinavian fermentation pits, such technologies may have existed before pottery (Bērziņš 2010). It is therefore arguable whether knowledge of ceramic production predated its need; the reasons for ceramic adoption may be more complex, linked in part due to dispersal dynamics, the presence of competing technologies, and demographic considerations. Notably, many surplus-producing hunter-gatherers living along resource-rich aquatic ecotones never produced pottery, such as Mesolithic foragers of the Atlantic facade in Western Europe (Elliott et al. 2020) or hunter-gatherers of the Northern Pacific coast of America (Ames and Maschner 2000).

Alternatively, large-scale feasting and other consumption activities could also be reasonably proposed to link pottery with surplus production and could have little to do with an economic need to process fish. Storage and accumulation of aquatic resources offers an alternative albeit related hypothesis, and pottery would seem well suited for this purpose. Wide-mouthed pottery vessels, which commonly characterize most early pottery assemblages, could have been easily covered with a lid made from wood or another perishable material when required. In classical antiquity, ceramic vessels were used to ferment fish to produce small batches of garum or salsamenta for consumption (Curtis 1991), and pottery in Southeast Asia is still used for this purpose (Yankowski, Kerdsap, and Chang 2015). These ferments invariably used salt, but in prehistory, pottery may have been particularly advantageous for controlling the fermentation and avoiding the buildup of harmful microorganisms in the absence of salt, for example, by sterilizing the ferment prior to inoculation, regulating the temperature, and arresting fermentation.

Storage and fermentation as opposed to cooking is hard to reveal directly in archaeological pottery using organic residue analysis, especially if the commodities are heated as part of the process. Indirect evidence may be gained by considering either the time elapsed or the distances traveled between the procurement of food products and their consumption. For example, an investigation of the pottery from the Yukura cave, an Incipient and Initial Jomon site in Kanto Province, Japan, shows that at least half the potsherds were clearly used for processing aquatic products, most likely salmonids (Lucquin et al. 2018). While this is not surprising in the context of Jomon pottery use, the site is located at over 1,500 m a.s.l. and some distance (15 km) from the nearest salmon river, implying that the fish had been preserved and transported to this remote site.

Aquatic products can be processed into a storable commodity in many ways, including fermentation, through drying, or by rendering fatty tissues to purify oils that can be consumed or used as lubricants or illuminants. The practice of grease production from fish oils is well documented ethnographically (Kuhnlein and Chan 1998) and is still a highly valued commodity for precisely these purposes. Residue analyses of Mesolithic Ertebolle "lamps" of southern Scandinavia (Heron et al. 2013) and stone bowls from the Arctic have shown they were used for burning and rendering aquatic oils (Admiraal et al. 2018), and therefore that prehistoric hunter-gatherers also possessed this technology. Oil production is, however, less likely for the majority of Jomon pots as well as many other hunter-gatherer "cooking pots" so far analyzed (Courel et al. 2020). Compared to the Ertebolle lamps or Arctic stone bowls, carbonized deposits adhered to the surface of cooking vessels contain a much greater relative proportion of nitrogen (Lucquin et al. 2018), suggesting that they were used instead for processing products relatively high in protein. The pots from Yukura cave were therefore most likely used for cooking preserved fish that was brought to the site either dried or fermented.

Fermentation, Dairying, and the Agricultural Neolithic

The origins of food production can be traced back to several centers of domestication around the world, each related to major cereal crops such as rice, wheat, maize, and millet. The timing for the domestication of each of these crops is variable, but in each case they only became a major staple from the Holocene. In Southwestern Asia cereal agriculture was already widespread several thousand years before the advent of pottery (Gibbs 2015) and capable of supporting large sedentary communities (Bar-Yosef 2012) with storage technologies. It has been suggested that beer production began in these Natufian and Pre-Pottery Neolithic A cultures at the very end of the Pleistocene (12,500–11,500 cal BP) as commodity for elaborate feasting, marking increasing social complexity at this time (Hayden, Canuel, and Shanse 2012). In this scenario, fermentation was achieved, without pottery, in large stone mortars that have traditionally been interpreted for bread making. Similar arguments have been made for the fermentation of sorghum in early pottery in the central Nile Valley from ca. 6000 cal BP (Haaland 2007). As will be discussed below, direct evidence for fermented cereal products is extremely difficult to demonstrate, and while early beer is conceivable in all early or proto-agricultural societies, these theories remain speculative.

A clearer case can be made for the fermentation of milk by early African and Western Eurasian pastoralists. First, without fermentation, raw milk would spoil quickly and would have been of limited nutritional value. Second, it is unlikely that a substantial portion of the population were able to digest the sugars (lactose) in raw milk until at least the Bronze Age in Europe, as they lacked the genetic adaptation responsible for the production of lactase as adults (Burger et al. 2020). Lactose can be greatly reduced in milk products through a range of processing methods, many of which involve fermentation, for example, production of yoghurts and cheeses. In other regions, such as central Asia, sophisticated prehistoric dairy economies were practiced by non-lactase-producing populations (Jeong et al. 2018).

It is reasonable to conclude, therefore, that when we observe evidence for dairy exploitation in prehistoric populations, long before adult lactase persistence, they possessed the technology to ferment. European ceramic sieves dating to the LBK (*Linearbandkeramik*) period (ca. 7000–6500 BP), seemingly well suited for separating fermented milk products, have been shown to contain milk lipids (Salque et al. 2013). These artifacts provide the clearest direct evidence of prehistoric fermentation in agricultural societies to date. Earlier pottery vessels from Southeast Asia, southwestern Europe, and North Africa also are implicated in dairying and were most likely used for heating raw milk in preparation for fermentation dairy products directly (Dunne et al. 2012; Evershed et al. 2008). It is clear from these studies that dairy products were exploited, albeit not systematically, as soon as domesticated ruminants (and pottery) were available. In the United Kingdom and Ireland, early Neolithic pottery seems to have been used almost exclusively for this purpose (Cramp et al. 2014), and dairy was a major commodity identified in early farmer pottery from southern Scandinavia (Craig et al. 2011; Cubas et al. 2020).

The significance of fermented dairy foods to early farming societies is less clear. The economic advantage of dairying over meat production is often emphasized and has even been suggested as a driver for ruminant animal domestication itself (Roffet-Salque et al. 2018). Dairy products or indeed the possession of herds of milk-bearing animals might well serve as an important surplus that could be accumulated and exchanged, or in the case of hard fermented cheese, consumed when other resources were scarcer, thus buffering risks. As food production spread to new regions, the initial role of such new foods and the motivations for their adoption has also been questioned. In Northern Europe, cereal-based products might have initially held greater significance as a prestige food (Fischer 2002) rather than as an economic staple. Similarly, it is dangerous to assume that dairying was a technology that could be simply adapted to different environments by migrating farmers or adopted by indigenous populations with little prior knowledge. The fermentation process requires specific biotechnological knowledge (Sibbesson 2019) in order to turn what was to them a toxic product into an edible one. It has been suggested that it was the transformation process itself and the symbolic meaning it represents that made dairy such an alluring product to early farmers (Saul, Glykou, and Craig 2014). Analysis of vessel types used to cook or prepare dairy products as opposed to other foods, and the context of their deposition offers an approach to understand the "value" that these products may have held in prehistory (Craig et al. 2015; Saul, Glykou, and Craig 2014).

Direct Evidence for Prehistoric Fermented Beverages

The chemical identification of fermented alcoholic beverages is one of the most controversial areas of biomolecular archaeology, and few claims are accepted without challenge. Early beer production is tentatively proposed from Pre-Pottery Neolithic B phases at Göbekli Tepe in southeastern Anatolia through chemical analysis of large limestone basins (Dietrich et al. 2012) and at Raqefet Cave, Israel, where Natufian stone mortars were found to be associated with cereal remains, both cases predating pottery (Liu et al. 2018). Claims have also been made for beer at Godin Tepe (ca. 5500 BP) in the Zagros Mountains of western Iran (Michel, McGovern, and Badler 2008) through chemical analysis of large earthenware jars.

Even though, as noted above, there is no reason to dispute these claims on theoretical or contextual grounds, the chemical analysis is lacking. These claims invariably rely on the detection of calcium oxalate (a major component of "beerstone") using a chemical spot test (Feigl 1956), which would seem wholly inappropriate considering that the test itself is not specific to the target analyte and that the oxalates may occur in many substances other than beerstone. A more reasonable claim is made for the identification of beer in Northern China (ca. 5000 BP; Wang et al. 2016). Here ion chromatography is used to more reliably identify oxalate, and although in no way specific for beerstone, the ceramic artifacts seem to be manufactured for specific liquid manipulation, and the inference is supported by macrobotanical remains of cereals. Other approaches have tried to match suites of compounds in ancient vessels with those in modern beers (Farag et al. 2019; Perruchini et al. 2018), but these generally fail to consider the many other sources for these compounds or the effects of molecular diagenesis. Few studies have attempted to link newly established biomarkers for cereals, such as alkylresorcinols for wheat and barley (Hammann and Cramp 2018) or millicin for broomcorn millet (Heron et al. 2016), to beer production.

The fermentation of seasonally available wild or domesticated fruits offers another obvious method for dealing with surpluses that would otherwise quickly spoil. The sugars in fruits are easily fermented through the action of aerobic yeasts (*Saccharomyces* spp.) that live on these plants. Evidence for harvesting and controlling the fermentation to make wine has also been linked with pottery. The earliest proposed dates for wine production (ca. 8000–7800 BP) derive from residue analysis of Early Neolithic potsherds from Georgia (McGovern et al. 2017). The identification of wine is achieved principally through the identification of tartaric acid which is at high concentration (1–5 g/L) in grape juice, although a whole range of other approaches have also been proposed, the majority of which lack specificity (Drieu et al. 2020). It should also be noted that tartaric acid (i) is also found in other fruits at high concentration, (ii) is present in many other organic substances at lower concentration including soils and sediments, and (iii) does not indicate fermentation (Drieu et al. 2020).

Considering these caveats, the earliest evidence of wine production seems best supported for the Late Neolithic of Northern Greece (Garnier and Valamoti 2016), where the chemical evidence is supported by archeobotanical remains of crushed grape pips. For earlier claims (McGovern et al. 1996, 2004, 2017) where the archeobotanical evidence is less forthcoming, the chemical evidence needs to be treated more critically. For example, tartaric acid has been identified in hunter-gatherer pottery from the site of Zamostje 2 in the Upper Volga region of Russia (Drieu et al. 2020), far from the nearest suitable land for grape production, showing the potential for false positive identification. In this case, the molecule is most likely derived from processing of *Viburnum* berries that were visibly charred to the ceramic surface. The appearance of large-scale pottery production in the Zamostje 2 sequence at ca. 7500 cal BP is intriguing in itself. Excavation of the earlier aceramic "Mesolithic" layers shows that the site's inhabitants were already adept at fishing and possessed mass capture technologies such as weirs and nets (Bondetti et al. 2020). Here, the earliest pottery vessels that contained residues of fish and fruits (Bondetti et al. 2020) may have been to help deal with surpluses generated at such a productive setting, rather than in response to intensification or economic change.

Sorting the Rotten from the Raw and the Cooked: Is There Biomolecular Evidence for Fermentation?

As the process of fermentation mirrors the initial stages of early diagenesis of organic matter, that is, degradation through the action of microorganisms, it is very difficult to distinguish chemically. For this reason, most of the evidence outlined above relies on identification of the raw food (milk, fruit juices, fish oils) rather than the fermented product or the fermentation agent itself. So, what are the prospects for identifying the smoking gun that would reveal conclusive chemical evidence of prehistoric fermentation?

Several approaches have been proposed. Organic acids (succinic, fumaric, pyruvic, citramalic, and lactic acids) produced during the fermentation of wine (Ribéreau-Gayon et al. 2006) are frequently identified in prehistoric vessels. But as these are also present in a wide range of other organic products, unless found in association with tartaric acid they offer little diagnostic resolution. Ergosterol, a sterol specific to fungi, has been proposed as a marker of yeast used to ferment cereals in Bronze Age/Early Iron Age vessels from eastern Sweden (Isaksson, Karlsson, and Eriksson 2010). Although ergosterol is widely present in soils and sediments, these authors consider this source less likely, noting that the compound was absent on earlier hunter-gatherer pottery from the region and that lipids are generally immobile in the burial environment.

More recently, bacteriohopanes have been identified in pottery from the Early Iron Age hill fort of Vix-Mont Lassois in eastern France (Rageot et al. 2019). These compounds are derived from hopanoids, present in a wide range of bacteria, including alcohol fermentation species such as *Zymomonas mobilis*. Similar hopane distributions have also been proposed to indicate fermentation of agave, following their identification in pottery with distinctive typologies from Teotihuacan in Mexico (Correa-Ascencio et al. 2014).

At Vix, the bacterial hopanoid proxies also seem to be more commonly associated with fine wares containing millet, plant waxes, and beeswax, suggesting these vessels held beer or mead and were used for elite feasting. Nevertheless, doubts still remain regarding the origin of these compounds, and while it seems entirely reasonable that alcohol consumption was practiced in later prehistoric highly stratified societies, the residue data remains equivocal. Both fungi and bacteria are key to the early diagenesis of organic matter and could be envisaged quickly engulfing discarded pottery vessels, leaving chemical signatures similar to those expected from fermentation. More detailed metagenomic and metaproteomic approaches may be useful for distinguishing specific "heirloom" microbes (Warinner, Speller, and Collins 2015) intentionally added as fermenting agents, from those invading the vessels following use, but such research is still in its infancy. Here and in other cases independent lines of contextual evidence, including vessel forms, the context of depositional environment, and the presence of other food/drink derived molecules will be needed in order to help infer fermentation.

Conclusions

Documenting the antiquity of fermentation is extremely challenging, but as Sibbesson points out, humans did not invent fermentation; they merely learned to use it to their advantage in varying degrees probably from early prehistory (Sibbesson 2019). Therefore, the challenge is to understand the larger shifts in the production of fermented products within a broader socioeconomic and technological context. I suggest that one of these began with surplus producing, so-called affluent hunter-gatherers, and is associated with the development and dispersal of pottery technology during the early Holocene. As discussed, there is convincing evidence for fermentation of fish in pits before pottery, for example, in southern Scandinavia (Boethius 2016). Whether this marks a significant economic practice at this time is difficult to discern, and more work is needed to identify and date similar features. Indeed, small caches that hunter-gatherers returned to seasonally most likely had a much longer antiquity than such specialized installations and do not imply sedentism nor any of the changes in social structure that are often associated with delayed-return economies (Ingold 1983; Testart 1982). In southern Scandinavia, as in other areas of the Baltic and central Russia, intensified fishing during the Holocene promoted sedentism, creating conditions for the acquisition of pottery from other hunter-gatherers or adjacent farmers once the technology was available. As with other Holocene Eurasian and North American hunter-gatherers, they invested time and labor in large-scale pottery production in anticipation of these resources that were then processed and presumably stored for consumption or exchange. Fermentation could easily be envisaged to be an important part of this technological complex, but whether pottery was directly involved remains to be demonstrated.

Almost identical arguments have been made, albeit far less controversially, for the manufacture of stone vats and pottery for dealing with grain surpluses in earliest agricultural societies, leading to what is commonly perceived to be the most fundamental social change in our history. Early pastoralists engaged in delayed-return economies through storage "on the hoof" and by creating fermented dairy products that could be stored or exchanged; pottery was almost certainly directly implicated in this process. A final thought is that delayed-return, surplus-producing economies also meant that communities were no longer living at the ecological limits and therefore had greater capacity to make decisions on what, when, and how to eat. In these societies, fermentation and pottery as well as other novel culinary technologies allowed foodstuffs to be transformed and combined to create a myriad of new edibles and cuisines. What value these new foods and "dishes" held is harder to discern. Indeed, the nutritional benefits may have been less important than their perceived value as intoxicants or medicines or even for their aesthetic qualities, such as taste, or notions of cleanliness, pollution, and identity: values that food often assumes in contemporary settings (Hastorf 2016:224; Pearson 2003; Saul, Glykou, and Craig 2014). If so, these qualities may have been more important at driving the dispersal of foodstuffs and associated culinary technologies than is often credited.

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