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Abstract

Ceramic containers, intentionally deposited into wetlands, offer detailed insights into Early Neolithic culinary practices. Additionally, they are key for ascertaining the Neolithisation process in Denmark since they appear to form a typo-chronological sequence. Here, we use a combination of organic residue analysis (ORA) of pottery alongside Bayesian chronological modelling of the radiocarbon dates obtained on these vessels to explore the initial stages of votive deposition in wetlands, a practice that stretches from the Mesolithic to the onset of Christianity in Northern Europe. We consider 34 Early-Middle Neolithic (c. 3900-2350 cal BC) 'bog pots' from Denmark, of which 20 have ORA data, and 26 have been dated directly. Carbonised surface residues and absorbed lipids from powdered sherds were analysed using a combination of bulk carbon and nitrogen stable isotope analysis, gas chromatography-mass spectrometry (GC-MS) and GC-combustion-isotope ratio MS (GC-C-IRMS). The molecular and isotopic compositions of the analysed samples revealed the presence of aquatic, ruminant carcass and dairy fats as well as plant waxes with the majority containing mixtures thereof. Dairy fats were present from the onset of the Funnel Beaker culture, whilst aquatic foods, prevalent at the close of the preceding Mesolithic period, continued to be processed in pottery for the following thousand years.

Keywords: Denmark; Early Neolithic; Funnel Beaker culture; pottery; organic residue analysis; Bayesian chronological modelling; votive deposition

Introduction

The Early Neolithic Funnel Beaker Culture

One of the most important economic changes in prehistory occurred with the introduction of domesticated fauna and flora. In the geographical region encompassing Denmark, Scania in s outhern Sweden and Schleswig-Holstein and Mecklenburg-Vorpommern in n orthern Germany, this coincided with a cultural change from the Late Mesolithic Ertebølle culture (hereafter EBK, c. 5400-4000 cal BC) to the Early-Middle Neolithic Funnel Beaker culture (Trichterbecherkultur, hereafter TRB, c. 3900-2800 cal BC), which represents the TRB North Group (Fraser et al. 2018). In this region, the transition is characterised by marked differences in material culture, mortuary practices, ritual activity and structures (Andersen 2007; Fischer 2002; Johansen 2006; Koch 1998; Richards et al. 2003; Rowley-Conwy 2004; Sørensen 2014). Coincident with these changes, the Early Neolithic also witnessed a noticeable increase in the deposition of artefacts in watery locations. Ceramic vessels represent a high proportion of these bog finds in Southern Scandinavia and are particularly prevalent on the Danish island of Zealand.

In Denmark, the TRB is conventionally divided into three phases: Early Neolithic I (EN I, c. 3900-3500 cal BC), Early Neolithic II (EN II, c. 3500-3300 cal BC), and Middle Neolithic A (MN A, c. 3300-2800 cal BC). It is followed by the Middle Neolithic B (MN B, c. 2800-2350 cal BC), which is represented by the Pitted Ware and Single Grave/Battle Axe cultures (Gron and Rowley-Conwy 2017; Koch 1998; Nielsen 1993; Price and Noe-Nygaard 2009). It is recognised that, to at least some degree, migrations of farmers into the hunter-gatherer-fisher landscapes of Southern Scandinavia drove these wider changes (Fort et al. 2018; Sørensen 2017; Nielsen and Nielsen 2020). Indeed, DNA analysis of human remains from Germany and Sweden has indicated that some TRB groups have a close genetic affinity with Early and Middle Neolithic populations in Central Europe (Brandt et al. 2013; Haak et al. 2015; Lee et al. 2014; Malmström et al. 2009, 2015; Skoglund et al. 2012, 2014), whilst a recent study has shown that a Danish TRB individual lacked Anatolian farmer ancestry (Jensen et al. 2019). Based on the analysis of faunal remains from EN I settlements there is a distinction between hunting stations, with few or no remains of domesticates present, and settlement sites, where domesticates make up a larger proportion of the assemblage (Gron and Sørensen 2018; Koch 1998).

In the latter part of the EBK (c. 4500-4000 cal BC), pointed-based ceramic vessels and the so-called 'blubber lamps' appeared. At c. 3900 cal BC new vessel types (including Funnel Beakers) with thin walls and rounded or flat bottoms were introduced (Andersen 2011, 2013; Fischer 2002; Koch 1998). Through their form and manufacture many of these vessels can quite easily be distinguished from those of the preceding period. In addition, regional variability and stylistic differences appear to have become more pronounced (Koch 1998). These changes have been associated with a major shift in diet and economic practices (Fischer et al. 2007; Gebauer 1995; Richards et al. 2003; Rowley-Conwy 2004), and even demographic change (Sørensen 2017).

Although the EBK-TRB transition was traditionally seen as an abrupt typological change, recent investigations have demonstrated that a more gradual development took place; for example, a reduction in wall thickness and a subtle change in pottery construction techniques throughout the course of the latter part of the EBK (Andersen 2010, 2011; Glykou 2016, 2020). Moreover, a number of transitional pottery forms have now been identified from coastal and inland localities in Southern Scandinavia, including Bjørnsholm, Krabbesholm II, Neustadt, Ringkloster and Åkonge (Andersen 1975, 1993, 1998, 2005; Fischer 2002; Glykou 2016, 2020).

Neolithic 'Bog Pots'

The Neolithic 'bog pots' are clay vessels that were intentionally deposited in wetland areas, including inland bogs, rivers and lakes. As prehistoric pottery is often fragmented during discard, discovery and recovery, bog pots are notable for their overall high degree of intactness (Figure 1) suggesting that the vessels were complete and subject to use prior to deposition. For this reason, they have become important for defining the Danish typological-chronological ceramic sequence of the period. In total, 688 vessels recovered from 254 find spots were analysed and interpreted by Koch (1998, 58). The majority were found accidentally during peat extraction between 1940 and 1955, although many vessels were also found during marine shell extraction in current fjord systems or construction work in reclaimed fjords between the 1950s and 1960s (Becker 1948; Bennike et al. 1987; Fischer 2018; Fischer and Petersen 2018; Koch 1998, 58; Sørensen 2020).

[Figure 1 near here].

In some cases, thorough descriptions of the find spots were made whilst the vessels were *in situ*. From these field investigations as well as pollen analyses undertaken on some vessels, it would appear that the pots in question were placed in shallow open water, typically at a water depth of between 0.5 and 2.0 m (Bennike et al. 1987; Fischer and Gotfredsen 2006; Koch 1998, 62). This practice of deliberately depositing whole vessels has been interpreted as a votive offering, but relatively little is known about the resources that had been processed in the vessels prior to deposition.

The practice of votive deposition is, however, not restricted to single vessels. Complex caches consisting of numerous vessels have also been documented, and occasionally vessels have been found in association with wooden platforms and stone pavements (Koch 1998, 143-146). In addition, these ceramic caches are frequently encountered alongside other artefacts including flint and greenstone axes, blades (often from the same core), amber beads as well as human skeletons and other faunal remains (e.g. Bennike et al. 1987; Fischer 2018; Fischer and Gotfredsen 2006; Fischer and Petersen 2018; Koch 1998, 207; Schülke 2019; Sjögren et al. 2017; Sparrevohn 2009; Sørensen et al. 2020). Other interpretations regarding their depositional context have ranged from fish lures, to storage vessels being placed in cooler, refrigerating waters during the summer months to vessels being lost during dishwashing - perhaps to loosen the partially carbonised surface residues that are frequently encountered (Craig et al. 2007; Koch 1998). Though occasionally intact vessels have been found on or near settlements, such as Åkonge and Øgårde in the Store Åmose, (Fischer 2002; Fischer and Gotfredsen 2006; Koch 1998), it seems that the majority of the vessels from Zealand’s wetland landscapes were indeed votive offerings based on their often highly structured and seemingly symbolic arrangements at the time of deposition. For example, a complete vessel and spoon were found at Tømmerup Mose, complete vessels and the remains of a domestic pig (*Sus scrofa domesticus*) were discovered at Skævinge, a large lugged jar was found at Sigersdal Mose, between the remains of two young females, one of which had been strangled with a rope, whilst at Veggerslev at least seven ceramic vessels, five flint axes and a flint chisel were found in connection with a wooden platform (Bennike et al. 1987; Koch 1998, 155-157).

This practice of depositing ceramics in watery locations commenced during the EBK (Ebbesen 1980) and persisted into the Middle Neolithic B period (c. 2800-2350 cal BC), with the peak of deposition taking place between EN I and MN A I (Koch 1998, 207-208). Although the majority of bog pots are known from Denmark, notably the island of Zealand, they have also been found in Germany (Langenheim 1941), the Netherlands (Wentink 2006), Poland (Lipinska 1950) and Sweden (Karsten 1994; Stjernqvist 1981). On Zealand they have an uneven distribution and have been primarily recovered from the two large mire basins, the Lille and Store Åmose located in the north-west (Figure 2), as well as Roskilde Fjord located in the north-east (Figure 2) of the island (Koch 1998, 58). In total, at least 100 wetland areas in Denmark are known to have yielded bog pots (Koch 1998, 135). More recently, excavations undertaken at the Syltholm complex of sites on the southern Danish island of Lolland, and dating to the EBK-TRB, have revealed “concentrations of potsherds that are presumed to represent whole vessels” (Sørensen 2020, 405) as well as intact vessels and other items, including wooden artefacts, flint axes and animal remains, of an apparent symbolic nature that had been intentionally deposited into near-shore marine waters (Sørensen 2017, 2020).

[Figure 2 near here].

The TRB bog pots from Zealand are important for a number of reasons. Firstly, numerous complete vessels have been recovered, which vary in terms of shape and were constructed to a high standard (Koch 1998, 15). This has allowed for rigorous typological sequencing. Secondly, the substantial assemblages represent an insight into the practices associated with votive deposition during the TRB (e.g. Koch 1998, 15; Schülke 2019; Sparrevohn 2009). Crucially though, interpreting these practices depends on reconstructing the use-life of the vessels that were deposited. Yet, until recently relatively little was known about the resources that were processed in the vessels prior to deposition.

A 'ritual' explanation has prevailed since Sophus Müller proposed it in 1886 but further interpretive details to expand upon this abstract categorisation have continued to be elusive. Throughout most of the 20th century, research focused upon establishing the criteria upon which to judge whether 'ritual' could be ascribed to find spots as an interpretive category, or not (see for example Becker 1948; Rech 1979; Winther 1938). Bradley's thorough (1990) investigation of the social role of 'hoards' across Northern Europe proposed that Neolithic votive deposits were sacrificial, giving way to competitive gifts to the gods in the Early Bronze Age. Above all, his analysis emphasised that withdrawing valuable materials from circulation maintained their importance and raised the status of those who disposed of them (Bradley 1990). A votive interpretation for Scandinavian Neolithic axes is indisputable for Bradley because they were placed in watery locations where they could not be retrieved, they were often unused, and were commonly in association with burials and ceramics. Here, we evaluate whether a finer interpretive scheme that disaggregates the explanatory class of 'votive' can be identified by enriching our current knowledge with biomolecular analysis of their use. As bog pots constitute some of the earliest Neolithic activity in Denmark, we also aimed to provide further detail regarding the speed and completeness of the transition to farming in this region by reconstructing their use and reconsidering radiocarbon evidence using a Bayesian chronological modelling approach.

Previously, a total of 11 bog pots (recovered from Roskilde Fjord III, Salpetermosen and the Store Åmose, including the site of Åkonge) were sampled for organic residue analysis (Craig et al. 2007, 2011), and published to varying degrees (see Table 1). In these studies, several vessels yielded *ω*-(*o*-alkylphenyl)alkanoic acids (hereafter APAAs), which are formed during the prolonged heating of polyunsaturated fatty acids that are abundant in the tissues of aquatic organisms (Cramp and Evershed 2014; Hansel et al. 2004), demonstrating that aquatic fats had been processed in the vessels. Indeed, the elevated $\delta^{15}N$ values (i.e. >8‰) obtained from carbonised surface residues as well as the presence of fish remains in some of these very same residues corroborated the molecular analysis. Despite clear evidence for the processing of aquatic resources in many of the vessels, $\delta^{13}C$ values of individual mid-chain fatty acids, $C_{16:0}$ and $C_{18:0}$, obtained from a subset of eight bog pots plotted within the reference ranges for ruminant carcass and dairy fats (Craig et al. 2007, 2011). The results of this preliminary study therefore suggest that bog pots were used for cooking a mixture of different foodstuffs, evidence that is consistent with their role as utilitarian cooking vessels with long-life histories rather than being associated with a particular foodstuff, which might be expected if their use was highly ritualised or controlled.

[Table 1 near here].

To investigate further, here, we report the as yet unpublished findings from additional bog pots (Figure 2) that were sampled from the collections of the National Museum of Denmark, Copenhagen as well as from a private collector (Figure 3) in order to investigate the use of a wider range of votive ceramics. We obtained bulk carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope data, molecular results, and $\delta^{13}C$ values of individual mid-chain fatty acids, $C_{16:0}$ and $C_{18:0}$, derived from 20 bog pots corresponding to 31 individual samples (as multiple samples were taken from the same vessel). Some of these data have been reported previously (Craig et al. 2007, 2011; Cubas et al. 2020; Koch 1998; Robson 2015). Further, we applied Bayesian chronological modelling to interpret radiocarbon (^{14}C) results obtained from carbonised surface residues adhering to 26 bog pots (some data reported in Fischer 2002; Koch 1998), and other samples directly related to these vessels, such as faunal remains from the Åkonge settlement (data reported in Fischer 2002; Fischer and Heinemeier 2003), to refine the chronology of Koch's (1998) original typological sequence. Full details of the samples and analyses undertaken on each bog pot are presented in Table 1, whilst the Materials and Methods are outlined in the SI.

[Figure 3 near here].

Results

Bulk $\delta^{13}C$ and $\delta^{15}N$ Stable Isotope Analysis

Bulk $\delta^{13}C$ and $\delta^{15}N$ stable isotope data were obtained from the carbonised surface residues adhering to 17 bog pots (*n* = 20 samples). Both the interior foodcrusts and exterior sooted deposits were analysed for three vessels (Jordløse Mose XX, NM I A 40882; Jordløse Mose XX, NM I A 40883; Jordløse Mose XX, NM I A 40884). Table 2 summarises these data, whilst the findings are plotted by archaeological site in Figure 4 (some data reported in Craig et al. 2007, 2011; Koch 1998; Robson 2015).

[Table 2 near here].

[Figure 4 near here].

The carbonised surface residues had a narrow range of $\delta^{13}C$ values (-25.2 to -30.2‰; Figure 4). On the other hand, they had a broad range of $\delta^{15}N$ values (1.0 to 10.4‰; Figure 4). In total, six bog pots (n = 8 samples) had $\delta^{15}N$ values that were above the threshold for aquatic organisms (>8.0‰) suggested by Craig et al. (2007). Of these, one of the four vessels from Jordløse Mose XX (NM I A 40882 (interior foodcrust)) had the highest $\delta^{15}N$ value (10.4‰). Based on these data alone, a range of both aquatic (i.e. fish, birds, beaver, and/or molluscs), and terrestrial foodstuffs are likely to have been processed in these vessels.

Interestingly, several of the carbonised surface residues had $\delta^{15}N$ values <8.0‰ and higher C:N atomic ratios (i.e. higher quantities of carbon relative to nitrogen). Since plant products tend to contain less protein, a plant contribution to these residues is implied (see Heron et al. 2016a; Yoshida et al. 2013), which was further supported by the macrofossil and molecular analyses (see Table 3 and below).

[Table 3 near here].

Molecular Results

Lipids were extracted and analysed from a total of 19 bog pots (n = 30 samples), and were found to contain a broad range of constituents, including unsaturated fatty acids (C_6-C_{36}), monounsaturated fatty acids ($C_{14:1}$-$C_{30:1}$), and polyunsaturated fatty acids ($C_{18:2}$), branched fatty acids (C_{15}-C_{18}), α,ω-dicarboxylic acids (C_3-C_{18}), hydroxy fatty acids (C_9-C_{18}), dihydroxy fatty acids (C_9-C_{24}), monoacylglycerols (hereafter MAGs), triacylglycerols (hereafter TAGs) and diacylglycerols (hereafter DAGs), diterpenoids (e.g. dehydroabietic acid and others), APAAs (C_{16}-C_{24}), isoprenoid fatty acids (4,8,12-trimethyltridecanoic acid (hereafter TMTD), 2,6,10,14-tetramethylpentadecanoic acid (hereafter pristanic acid) and 3,7,11,15-tetramethylhexadecanoic acid (hereafter phytanic acid)), *n*-alkanes (C_{13}-C_{33}), sterols (e.g. cholesterol and others), ketones (C_{31}-C_{37}), alcohols (C_{24}-C_{32}) as well as other compounds (see below).

Touch not the fish? Evidence for the Processing of Aquatic Resources

In total, seven bog pots (n = 10 samples) had been used to process aquatic organisms (i.e. freshwater fish, birds, beaver, and/or molluscs). APAAs (C_{16}-C_{24}), formed during the prolonged heating of polyunsaturated fatty acids that are in abundance in the tissues of aquatic organisms (Cramp and Evershed 2014; Hansel et al. 2004), were identified together with at least one isoprenoid fatty acid (i.e. TMTD, pristanic acid or phytanic acid), which meet the established criteria for the processing of aquatic resources in archaeological pottery (Cramp and Evershed 2014; Evershed et al. 2008a). Moreover, four bog pots (*n* = 7 samples) had the C_{18} APAAs with at least one isoprenoid fatty acid, and were probably used to process aquatic organisms. Indeed, the presence of the C_{22} dihydroxy fatty acid in two of these bog pots (*n* = 2 samples) lends further weight for the processing of aquatic resources (Hansel and Evershed 2009; Heron et al. 2010). Although a further three bog pots did not meet the established criteria defined by Evershed et al. (2008a), fish remains (i.e. bones and scales) were identified within the carbonised surface residues by Koch (1998), which when combined with the above demonstrates that the majority (13/20; 65%) of the bog pots analysed in this study had been used to process aquatic resources. Clearly, in this region, taboos or other sanctions regarding their consumption, as suggested for other regions of Neolithic Europe (e.g. Craig et al. 2011; Cubas et al. 2020; Milner 2011; Richards and Hedges 1999), did not apply.

Wild and Wet: Presence of Animal and Dairy Fats

Thirteen bog pots (*n* = 24 samples) contained unsaturated (C_6-C_{36}), monounsaturated ($C_{14:1}$-$C_{30:1}$), polyunsaturated ($C_{18:2}$), and branched chain (C_{15}-C_{17}) fatty acids, whilst mono-, di- and tri-acylglycerols (MAGs, DAGs, and TAGs) were identified in 11 bog pots (*n* = 16 samples). Overall, their presence indicates that the residues were characterised by degraded animal fats, including ruminant products (Regert 2011), and demonstrates that the general waterlogged nature of the find spots from which the majority of the bog pots were recovered from is conducive to lipid preservation (see Smyth and Evershed 2016). The presence of mid-chain ketones (C_{29}-C_{35}) in four bog pots (*n* = 6 samples) provides confirmatory evidence for the heating of animal fats as these compounds form at temperatures in excess of 300°C (Correa-Ascencio and Evershed 2014; Evershed et al. 1995, 2008a; Raven et al. 1997). Moreover, short-chain fatty acids (C_6-C_{10}), found in dairy fats (Christie 2014; Pollard et al. 2016), were identified in four bog pots (*n* = 5 samples), which was further corroborated by the fatty acid $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ (see below). α,ω-dicarboxylic acids (C_3-C_{18}) were present in nine bog pots (*n* = 17 samples), whilst dihydroxy fatty acids (C_9-C_{24}) were identified in five (*n* = 9 samples).

Despite being ubiquitous constituents of fats and oils, both α,ω-dicarboxylic acids and dihydroxy fatty acids are formed during the oxidation of unsaturated fatty acids (Evershed et al. 2008a; Frankel 2005; Passi et al. 1993; Regert et al. 1998). Cholesterol and their derivatives (e.g. cholestan-3-one and cholesta-3,5-dien-7-one) were identified in 10 bog pots (*n* = 20 samples). Whilst cholesterol is a confirmatory proxy for the presence of animal-derived fats (Evershed 1993), particularly since it survives over time, the presence of squalene in three bog pots (*n* = 4 samples) was probably introduced during post excavation and recent handling of the material since it is present in human skin (Weyermann et al. 2011).

With the Grain: Plant Processing in the Early Neolithic

Odd-numbered *n*-alkanes (C_{13}-C_{33}), perhaps derived from degraded plant waxes or beeswax (Dunne et al. 2017; Whelton et al. 2018), were identified in 10 bog pots (*n* = 14 samples), whilst even-numbered long-chain alcohols (C_{24}-C_{32}) were present four bog pots (*n* = 5 samples), which when taken together indicates that plants or beeswax had been processed or stored (Smyth and Evershed 2015). In addition, unidentified sugars and related compounds were present in five bog pots (*n* = 6 samples) lending further support for the processing of starchy plants (Heron et al. 2016a; Shoda et al. 2018). Moreover, plant and/or fungal sterols, including β-sitosterol, ergosterol, stigmasterol and related compounds as well as degradation products of phytosterols (e.g. stigmastan-3,5-diene) (Cert et al. 1994), were identified in five bog pots (*n* = 6 samples), which provides additional support.

Whilst we were unable to determine whether the plants were domestic or wild due to a number of reasons, including for instance a lack of specific plant biomarkers, and the broad range of $\delta^{13}C$ values of individual mid-chain fatty acids, $C_{16:0}$ and $C_{18:0}$, exhibited by plants (e.g. Bondetti et al. 2020; Colonese et al. 2017; Hamman and Cramp 2018; Hamman et al. 2018; Heron et al. 2016b), macrofossil analysis of the carbonised surface residues by Koch (1998) revealed seed impressions, possibly cereal grain, in 11 bog pots (*n* = 11 samples) analysed in this study.

Something Sticky in the Neolithic: Presence of Resin

Degradation products of diterpenoids, including dehydroabietic acid, didehydroabietic acid, 7-oxodehydroabietic acid, and 9-oxodehydroabietic acid were identified in three bog pots (*n* = 4 samples). These compounds are formed after aromatisation and oxidation of natural products (e.g. abietic acid) found in species of the *Pinaceae* genus (Colonese et al. 2017; Heron et al. 2015). Moreover, triterpenoid constituents from the lupane family, specifically betulin and lupenone, were recognised in one bog pot (Maglelyng 2, NM I A 49819 (interior foodcrust)) indicating the presence of birch bark (*Betula* spp.) tar (Cole et al. 1991; Ekman 1983; O'Connell et al. 1988). Overall, their presence in a range of samples (including carbonised surface residues, and powdered sherds) either indicates that the bog pots had been used to extract the resin(s) for tar production followed by storage, or perhaps reflects the application of a lining or sealant "to facilitate storage of liquid contents" (Heron et al. 2015, 40) as has been suggested for Early Neolithic pottery in the South-eastern Baltic region. Alternatively, their presence may represent repair in which tar and cordage were threaded through holes that had been drilled in the vessel walls. That said, their presence may also be derived from wood smoke in which pine and/or birch timber had been used as the fuel source during manufacture or indeed use of the bog pots (Reber et al. 2018).

Mixing it up: Isotopic Analysis of Individual Mid-chain Fatty Acids

Carbon ($\delta^{13}C$) stable isotope values of individual mid-chain fatty acids (palmitic , $C_{16:0}$ and stearic , $C_{18:0}$ acid) were obtained from 18 bog pots (*n* = 20 samples) - all with well-preserved lipids. Duplicate measurements were undertaken on three samples (Målevgård Mose, NM I A 40211; Jordløse Mose XX, NM I A 40883; Maglelyng 2, NM I A 49818). Table 4 summarises these data, whilst the data are plotted by archaeological site in Figures 5 and 6 (some data reported in Craig et al. 2011; Cubas et al. 2020; Robson 2015) alongside reference ranges, calculated at 95% confidence, from fats obtained from the tissues of modern authentic animals (Courel et al. 2020; Craig et al. 2011, 2012; Dudd 1999; Lucquin et al. 2016; Pääkkönen et al. 2020; Spangenberg et al. 2006; Spiteri 2012).

[Table 4 near here].

[Figure 5 near here].

[Figure 6 near here].

The $\delta^{13}C$ values of the individual mid-chain fatty acids, $C_{16:0}$ and $C_{18:0}$, for all bog pots ranged from -32.8 to -26.8‰, and -34.7 to -26.0‰ respectively, demonstrating great variation in their use. Although one bog pot (Salpetermosen, NM I A 53073) had values consistent with either marine or porcine fats (Figure 5), macrofossil analysis of the interior foodcrust by Koch (1998) yielded fish and plant remains indicating that a mixture of different foodstuffs had been processed during its use life. Moreover, despite overlap in the $\delta^{13}C$ values of ruminant carcass and dairy fats (Craig et al. 2012), three bog pots (Jordløse Mose XV, NM I A 40871; Roskilde Fjord III, NM I A 44729; Øgårde 5, NM I A 51872) had been used to process or store dairy fats, perhaps milk, butter or cheese (Figure 5), as evidenced by their $\Delta^{13}C$ ($\delta^{13}C_{18:0}$-$\delta^{13}C_{16:0}$) values of -4.4, -4.4 and -6.2‰ respectively, which were below the maximum reported value of -4.3‰ (see Figure 6) for wild ruminant carcass fats (Craig et al. 2012). Despite the presence of short-chain fatty acids (C_8 to C_{14}) in the vessel from Roskilde Fjord III (NM I A 44729) supporting the presence of dairy fats (Christie 2014), Koch (1998) identified fish remains within the interior foodcrust, whilst macrofossil analysis of the interior foodcrust of the Øgårde 5 (NM I A 51872) vessel yielded plant remains, which similarly show that they had not been solely used to process or store one commodity.

Four bog pots (Jordløse Mose VIII, NM I A 40764; Maglelyng 2, NM I A 49818 (interior absorbed residue); Målevgård Mose, NM I A 40211 (interior foodcrust); Øgårde 3, NM I A 51879) yielded values that matched the ranges for wild ruminant carcass and dairy fats (Craig et al. 2012) (Figure 5). Interestingly, three of these vessels (Jordløse Mose VIII, NM I A 40764; Maglelyng 2, NM I A 49818 (interior absorbed residue); Øgårde 3, NM I A 51879) also met the established criteria for the processing of aquatic organisms in archaeological pottery (see above), whilst the bog pot from Målevgård Mose (NM I A 40211 (interior foodcrust)) had the C_{18} APAAs alongside phytanic acid, and might therefore have been used to process aquatic organisms as well. Furthermore, in four of these vessels (Jordløse Mose VIII, NM I A 40764; Maglelyng 2, NM I A 49818 (interior absorbed residue); Målevgård Mose, NM I A 40211 (interior foodcrust); Øgårde 3, NM I A 51879) evidence for plant processing was present either in the form of plant macrofossils that were embedded within carbonised surface deposits (Koch 1998) and/or molecular evidence (i.e. *n*-alkanes (C_{15}-C_{25})). Moreover, short-chain fatty acids (C_7-C_{10}), present in dairy fats (Christie 2014; Pollard et al. 2016), and degradation products of diterpenoids were identified in the vessel from Målevgård Mose (NM I A 40211 (interior foodcrust)). Overall then, the data either demonstrates the mixing of different foodstuffs or indeed represents different culinary or non-culinary episodes, potentially including storage and later re-use, of the vessels by Early Neolithic communities.

Although the $\delta^{13}C$ values of three bog pots (Jordlose Mose XXI, NM I A 40220; Målevgård Mose, NM I A 40211 (interior absorbed residue); Åkonge, KML Peter's Pot) plotted within the range established for ruminant carcass fats, further mixing of different foodstuffs was evident. In the flat open bowl from Jordlose Mose XXI (NM I A 40220) short-chain fatty acids (C_6-C_{10}) were identified alongside *n*-alkanes (C_{15}-C_{33}), alcohols (C_{24}-C_{32}), and degradation products of diterpenoids (Table 3) indicating a mixture of domesticated ruminant carcass and/or dairy fats with plant products and pine resin. Short-chain fatty acids (C_8-C_{10}), and *n*-alkanes (C_{15}-C_{29}) were present in Peter's Pot from the site of Åkonge demonstrating a mixture of wild ruminant carcass and/or dairy fats with plant products. Interestingly, the analysed interior absorbed residue from the bog pot at Målevgård Mose (NM I A 40211) yielded different $\delta^{13}C$ values to the interior foodcrust (see above). It can be seen from Figure 6 that the interior absorbed residue had a higher $\Delta^{13}C$ value (-2.4‰) than the interior foodcrust (-2.8‰) suggesting that tissues and/or products from either domesticated or wild animals, or indeed a combination of the aforementioned, had been processed in the vessel during use (see Craig et al. 2012; Saul et al. 2014). Short-chain fatty acids (C_6-C_{10}), C_{18} APAAs alongside phytanic acid, *n*-alkanes (C_{13}-C_{33}), β-sitosterol, and degradation products of diterpenoids were also present indicating that aquatic resources, plant products and pine resin had been processed or perhaps stored.

A further five bog pots (Jordløse Mose XX, NM I A 40883 (interior foodcrust and interior absorbed residue) and NM I A 40884; Maglelyng 2, NM I A 49818 (interior absorbed residue) and NM I A 49819; Neverkær) yielded $\delta^{13}C$ values that could not be securely assigned to either freshwater or ruminant carcass fats as they fell between the established ranges (Figure 5). However, of these, two vessels (Jordløse Mose XX, NM I A 40883; Maglelyng 2, NM I A 49818) had been used to process aquatic resources (see above), and a further two, including a lugged flask (Maglelyng 2, NM I A 49819; Neverkær) had probably been processed to process aquatic organisms (Table 3). Four of the vessels (Jordløse Mose XX, NM I A 40883 and NM I A 40884; Maglelyng 2, NM I A 49818 and NM I A 49819) also yielded macrofossil and/or molecular evidence (i.e. *n*-alkanes (C_{15}-C_{29}), alcohols (C_{22}-C_{30}), β-sitosterol and stigmasterol) for plant processing.

In total, three bog pots (Jordløse Mose XX, NM I A 40882; Maglelyng 3, NM I A 44340; Ulkestrup Lyng, NM I A 43323) yielded $\delta^{13}C$ values that plotted within the established range for freshwater fish, which was corroborated by the presence of aquatic biomarkers and/or fish remains. Moreover, plant macrofossils were also identified in two of these vessels (Maglelyng 3, NM I A 44340; Ulkestrup Lyng, NM I A 43323) by Koch (1998) demonstrating yet again that they did not have one single use.

Chronology

Our Bayesian chronological model demonstrates that Koch's Funnel Beaker Types do indeed form a typo-chronological sequence, and show that Koch's (1998) Type-0 Funnel Beakers probably appeared in Zealand in the late 40th century BC. During the following 300-400 years they were gradually superseded by Types-I to III (Figures 7 and 8). This scheme should be robust, being based on multiple dated occurrences, and both foodcrust and fully terrestrial samples associated with each type. Only nine ^{14}C dates (all on interior foodcrusts) are known from Koch's (1998) Types-IV to -VIII, spanning the later 4th millennium BC (SI). Figure 8 also shows the dates of beakers with aquatic and/or dairy biomarkers, demonstrating that both food types were used throughout this period. Peter's Pot (Type-0) from the Åkonge site shows that dairy products were already available at c. 3900 cal BC (Fischer 2002; Saul et al. 2013), whilst Jordløse Mose VIII (Koch Type-MN A V) suggests that aquatic products were still processed in bog pots after c. 3000 cal BC.

[Figure 7 near here].

[Figure 8 near here].

Discussion

Pottery Use and the Continued Processing of Aquatic Resources

Our findings not only align with previous studies demonstrating that aquatic resources continued to be processed in ceramics across the EBK-TRB transition (Craig et al. 2007, 2011; Cubas et al. 2020; Isaksson and Hallgren 2012; Robson 2015), but show that this practice was pervasive throughout the region and continued well into the Neolithic period. Moreover, our Bayesian chronological modelling demonstrates that aquatic resources continued to be processed in pottery for over 1000 years after the introduction of domesticated plants and animals in the region.

When combined, the macrofossil, molecular and isotopic data show that a main constituent of the analysed bog pots were aquatic organisms and we were able to confidently assign them to a freshwater origin. This agrees somewhat with the zooarchaeological evidence from the EBK-TRB and TRB sites of Muldbjerg I, Nøddekonge, Vejkonge and Åkonge in which aside from being dominated by wild terrestrial mammals (e.g., red deer, *Cervus elaphus*; roe deer, *Capreolus capreolus*; swine, *Sus* sp.), aquatic mammals, including Eurasian beaver (*Castor fiber*), European water vole (*Arvicola amphibius*), and Eurasian otter (*Lutra lutra*) were frequently identified alongside waterfowl (e.g., coot, *Fulica atra;* garganey, *Anas querquedula*; greylag goose, *Anser anser*; mallard, *Anas platyrhynchos*; mute swan, *Cygnus olor*; pochard, *Aythya ferina*; teal, *Anas crecca*), freshwater molluscs (e.g., swan mussel, *Anodonta cygnea*), and low trophic level freshwater fish (e.g., some carps and minnows, Cyprinidae), all of which made a contribution to the subsistence economy (Enghoff 1994, 2011; Fischer and Heinemeier 2003; Gotfredsen 1998; Koch 1998; Noe-Nygaard 1995).

Interestingly, further comparison with a range of analysed TRB ceramics from a variety of sites throughout the region, including coastal (Neustadt LA 156, Oldenburg-Dannau LA 77, Rødbyhavn (MLF906-1 and MLF939-1) and Wangels LA 505) and inland (Stenø and Åkonge) settlement sites, coastal shell middens (Bjørnsholm, Havnø and Norsminde), an inland ‘offering fen’ site (Skogsmossen) as well as a coastal megalith (Wangels LA 69), (Table 5) shows that aquatic biomarkers are significantly more frequently found in pottery deposited into wetlands (i.e. the bog pots and the ‘offering fen’ site of Skogsmossen in Sweden (Isaksson and Hallgren 2012, 3608)) compared to the other sites (X^2-squared = 9.067, df = 1, *p*-value = 0.002603).

Whilst this prevalence might reflect a utilitarian function, it is also possible that their frequency reflects their cultural suitability for selection based on their symbolic affordances. For instance, Sørensen (2020) has suggested watery-places may have been considered liminal points of contact between worlds in TRB cosmology. Vessels used to process aquatic resources may have been preferentially selected for deposition because of a perceived correspondence between the watery microcosm of the vessel and its final resting place in a wetland.

[Table 5 near here].

Previously, stable isotope analysis of human bone collagen has demonstrated a clear dietary change across the EBK-TRB transition (Fischer et al. 2007; Noe-Nygaard 1988; Persson 1999; Richards et al. 2003; Tauber 1981). Whilst these studies have shown that EBK groups primarily consumed aquatic-derived protein, specifically from marine environments, and TRB communities consumed terrestrial-derived protein, though inclusive of a small contribution of foodstuffs from both freshwater and marine environments (Figure 9; cf. Fischer 2007, 65; Fischer et al. 2007, 2147), it is worth exploring why this differs to pottery use.

[Figure 9 near here].

One hypothesis is that incoming TRB groups assimilated elements of the EBK, including the processing of aquatic resources in pottery, as has been previously proposed (Craig et al. 2011). An alternative hypothesis is population dualism, where ideas or people were exchanged between an extant EBK hunter-gatherer-fisher community(ies) and incoming TRB farmers. To corroborate, it has recently been shown that "genetically distinct hunter-gatherer groups" (Jensen et al. 2019, 5) lacking Anatolian farmer ancestry were present in Denmark at the onset of the TRB, as evidenced from the DNA analysis of chewed birch bark tar recovered from the site of Syltholm, and directly dated to c. 3900-3700 cal BC (Jensen et al. 2019). Whilst this result probably represents population dualism, it is possible that the item was exchanged. Elsewhere, DNA analysis of human remains assigned to the 'Subneolithic' and Middle Neolithic (Brześć Kujawski Group of the Lengyel culture) periods from three sites in Germany and Poland, namely Blätterhöhle, Ostorf, and Brześć Kujawski (site 3), has indicated the coexistence of hunter-gatherer-fisher and farming populations (Bollongino et al. 2013; Bramanti et al. 2009; Fernandes et al. 2018; Lipson et al. 2017). Moreover, DNA analysis of later TRB human remains from several sites in Sweden (Ansarve, c. 3300-2800 cal BC; Frälsegården, c. 3200-2900 cal BC; and Resmo, c. 3300-3000 cal BC) has demonstrated that the individuals had maternal affinities with Early and Middle Neolithic cultural groups in Central Europe, thus differing from both the individual from Syltholm and the somewhat partly contemporaneous Pitted Ware communities located nearby (Coutinho et al. 2020; Fraser et al. 2018; Malmström et al. 2015; Paulsson 2010). Interestingly, data from the sites of Ansarve and Resmo (on the islands of Gotland and Öland respectively) indicate that cultural dualism was present for a prolonged period of time (Fraser et al. 2018), all of which could have been in existence in Southern Scandinavia located to the south-west.

The Introduction and Significance of Dairy Products

Our analyses revealed that three bog pots had been unequivocally used to process and/or store dairy fats (i.e. butter, cheese, milk) as demonstrated by their Δ^{13}C values, which were below the minimum reported value of -4.3 for ruminant carcass fats (Craig et al. 2012), whilst a further three bog pots had evidence suggesting mixtures of ruminants and their products (i.e. short-chain fatty acids and/or Δ^{13}C values between -3.4 and -4.2 (Craig et al. 2012)). In comparison with previous studies (Craig et al. 2007, 2011, Cubas et al. 2020; Isaksson and Hallgren 2012; Robson 2015; Weber et al. 2020), and when combined with other lines of evidence (e.g. carbon, oxygen and strontium isotope analysis of domestic cattle (*Bos taurus*) remains), it is apparent that a small-scale dairy economy, integrated with other agrarian practices, was prevalent throughout Southern Scandinavia from the onset of the TRB (Gron et al. 2015, 2016; Gron 2020). Even if an extant hunter-gatherer-fisher community had prevailed (cf. Jensen et al. 2019), it seems unlikely that they would have had the know-how to obtain dairy fats meaning that interaction (e.g. transfer of knowledge and/or products) between hunter-gatherer-fishers and farmers seems the more likely hypothesis. Indeed, this hypothesis is supported by other forms of material culture, including shoe-last axes, LBK and post-LBK ceramics, and the so-called 'double-buttons' - pearl-like ornaments - on EBK sites (Hartz et al. 2002, 2007, 2014; Sakalauskaite et al. 2019; Terberger et al. 2009). Moreover, DNA analysis of human remains has demonstrated "biological interaction" (Nikitin et al. 2019, 6) between hunter-gatherer-fishers and farmers in several regions of the European continent, including Central and South-eastern Europe (Brandt et al. 2013; González-Fortes et al. 2017; Mathieson et al. 2018; Lipson et al. 2017), Western (Brunel et al. 2020; Rivollat et al. 2020), and Northern Europe (Mittnik et al. 2018; Skoglund et al. 2012), which could also have taken place in Southern Scandinavia.

For nearly two decades dairy fats have been commonly identified in Early Neolithic ceramics meaning that we are now in a position to ascertain its inception throughout the European continent. Whilst its uptake varies from region to region, it has recently been shown that the frequency of dairy fats in Early Neolithic pottery increases along a northerly latitudinal gradient (Cubas et al. 2020). Despite this, dairy fats appear not to predominate over other wild and domestic foodstuffs in the TRB ceramics of Southern Scandinavia.

Mixtures of Wild and Domestic Foodstuffs

Although a distinction between wild and domestic foodstuffs is apparent at settlement sites and hunting stations based on the zooarchaeological evidence (Koch 1998; Gron and Sørensen 2018; Sørensen 2017), it is not evident in the use of the bog pots. Of the 20 vessels considered, the macrofossil, molecular and isotopic analyses demonstrate that the majority, *n* = 18, had been used to process a combination of both wild and domestic resources, including feral animals, and their products (Table 3). Further still, such mixtures are evident in one of the earliest vessels, Peter's Pot (ruminant carcass, dairy and plant), which dates to the period when domesticates were initially introduced in the Åmose region based on our Bayesian chronological modelling that is consistent with the calibrated date of c. 4000-3810 BC (AAR-4452, 5120 ± 40) made on *Bos taurus* remains from the Åkonge site itself (Fischer and Gotfredsen 2006; Noe-Nygaard et al. 2005). From the outset of Neolithic votive deposition, domesticated products were processed as evidenced in this very same vessel (Peter's Pot), which intriguingly was deposited beyond the Åkonge settlement into the lake. Moreover, the analyses of contemporaneous TRB vessels from the 'offering fen' site of Skogsmossen in Sweden align with our results: three vessels had been used to process dairy fats (two of these also had the C_{18} APAAs and isoprenoid fatty acids), whilst one each had been used to process ruminant carcass and non-ruminant (i.e. aquatic resources) fats, the latter of which met the established criteria for the processing of aquatic resources in pottery (Isaksson and Hallgren 2012).

The diversity of foods that were mixed in these vessels, many of them commonplace in faunal assemblages from habitation sites, indicate that votive deposition may have been an end-point in vessel life-histories that included earlier use on settlements. This could be on a habitation site in the immediate vicinity, as in the case of Åkonge or perhaps a distant locality as in the case of the Tømmerup II bog pot, also from the Store Åmose. Indeed, the measured foodcrust from this Type-VIII funnel beaker (Koch 1998, 322) had a $\delta^{13}C$ value of -17.2‰ (Rahbek and Rasmussen 1996, 313), which demonstrates that marine resources are likely to have been processed in the vessel, despite being located c. 20 km away from the coast (Fischer 2004; Fischer and Heinemeier 2003).

Elsewhere under the influence of the TRB, pottery use redolent of symbolism has been argued for. Recently, Weber et al. (2020) have shown that TRB pottery, dating from c. 3600-2900 cal BC, and recovered from the megalith site of Wangels LA 69 and the nearby settlement site of Oldenburg-Dannau LA 77 in northern Germany (Figure 2), was used to process both ruminant carcass and dairy fats. Whilst their analysis demonstrated that aquatic foodstuffs and cereals had not been processed, the presence of oils from wild plants, namely sea buckthorn (*Hippophae rhamnoides*), were suggested in the youngest, Globular Amphora Ware, vessels (c. 3000-2900 cal BC) based on the molecular and isotopic analysis (Weber et al. 2020).

Conclusions

Our findings demonstrate a clear mixing of both wild and domestic animal fats and their products in the use of pottery by the earliest farmers of Southern Scandinavia. Often, both categories of foodstuffs were present within the same vessel. There is also clear evidence that aquatic resources had been processed in the bog pots. Indeed, the presence of freshwater fats is further corroborated by other lines of evidence, including zooarchaeological assemblages and macrofossil analyses, whereby fish remains (i.e. bones, fin rays and scales) were previously identified in the latter analyses (Koch 1998; Saul 2011). In addition, porcine, ruminant carcass and dairy fats as well as plant waxes and occasionally resins were identified in several of the vessels. Indeed, the diversity of foodstuffs that were mixed in these vessels indicates that votive deposition may have been an end-point in vessel life histories that included earlier use on settlements.

When the ^{14}C results are taken into consideration it is evident that dairy products were already available as early as c. 3900 cal BC, as demonstrated by Peter's Pot from Åkonge. Consequently, and in conjunction with other lines of evidence, a small-scale dairy economy was probably in place from the onset of the TRB in Denmark. In addition, aquatic resources, associated with hunter-gatherer-fisher lifeways, continued to be processed throughout the Early Neolithic and into the Middle Neolithic. The introduction of culinary novelties ultimately originating in the Middle East surely did not result in neglect of the local food sources that had formed the basis of diet during the previous millennia.

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