First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300–4000 BC)

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Abstract

This paper focuses on the functional analysis of Swifterbant pottery from North-western Europe (ca. 4300–4000 BC) through lipid residue analysis. The main aim is to understand the role of pottery in terms of its relation to hunter-fisher-gatherer lifestyle, and the change in available food resources brought about by the arrival of domesticated animal and plant products. We conducted lipid residue analysis of 62 samples from three Swifterbant sites S2, S3 and S4. A combined approach using both GC-MS and GC-C-IRMS of residues absorbed into the ceramic was employed to identify their context. Our results demonstrate that Swifterbant ceramics were used exclusively for processing aquatic resources. We also found no evidence of inter-site variation in the use of pottery or variation based on both typological and technological features of the pottery. We found no evidence for any domesticated resources despite their presence in the faunal and botanical assemblages.

Keywords NW Europe · Hunter-fisher-gatherers · Early pottery use · Lipid residue analysis · Swifterbant culture

Introduction

In many parts of Europe, the transition to farming and the start of pottery production occurred at the same time and both innovations are often considered to be part of a 'Neolithic package' (Barker 2006; Gronenborn 2007; Bailey and Spikins 2008). In contrast, in the western Baltic, so-called Ertebølle pottery was present much earlier than farming and appears to be a forager innovation perhaps derived from contact with ceramic using hunter-gatherers based in the eastern Baltic. The Dutch wetlands also witnessed a somewhat different socio-economic trajectory. Here, pottery production was invented or adopted by hunter-gatherers from ca. 5000 cal BC, but domesticated animals, particularly domesticated cattle, and cereals do not appear in the sequence until ca. 4700 and

4300 cal BC, respectively (Raemaekers 1999, 2003; Louwe Kooijmans 2003). These groups are commonly termed the 'Swifterbant culture' due to their distinctive material culture, with sites often located in wetlands, between the Scheldt valley (Belgium) and Lake Dümmer (Lower Saxony, Germany) (Raemaekers 1999; Amkreutz 2013). Unlike most other parts of Europe, the adoption of farming in this region did not necessarily lead to large-scale changes in material culture or economic practices. A major economic transition is seen only later, with the introduction of TRB (*Trichterbecherkultur*) pottery, at ca. 4000 cal BC (ten Ancher 2012; Raemaekers 2012) Here, we investigate the relationship between economic practices and material culture by undertaking the first lipid residue analysis of Swifterbant ceramics to determine their use. A key question is whether Swifterbant ceramics were associated with domesticated animal and plant foods once these became available or whether culinary practices remained essentially unchanged and continued to reflect the hunter-fisher-gatherer economy.

Our initial research focuses on three contemporaneous sites (S2, S3 and S4) in a small area of the Netherlands known as Swifterbant, the type site for the Swifterbant culture, dating from between 4300 and 4000 cal BC. By this time, cereals and domestic animals had become established in the region and had been incorporated into a broader, pre-existing economy based on fishing, hunting and gathering (leading to a so-called

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'extended broad spectrum economy') (cf. Louwe Kooijmans 1993). As well as investigating the role of pottery in these forager-farmer societies, this study also offers an opportunity to examine inter-site variation in pottery given the different domestic (S3 and S4) and funerary/ritual (S2) functions that have been proposed for these sites (Devriendt 2014: 220). Lipid residue analysis on Swifterbant pottery is also relevant to the broader debate regarding the transition to farming and the role of ceramics therein; a debate that in Northern Europe is dominated by the Ertebølle culture. From its inception in the 1970s, the Swifterbant culture has been considered a western branch of the Northern European Ertebølle culture (De Roever 1979), an interpretation that still finds an audience (cf. De Roever 2004; Rowley-Conwy 2013). A competing interpretation is that its emergence was unrelated to the Ertebølle culture (Raemaekers 1997; Andersen 2010; ten Anscher 2012), whereas this discussion has until now been based primarily on the technology and typology of the ceramics, the functional analysis provided here will add new fuel to this fire.

The archaeological sites

The sites of the Swifterbant cluster (Fig. 1) are located in Oostelijk Flevoland, the Netherlands. Oostelijk Flevoland is a large polder, a reclaimed floor of a lake, the Ijsselmeer. The sites were discovered when the ditches between the agricultural plots were dug and are part of a covered and well-preserved prehistoric landscape which consists of a Neolithic creek system and adjacent sand ridges (occupied during the

Mesolithic and Neolithic). Swifterbant sites S2, S3 and S4 are located on the banks of the Neolithic creek system. S2 (52°, 35' 3.0" N, 5°, 34' 54.5" E) is located along the main Neolithic creek, while the adjacent S3 (52°, 34' 44.8" N, 5°, 34' 56.8" E) and S4 (52°, 34' 46.5" N, 4°, 34' 57.9" E)[1], are located along a side branch, 600 m south of S2 (Devriendt 2014) (Fig. 1). Several ^{14}C dates from the sites confirms that they were occupied ca. 4300–4000 cal BC (Peeters 2007; Devriendt 2013). The pottery from these sites was extensively studied by De Roever (1979, 2004). The archaeological remains indicate the exploitation of both domestic animals, such as pig, cattle and sheep/goat, and game animals, such as beaver and otter. The game animals were hunted for their fur and their meat (Zeiler 1997a). The faunal analysis indicates that pig bones, wild and/ or domesticated, dominate the assemblage (Zeiler 1997a). In terms of fish remains, the sites provide clear evidence for both anadromous (sturgeon, grey mullet and eel) and freshwater (pike, perch and catfish) species (Brinkhuizen 1976; Clason 1978). In addition, archaeobotanical analyses indicated the presence of two types of cereals (naked six-row barley [*Hordeum vulgare*] and hulled emmer wheat [*Triticum turgidum ssp. dicoccum*]) and several different wild plant species, such as hazelnut, hawthorn, rose-hip, wild apple and

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[1] The DMS coordinates mentioned in the text correspond to the location of the archaeological sites. The degree of reliability is 1 m for all three sites. These coordinates were generated by Erwin Bolhuis (Groningen Institute of Archaeology) based on the information available online on the Dutch Ministry of Education, Culture and Science, National monument register page (for S2, https://monumentenregister.cultureelerfgoed.nl/monumenten/532464; for S3 and S4 https://monumentenregister.cultureelerfgoed.nl/monumenten/532465).

blackberry (van Zeist and Palfenier-Vegter 1981; Cappers and Raemaekers 2008).

Materials and methods

Sample selection

All three Swifterbant sites mentioned in this paper, S2, S3 and S4, are identified as unstratified midden deposits with no clear contextual information (Huisman and Raemaekers 2014). Therefore, sherds with different typological and technological features were sampled to make the collection as representative as possible. A selection of 62 sherds (S2, $n = 14$; S3, $n = 19$; and S4, $n = 29$), all representing individual ceramic vessels, were sampled for lipid residue analysis.

During the process of selecting samples, each fragment was studied from the perspective of form, size, decoration, rim diameter and wall thickness (Online Resource 1). The samples were also analysed under the microscope in order to get a clear understanding of the temper (Online Resource 1). Based on the information collected, the sample set consists of 14 base fragments with either pointed or rounded base, 28 rim fragments and 20 body fragments. The average wall thickness for the pottery is 10 mm for all three sites. Of the 28 rim fragments, 4 did not provide rim diameter information due to their small size. For the remainder, the rim diameter varied between 20 and 30 cm with an average of 25 cm although there are 5 samples smaller than 20 cm and 3 samples greater than 30 cm with examples of each appearing at all three sites. Although one of the rim fragments from S2 has more prominent decoration than is usual, overall decoration appears to be uncommon, and where present, simple and matching with the general description of Swifterbant pottery. The base fragments and body sherds show no decoration, with the exception of five body fragments that are decorated with nail impressions (four from S4 and one from S2). In contrast, rim fragments do show decorative patterns mainly on the top of the rim and/or just below the rim, both interior and exterior as well as around the neck again both interior and exterior. The decoration on the top of the rim is a series of spatula or nail impressions, while those below the rim or on the neck area seems to consist of a series of shallow impressions and occasionally, fingertip impressions, which circle the vessel (Fig. 2).

In terms of temper, our samples fit into the general scheme of Swifterbant pottery (Raemaekers and de Roever 2010). The majority of sherds from S3 ($n = 14$, out of 19) and S4 ($n = 26$, out of 29) indicate plant material together with mica, grit and sand (Online Resource 1). The sherds from S2, in contrast, show an even distribution between plant material ($n = 7$) and grit ($n = 7$) as the most abundant temper. Like S3 and S4, S2 also shows the presence of mica and sand as other tempers. The analysis of the temper does not indicate any correlations with wall thickness or decoration as it was suggested in a previous study on Swifterbant pottery (cf. Raemaekers et al. 2013). The fabric is extremely coarse with no deliberate surface treatment other than occasional hand smoothing. The hand smoothing is more visible on the S2 sherds than it is on the S3 and S4 sherds.

Acidified sulphuric acid extraction extraction of lipids

Ceramic was drilled from the interior portion of each vessel ($n = 62$) and analysed using the established standard protocol, one-step methanol/sulphuric acid extraction (Craig et al. 2013; Correa-Ascencio and Evershed 2014; Papakosta et al. 2015). The outer surface (~ 0–1 mm) of the sampling area was first removed, using a Dremel drill, to reduce the external contamination to a bare minimum. Then, the sherds were drilled to a depth of up to 5 mm on the interior surface to produce ca. two grams of pottery powder. An internal standard (alkane C34, 10 μL) was added to a subsample of powdered sherd (ca. 1 g) followed by 4 mL methanol. The suspended solution was sonicated for 15 min, then acidified with concentrated sulphuric acid (800 μl) and heated for 4 h at 70 °C. Lipids were sequentially extracted with n-hexane (2 mL × 3). The extracts were combined and dried under nitrogen at 35 °C. Finally, an additional internal standard (n-hexatriacontane, 10 μg) was added to each sample prior to their analysis by gas chromatography-mass spectrometry (GC-MS) and gas chromatography-combustion isotope ratio mass spectrometry (GC-C-IRMS) in order to obtain molecular and carbon single-compound isotope results. To control for any contamination introduced during the sample preparation, a negative control, containing no ceramic powder, was prepared and analysed with each sample batch.

Gas chromatography-mass spectrometry (GC-MS)

GC-MS analysis was carried out on an Agilent 7890A series GC attached to an Agilent 5975C Inert XL mass-selective detector. A splitless injector was used and maintained at 300 °C. The column was inserted into the ion source of the mass spectrometry directly. Helium was used as the carrier gas, with a constant flow rate at 3 mL/min. The ionisation energy was 70 eV, and spectra were obtained by scanning between m/z 50 and 800. Samples ($n = 62$) were analysed by using an Agilent DB-5ms (5%phenyl) methylpolysiloxane column (30 m × 0.25 mm × 0.25 μm). The temperature was set to 50 °C for 2 min. This was followed by a rise of 10 °C per minute up to 350 °C. The temperature was then held at 350 °C for 15 min. Compounds were identified by comparing them with the library of mass spectral data and published data.

All samples ($n = 62$) were also analysed by using a DB-23ms (50%-cyanopropyl)-methylpolysiloxane column (60 m × 0.25 mm × 0.25 μm) in simulation (SIM) mode to

Fig. 2 Illustrations of selected sherds from Swifterbant S2, S3 and S4 (scale 1:3)
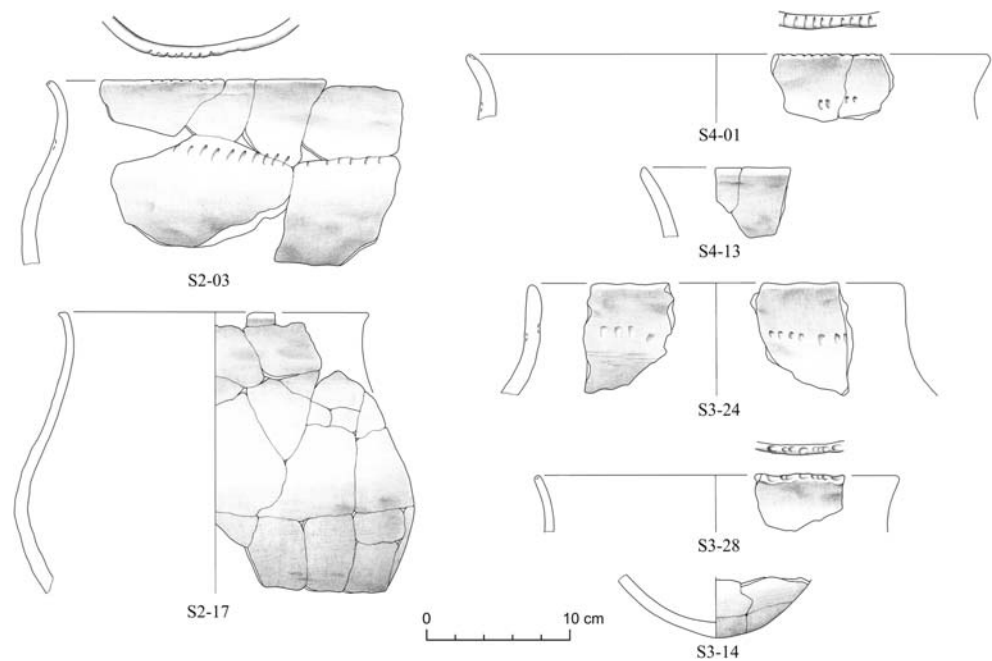
increase the sensitivity for the identification of isoprenoid fatty acids and ω-(o-alkylphenyl) alkanoic acids (APAAs), which can be used to characterise aquatic foods (Cramp et al. 2014; Admiraal et al. 2018). The temperature was set to 50 °C for 2 min. This was followed by a rise of 4 °C per minute up to 140 °C, then 0.5 °C per minute up to 160 °C and then 20 °C per minute up to 250 °C. The temperature was then held at 250 °C for 10 min. Scanning then proceeded with the first group of ions (m/z 74, 87, 213, 270), equivalent to 4,8,12-trimethyltridecanoic acid (TMTD) fragmentation; the second group of ions (m/z 74, 88, 101, 312), equivalent to pristanic acid; the third group of ions (m/z 74, 101, 171, 326), equivalent to phytanic acid; and the fourth group of ions (m/z 74, 105, 262, 290, 318, 346), equivalent to ω-(o-alkylphenyl) alkanoic acids of carbon length C16 and C22. Helium was used as the carrier gas with a constant flow rate at 2.4 mL/min. Ion m/z 101 was used to check the relative abundance of two diastereomers of phytanic acids. Quantifications for the peak measurements were calculated by the integration tool on the Agilent ChemStation enhanced data analysis software.

Gas chromatography-combustion isotope ratio mass spectrometry (GC-C-IRMS)

Forty-two samples which had lipid concentration over 5 μg g^{-1} were analysed by GC-C-IRMS in duplicates based on the existing protocol (Craig et al. 2012), in order to measure stable carbon isotope values of two fatty acid methyl esters, methyl palmitate ($C_{16:0}$) and methyl stearate ($C_{18:0}$). Samples were analysed by using Delta V Advantage isotope

ratio mass spectrometer (Thermo Fisher, Bremen, Germany) linked to a Trace Ultra gas chromatograph (Thermo Fisher) with a GC Isolink II interface (Cu/Ni combustion reactor held at 1000 °C; Thermo Fisher). All samples were diluted with hexane. Then 1 μL of each sample was injected into DB5ms fused-silica column (60 m × 0.25 mm × 0.25 μm; J&W Scientific). The temperature was fixed at 50 °C for 0.5 min. This was followed by a rise by 25 °C per minute to 175 °C, then by 8 °C per minute up to 325 °C. The temperature was then held at 325 °C for 20 min. Ultrahigh-purity-grade helium was used as the carrier gas with a constant flow rate at 2 mL/min. Eluted products were ionized in the mass spectrometer by electron ionization and the ion intensities of m/z 44, 45 and 46 were recorded for automatic computation of $^{13}C/^{12}C$ ratio of each peak in the extracts (Heron et al. 2015). Isodat software (version 3.0; Thermo Fisher) was used for the computation, based on the comparison with a standard reference gas (CO_2) with known isotopic composition that was repeatedly measured. The results of the analyses were recorded in ‰ relative to an international standard, Vienna Pee Dee belemnite (VPDB).

N-alkanoic acid ester standards of known isotopic composition (Indiana standard F8–3) were used to determine the instrument accuracy. The mean ± standard deviation (SD) values of these n-alkanoic acid ester standards were − 29.60 ± 0.21‰ and − 23.02 ± 0.29‰ for the methyl ester of $C_{16:0}$ (reported mean value vs. VPDB − 29.90 ± 0.03‰) and $C_{18:0}$ (reported mean value vs. VPDB − 23.24 ± 0.01‰), respectively. Precision was determined on a laboratory standard mixture injected regularly between samples (28 measurements).

The mean $\pm$ SD values of n-alkanoic acid esters were $-31.65 \pm 0.27‰$ for the methyl ester of $C_{16:0}$ and $-26.01 \pm 0.26‰$ for the methyl ester of $C_{18:0}$. Each sample was measured in replicate (average SD is 0.07‰ for $C_{16:0}$ and 0.13‰ for $C_{18:0}$). Values were also corrected subsequent to analysis to account for the methylation of the carboxyl group that occurs during acid extraction. Corrections were based on comparisons with a standard mixture of $C_{16:0}$ and $C_{18:0}$ fatty acids of known isotopic composition processed in each batch under identical conditions.

Results and interpretations

Results of molecular analysis (GC-MS)

Based on the molecular analysis of the samples, 98% of the samples yielded sufficient lipids required for interpretation (i.e. > 5 µg g^{-1}) (Evershed 2008; Craig et al. 2013) with an average of 243 µg g^{-1} (ranging from 3 to 6186 µg g^{-1}). The variation between ranges of lipid preservation exists in all three sites. Samples with lipid yields lower than 5 µg g^{-1} were not analysed by GC-C-IRMS.

In general, the molecular analysis results indicate a high abundance of saturated palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids in all the samples together with the carbon range changing from C_{12} to C_{28}. The palmitic/stearic acid ratios (P/S ratios) of all the samples are listed Online Resource 1. Although palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids are present in both animal and plant sources, stearic acid is generally found in higher concentration in terrestrial animals than aquatic and plant food sources (Craig et al. 2007; Papakosta et al. 2015). Higher relative amounts of palmitic acid ($C_{16:0}$) (P/S ratios > 1) in almost all the Swifterbant samples suggest that these vessels were used for processing aquatic food resources or plant products rather than terrestrial animal products.

Forty-five of all the samples yielded unsaturated fatty acids ranging between $C_{16:1}$ and $C_{22:1}$. Only five samples indicated presence of dicarboxylic acids all with carbon chain length nine. Based on the experimental study, dicarboxylic acids ranging between C_8 and C_{11} are formed during the heating of aquatic oils (Evershed et al. 2008). A total of eleven samples contained cholesterol indicating presence of animal fats (Evershed 1993). Although cholesterol may be derived from vessel use, it may also be a contaminant arising during handling of the sherds.

Thirty-one of 62 samples contained ω-(o-alkylphenyl) alkanoic acids (APAAs), with carbon atoms ranging from 18 to 22, and isoprenoid fatty acids, including TMTD (4,8,12-trimethyltridecanoic acid), pristanic acid (2,6,10,14-tetramethylpentadecanoic acid) and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid). These data meet the established criteria for identifying aquatic lipids in the ancient

pottery (Evershed et al. 2008; Hansel et al. 2004; Craig et al. 2007; Cramp and Evershed 2014; Heron et al. 2015); Heron et al. 2015). In addition, APAAs are formed by heating of polyunsaturated fatty acids obtained in aquatic organisms; therefore, must have been derived from primary use of the vessels (Hansel et al. 2004; Craig et al. 2007). Two samples yielded only C_{18}, C_{20} and/or C_{22} APAAs with no isoprenoid acids. They are also considered an evidence of aquatic products because C_{20} and C_{22} APAAs are formed from long-chain polyunsaturated fatty acids (C_{20} and C_{22}) which are not present in terrestrial animal fats (Hansel et al. 2004). Another four samples yielded partial aquatic biomarkers containing C_{18} APAA and isoprenoid acids (Online Resource 1).

None of the samples yielded plant derived lipids (e.g. phytosterols) (Online Resource 1). Interestingly, scanning electron microscope (SEM) analysis on the carbonized surface deposits (foodcrust) collected from pottery from the S3 site has indicated the processing plant material (Raemaekers et al. 2013), albeit relating to different sherds than those analysed here. SEM analysis on S3 vessels identified plant fragments such as chaff and leaf tissues of emmer (*Triticum dicoccum*) as they survived the food processing and cooking stages. The SEM results indicated that plant products were cooked with other food sources, as one vessel also contained fish scale remains (Raemaekers et al. 2013). Given the evidence of the use of the emmer in the foodcrusts from S3 vessels, the absence of plant biomarkers in our results may come as a surprise. As plant foods have low lipid content, they may be overprinted by other animal fats and may therefore be very difficult to detect through lipid residue analysis (Colonese et al. 2017; Hammann and Cramp 2018). This opens up a new discussion on whether Swifterbant vessels are used for mixing freshwater fish and plant food sources. Resolving this requires further combined lipid residue and SEM analyses.

Isotopic identification of individual fatty acids (GC-C-IRMS)

Forty-two samples with sufficient fatty acid yields (< 5 µg g^{-1}) were analysed by GC-C-IRMS in order to determine the carbon stable isotopes values of their C_{16} and C_{18} fatty acids. The data from the samples are listed in Dataset-1 (Online Resource 1) and plotted in Fig. 3a against reference ranges of authentic modern animal fats collected from the Western Baltic. In Fig. 3b, the $\delta^{13}C$ values of the $C_{16:0}$ acid are plotted against $\Delta^{13}C$ values (difference between $\delta^{13}C_{18:0}$ and $\delta^{13}C_{16:0}$) which allows us discrimination of ruminant adipose, non-ruminant and dairy fats (Craig et al. 2012, 2013; Cramp et al. 2014).

In general, the carbon isotope values from all three sites provided $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids consistent with freshwater organisms (Fig. 3a), confirming the results of the molecular analysis. The majority of the
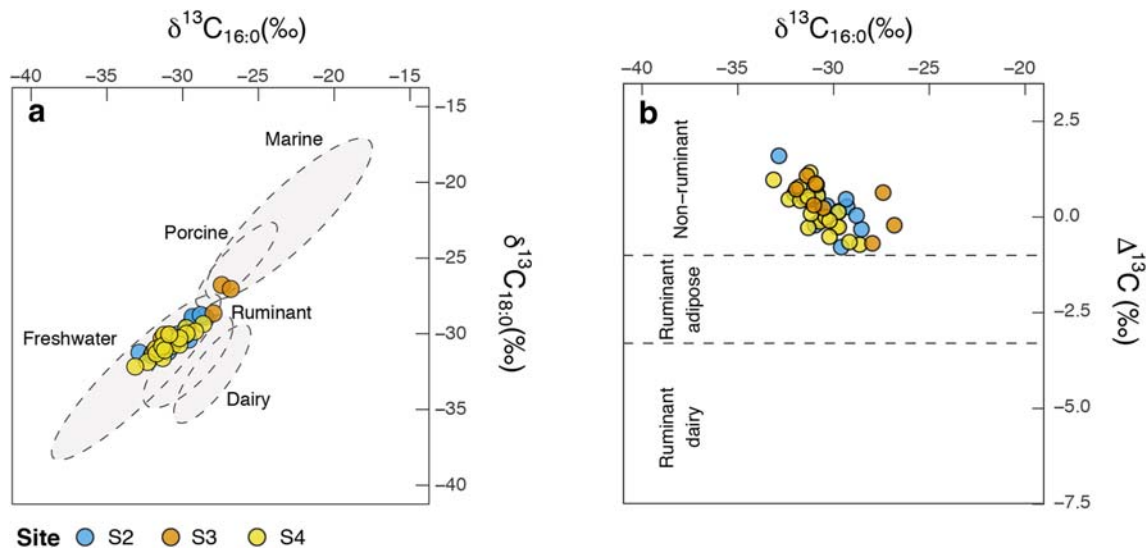
Fig. 3 Stable carbon isotope measurements of $C_{16:0}$ and $C_{18:0}$ fatty acids obtained from ceramic matrices of Swifterbant pottery by site. **a** Plot of $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values against ranges of authentic reference fats and oils. Ellipses indicate the 95% confidence interval. **b** Plot of $\Delta^{13}C$ ($\delta^{13}C_{18:0}$ and $\delta^{13}C_{16:0}$) values against $\delta^{13}C_{16:0}$ values obtained from ceramic matrices

samples which plot in this area (21 out of 35) have fully aquatic biomarkers (Online Resource 1), verifying that they were used for processing aquatic products, mainly freshwater fish.

Two samples (S305 and S328) from S3 plot within the range of modern porcine and marine fats (Fig. 3a). Wild and possibly domesticated pig *(S. scrofa/Sus domesticus)* are the most abundant terrestrial species at S3 (Zeiler 1997a, p.99). There is no evidence for marine mammals at the Swifterbant sites, and there are only two marine fish species, thin-lipped grey mullet (*Mugil capito* Cuvier) and flounder (*Platichths flesus* L.) representing a very small percentage (1% of in situ material, $n = 611$; 0.4% of sieved material, $n = 3825$) of the total fauna material found in S3 (Brinkhuizen 1976; Clason 1978). In addition, both of these marine species are known to swim far upstream into freshwater environments (Brinkhuizen 1976; Clason 1978; Zeiler 1997a). Sturgeon (*Acipenser sturio* L.), an anadromous fish that migrates from the sea to the rivers in springtime to spawn and would be expected to have a marine carbon isotope signature, is also present in Swifterbant sites (Brinkhuizen 1976; Clason and Brinkhuizen 1978) but again at a very small percentage (< 1%) (Zeiler 1997a). Based on these, it is clear that marine species were not a major part of the diet at Swifterbant S2, S3 and S4 and that there was no deliberate exploitation of the coastal areas for fishing or sea mammal hunting. Thus, it is unlikely that these ceramic vessels were used to process marine resources. As only one of these two samples contained fully aquatic biomarkers (S328) (Online Resource 1), a more plausible hypothesis is that this residue contains a mixture of freshwater and porcine derived lipids.

None of the samples had $\Delta^{13}C$ values lower than − 1‰, the value that is an indicator for ruminant fat (Evershed et al.

2002; Copley et al. 2003; Craig et al. 2012) (Fig. 3b; Online Resource 1). It is known that ruminant animals, especially domesticated cattle, were present in all three Swifterbant sites (Raemaekers 1999), and they must have been part of the diet. However, based on the molecular and isotopic results of the samples, it is likely that ruminant products were processed and cooked in different ways rather than using pottery. Finally, the isotope values clearly indicate that there are no dairy products in any of the Swifterbant pots analysed, as the $\Delta^{13}C$ values of the samples are all higher than − 3.3‰ (Fig. 3b). It should be noted that even a minor contribution of ruminant fat would be expected to be detected given there is a strong bias against aquatic oils when mixed with ruminant fats due to the differences fatty acid concentration between these products (Cramp et al. 2019).

Discussion

Relationship between form and function

The starting point for this analysis was the pilot study that was carried out on 32 vessels from Swifterbant S3 (Raemaekers et al. 2013). The combination of scanning electron microscope (SEM) and organic residue analysis using direct temperature-resolved mass spectrometry (DTMS), a form of in-source pyrolysis mass spectrometry, distinguished two functional groups. The first group of grit-tempered, thin-walled and relatively well-made pots, contained emmer wheat based on the SEM analysis, whereas the second group of plant-tempered, thick-walled and relatively poorly made pots showed no such evidence (Raemaekers et al. 2013). The lipid residue data presented here seemingly contradicts this previous study.

Although we tested different pots, we see no variation in vessel function by typological or technological features (Online Resource 1). According to the lipid residue evidence, Swifterbant pottery was used for processing freshwater fish regardless of vessel form, size, decoration or temper. In reconciling these studies, we need to take into account that the functional differences proposed in the Raemaekers et al. (2013) pilot study were revealed only by SEM analysis rather than by DTMS and that processing of fish and cereals either together or sequentially could provide an explanation. Our current study underlines the relevance of combining lipid residue analysis and SEM analysis for the functional interpretation of ceramics, and it clearly outlines an avenue for future research.

Comparison between pottery use and other evidence for subsistence strategies

Based on analysis of the zooarchaeological and archaeobotanical remains, the subsistence economy at all three sites appears to have relied on a mixture of aquatic and terrestrial animal and plant resource, pointing to an economic pattern based on hunting-fishing-gathering, horticultural-scale cereal cultivation and small-scale animal husbandry (Cappers and Raemaekers 2008; Huisman et al. 2009; Huisman and Raemaekers 2014). Other dietary evidence such as stable isotope analysis of human bones from two of the Swifterbant sites (6 human teeth from S2 and 4 human teeth from S3) indicates a high intake of aquatic foodstuffs together with a definite terrestrial input (Smits and van der Plicht 2009; Smits et al. 2010: Table 1). Evidence of butchery found on S3 pig/wild boar and cattle bones also supports this evidence (Zeiler 1997b). We conclude that while there is a bias against the identification of plant foods through lipid residue analysis, carcass fats from pigs and cattle should be readily identifiable, and therefore, pigs and cattle must have been processed and cooked in different ways. Significantly, we found no evidence for dairy products which are readily identifiable in prehistoric pottery from other sites in Northern and other areas of Europe (Craig et al. 2011;Cramp et al. 2019; Heron et al. 2015). The use of pottery vessels was instead focused on processing freshwater fish which were selected from a much wider range of animal resources available.

Inter-site variation

There are important differences between the three sites. Most striking is the difference in the presence of burials. S2 has nine burials, whereas S3 has no burials and S4 has only a single inhumation (Raemaekers et al. 2009). Another difference is the presence of postholes. Site S3 yielded many postholes which are interpreted to be the remnants of a rebuilt house (c. 4.5 × 8 m). Site S4 yielded only few postholes and these

could not be attributed to a structure (Geuverink 2020). Site S2 produced only one line of postholes, and these did not correspond to a house plan (De Roever 2004). In addition, Devriendt proposes that S3 and S4 had a domestic or residential function on the basis of the dominance of scrapers in the flint tool assemblage, whereas S2 has many more retouched blades (Devriendt 2014). Some of these blades must have been imported as finished products, because they are larger than the flint cores found. One hypothesis was that S3 and S4 were domestic sites, where one might expect a full range of foods to have been cooked in the ceramic vessels, whereas S2 was a special-function site, where vessels use was primarily related to the burial ritual. It was not possible to support this hypothesis on the basis of our analysis. The lipid residue analysis does not indicate any inter-site functional variation in the Swifterbant pottery.

Interregional perspective: Swifterbant vs Ertebølle

While both Swifterbant (5000–4000 cal BC) and Ertebølle (4800–4000 cal BC) were contemporary, the relationship between these groups is the subject of on-going discussion, notably based on similarities and differences in ceramic vessels (De Roever 1979; Raemaekers 1997; De Roever 2004; Andersen 2010; Louwe Kooijmans 2010; ten Anscher 2012; Rowley-Conwy 2013). Along with pointed-based pottery present in both cultural groups, the Ertebølle pottery repertoire also includes elongated bowls (blubber lamps) used for illumination (Heron et al. 2013) which are completely absent in Swifterbant assemblages. Later comparisons have focused on other material cultures, such as lithic tools as well as subsistence practices, which have highlighted greater differences between these two cultures (Deckers 1982; Raemaekers 1997; Raemaekers 1998; Stilborg 1999; Andersen 2010; Ballin 2014). An important difference is that compared with the Swifterbant, there is very little evidence for domesticated plants and animals at any Ertebølle sites, and the occasional find is interpreted to be the result of contact with nearby farmers (Krause-Kyora et al. 2013). With the new data we generated from the lipid residue analysis of Swifterbant S2, S3 and S4 pottery assemblages, we now can contribute to the discussion from the perspective of pottery use.

Lipid residue analyses indicates Late Mesolithic Ertebølle pottery (ca.4600–3950 BC) from both coastal and inland sites had a broad range of functions including processing of aquatic resources, both marine and freshwater (Craig et al. 2007), but also terrestrial animal fats, particularly ruminant fats (Craig et al. 2007; Philippsen et al. 2010; Heron et al. 2013; Philippsen and Meadows 2014; Papakosta et al. 2019). A recent study (Papakosta et al. 2019) shows mixing of aquatic and terrestrial food products in the Ertebølle pots based on their isotope values. Stable isotope analysis of carbonised surface deposits (foodcrust) from inland Ertebølle sites also

suggests a mixture of freshwater and terrestrial ingredients and is not able to rule out the presence of terrestrial plants (Philippsen et al. 2010; Philippsen and Meadows 2014). Moreover, phytoliths from garlic mustard seed were also found in Ertebølle pottery at Neustadt and Stenø (Saul et al. 2013), although no evidence for cereals in Ertebølle pottery has so far been recorded. The residue analysis undertaken on Ertebølle pottery contrasts with our results from the three Swifterbant sites. Swifterbant pottery, at least based on evidence from these three sites had a more specialised function associated with freshwater fish. We, therefore, conclude that these different cultures did not share the same kind of approach towards the use of pottery, even when sites located in similar wetland environments are compared, e.g. Store Åmose basin and Ringkloster in Denmark (Craig et al. 2011), although most of the Ertebølle lipid residue data are from coastal settlement sites. Unfortunately, comparable Swifterbant coastal settlements are absent due to erosion of the coastal zone preventing a more detailed comparison.

Conclusion

The first combined molecular and isotopic analysis of lipids provides clear evidence for the processing of freshwater fish at all three studied Swifterbant sites. The homogeneity of the results is striking and shows that variation in size, decoration and temper is not mirrored in the use history of the vessels. Currently we have no evidence for different uses of vessels across the three sites, i.e. between 'domestic sites' (S3 and S4) and the 'ritual site' (S2). The absence of ruminant fats and dairy products in the Swifterbant pottery is quite clear and in sharp contrast to European Neolithic pottery, where these products are readily detected (e.g. Cramp et al. 2019). While it may be that any differences are only manifest in the use of plant foods which are difficult to detect through lipid analysis, it may also be a true reflection of homogeneity in Swifterbant pottery use. This possibility opens up other avenues of research, rethinking the production, exchange and use of pottery and the role pottery played in the expression of social identities and cultural preferences as has been debated previously (Taché and Craig 2015; Robson et al. 2018). Additional analysis of Swifterbant pottery from different sites is clearly needed to contribute to the debate regarding the function of the hunter-gatherer pottery in Northern Europe, nevertheless the data presented here provide a significant advance in our knowledge for this period and region and points to different culinary practices to contemporary hunter-gatherers in adjacent regions.

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