Regional Variation in the use of the earliest pottery in North-western Europe: Organic Residue Analysis of Swifterbant pottery (5000 - 4000 cal. BC)

PhD thesis

by

Özge Demirci

University of Groningen and University of York

(Under a double doctoral degree programme)

Department of Archaeology

February 2021

Abstract

This thesis aims to investigate the function and functional variation of ceramic vessels of Swifterbant culture (c. 5000-4000/3400 cal BC) in the Dutch Wetlands through the application of lipid residue analysis. It is the first systematic application of this method to Swifterbant pottery. In addition, having gained access to numerous assemblages, it is also the first large-scale study of Swifterbant pottery. Swifterbant culture is a hunter-gatherer-fisher society with pottery which demonstrates a continuation of hunter-gatherer subsistence strategies alongside a gradual shift towards agricultural cultivation and domestic food production. Whilst the earliest Swifterbant pottery is dated to c. 5000 cal BC, the arrival of domesticated animals is dated to c. 4500 cal BC and cereals at c. 4300 cal BC. Here, lipid residue analysis was applied to 148 samples, representing 146 individual vessels recovered from eight archaeological sites: Swifterbant type sites S2, S3 and S4 (c. 4300-4000 cal BC) in Flevoland, the Netherlands; Polderweg, De Bruin, Brandwijk, and Hazendonk (c. 5000-3800 cal BC) in the Lower Rhine-Meuse area, the Netherlands; and finally Hüde I (4700-3500 cal BC) in the Lower Saxony. Overall, the new data generated for this thesis shows that Swifterbant pottery has been continuously and primarily used for processing of aquatic resources, almost exclusively freshwater fish despite its highly diversified subsistence strategies, which include large and small game animals, terrestrial and aquatic food resources. The results also present temporal changes in the exploitation of food resources in the Lower Rhine-Meuse area where we see pottery being also used to process different ranges of foodstuffs such as terrestrial resources and dairy products. The identification of dairy residue is the first direct evidence so far from Swifterbant pottery. Overall, this study shows that the motivation for the uptake of pottery into the Swifterbant culture did not necessarily related to changing subsistence strategies as we see a clear continuity in culinary traditions after the introduction of domesticates into the Swifterbant culture.

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Acknowledgements

Throughout this PhD, I had the greatest opportunity of working alongside with highly skilled researchers, colleagues, and friends in several different countries, mainly in the Netherlands, UK, and Germany. Without their valuable contributions and continued support, it would have been very difficult to complete this research.

I would like to start with expressing my deepest gratitude to my supervisors Daan Raemaekers in the University of Groningen and Oliver E. Craig in the University of York for their precious guidance over the last four and a half years, for believing in me, and giving me the opportunity to be part this amazing research project. I learned so much from both of you. Special thanks to Daan who enthusiastically shared his valuable knowledge on European prehistory with me, answered all my questions -repeatedly.

Likewise, I am very thankful to Alexandre Lucquin from University of York-BioArCh for teaching me everything I know about lipid residue analysis and lab work during my secondment at the University of York. You have been my *third* supervisor throughout this project. Thank you very much for always being there to help, assist and advice with great patience.

I am very thankful for the opportunity to be part of ArchSci2020 which was a Marie Sklodowska-Curie European Joint Doctoral Training Program, funded by the European Union's EU Framework program for Research and Innovation Horizon 2020 under the Grant Agreement No 676154 (ArchSci2020 program). I especially thank to Matthew Collins, Cecilie Toudal Pedersen and Hannes Schröder for dealing with the project management of ArchSci2020 and being there to remind us all the necessary steps for completing our research projects as smoothly as possible.

One of the biggest thanks goes to other fourteen ArchSci2020 PhD researchers – Manon Bondetti, Jack Dury, Tatiana Feuerborn, Alison Harris, Maiken Hemme Bro-Jørgensen, Theis Jensen, Aripekka Oskari Junno, Xénia Keighley Weber, Mariana Muñoz-Rodriquez, Madison Llewellin, Jonas Niemann, Anne Katrine Runge, Eden Slidel and Anne-Marijn Snaaijer-van Spelde. We supported one another every step of the way and I cannot express how grateful I am for all the support I got from all of you!

The materials studied in this research project came from different depots, museum and university collections in the Netherlands and also in Germany. A substantial part of this research was made possible thanks to the generous collaboration of the Dutch National Museum of Antiquities, Leiden University, the provincial depot for soil finds of Flevoland, and the depot of the province of Zuid-Holland in the Netherlands. I also thank to Florian Klimscha and the staff of the Landesmuseum in Hannover, Germany for their collaboration and help during the material selection and their transfer to Groningen and York with great care.

In the Netherlands, I would like to thank my colleagues at the Arctic Centre and the Groningen Institute of Archaeology at the University of Groningen, Eirik Haug Røe, Marjolein Admiraal, Frits Steenhuisen, Matilda Siebrecht, Sean Desjardins, Maarten Loonen, Annette Scheepstra, Gert J. M. van Oortmerssen, Miriam A. Los-Weijns, Erwin Bolhuis, and Sander Tiebackx for their great help and support throughout the project. I also thank to Mike W. Dee of the University of Groningen for his guidance and to Adriaan J. Minnaard, the head of the department of Chemical Biology at University of Groningen, and his team for welcoming me into their lab and giving me the necessary time and space to complete my sampling process in my first year at Groningen. I also would like to thank to Lucy Kubiak-Marten of Biax-Cosult for our very constructive conversations on different ways of understanding the ancient diet and for her contagious enthusiasm about archaeology and research.

In the UK, I would like to thank to all my colleagues and friends for making my stay memorable and successful, but especially to Matthew von Tersch, Helen Talbot, Harry Robson, and also Alizon Holland for their endless kindness, continued help, assistance and support during my secondment at BioArCh, University of York.

Special thanks also to my fellow ArchSci researchers and now very close friends Ari and Maddie for their continued support during the project, it has been great fun sharing an office with you! Thank you to Eirik Haug Røe for all the coffee breaks and long chats and Marjolein Admiraal for our long and fun discussions about archaeology and methodology. Also, I wish to thank Manon Bondetti not only for her constant help with all the methodological questions and data, but also for her continuous support and encouragement and her valuable friendship.

I also wish to give thanks to Marie-Henriette Gates of Bilkent University, Timothy P. Harrison of the University of Toronto, and Elif Denel of American Research Institute in Turkey for always feeding my curiosity and being my mentors in the field of archaeology. I could not have come this far if I did not have your guidance, support, and encouragement. I also thank to Matthew Harpster of Koç University for all the proofreading he did for me during my application process for this project and Setenay Erdoğan for opening her house to me and leaving me a wine glass full of chocolate so I can focus and successfully submit my application for this very project right before the deadline! Also, a very big thank you to Canan Çakırlar, Saliha Metinsoy, Sezen Kayhan, Ayşegül Erdem, Safoora Kamjan, Guro Linnerud Rolandsen, Ioannis Kontopoulos, Dimitri Teetaert and finally Nadia Adesoji for being there for me, listening to me, and supporting me.

One of my biggest thank you goes to my partner Yassir Rahouti! Thank you for your endless understanding, your kindness, your patience, and your support over the last three years! You have always been there for me, believed in me and cheered for me endlessly. Thank you for facing every

obstacle I brought home with a big smile on your face, for our happy and sad *halay* rituals, and of course for all the amazing food you have cooked for me so I could keep working. *The force is strong with you*.

Finally, I thank to my parents who taught me from a young age that knowledge is a strong and a fun tool to have in life. Thank you for always supporting me and encouraging me to pursue my goals and my dreams. I also thank to my sister Özlem who inspires me in every single day and reminds me that I got this. You are my rock and none of this would be possible without you!

Author`s declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References. The work carried out as part of this thesis has resulted in the following publications:

1- **Demirci, Ö.**, Lucquin, A., Craig, O. E., & Raemaekers, D. C. M. (2020). First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300–4000 BC). *Archaeological and Anthropological Sciences*, *12*(5), 105.

2- **Demirci, Ö.**, Lucquin, A., Çakırlar, C., Craig, O. E., & Raemaekers, D. C. M. (2021). Lipid residue analysis on Swifterbant pottery (c. 5000-3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process. *Archaeological Science: Reports,* 36(3), 102812.

3- **Demirci, Ö.**, Lucquin, A., Klimscha, F., Craig, O. E., & Raemaekers, D. C. M. Lipid residue analysis of ceramics from Hüde I (Lower Saxony, Germany): New data to understand the transition to farming. In Florian Klimscha, Marion Heumüller, Daan Raemaekers, Hans Peters & Thomas Terberger (eds.), *Stone Age Borderland Experience. Mesolithic and Neolithic Parallel Societies in the North European Plain (forthcoming)- Submitted.*

4- **Demirci, Ö.**, Robson, H. K., Lucquin, A., Andersen, S. H., Raemaekers, D. C. M.& Craig, O. E. Fusion cuisine: the impact of farming on hunter-gatherer culinary traditions in Northern Europe.

CHAPTER 1

Introduction

Pottery is one of the oldest human inventions that have been used worldwide from prehistoric times to the present for various utilitarian or non-utilitarian purposes, including storage, transportation of goods, processing and/or cooking (Rice 1987). Due to its low susceptibility to degradation (Schneider 2016), pottery is usually the best-preserved and the most common type of artefact found in archaeological contexts. Whilst its morphological and technological characteristics have traditionally been used to construct general chronologies between different cultures (Jordan and Zvelebil 2009; Damm 2012), studies on its possible use and importance have been providing information on the everyday lives of past cultures, human subsistence as well as culinary practices (Stilborg et al. 2002).

Pottery technology was initially thought to be a central component of the Neolithic package, first made by settled early farming communities in the Near East. It had been accepted as part of the cultural trait that was introduced, developed and spread together with agriculture and more sedentary lifestyle. However, this assumption has been discredited as the earlier examples of pottery, dating between 20,000 and 12,000 years cal BC, from Late Pleistocene mobile or semimobile hunter-gatherer contexts across northern Eurasia, in particular from East Asia - South China, Japan, and the Russian Far East, were abundantly discovered (Galili et al. 2002; Kubo 2004; Dolukhanov et al. 2005; Jordan and Zvelebil 2009; Wu et al. 2012; Craig et al. 2013; Hommel 2014; Jordan et al. 2016; Kuzmin 2017; Hommel, 2018). On the basis of evidence from these areas, it is now widely accepted that pottery production precedes the introduction of farming and has been abundantly present in the hunter-gatherer societies extending beyond Europe and the Near East.

The discussion on origins, adoption and dispersal of pottery in the hunter-gatherer societies have occupied a central place in archaeological debate for over a century as several regional case studies focusing on East Asia, North Africa, the Americas as well as Northern Europe have explored the emergence and dispersal of pottery technology (Bakels 2009; Hauzeur 2009; Piezonka et al. 2011; Oras et al. 2017; Lucquin et al. 2018; Bondetti et al. 2019, 2020; Kherbouche et al. 2016; Morisaki 2020; Admiraal et al. 2020)

As the invention of pottery introduced fundamental shifts in cooking practices and human subsistence, understanding the use of pottery in the hunter-gatherer contexts is required to understand the motivation of innovation and/or adoption of this new material culture into hunter-gatherer societies. Indeed, several studies have focused on the functional analyses of hunter-gatherer as well as early farmer pottery in Northern Europe to understand the reason behind adoption of, its use and its relationship to changing

subsistence strategies through time (Zvelebil & Dolukhanov 1991; Craig et al., 2007, 2011; Cramp et al. 2014; Povlsen, 2014; Robson 2015; Robson et al. 2018; Cubas 2019; Courel et al. 2020). Although, hunter-gatherer pottery in Northern Europe have been studied extensively, there has been a gap in terms of extensive and detailed research on pottery function of Swifterbant culture and its relation to neighbouring cultures, both hunter-gatherers and early farmers.

Swifterbant culture (c. 5000-4000/3400 cal BC) is a hunter-gatherer-fisher society located between the Scheldt valley (Belgium) and Lake Dümmer (Lower Saxony, Germany) (Raemaekers 1999; Amkreutz 2013). The research area of this thesis specifically focuses on the Swifterbant culture located in the Dutch Wetlands. In this region, pottery production was invented or adopted by the hunter-gatherer communities of Swifterbant culture from c. 5000 cal BC (Peeters 2010; Raemaekers 2011). The first evidence for the introduction of domesticated animals and cereals do not appear in the sequence until ca. 4500 and 4300 cal BC, respectively (Cappers & Raemaekers 2008; Out 2008; Çakırlar et al. 2020).

Unlike most other parts of Europe, the transition to farming in the Dutch Wetlands which started prior to that of neighbouring areas in northwest Europe, e.g. the British Isles and southern Scandinavia (e.g. Zvelebil & Rowley-Conwy 1986; Richards & Hedges 1999; Shennan 2018) did not necessarily lead to large-scale changes in material culture or economic practices in the Swifterbant culture. The data from the Swifterbant culture demonstrates a continuation of hunter-gatherer subsistence strategies alongside a gradual shift towards agricultural cultivation and domestic food production.

Studies on adoption of early pottery and it use suggest that although cooking was the primary techno-functional driver for pottery adaptation in the hunter-gatherer societies, the contents of these early pottery indicate substantial differences in the use of pottery which cannot be just explained by the subsistence economies and resource availability (e.g. Courel et al. 2020). This further indicate different processes and motives for the uptake of pottery. In the light of these, understanding the function of Swifterbant pottery and its relationship to subsistence strategies through the Neolithisation process in the Dutch Wetlands is necessary to further develop knowledge about what ceramics in this region were used for, and whether intra- and/or inter-regional variations occurred contributing to the previous discussions.

Aims and objectives

This thesis aims to examine the ceramic tradition of Swifterbant culture, by specifically establishing a well-illustrated functional classification of its pottery in attempt to investigate culture-specific responses towards regional resources. What was the function of Swifterbant pottery? Why was the drive behind its adoption into the culture? Was there any functional variation between the use of Swifterbant pottery?

To answer these main research questions, this study focused on several objectives. These are: 1) to investigate the research context and review existing literature on Swifterbant pottery to provide general information on the pottery tradition, its chronology, its distribution area, and the previous debates on its function; 2) Produce a new and extended dataset through lipid residue analysis to determine the pottery function and illustrate any possible functional variation across the Mesolithic-Neolithic transition in the Dutch Wetlands; and 3) to form a comparative discussion around the Swifterbant dataset specifically produced for this study and the late Ertebølle and early Funnel Beaker datasets to expand our understanding on regional differences of pottery use and its relationship to subsistence strategies through time in Northern Europe.

These objectives were addressed through a systematic application of lipid residue analysis of the pottery remains from eight archaeological sites in three different regions of Northwest European Lowlands dating to the 5th and early 4th millennium BC (Fig. 1). The findings are presented as four journal papers of which two are published, one accepted for publication and one drafted.

Thesis structure

This study starts with providing an overview on Swifterbant, Ertebølle, and Funnel Beaker pottery traditions as well as detailed explanation of the method of lipid residue analysis on ancient pottery (chapter 2).

The following three chapters form the three main case-studies of this study. The study of pottery use in the Swifterbant culture was approached through these three separate case studies, each focusing on different regions in North-western Europe (Fig. 1). In the first case-study (chapter 3), function of Swifterbant pottery from the three main Swifterbant type sites, S2, S3, and S4 (ca. 4300–4000 BC), in Oostelijk Flevoland, the Netherlands, was investigated through lipid residue analysis. The main aim is to understand the role of pottery in terms of its relation to hunter-gatherer-fisher lifestyle, and the change in available food resources brought about by the arrival of domesticated animal and plant products. For this study, a total of 62 sherds were sampled and subjected to lipid residue analysis. Results were published in the *Journal of Archaeological and Anthropological Sciences* under the title of *First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300–4000 BC).*

The second case-study (chapter 4) focuses on the functional analysis of Swifterbant pottery (c. 5000–3800 cal BC) from sites Hardinxveld-Giessendam Polderweg, Hardinxveld-Giessendam De Bruin, Brandwijk-het Kerkhof and Hazendonk in the Lower Rhine-Meuse area, the Netherlands. It aims to examine pottery use across the transition to agriculture and aims to assess temporal changes in human-animal relations during the 5th millennium BC in the Lower Rhine-Meuse area through lipid residue analysis. For this study, a total of 49 sherds were samples and subjected to lipid residue analysis. Results

were published in the J*ournal of Archaeological Science: Reports* under the title *of Lipid residue analysis on Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process.*

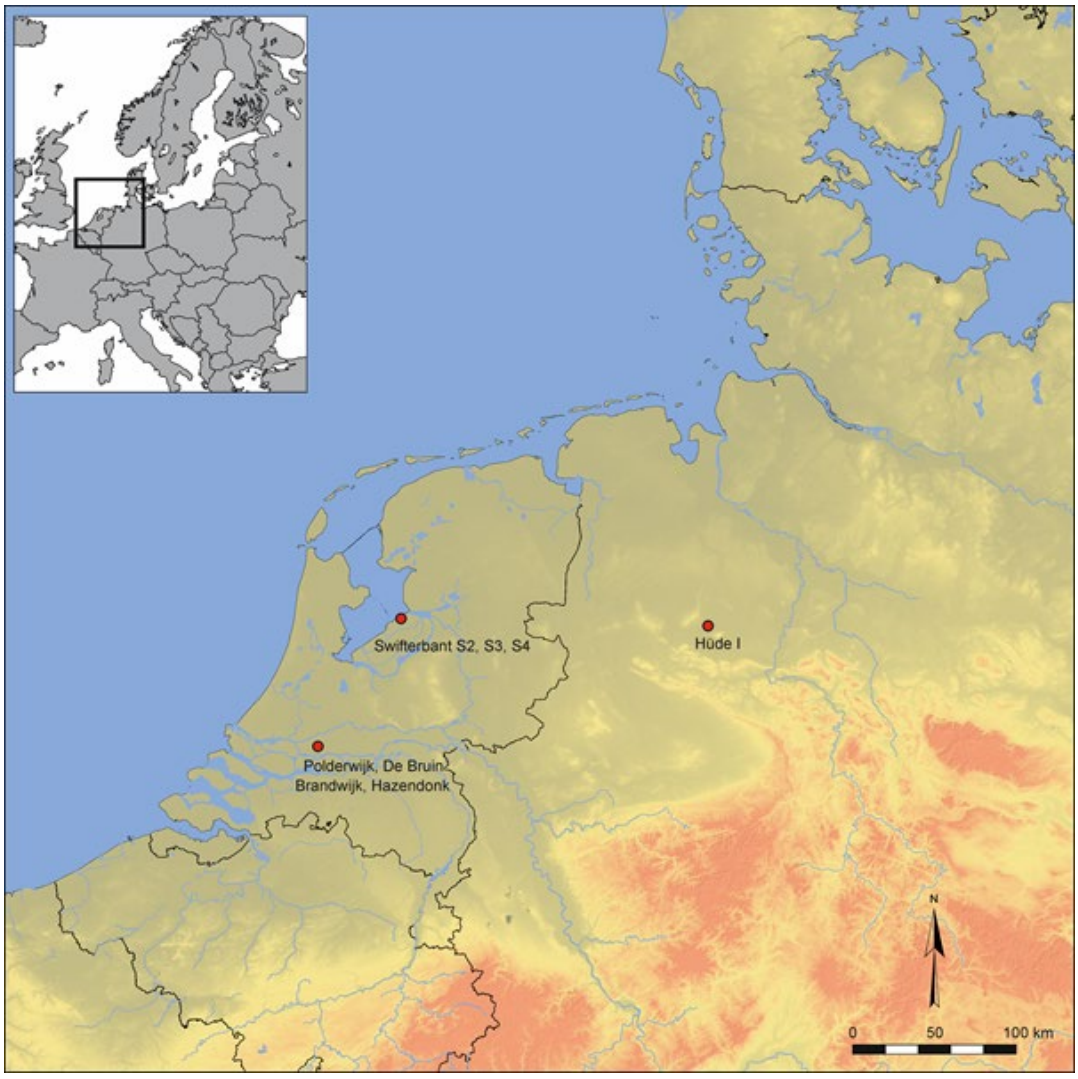


Fig. 1 Location of the studied archaeological sites: Swifterbant type sites S2, S3, and S4; Polderweg, De Bruin, Brandwijk, and Hazendonk in the Lower Rhine-Meuse area; and Hüde I in the Lower Saxony. Insert map showing the location of research area in relation to Europe

The third case-study (chapter 5) was designed as a pilot study aiming to question the use and function of the pots from Hüde I (4700-3500 cal BC), in Lower Saxony, Germany, while contributing to the discussion of the Mesolithic-Neolithic transition in Northern Europe. Due to its crucial position and its long occupation span in between the hunter-gatherer and farming communities, Hüde I has a key role in in reference to the transition from the Ertebølle culture to the Funnel Beaker culture in Southern Scandinavia and Northern Germany, but also in reference to the Swifterbant culture chronology that

spans the Mesolithic-Neolithic transition. For this study, a total of 35 sherds were sampled and analysed through lipid residue analysis. Results were accepted for publication in *Stone Age Borderland Experience. Mesolithic and Neolithic Parallel Societies in the North European Plain (forthcoming),* edited by Florian Klimscha, Marion Heumüller, Daan Raemaekers, Hans Peters and Thomas Terberger.

Chapter 6 of this study brings the entire Swifterbant dataset produced for this study together and compares it with late Ertebølle and early Funnel Beaker datasets with the aim of completing a diachronic comparison of pottery use across inland sites in the Dutch wetlands and Southern Scandinavia that encompasses the transition to farming. By comparing ceramic traditions, pottery use, animal bone assemblages and stable isotope data from human bones, this concluding chapter aims to answer two main questions: (1) Did Late Mesolithic foragers of Southern Scandinavia and the Dutch wetlands have similar uses of pottery? and (2) How did Late Mesolithic foragers respond to the arrival of farming? Results that are presented in this paper is in the preparation for submission to Journal of Anthropological Archaeology in the very near future.

Finally, the last chapter (Chapter 7) presents the overall conclusions on the functional analysis of Swifterbant pottery by providing an overview of the most important results of this study together with some implications for further research on Swifterbant pottery.

References

Amkreutz, L. W. S. W. (2013). *Persistent traditions: a long-term perspective on communities in the process of Neolithisation in the Lower Rhine Area (5500-2500 cal BC)*. Sidestone Press: Leiden. https://openaccess.leidenuniv.nl/handle/1887/22968.

Bakels, C. C. (2009). The Beginning: 5300 BC–4900 BC. In: Bakels, C. C. (ed.), *The Western European Loess Belt: Agrarian History, 5300 BC - AD 1000*. Springer Netherlands, pp. 29–54.

Cappers, R. T. J., and Raemaekers, D. C. M. (2008). Cereal Cultivation at Swifterbant? Neolithic wetland Farming on the North European Plain. *Current Anthropology*, *49*(3), 385–402.

Craig, O. E., Forster, M., Andersen, S. H., Koch, E., Crombé, P., Milner, N. J., Stern, B., Bailey, G. N., & Heron, C. P. (2007). Molecular and Isotopic Demonstration of the Processing of Aquatic Products in Northern European Prehistoric Pottery. *Archaeometry*, *49*(1), 135–152.

Craig, O. E., Steele, V. J., Fischer, A., Hartz, S., Andersen, S. H., Donohoe, P., Glykou, A., Saul, H., Jones, D. M., Koch, E., & Heron, C. P. (2011). Ancient lipids reveal continuity in culinary practices

across the transition to agriculture in Northern Europe. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(44), 17910–17915.

Craig, O. E., Saul, H., Lucquin, A., Nishida, Y., Taché, K., Clarke, L., Thompson, A., Altoft, D. T., Uchiyama, J., Ajimoto, M., Gibbs, K., Isaksson, S., Heron, C. P., & Jordan, P. (2013). Earliest evidence for the use of pottery. *Nature*, *496*(7445), 351–354.

Cramp, L. J. E., Evershed, R. P., Lavento, M., Halinen, P., Mannermaa, K., Oinonen, M., Kettunen, J., Perola, M., Onkamo, P., & Heyd, V. (2014). Neolithic dairy farming at the extreme of agriculture in northern Europe. *Proceedings of the Royal Society of London B: Biological Sciences*, *281*(1791), 20140819.

Courel, B., Robson, H. K., Lucquin, A., Dolbunova1, E., Oras, E., Adamczak, K., Andersen, S. H., Astrup, P. M., Charniauski, M., Czekaj-Zastawny, A., Ezepenko, I., Hartz, S., Kabaciński, J., Kotula, A., Kukawka, S., Loze, I., Mazurkevich, A., Piezonka, H., Piličiauskas, Sørensen, A. S., Talbot, H. M., Tkachou, A., Tkachova, M., Wawrusiewicz, A., Meadows, J., Heron, C. P., and Craig, O . E. (2020). Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter-gatherers. *Royal Society Open Science*, 7. https://doi.org/10.1098/rsos.192016.

Çakırlar, C., Breider, R., Koolstra, F., Cohen, K. M., and Raemaekers, D. C. M. (2020). Dealing with domestic animals in the fifth millennium cal BC Dutch wetlands: new insights from old Swifterbant assemblages. In: Gron, K.J., L. Sørensen, and P. Rowley-Conwy (eds.), *Farmers at the Frontier: A Pan-European Perspective on Neolithisation,* Oxbow Books, pp. 263–287.

Damm, C. B. (2012). From entities to interaction: Replacing pots and people with networks of transmission. In: Grünthal, R., Kallio, P. (eds.). *A linguistic map of northern Europe*. Mémoires de la Societé Finno-Ugrienne 266, The Finno-Ugrian Society, Helsinki, pp. 41–62.

Dolukhanov, P., Shukurov, A., Gronenborn, D., Sokoloff, D., Timofeev, V., & Zaitseva, G. (2005). The chronology of Neolithic dispersal in Central and Eastern Europe. *Journal of Archaeological Science*, *32*(10), 1441–1458.

Galili, E., Rosen, B., Gopher, A., Horwitz, L. K. (2002) The emergence and dispersion of the Eastern Mediterranean fishing village: evidence from submerged Neolithic settlements off the Carmel coast, Israel. *J Mediterr Archaeol* 15:167–198.

Hauzeur, A. (2009). First appearance of pottery in western Europe: the questions of La Hoguette and Limburg ceramics. In: Gheorghiu, D. (ed.), *Early Farmers, Late Foragers, and Ceramic Traditions:*

On the Beginning of Pottery in the Near East and Europe. Cambridge Scholars Publishing, pp. 167–188.

Hommel, P. (2014). Ceramic Technology. In: Cummings, V., Jordan, P. D., Marek, Z. (eds.). *The Oxford Handbook of the Archaeology and Anthropology of Hunter-gatherers*. Oxford University Press, pp. 663–693.

Hommel, P. (2018). What's the Point?: Globalization and the Emergence of Ceramic-using Hunter-gatherers in Northern Eurasia. In *Globalization in Prehistory: Contact, Exchange, and the "People Without History"* (pp. 15–42). Cambridge University Press.

Jordan, P. D., & Zvelebil, M. (2009). *Ceramics Before Farming: The Dispersal of Pottery Among Prehistoric Eurasian Hunter-Gatherers*. Left Coast Press.

Jordan, P., Gibbs, K., Hommel, P., Piezonka, H., Silva, F., & Steele, J. (2016). Modelling the diffusion of pottery technologies across Afro-Eurasia: emerging insights and future research. *Antiquity*, *90*(351), 590–603.

Kherbouche, F., Dunne, J., Merzoug, S., Hachi, S., & Evershed, R. P. (2016). Middle Holocene hunting and herding at Gueldaman Cave, Algeria: An integrated study of the vertebrate fauna and pottery lipid residues. *Quaternary International: The Journal of the International Union for Quaternary Research*, *410, Part A*, 50–60.

Kubo, Y. (2004). Reconsidering the geochronological and archaeological framework of the late Pleistocene-early Holocene transition on the Japanese islands. *Internationale Archaologie, Arbeitsgemeinschaft, Symposium, Tagung, Kongress*, *5*, 253–268.

Kuzmin, Y. V. (2017). The origins of pottery in East Asia and neighbouring regions: An analysis based on radiocarbon data. *Quaternary International* 441, 717–722.

Morisaki, K. (2020). What motivated early pottery adoption in the Japanese Archipelago: A critical review. *Quaternary International: The Journal of the International Union for Quaternary Research*. https://doi.org/10.1016/j.quaint.2020.10.006.

Oras, E., Lucquin, A., Lõugas, L., Tõrv, M., Kriiska, A., & Craig, O. E. (2017). The adoption of pottery by north-east European hunter-gatherers: Evidence from lipid residue analysis. *Journal of Archaeological Science*, *78*, 112–119.

Out, W. A. (2008). Growing habits? Delayed introduction of crop cultivation at marginal Neolithic wetland sites. *Vegetation History and Archaeobotany*, *17*(1), 131–138.

Peeters, H. (2010). Early Swifterbant pottery from Hoge Vaart-A27 (Almere, the Netherlands). In B. Vanmontfort, L. Amkreutz, L.P. Louwe Kooijmans & L. Verhart (Eds.), *Early Pottery Traditions in the Lower Rhine Area*. (pp. 151–160). Leiden: Leiden University Press.

Piezonka, H., Hartz, S., Lüth, F., & Terberger, T. (2011). The earliest pottery east of the Baltic Sea. *Early Pottery in the Baltic--Dating, Origin and Social Context*, 301–346.

Povlsen, K. (2014). The introduction of ceramics in the Ertebølle Culture. *Danish Journal of Archaeology*, *2*(2), 146–163.

Raemaekers, D. C. M. (1999). *The articulation of a "New neolithic"*. Dissertation University of Leiden.

Raemaekers, D.C.M. (2011). Early Swifterbant pottery (5000-4600 BC): research history, age, characteristics and the introduction of pottery. *Berichte Römisch-Germanische Kommission, 89*, 485-500.

Rice, P. M. (1987). *Pottery analysis. A sourcebook*, University of Chicago Press, Chicago.

Richards, M. P., & Hedges, R. (1999). A Neolithic revolution? New evidence of diet in the British Neolithic. *Antiquity*, *73*(282), 891–897.

Robson, H. (2015). *Evaluating the change of consumption and culinary practices at the transition to agriculture: a multi-disciplinary approach from a Danish kitchen midden*. Dissertation University of York.

Robson, H., Oras, E., Hartz, S., Kabaciński, J., Gumiński, W., Tielen, L., Akotula, A., Czekaj-Zastawny, A., Lucquin, A., Craig, O., & Heron, C. (2018). Illuminating the prehistory of Northern Europe: organic residue analysis of lamps. *Subsistence Strategies in the Stone Age, Direct and Indirect evidence for fishing and fathering,* 214–217.

Schneider, G. (2016). Mineralogical and Chemical Alteration. In: Hunt, A. (ed.). *The Oxford Handbook of Archaeological Ceramic Analysis.* Oxford University Press, pp. 162–180.

Shennan, S. (2018). *The first farmers of Europe. An evolutionary perspective*. Cambridge: Cambridge University Press.

Stilborg, O., Lindahl, A., Olausson, D. S., Carlie, A. (2002). *Keramik i Sydsverige: en handbok för arkeologer.* Keramiska forskningslaboratoriet. Lund.

Sørensen, L., & Karg, S. (2014). The expansion of agrarian societies towards the north – new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. *Journal of Archaeological Science*, *51*, 98–114.

Wu, X., Zhang, C., Goldberg, P., Cohen, D., Pan, Y., Arpin, T., & Bar-Yosef, O. (2012). Early Pottery at 20,000 Years Ago in Xianrendong Cave, China. *Science*, *336*(6089), 1696–1700.

Zvelebil, M. & P. Rowley-Conwy (1986). Foragers and Farmers in Atlantic Europe. In: Zvelebil, M. (ed.), *Hunters in Transition. Mesolithic societies of temperate Eurasia and their transition to farming* Cambridge: Cambridge University Press, pp. 67-93.

Zvelebil, M., & Dolukhanov, P. (1991). The transition to farming in Eastern and Northern Europe. *Journal of World Prehistory*, *5*(3), 233–278.

CHAPTER 2

Research context and methodology

This chapter consists of two main parts. The first part describes the relevant ceramic groups mentioned in this thesis and provides an overview of their time span, distribution areas, shape, and technology as well as function. They provide a general background to the material that had been discussed in the following chapters. The second part of this chapter introduces the core methods of lipid residue analysis on ancient pottery which will be used in this thesis. In addition, it aims to provide a series of baselines which will be used for interpreting the molecular and isotopic results produced for this thesis.

2.1. Hunter-gatherer and early farmer pottery in Northern Europe

2.1.1. Swifterbant pottery

Introduction to the Swifterbant culture

Swifterbant pottery is the earliest pottery in the western part of the North European Plain. It has been found in modern-day Netherlands, in the IJssel-Vecht-Eem area, Flevoland (e.g. site of J112 (Hogestijn 1991), Schokkerhaven-E170 (Raemaekers 2004), Schokland-P14 A-C (ten Anscher 2012; 2015), Urk (Peeters and Peeters 2001) and Swifterbant cluster sites, including S2, S3, and S4 (De Roever 1979; 2004; Raemaekers et al 2020)) and in the Lower Rhine-Meuse area (e.g. Zoelen-Buren (Hogestijn and Lauwerier 1992), Polderweg and De Bruin (Raemaekers 2001a, 2001b), Brandwijk and Hazendonk (Raemaekers 1999, 42, 61)) as well as in Belgium, in Scheldt area (i.e. Bavel, Bazel *Sluis*, and Doel-*Deurganckdok*) (Crombé et al. 2008; Teetaert 2020) and in north-western Germany, in Dümmer, Lower Saxony (i.e. Hüde I) (Kampffmeyer 1991). The earliest appearance of Swifterbant pottery is dated to c. 5000 cal BC. This date is based on large numbers of ^{14}C dates from the stratified river dune sites Polderweg and De Bruin, both located in Hardinxveld-Giessendam, the Lower Rhine-Meuse area, the Netherlands (Raemaekers 2001a, 2001b, 2011). In addition, the site Hoge Vaart-A27, located on a covered sandy ridge in Flevoland, the Netherlands, c. 100 km to the north of Hardinxveld-Giessendam, provides c.4900 cal BC as the earliest date for the introduction of pottery at the site (Peeters et al. 2001).

Swifterbant sites are inland sites, located in the wetland areas of the Netherlands and adjacent areas (Raemaekers and de Roever 2010). Coastal Swifterbant settlements are completely absent due to the erosion of the coastal zone, especially in the present-day coastline of the Netherlands, while the remaining coastal landscapes are buried under thick deposits, therefore not accessible (Raemaekers 2003). Zooarchaeological and archaeobotanical remains from several Swifterbant sites present a mixed

subsistence economy based on hunting wild animals, fowling and fishing (mainly freshwater and anadromous species) and gathering wild food plants (Clason 1978; Brinkhuizen 1979; Zeiler 1997, Table 3; Louwe Kooijmans 2003). In its younger phase, domesticated animals and cereals occur as well.

The earliest date for the arrival of domesticated animals in the Swifterbant culture comes from few sheep/goat (*Ovis aries/Capra hircus*) remains found at De Bruin in the Lower Rhine-Meuse area which are directly dated to 4520-4356 cal BC (Çakırlar et al. 2020). The earliest date for the arrival of domesticated pig (*Sus domesticus*) and cattle (*Bos taurus*) is, however, more difficult to determine and in need of more detailed zooarchaeological work from the entire spectrum of Swifterbant sites. The most reliable information regarding the earliest presence of domesticated pig and cattle comes from a recent study done by Çakırlar et al. (2020). Çakırlar et al. focus on the reconstructions of mortality patterns, body part representation, relative abundance and size as well as bone collagen isotope analysis of both Sus and Bos sp. remains from De Bruin and Brandwijk in the Lower Rhine-Meuse area and suggests the presence of a small-scale cattle herding at De Bruin (phase 3) and a small population of domesticated pig, possibly interbred with wild boar, at Brandwijk (layer L60). The NWO (=Dutch Research Council)-funded Project The Emergence of Domesticated Animals in the Netherlands (EDAN, 2020-2022) addresses the introduction of domesticated animals into the Swifterbant culture amalgamating zooarchaeology with high-resolution radiocarbon, stable isotope, and palaeogenomic analyses.

Introduction of cereal cultivation (emmer wheat [*Triticum turgidum ssp. dicoccum*] and naked barley [*Hordeum vulgare var. nudum*]) into the Swifterbant culture is dated to around 4300-4000 cal BC (Cappers and Raemaekers 2008; Out 2009). Presence of cultivated fields below the find layers at some of the Swifterbant sites such as S3 and S4 (Huisman et al. 2009; Huisman and Raemaekers 2014; Raemaekers and de Roever 2020), indicates a local small-scale cereal cultivation. This kind of mixed subsistence economy allows us to identify Swifterbant pottery as both hunter-gatherer and farmer pottery.

Shape and technology

Swifterbant pottery is characterised as S-shaped vessels with low or higher necks and pointed or rounded bases (Fig. 1). Bowl-shaped pots, typical of the Belgian Swifterbant culture, also occur but are less frequent (Crombé et al. 2005, 57; Crombé 2010; Teetaert 2020). Open forms appear to be the most common forms, but some examples with slightly curved inward rims from early Swifterbant examples are present and may be characterised as closed forms (Raemaekers and de Roever 2010; Raemaekers 2011). The most common rim diameter appears between 20 and 35 cm but few examples with smaller than 20 cm and bigger than 35 cm are also present. Wall thickness of Swifterbant pottery can show some variables but generally is between 8 and 11 mm, with the average of 9-10 mm.

Swifterbant pottery was constructed using coiling technique. It is important to note here that the terminology used in the Netherlands for the coiling technique does not match with the internationally used terminology, therefore need to be interpreted cautiously. In Dutch publications, the international term U-technique is referred to as H-technique and the international term Hb-technique is referred to as N-technique and Z-technique. Based on this, the H-technique used in northern Europe (to describe the Ertebølle pottery coiling technique) does not exist in Swifterbant pottery. In this study, the definition of the coiling technique was based on the international terminology (Stilborg and Bergenstråhle 2000).

While U-technique is the only coiling technique corresponding to the earlier Swifterbant vessels (e.g. Polderweg and De Bruin) (Raemaekers 2011), later pottery assemblages from the Swifterbant cluster sites in IJssel-Vecht-Eem area (e.g. S2, S3 and S4) present examples of U-technique (the most common one) and Hb-technique (De Roever 2004; Raemaekers 1999, 31). Swifterbant pottery is characterized as coarse pottery with mostly uneven surfaces. The surface treatment is rare but there are few examples with smoothed (possibly by wet fingers or with grass) or polished (with a pebble) surfaces (Raemaekers and de Roever 2010). In terms of decoration, Swifterbant pottery demonstrates a temporal variation between earlier and later pottery assemblages. The earlier Swifterbant pottery assemblages from Polderweg, De Bruin as well as Hoge Vaart-A27 are rarely decorated with occasional appearance of series of spatula impressions on the top of the rim (*Randkerbung*). Later pottery assemblages coming from Brandwijk and Hazendonk in the Lower Rhine-Meuse area, and from S2, S3 and S4 in the IJssel-Vecht-Eem area demonstrate a higher proportion of wall decorations which mostly consist of fingertip and/or fingernail impressions (Raemaekers 1999; De Roever 2004; Louwe Kooijmans 2010). In addition, one or two rows of elongated impressions on the neck or shoulder, on the top of the rim, or along the inside of the rim are also very common decoration features in the later Swifterbant pottery assemblages. Although the intensity of the decoration decreases on the latest Swifterbant pottery assemblages such as the pottery from Schokkerhaven in Flevoland (Hogestijn 1991), it is possible to see a continuation of both series of impressions on shoulder area and surface-covering decorations as well as rim decoration, restricted to outside of the rim (Raemaekers 2004). Handles are completely absent in Swifterbant pottery, but there are some examples with unperforated knobs in Doel-Deurganckdok (Sergeant et al. 2006) and Schokland-P14 assemblages (ten Anscher 2015). The main fabric inclusion material of Swifterbant pottery is plant material mixed with stone grit, but there are also occasional mixing with sand and/or grog. (De Roever 2004; Raemaekers and de Roever 2010). X-ray diffraction analysis showed that the pots were probably fired for a short period of time in an open fire, at a temperature below 600ºC, although the ones with grit and sand temper and with thinner walls were probably fired a little longer (de Roever 2009).

Function

Swifterbant pottery has been interpreted as storage vessels and cooking pots used in domestic contexts due to the presence of thick layers of carbonized food residues found on both interior and exterior surfaces of the vessels. There are few examples of complete pots found in depositional contexts such as the ones from the sites Bronneger (Kroezenga et al. 1991), De Bruin (Raemaekers 2001b) and Urk-E4 (Verneau 2001) suggesting a ritual function; however, the presence of carbonized surface residues on them also indicate cooking activities as the initial use of these pots (Raemaekers and de Roever 2010).

The first direct evidence for the function of Swifterbant pottery comes from the analyses of carbonized surface residues of 11 vessels from the site Doel-Deurganckdok, Sector B and J/L, layers associated with Swifterbant culture (Craig 2004; Craig et al. 2007). The analyses were done by the applications of Elemental Analysis Isotope Ratio Mass Spectrometry (EA- IRMS) and Gas Chromatography-Mass Spectrometry (GC-MS). EA- IRMS analysis provided $\delta^{13}C$ (between −26 and −28.5‰) and $\delta^{15}N$ values (between +6 and +10) that are consistent with freshwater fish for all samples (see Craig et al. 2007). Based on the molecular analysis on the lipid extractions, also done on the carbonized surface residues, three samples from Sector B indicated presence of aquatic biomarkers (Craig et al. 2007, Table 1), while two samples from Sector J/L yielded trace amounts of fatty acids and β-sitosterol, possibly indicating presence of terrestrial (animal and plant) products being processed in the vessels (Craig 2004, Table 2). Due to the low concentration of fatty acids in these two samples, however, it was not possible to determine the origins for the terrestrial products. The combination of these results suggests that the Swifterbant vessels from Doel-Deurganckdok were used for processing freshwater fats (most probably freshwater fish) which may also be mixed with fats from terrestrial (animal and/or plant) products.

Another direct evidence on the function of Swifterbant pottery comes from a study that was based on the applications of two different methodologies: the scanning electron microscope (SEM) and direct temperature-resolved mass spectrometry (DTMS) on the carbonized surface residues of 25 vessels from the Swifterbant site S3 (Raemaekers et al. 2013). SEM analysis by Lucy Kubiak-Marteens identified emmer chaff epidermis, stem and leaf tissues of green vegetables, starch granules of indeterminable plant species, fish scales and indeterminable animal bones in 16 of the analysed carbonised food residues, suggesting that these food resources were processed and cooked in the Swifterbant pottery together or consecutively. DTMS analysis on the same material was carried out by Tania F. M. Oudemans and presented 17 residues containing protein remains. The analysis showed the presence of proteinaceous material which could originate from terrestrial animals, fish, birds, shellfish as well as certain edible plant materials (i.e. in pulses, seeds and in some roots or sprouts), although the latter occur in low concentrations. The chemical characterisation of charred proteins provides a complex DTMS spectra and therefore it does not allow to determine the exact origin of the proteinaceous material detected in the sample. As a result, it was not possible to give specific origins for the detected animal

and/or plant proteins through this analysis. However, DTMS analysis was also able to detect the lipid profiles of the samples which indicated presence of terrestrial animal and plant oil in few samples with total absence of ruminant dairy fats. The combination of these results with the SEM analysis clearly indicates that the vessels from S3 were used to cook fish and/or meat mixed with green vegetables or cereals.

The most recent direct analysis of the function of Swifterbant pottery focuses on the pottery production in the Scheldt area, Belgium (Teetaert 2020). One part of this study is based on the applications of Elemental Analysis Isotope Ratio Mass Spectrometry (EA- IRMS) and stereo microscope analysis on the carbonized surface residues of 22 Swifterbant vessels from the site Bazel Sluis. While EA- IRMS analysis done by Mathieu Boudin demonstrated that majority of the samples have $\delta^{13}C$ (<−25 ‰) and $\delta^{15}N$ (between +6‰ and +10‰ or higher) values consistent with freshwater fish (see Craig et al. 2007), stereo microscope analysis done by Dimitri Teetaert yielded visible fish remains (fin rays, bones, scales) in six of the same samples, clearly indicating that these vessels were used for processing freshwater fish.

The end of the Swifterbant pottery tradition

While the start of the Swifterbant culture is clearly illustrated with the appearance of its earliest pottery at c. 5000 cal BC, its disappearance and its possible transition to the Funnel Beaker culture is still a subject to an on-going debate, mainly due to the near lack of archaeological sites from the period 4000–3400 cal BC. In the Lower Rhine-Meuse area, the final phase of Swifterbant pottery culture is marked by the appearance of so-called Hazendonk pottery at around 3700/3600 cal BC, presenting mixed characteristics of Swifterbant and Michelsberg pottery cultures (Louwe Kooijmans 1974, 1976; Raemaekers et al. 1997; 1999, 112). In the IJssel-Vecht-Eem area, Flevoland, however, final phase of Swifterbant pottery culture was not replaced by another pottery group but gradually transformed into the early Funnel Beaker pottery culture starting from c. 4300-4000 cal BC (Raemaekers 2012, 2015; ten Anscher 2012, 2015).

As ten Anscher (2015) proposes, by c. 4000 cal BC, the pottery from the Swifterbant site Schokland-P14 layer B, located in the IJssel-Vecht-Eem area, starts to present technological and morphological characteristics similar to those of the Funnel Beaker culture (TRB) North Group pottery. He calls this stage the Pre-Drouwen TRB phase, dated to c. 3900–3400 cal BC. Layers C-E from Schokland-P14 are interpreted as Pre-Drouwen phase, as most ceramics finds are with round or rectangular impressions below the rim or on the shoulder, or with perforations below the rim, indicating signatures of both Funnel Beaker and Swifterbant pottery cultures (Raemaekers and De Roever 2010; ten Anscher 2015). Based on this, ten Anscher (2015) argues that the Pre-Drouwen TRB style pottery originates in the late Swifterbant pottery and presumably spreads also to northern Germany at around 4000 cal BC. The

appearance of TRB Pre-Drouwen style pottery in Swifterbant contexts is also argued to be linked with the appearance of the thin-walled, well-fired, grit tempered ceramics in Swifterbant S3 (c. 4300-4000 cal BC) (Raemaekers 2015). Raemaekers (2015) proposes that this is a technological shift towards Funnel Beaker culture ceramics which is closely associated with the introduction of cereals into the culture at around the same time.

2.1.2 Ertebølle pottery

Introduction to the Ertebølle culture

Ertebølle pottery is a hunter-gatherer-fisher pottery that appears in the southwestern Baltic area, some hundreds of years before the introduction of agriculture (Rowley-Conwy 2004; Fischer 2002; Andersen 2010). It has been found in southern Scandinavia (modern-day Denmark and southern Sweden), Poland, and northern Germany (Schleswig-Holstein and Mecklenburg-Vorpommern, Brandenburg Havelland), although the area of distribution in Germany is still not fully established (Klassen 2002, 2004, 27). The earliest appearance of Ertebølle pottery comes from Denmark and is dated to 4800-4600 cal BC at both coastal and inland settlements (corresponding to the middle Ertebølle period) (Mathiassen 1935; Hartz and Lübke 2006; Andersen 2010, 2011; Hartz 2011). Although previous dates from the carbonized surface residues (foodcrusts) collected from the inland site of Schlarmersdorf LA 5 suggested an earlier date, as early as end of 6th millennium BC, for the first appearance of Ertebølle pottery in the inland site of Schleswig-Holstein (Hartz et al, 2000, 140; Klassen 2004, 109), it has now been shown that these data are unreliable due to a significant freshwater reservoir effect originating from the recycling of old calcium carbonates that are dissolved with the groundwater (Philippsen et al. 2010). Current earliest dates for this area match those from Denmark (ca. 4700 cal BC) indicating a rapid dispersal of pottery in the region (Hartz and Lübke 2006; Andersen 2011; Kotula et al. 2015). There is no ^{14}C dating of early Ertebølle pottery from Zealand and Scania (the eastern group of Ertebølle culture) and therefore the dates on the onset of pottery production in these areas are based on the comparisons to the finely dated typologies coming from western Danish sites, leaving the synchronism of the pottery phenomenon at both areas open to discussion (Andersen 2010, 2011; Jennbert 2011).

The Ertebølle culture is mostly known by large coastal shell midden sites which were occupied either on a year-round basis or seasonally, functioning as fowling, hunting or fishing stations (Gjessing 1955; Rowley-Conwy 1983). The information on inland settlements is more limited but present, especially in the Åmosen region of Sjælland, Denmark with several inland Ertebølle sites (Andersen 1983; Noe-Nygaard 1983; Fisher 1993). Zooarchaeological remains recovered from the numerous excavated sites indicate that hunting wild terrestrial mammals, fowling and fishing both marine and freshwater species as well as gathering wild foodplants were the main aspects of the Ertebølle subsistence (Kubiak-Martens 1999; Piezonka et al. 2011; Kriiska 2017). The evidence for the presence of domesticated plants and

animal products in the Ertebølle contexts is restricted to the few cereal imprints on ceramic vessels from Löddesborg and Vik in Scania (Koch 1998; Jennbert 2011) and few bone remains of domesticated cattle and pig in northern Germany (Krause-Kyora et al. 2013; Rowley-Conwy and Zeder 2014). Therefore, they were considered absent in the main Ertebølle subsistence. These bones from domesticated animals may suggest interactions between inhabitants of the Ertebølle culture and the neighbouring farming communities such as post-Linear Band cultures in the South (e.g. Stichbandkeramik, Rössen) (Terberger et al. 2009; Sørensen 2014). The idea of pottery making may have been also adopted through contacts with these southern neighbours (Povlsen 2014), however, without the morphological features of the local farming pottery as Ertebølle pottery has no clear morphological similarities with the contemporary pottery of nearby communities (Klassen 1997).

Shape and technology

Ertebølle pottery is characterized by two main vessel forms, pointed-based vessels and oblong bowls, also known as "blubber lamps" (Fig. 2) (Prangsgaard 1992). The pointed-based vessels are known from all over the Ertebølle area and are generally characterised by conical shaped open forms with pointed bases. They appear in four different sizes and are predominated by the largest examples (Andersen 2011). The profile is either a sharp S-shaped (more common in south Jutland; Andersen 2011, 196) or cylindrical without any marked transition from neck to body (more common in north Jutland; Andersen 2011, 196). The rim is often everted, but straight rim profiles and incurving rims are also present (Povlsen 2014). The bases can vary spatially within the same settlement or regionally without showing any chronological distinction (Prangsgaard 1992; Glykou 2010). One good example for spatial variation of bases is the site of Neustadt LA 156 in Schleswig-Holstein where four different base shapes (pointed end, conical shaped, rounded and smaller but sharp pointed end) have been identified (Glykou 2010).

Ertebølle pottery is characterized by its coarseness and thickness. The wall thickness of pointed-based vessels varies between 5 to 27 mm which may, in some occasions, correspond to different coiling techniques (H, N, or U) different time spans and/or different regions. The typical Ertebølle coiling technique is often what is known as H technique (Andersen 2010); however, there are also examples of thicker sherds which present techniques other than H (U and N) (e.g. Soldattorpet in western Scania; Stilborg and Bergenstråhle 2000). In addition, settlements with a clear stratigraphic sequence demonstrate that there can be gradual change in wall thickness through time. While the oldest layers produce the thickest sherds, sherds get thinner towards the younger layers (Andersen 1975, 57). On a regional scale, the difference in wall thickness varies from east and northeast regions (north-eastern part of Denmark and Scania) with relatively thick sherds to southwest regions (south-western parts of Denmark) with clearly thinner sherds (Andersen 2011).

Decoration on Ertebølle pottery is very rare and generally consists of small, isolated spatula impressions on the top of the rim which are believed to have appeared only at c. 4500-4400 cal BC (Andersen 2011). There are also rare appearances of geometric patterns or incised fishnet motifs covering the upper part of the body. The examples of these comes from a number of sites in east central Jutland as well as Scania and northern Germany (Andersen 2010; Brinch Petersen 2011). Features like handles, knobs and lugs are completely absent. The raw material of the point-based Ertebølle vessels is clay tempered with feldspar (2-7 mm) with rare addition of sand and quartz which are consistent with the geology of the area, indicating local production. Based on the experimental studies, it is assumed that they were fired in an open fire at temperatures ranging from 600-800 °C (Hulthén 1977, 42).

Ertebølle pottery also includes what are known as lamps: oblong bowls which were probably used to burn blubber (Prangsgaard 1992; Heron et al. 2013). In comparison to the pointed-based vessels, bowls seem to have a more restricted distribution. They appear in both coastal and inland locations in Denmark as well as northern Germany (e.g. Schleswig-Holstein) but there are no examples coming from northern Jutland (Andersen 2011; Hartz 2011). Due to the lack of earlier examples in the earliest phase of adaptation to pottery, the bowls are explained as a later phenomenon which came into the picture a couple of centuries after the pointed-based vessels and were mostly associated with coastal sites (Andersen 2010; Brinch Petersen 2011).

Ertebølle bowls have an elongated outline with smooth and rounded rim, rounded or flat bottom on the inside and round or pointy ends on the outside. Some vessels are decorated with fingernail impressions (Andersen 2009, 2010). The two edges of the bowls do not always give the exact same profile. They vary in shape and size. The width can vary between 2 to 15 cm and the length between 8 to 30 cm. The wall thickness is generally between 15 and 30 mm. The raw material of bowls differs from what has been used for the pointed-based vessels. It is fine calciferous clay mixed with organic materials in addition to either crushed stone or grog. They were either built by coiling or from a lump of clay (Van Diest 1981) which do not indicate any regional and temporal variability (Andersen 2011). The bowls show a high degree of reuse as many have breaks covered with charred crusts indicating continued use (Andersen 2011).

Function

In terms of the function of the pointed-based vessels, the initial assumptions had been based on the shape and the presence of carbonized surface residues (foodcrust) on both interior (mostly near the bottom) and exterior (on the rim) surface of the pots, indicating storage and cooking activities. Several point fragments from pointed-based vessels were found *in situ* in hearths (Andersen and Molmros 1985) supported at least one part of the hypothesis and clearly indicated that pointed-based vessels were used for cooking activities in domestic contexts. The microscopic analysis of the charred residues on the

pointed-based vessels showing occasional presence of fish scale and fish bone fragments (Andersen and Molmros 1985; Glykou 2011) was taken as a clear indication of the vessel use. These assumptions were carried to a more concrete level by the application of lipid residue and carbon isotope analyses on the residues coming from inland and coastal Ertebølle sites. The results of these analyses showed that pointed-based vessels from both coastal and inland sites had a broad range of functions including processing of aquatic resources, both marine and freshwater, and terrestrial animal products (Craig et al. 2007; Philippsen et al. 2010; Heron et al. 2013; Heron and Craig 2015; Papakosta et al. 2019; Courel et al. 2020). Additionally, a recent study done by Courel et al. (2020) demonstrated possible processing of dairy products in four late Ertebølle vessels, two from Grube-Rosenhof and another two from Neustadt LA 156, both in Schleswig-Holstein, northern Germany, contributing to the debate of possible interactions and exchange between hunter-gatherer and farming communities in this region.

Oblong bowls of Ertebølle culture have been interpreted as blubber lamps burning animal fat, used for cooking, heating or illumination. This was firstly argued by Mathiassen (1935) based on their similarity to the soapstone or ceramic lamps of the Arctic Inuit and also their oily interior surface with deposited carbonized remains. Mathiassen`s argument was supported by animal fat traces found in the clay by Hulthén (1977) and the experimental analysis done by van Diest (1981). Van Diest made tests on the reconstructed lamps using seal blubber and a moss wick and as a result, he managed to get patterns of sooting and burnt deposits that are consistent with those observed on Ertebølle lamps. Similarly, a lipid residue analysis was carried out on an Ertebølle lamp from the site of Grube-Rosenhof, Northern Germany, indicating presence of aquatic oils (van Diest 1981). Another analysis done on the extracted lipids from an Ertebølle lamp from the site of Agernæs, Denmark showed a mixture of marine and terrestrial resources being processed in these lamps (Richter and NoeNygaard 2013). Finally, the lipid residue analysis carried on lamps from both inland and coastal Ertebølle sites reported that marine organisms had been processed in several Ertebølle lamps from coastal sites, whilst an Ertebølle lamp from the inland site at Åkonge, Denmark was consistent with terrestrial and/or freshwater resources (Heron et al. 2013).

Pointed-based vessels and lamps of Ertebølle culture disappeared around 4000 cal BC which also marks the beginning of the Funnel Beaker culture (Meurers-Balke and Weniger 1994; Andersen 1993; Fischer 2002). Continued use of the lamps into the Early Neolithic, however, was assumed based on the excavation data from sites like Siggeneben-Süd and Åkonge, where it is difficult to separate the stratigraphic layers from the Late Ertebølle and Funnel Beaker culture (Sørensen 2014). A lamp from Polish site Dąbki 9 which had decorations that are similar to the ones found on early Funnel Beaker vessels supported the argument of continuation of lamps into the earliest part of Funnel Beaker culture (Czekaj-Zastawny et al. 2011).

2.1.3. Funnel Beaker pottery

Introduction to the Funnel Beaker culture

Funnel Beaker pottery is pottery produced by farming groups in northern Europe in the 4th millennium BC. It has been found in southern Scandinavia, Denmark and Central Sweden as well as northern Germany (sites in Schleswig-Holstein such as Rosenhof, Siggeneben-Süd and Südensee-Damm (Satrup)) with western extensions in the modern-day Netherlands and eastern extensions in modern-day Poland (e.g. Sarnowo phase at the site of Redecz Krukowy; Wstępne 2012) (Müller 2011). The earliest appearance of Funnel Beaker pottery in Denmark is dated to 3950 BC (Fischer 2002; Hartz and Lübke 2006; Glykou 2011) while the earliest dates from northern Germany is between 4300 and 3900 BC, based on the ^{14}C dates coming from flake cores and scrapers found together in a pit filled with short-necked funnel beakers at the site of Flintbek in Schleswig-Holstein (Zich 1993; Jansen et al. 2013). There are also absolute dates coming from the inland site of Bebensee and the coastal site of Wangels, both in northern Germany. The pottery from Bebensee dates the earliest Funnel Beaker pottery to 4130-3970 cal BC (Hoika and Lübke 2000) while carbonised surface residues collected from Wangels indicates 4100-3800 cal BC for the appearance of earliest Funnel Beaker pottery at the site (Hartz et al. 2002).

The Funnel Beaker culture, traditionally abbreviated TRB after the German term *Trichterbecher Kultur*, replaces both the Ertebølle culture (Andersen 1993; Fischer 2002) and Swifterbant culture (Raemaekers 2012; ten Anscher 2012, 2015; ten Anscher et al. 2013). Based on the zooarchaeological and archaeobotanical remains found in several Funnel Beaker sites, cereal cultivation with domesticated plants including emmer and einkorn wheat and naked and hulled barley (Koch 1998) and animal husbandry, domesticated cattle, pig, sheep, and dog, were part of the subsistence economy. In the area of the Ertebølle culture, the appearance of Funnel Beaker pottery is contemporary with the earliest agrarian evidence in many parts of northern Europe (Klassen 2004; Sørensen 2014), corresponding to the distribution of cereals and domesticated animals into the region (Hallgren 2008, 2011).

Shape and technology

Funnel Beaker pottery is associated with a great variety of forms which include flat-based beakers, bowls and flasks (Koch 1998) as well as new forms such as clay spoons and discs (Fig. 3) (Klassen 2004). Based on varying size and decoration styles of Funnel Beaker pottery, specifically flat-based beakers, there have been different typologies suggested. The typology by Eva Koch, most commonly accepted and used in Funnel Beaker typology, suggested that there are three main beaker groups. The A-group (Oxie/type 0-I) is characterized by short-necked beakers. The B-group (type II and III) contains beakers with a medium height and many local decoration styles and the C-group (type IV and V) is characterized by beakers with longer necks and vertical lines on the belly of the vessels (Koch 1998).

^{14}C dates coming from the contexts of short-necked funnel beakers (type 0 and I) or from the carbonized surface residues of them date to 4000-3800 cal BC and beakers with a medium-height neck (type II and III) to 3800-3600 cal BC whereas dates for beakers with a longer neck (type IV and V) indicates 3600-3300 cal BC (Koch 1998).

Funnel beaker pottery is characterised by its higher quality compared to the pottery of the Ertebølle and Swifterbant cultures. The body parts were built by coiling technique in which coils were placed on a clay disk forming the flat base. The diameter of the coils is directly correlated with wall thickness of the vessels and ranges from 10 to 15 mm (Hulthén 1977; Koch 1998). The rim diameter of the funnel beakers varies from smaller (5-6 cm) and medium (10-15 cm) to larger (15-20 cm) vessels while the medium sized beakers appear to be the most common ones (Koch 1998). Early Neolithic funnel beakers (c. 4000-3800 cal BC) are characterized by having a simple decoration just below or on the top of the rim (Koch 1998). They present regular and high tempering density. The most common tempering material is crushed granite although some funnel beakers from Early Neolithic sites show presence of only fine sand (Nielsen 1984; Skousen 2008).

Function

Funnel Beaker pottery played a significant role in the domestic activities and served as cooking pots, although they were also found in burials and intentional depositions along with other sacrificial materials (Koch 1998). The lipid residue analyses of Funnel Beaker vessels from coastal or lake shore sites showed that they were used for the processing of marine and freshwater resources (Craig et al. 2011), while Funnel Beaker vessels from the inland site of Skogsmossen in Västmanland, Sweden presented a somewhat different pattern in term of vessel use and indicated evidence for the processing of a wide range of foodstuff such as aquatic resources, terrestrial animals, dairy products and possibly plants (Isaksson and Hallgren 2012). A further analysis on Funnel Beaker vessels from Neustadt (LA 156), a coastal site in northern Germany, demonstrated that there is a preference in the use of vessel types; small cup-sized beakers (rim diameter <15cm), as well as bowls and flask were used for processing dairy products and larger vessels were preferred processing aquatic resources and terrestrial animals (Saul et al. 2014).

2.2. Lipid residue analysis on ancient pottery

2.2.1. Application of Lipid Residue Analysis

Lipid residue analysis, included in biomolecular analysis (Brown and Brown 2013), is a robust method used for identifying food remains that would otherwise have been invisible in the archaeological record. It has been extensively applied to archaeological studies to understand the adaptation and functional

variation of pottery (Charters et al. 1993; Gregg et al. 2009; Debono-2012; Craig et al. 2013; Taché and Craig 2015; Lucquin et al. 2016; Bondetti et al. 2019; Courel et al. 2020; Demirci et al. 2020; Junno et al. 2020), to determine the original contents of vessels (Patrick et al. 1985; Evershed et al. 1991; Malainey et al. 1999; Hansel et al. 2004; Craig et al. 2007; Robson et al. 2018), and to contribute to the discussion of the ancient diet, culinary practices and subsistence economy (Copley et al. 2004; Evershed et al. 2008b; Craig et al. 2011; Robson et al. 2019; Cubas et al. 2020).

Studies focusing on the analysis of chemical characteristics of organic residues in archaeological vessels have started with the development of an applicable methodology and the use of Gas Chromatography (GC) and Gas Chromatography-Mass Spectroscopy (GCMS) in the early 1990s (Evershed et al. 1991,1992; Oudemans and Boon 1991; Oudemans 2007; Evershed 2008). It slowly developed into an established discipline with the addition of different and innovative applications such as stable isotope analysis conducted by Gas Chromatography -Combustion- Isotope Ratio Mass Spectrometry (GC-C-IRMS) and Elemental Analysis-Isotope Ratio Mass Spectroscopy (EA-IRMS). This chapter focuses on the lipid residue analysis on ancient pottery in direct relationship with this study.

2.2.2. Definition of organic residues

Organic residues are a wide range of amorphous organic materials from natural substances found in archaeological contexts (Heron and Evershed 1993). The term “organic” corresponds to materials that are mainly composed of carbon, hydrogen, oxygen and nitrogen such as DNA, carbohydrate, lipids and proteins (Evershed 1993; Dunne 2017). Amorphous materials, lacking morphology, cannot be characterised with a visual examination unlike other biological materials such as bones, wood, leather, textiles, seeds, and pollen. Hence, organic residues describe all soft-materials without morphological structures such as pitches, waxes, fats, milk, resin or materials derived from other anthropogenic processes like vegetable tars, wines, beer, waxes, oils (Heron and Evershed 1993; Regert 2011). By the application of lipid residue analysis, it is possible to extract chemical information of the organic substances which may have been stored, processed and/or cooked in the archaeological pottery. Besides the foodstuff, these organic substances can also originate from materials that are used as part of the specific manufacturing processes (e.g. tar, pitch) and/or surface treatments (e.g. resins, tars and bitumen) of pottery. They can also originate from the use of fuels or wicks burned in lamps (Copley et al. 2005).

Organic residues survive in three main forms in association with archaeological pottery. They are: (1) actual contents preserved *in situ* as vessel fills, (2) carbonized surface residues (foodcrusts) appearing as visible residues on the exterior and/or interior surfaces of vessels and (3) absorbed residues preserved within the porous structure the vessel wall, invisible to the naked eye and can survive for thousands of

years (Heron and Evershed 1993; Evershed 2008). The absorbed residue is the most commonly occurring in pottery. Their widespread occurrence, their protected nature, their survival over long archaeological timescales and the fact that they can provide an integrated record of lifetime of use of the vessel from which they derived from allows us to chemically analyse them.

2.2.3. Molecular analysis

2.2.3.1. Lipids

Lipids are organic compounds which are required by all living organisms to satisfy several biological functions including structural, metabolic and physiological processes and energy stores and they can often be traced in archaeological materials (Evershed 1993; Heron and Evershed 1993; Gurr et al. 2002; Malainey 2012). They are composed of carbon, oxygen and hydrogen and structured as linear, branched and cyclic carbon skeletons which are substituted with hydrogen atoms (Evershed 1993). Lipids are defined as having low solubility in water which reduces their loss from artifacts by water leaching and can only be extracted with non-polar organic solvents (Evershed 1993; Malainey 2012). Although physico-chemical conditions (e.g. pH, redox potential, temperature, dry vs waterlogged environment, biomass) at the original site of deposition may alter the structure of lipids, therefore may affect the designation of their origins, due to their hydrophobicity and resistance to decay, lipids can be used as biomarkers to identify ancient residues in archaeological research (Evershed 1993; 2008a). Lipids include different classes of organic compounds such as fatty (carboxylic) acids and derivatives, triacylglycerols (TAGs), sterols, waxes, and terpenes (Christie 2010; Malainey 2012).

Fatty acids

Fatty acids are a type of carboxylic acid with hydrocarbon chains ranging from 4 to 36 carbons in length in which the range between 12 to 24 carbons are the most common appearing in plant and animal food sources (Dudd 1999; Christie 2010; Malainey 2012). They are the central components of lipids; therefore, a fundamental ingredient of food. Fatty acids vary as saturated fatty acid (contains single bond) and unsaturated fatty acid (contains at least one double bond). Those that have only one double bond are called mono-unsaturated fatty acids, while the ones with multiple double bonds are polyunsaturated fatty acids. In the shorthand convention, designation of fatty acids consists of three components: Cx:yωz. While “Cx” indicates the fatty acid with x number of carbon atoms, “y” refers to the number of double bonds and “ωz” to position of the double bond respectively (Christie 2010; Malainey 2012). The majority of fatty acids cannot be found as isolated molecules called free fatty acids but rather combined with other molecules and most often appear as part of triacylglycerols (Malainey 2012).

Triacylglycerols (TAGs)

Triacylglycerols (TAGs) are the predominant lipid components animal and plant organisms produce: fats and oils (Oudemans 2007; Malainey 2012; Debono-Spiteri 2012). They exist in biological systems as energy stores. In food fats and oils, fatty acids (n = 3) are esterified to glycerol molecules resulting in triacylglycerols. The nature and the position of the glycerol skeleton, whether the three fatty acids forming the TAGs are all the same or different, can be informative about the TAGs` original sources (Evershed 2008). Monoacylglycerol (MAGs) and diacylglycerol (DAGs) which are formed by breaking the ester bond (by the hydrolysis process) have one or two fatty acids respectively (Gunstone 2004).

Sterols

Sterols are defined as structural lipids occurring in cell membranes (Voet and Voet 2011; Malainey 2012). They are minor components of animal and plant lipids (Evershed 1993). Being a specific kind of alcohol that serve as precursors to a variation of steroid products with different biological activities, differences in sterols can be recognized as an indicator of its origin; therefore, used as biomarkers to identify the ancient residues (Evershed et al. 1991; Evershed 1993; Malainey 2012). Cholesterol is the main sterol found in animal tissues (animal fats, fish and marine oils and fats) (Evershed et al. 1991; Evershed 1993; Heron and Evershed 1993; Dudd 1999; Malainey 2012; Debono-Spiteri 2012). It also occurs in plant tissue but only an insignificant amount (Deman 1999). Lanosterol is another sterol which may also occur in animal fat in small amounts. Phytosterols, including β-sitosterol, stigmasterol and campesterol are found in plants (Evershed et al. 1991; Evershed 1993; Heron and Evershed 1993; Malainey 2012; Debono-Spiteri 2012). Another indicative sterol is ergosterol which occurs mainly in eukaryotic microorganisms such as algae, yeast, mould, and fungi (Dudd 1999; Weete et al. 2010; Malainey 2012) and is a potential indicative for alcohol fermentation in lipid residues from prehistoric pottery (Isaksson et al. 2010).

Wax esters

Waxes are mainly found in animals and plants. They are formed by living organisms of a long-chain alcohol (between 16 and 30 carbons) linked to long-chain fatty acids (ranged from 14 to 36 carbons; saturated/unsaturated) by an ester linkage (Cristie 2010; Malainey 2012). Waxes created by different organisms present distinct and individual compositions and they are relatively resistant to decay over time (Evershed 1993). This allows them to be used as biomarkers for identifying ancient residues. Lipids found in organic residues from vessels that might originate from food products include natural waxes (beeswax) and waterproof coatings on the outer surface of the plants (epicuticular waxes) against water loss through evaporation.

Terpenes

Terpenes are important components for essential oils and dominantly found in plants. They are derived from the polymerization of isoprene (C_5H_8). Terpenes can be found in linear or cyclic form and are classified by two or more five-carbon structures known as isoprene units. As they are differentiated by the number of carbon atoms present in their structure, mono-, sesqui-. di-, and triterpenes, associated with 10, 15, 20, and 30 carbon atoms respectively, can be determined (Connolly and Hill 1991; Malainey 2012). These separate compositions of terpenes are related to their plant source which allows them to be used as effective biomarkers for identifying ancient residues.

2.2.3.2. Sampling

Sample selection for lipid residue analysis on pottery is one of the primary stages of the research and it mainly depends on the research question(s) of the study. It is important to start with establishing a well-functioning sampling strategy which is properly adjusted according to the objectives of each study and also based on the availability, accessibility, quantity and quality of the material.

Depending on whether selection is made from freshly excavated material or museum collection, studies should seek to collect samples from:

- Sherds coming from secure contexts and if possible, contexts that are already dated. In terms of working on the functional variation of the pottery, the secure context information provides a basic introduction for the possible functions of the vessels. Pottery coming from mixed or disturbed contexts make it harder to correlate the results of residue analysis as well as the spatial use of the settlement.
- Sherds that are less processed, preferably the ones that have no glue, nail polish or writing on them to avoid contamination. If it is known that the pottery will be used for residue analysis at the excavation stage, it should be collected separately with a sample of surrounding soil it was buried in and should be packed/stored in a dry, dark and cold atmosphere without any cleaning. The surrounding soil may also be analysed and used as a control sample to detect of burial contamination in lipid residue analysis, when possible.
- Sherds that are big enough to be drilled into and can produce ~2 grams of pottery powder (1 gr for each extraction method discussed below) without losing any of their specific morphological and typological characteristics for further research.
- Sherds represent the pottery variation of the site and/or context they are coming from. This depends on whether the research is based on site-scale functional variation or if it focuses on a particular pottery assemblage and/or form.

Due to the limitation on clear contextual information in all Swifterbant sites and the high fragmentation of the Swifterbant material, in this study, the sampling strategy for all three case studies (Chapter 3, 4 and 5) was based on the combination of availability and quality of the material. In all three case studies, the sample size was consisted of individual vessel fragments that provided different typological and morphological features and are large enough to be sampled. Any vessel fragment that is not big enough to provide its specific morphological and typological characteristics was left out. This kind of sampling strategy resulted differences in the sample size for each site and therefore eliminated any possible application of statistical analysis on the Swifterbant dataset produced for this study.

2.2.3.3. Lipid extraction methods

There are two main extraction methods that have been commonly used for sample preparation for the lipid residue analysis. The first method is solvent extraction, a mixture of chloroform ($CH\text{-}Cl_3$) or dichloromethane and methanol ($CH_3\text{-}OH$) in which lipids dissolve (Craig et al. 2004; Jansen et al. 2006). Solvent extraction can be used to recover the usual classes of lipids including fatty acids, acylglycerols, long-chain ketones, wax esters, n-alkanols and n-alkanes deriving from animal fats and/or plant oils and waxes.

The second method is one-step methanol/sulphuric acid extraction (Craig et al. 2013; Correa-Ascencio et al. 2014). This protocol allows us to recover a greater quantity of lipids, unsaturated fatty acids as well as diacids and hydroxyacids (Correa-Ascencio and Evershed, 2014). Due to this, in this study, one-step methanol/sulphuric acid extraction method was used as the main extraction method for all the absorbed lipid samples. One of the challenges of acid extraction is the loss of information concerning the complex lipids such as triacylglycerols and wax esters which hydrolyse during the process. Nevertheless, the presence of n-alkane, visible in the acid extraction results, can suggest the presence of waxes. If that is the case, solvent extraction can be carried out to test the presence of wax esters and acylglycerols in the sample (Correa-Ascencio et al. 2014). The minimum amount of pottery powder required for each of these extraction methods is usually 1 g. Absorption of lipids by the ceramic fabric will not be homogenous throughout the wall of the vessel, therefore taking samples from different portions of the vessel (rim, shoulder, body or base) may yield additional information (Charters et al. 1995; Stern et al. 2000).

2.2.3.4. Identification of Compounds and Biomarkers Using GC–MS

Molecular analysis of the lipid extractions is done by the Gas Chromatography Mass Spectrometry. Gas chromatography (GC), coupled with mass spectrometry (MS), separates and measures the individual molecules in a compound on the basis of their physical behaviour. All the major classes of lipids in

biological materials can be identified and separated on a GC by comparing retention times with known standards (Evershed 1992a) but before solid residues from potsherds can be analysed, preserved compounds must be released from the fabric of the pottery fragment to which they are bound. Because different compounds often share similar molecular components that vary only to a small degree, mass spectrometry provides confirmation of the identification and the separation of the compounds that are required for the study of biomarkers through the use of gas chromatography (Evershed 1992b; Barnard et al. 2007). It also provides increased efficiency and reliability in the identification of complex mixtures. The high sensitivity which is obtained by GC and GCMS allow us to get detailed results from the analysis of archaeological materials, especially when the amounts of samples are limited. GC and GCMS allows us to get the quantification of specific lipid biomarkers in total lipid extracts (Evershed 1993).

Definition of archaeological biomarkers

Biomarkers are organic compounds associated with "chemical fingerprints", corresponding to specific carbon structures or distributions of molecules which enable the biological source of the residue to be identified with a high accuracy and provide information related to human activity in the past (Evershed 1993; 1999; 2008a; Regert 2011; Malainey 2012). In archaeology, the biomarker concept is an idea that is borrowed from organic geochemistry and palaeontology which was used to establish the nature of biomolecular components in ancient sediment deposits (Evershed 1993; 2008a; 2008b; Evershed et al. 1999; Regert 2011). The source of the archaeological biomarkers is determined by comparing the properties of individual compounds or mixture of compounds present in the sampled material, in our case ancient pottery, to those occurring in the reference materials such as contemporary plants and animals.

Biomarkers for aquatic food products

Aquatic fats are identified by the presence of high abundances of long-chain mono- and polyunsaturated fatty acids (PUFAs) ($C_{16:1}$, $C_{18:1}$, $C_{20:1}$, $C_{22:1}$, $C_{20:5}$, and $C_{22:6}$), saturated fatty acids ($C_{14:0}$, $C_{16:0}$, and $C_{18:0}$), and specific isoprenoid acids (IPAs) (Hansel et al. 2004; Brown and Heron 2005; Gunstone et al. 2007; Craig et al. 2007; Evershed et al. 2008a; Regert 2011; Cramp and Evershed 2014). These fatty acids go under chemical and biological degradation during the vessel use and/or post-depositional burial. PUFAs are highly subjected to oxidation during vessel use and burials; therefore, they often do not survive in archaeological residues (Craig et al. 2007; Evershed et al. 1992; 2008; Cramp and Evershed 2014). However, being subjected to thermal degradation during the use of the vessel, PUFAs form stable compounds which are called *ω*-(*o*-alkylphenyl)alkanoic acids with 16 to 22 carbon atoms (APAAs) (Hansel et al. 2004; Cramp and Evershed 2014). They are known to be formed during the heating of tri-, di-, and/or monounsaturated fatty acids of the corresponding carbon length at high temperatures (≥200 ^{o}C, 5h (Bondetti et al. 2020). They often provide direct evidence for processing aquatic products due to

their survival in archaeological residues (Copley et al. 2004; Craig et al. 2007; Evershed et al. 2008a). It is important to note here that PUFAs C_{18} and C_{20} occur not only in aquatic oils but also in terrestrial adipose and vegetable fats (Hansel et al. 2004; Evershed et al. 2008a; Bondetti et al. 2020). Therefore, presence of APAAs C_{18} and C_{20} in archaeological residues cannot be directly used to detect the aquatic origin by themselves (Heron and Evershed 1993; Evershed et al. 2008a) but have to be combined with the presence of APAA-C_{22} as PUFA-C_{22} is present at higher abundance in aquatic oils and therefore can be used an indicator for processing aquatic (marine and freshwater) food resources in archaeological pottery (Bondetti et al. 2020).

Although the presence of APAA-C_{20} cannot be directly used to detect the aquatic origin by itself, a recent experimental study (Bondetti et al. 2020) shows that the abundance of APAA-C_{20} (obtained by the integration of the *m/z* 318 ion) in aquatic products is much greater than those detected in other foodstuffs. As the ratio of APAA-C_{20} to APAA-C_{18} (APAA C_{20}/C_{18}) in aquatic products appears to be notably high (the lowest detected ratio for aquatic products is 0.06) compared to both terrestrial animals and terrestrial plants. Therefore, this ratio can be also applied as a useful criterion to distinguish aquatic products from the other foodstuff processed/cooked in the vessels.

Other biomarkers also characterized as biomarkers for aquatic fats and oils are specific isoprenoid acids (IPAs) such as TMTD (4,8,12,trimethyltridecanoic acid), phytanic acid (3,7,11,15,tetramethylhexadecanoic acid), and pristanic acid (2,6,10,14,tetramethylpentadecanoic acid) (Ackman and Hooper 1970; Copley et al. 2004; Hansel et al. 2004; Craig et al. 2007). These biomarkers are resistant to degradation due to their highly branched chemical structure (Cramp and Evershed 2014). While TMTD is present only in aquatic environments, phytanic acid also occurs in terrestrial animals; however, in very low concentrations (Copley et al. 2004; Heron and Craig 2015). Therefore, phytanic and pristanic acids can be only considered as aquatic biomarkers when they occur along with TMTD (Copley et al. 2004; Corr et al, 2008; Cramp and Evershed 2014). In addition, the ratio of 3S,7R,11R,15-phytanic (SRR) and 3R,7R,11R,15-phytanic acid (RRR) has been used to distinguish the two phytanic sources which vary between organisms and are related to dietary predecessor (Lucquin et al. 2016). As the SRR/RRR ratio has been found to be higher in aquatic resources compared to ruminant products, SRR % >75.5% is used to indicate the presence of aquatic food sources in archaeological pottery.

Biomarkers for terrestrial animal fats

Animal fats include various fats coming from different nature and origin such as subcutaneous fats of cattle, sheep, goats, pigs, dairy products, and marine environment. They are composed of high degree of triacylglycerols (TAGs) (over 95%), holding mostly even numbers of carbon atoms ranging from C_{40} to C_{54} (Evershed et al. 1997a; Dudd 1999; Regert 2011). Differentiating animal fats based on their

molecular characteristics has been proposed by checking triacylglycerols distribution, distribution of fatty acids with branched and odd carbon number components, composition of monounsaturated fatty acids, and stable carbon isotope values of $C_{16:0}$ and $C_{18:0}$ (Evershed et al. 1997a; Mottram et al. 1999).

The distribution of triacylglycerols in fresh adipose fats can provide information on the origin of the animals, such as ruminant, non-ruminant fats and dairy products (Dudd and Evershed 1998; Dudd 1999; Regert 2011; Malainey 2012). In ruminant adipose fats, triacylglycerols ranges from C_{42} to C_{54} for bovine and C_{44} (in trace amounts) to C_{54} (for ovine); in adipose fat originated from non-ruminant species -porcine-, from C_{44} to C_{54} with very low presence of C_{44}, C_{45}, and C_{48}; and in dairy products, from C_{28} to C_{54} due to the presence of short-chain fatty acids (Dudd et al. 1998; 1999; Copley et al. 2005a; Mukherjee et al. 2007). Despite the presence of clear criteria that present distribution of triacylglycerols, it is crucial to note here that triacylglycerols are heavily subjected to degradation (Evershed et al. 2002a; Evershed 2008; Dudd and Evershed 1998; Regert 2011); therefore, should be approached with caution.

Fatty acids are another class of biomolecular constituents which appear in animal adipose fats in high amounts; therefore, can be used to detect origin of fats. They are formed by degradation of triacylglycerols over time or during cooking activities (Evershed 2008; Regert 2011). Palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids are the two main free acids present in animal fats (Dudd and Evershed 1998). The ratio between $C_{16:0}$ and $C_{18:0}$, also called as P/S ratio has been calculated to differentiate origins of animal fats as ruminant adipose fats have a P/S ratio <1 and it tends to be >1 for non-ruminant origins (Romanus et al. 2007; Regert 2011; Baeten et al. 2013).

Furthermore, branched fatty acids with carbon atoms 15 ($C_{15:0}$) and 17 ($C_{17:0}$) are also detected in ruminant fat adipose in high amounts (Evershed et al. 1997a; Dudd et al. 1999). While these fatty acids are formed in the ruminant gut by bacterial synthesis; therefore, can be an indication for ruminant adipose fat, they also widely occur in nature and their appearance in archaeological residues must be approached by suspicion (Evershed 1993; Dudd et al. 1998; 1999). The ratio between $C_{17:0}$ (branched-chain) and $C_{18:0}$ has also been calculated to differentiate origins of animal fats, separating ruminant from non-ruminant and also from dairy fats (Dudd et al. 1999). Although the separation is clear between dairy fats and ruminants, as dairy fats tend to have higher $C_{17:0}$ (branched-chain) / $C_{18:0}$ ratio compared to non-ruminant and ruminant adipose fats, due to possible mixing activities in archaeological pottery, the separation may not be clear enough to identify specific origins of animal fats.

Biomarkers for dairy products

Lipids of undegraded fresh milk is primarily composed by triacylglycerols (TAGs) ranging from C_{26} to C_{54} acyl carbon atoms, holding fatty acids between C_4 and C_{20} (Evershed 1993; Dudd et al. 1998; Dudd

and Evershed 1998; Dudd 1999; Jensen 2002; Copley et al. 2005). Although it is possible to separate dairy fats from adipose fats due to the presence of high abundance of short chain fatty acids (ranging from C_4 to C_{12}) present in degraded milk products (Evershed 1993; Dudd and Evershed 1998; Copley et al. 2003), it has been proven difficult to positively identify dairy fats in archaeological residues due to compositional alteration during burial (Evershed 1993; Dudd and Evershed 1998; Dudd et al. 1998).

Short-chain fatty acids (ranging from C_4 to C_{12}) exist in dairy products and are affected by enzymatic or chemical hydrolysis degradation processes during the processing of the milk fats or during burial (Dudd et al. 1998; Copley et al. 2003). Compared to long-chain fatty acids, they have much more water soluble and volatile structure and therefore they often do not survive this hydrolysis degradation process and become undetectable in archaeological residues (Dudd and Evershed 1998; Copley et al. 2003). In addition, by this degradation process, the lipid structure in milk indicates a shift to which also resembles adipose fat by producing free monounsaturated and saturated fatty acids, predominantly $C_{14:0}$. $C_{16:0}$, and $C_{18:0}$ (Dudd et al. 1998; Copley et al. 2005a). Therefore, although the presence of short-chain fatty acids is an indication of dairy, it is not an absolute evidence of milk. It is important to mention here that the absence of short-chain fatty acids is never an absolute evidence of absence of dairy in the pots.

Biomarkers for plant products

Plant oils are predominantly formed by triacylglycerols (TAGs) (Evershed 1993; Copley et al. 2005b). They contain relatively more mono-, di-, and tri-unsaturated C_{18} fatty acids compared to animal fats (Baeten et al. 2013). However, they are not always evident in archaeological residues due to their low resistance to degradation processes, primarily through oxidation (Evershed 1993; Dudd et al. 1998; Regert et al. 1998).

Plant waxes (epicuticular waxes) are long-chain alkyl compounds formed by plants as waterproof coatings on the outer surface against water loss through evaporation (Evershed 1993; Malainey 2012). These fully saturated compounds are relatively repellent of decaying over archaeological time; therefore, relative proportions of individual components can be used to differentiate the origins of the wax (Evershed 1993; Baeten et al. 2013). The main component for identification of plant waxes is long chain n-alkanes with carbon atoms C_{21} to C_{37} (Baeten et al. 2013). The distribution of n-alkanes in plant waxes have predominantly odd-over-even carbon numbers which can be also used to determine the plant types they were originated from (Dunne et al. 2012; Bush and McInerney 2013). For instance, predominance of n-alkanes C_{27} and C_{29} appear to be the indicators for woody plants and n-alkane C_{31} is for grass (graminoids) (Bush and McInerney 2013).

Although they may also be derived as a result of intensive heating of adipose fats, linear long-chain alkenones (also known as mid-chain ketones) can be an indicator for higher plants (vascular plants) and

bacteria (Raven et al. 1997; Dudd 1999; Baeten et al. 2013). The origin of these compounds can be distinguished by their carbon number distribution, simultaneous appearance of related mid-chain alkanols and alkanes, and position of the carbonyl group (Evershed et al. 1995; Raven et al. 1997; also see Baeten et al. 2013). Terpenoids are also mainly found in higher plants (Dudd 1999).

Cereals provide low lipid content, and they are highly subjected to degradation through cooking or during burial (Colonese et al. 2017; Hammann and Cramp 2018). As a result, they are very difficult to detect through lipid residue analysis (Hammann and Cramp 2018). Nevertheless, there are some compounds which can be identified as cereal grain biomarkers such as a series of phenolic lipids, also known as alkylresorcinols (ARs). ARs are 3,5-dihydroxy-phenolic lipids with an odd numbered alkyl chain ranging between C_{15} to C_{25}. They are only found in the outer parts of wheat, rye, barley, and triticale and do not occur in any food plants (Ross 2012). They are also not destroyed during food processing (Ross et al. 2003). Therefore, ARs can be used as potential biomarkers for cereal foods, especially for wheat and rye (Ross et al. 2003; Ross 2012; Ziegler et al. 2015; Colonese et al. 2017). The ratio between C_{17} and C_{21} can be used to differentiate wheat from rye (approx. 0.1 vs 1.0 respectively) or observe a mixture of both (Ross 2012).

Plant sterols such as stigmasterol, campesterol, and b-sitosterol are also biomarkers indicating the presence of plant products in archaeological pottery (Evershed et al. 1991; Evershed 1993). Although they do not provide detailed information on the plant species, they occur as the most common steroids (phytosterols) in vascular plants (Baker 1982; Harwood and Russell 1984; Bianchi 1995). They often do not survive due to their low presence in plant tissues (Heron and Evershed 1993).

2.2.4. Isotopic analysis

The detection and identification of lipid biomarkers in archaeological vessels allow us to investigate nature, origin, and transformations of lipid residues. However, the degree of preservation, degradation and alteration might be limiting to fully understand them. Therefore, calculations of the ratio of stable carbon and nitrogen isotopes (^{13}C, ^{12}C, ^{15}N, ^{14}N) have been used as an additional criteria for fully identifying organic residues absorbed by the archaeological pottery (Hastorf and DeNiro 1985; DeNiro 1987; Evershed et al. 1994; Evershed 2009).

2.2.4.1. Compound-specific stable isotope analysis

By the mid-1990s, carbon isotopes, examined by the Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry (GC-C-IRMS), have been started to be used to determine the $\delta^{13}C$ values of individual components in lipids extracted from archaeological pottery, addressing the questions

concerning the source of the lipids and the function of pottery (Evershed et al. 1994; 1999). Separation of compounds by Gas Chromatography (GC) and then combustion in online reactor (C) -which is connected to the mass spectrometer (IRMS)- to carbon dioxide (CO_2) allows to measure relative abundance ratio of the $^{13}C/^{12}C$ from individual biochemical components (Matthews and Hayes 1978; Evershed et al. 1994; Evershed 2009).

N-alkanoic acids $C_{16:0}$ (palmitic acid) and $C_{18:0}$ (stearic acid) are mainly focused molecules in isotope analysis of archaeological residues due to their stable carbon isotope compositions which is resistant to degradation; therefore, commonly observed in archaeological pottery (Evershed 2008b; 2009). Plotting the $\delta^{13}C$ values of the $C_{18:0}$ and $C_{16:0}$ collected from archaeological residues against the isotopic measurements of modern reference material (coming from terrestrial and aquatic animal tissues) allow to differentiate the origins of animal fats extracted from archaeological residues. It is, however, important to note that, the carbon isotopic measurements coming from the modern reference data have to be corrected for the burning of fossil fuels since the 19th century that has introduced more ^{12}C to ^{13}C in the atmosphere to make it comparable with the archaeological data (Evershed et al. 1997; Spangenberg et al. 2006; Regert 2011; Lucquin et al. 2016).

Detecting and separating ruminant adipose fats (coming from deer, cattle/aurochs, sheep/goat) from non-ruminants (pig/wild boar) has been one of the main subjects of Compound-Specific Stable Isotope Analysis (CSIA) of lipids (Evershed et al. 1997a; 2002a, 2002b; Dudd and Evershed 1998; Dudd 1999). The separation is based on the specific digestive systems of ruminant and non-ruminant animals. Plant lipids consumed by ruminants undergo a substantial transformation in the rumen such as triacylglycerol hydrolysis and biohydrogenation of unsaturated fatty acids, while they are subjected to less complex transformation when they are consumed by non-ruminant animals (Harfoot 1981, also see Copley et al. 2003). This leads to a differentiation in the incorporation of lipids by ruminant and non-ruminant animals and also clear distinction of $\delta^{13}C$ values between them.

Stable isotope analysis has also been used as an alternative approach to detect ruminant dairy fats in archaeological residues and distinguish them from adipose fats (Dudd and Evershed 1998; Copley et al. 2003; 2005). The $\delta^{13}C$ $C_{16:0}$ of dairy fats has been proven to be higher than the $\delta^{13}C$ $C_{18:0}$ values because the mammary gland can biosynthesize $C_{16:0}$ but is unable to biosynthesize $C_{18:0}$ and therefore obtains the $C_{18:0}$ from the unsaturated fatty acid component of dietary plants ($C_{18:1}$, $C_{18:2}$, and $C_{18:3}$) (Copley et al. 2003). Therefore, the comparison of $\delta^{13}C$ values of fatty acids extracted from the archaeological materials to modern reference collections coming from the fats of animals raised on strict C3 diets make it possible to distinguish the dairy lipids in the archaeological residues (Copley et al. 2003; 2005; Malainey 2012). In dairy fats, the $\delta^{13}C$ values of the $C_{18:0}$ fatty acid is 3-3.7‰ lighter than the $\delta^{13}C$ values of the $C_{16:0}$ component (Copley et al. 2003; Craig et al. 2005).

Identifying aquatic resources and their origins has been another important subject to stable isotope analysis (Craig et al. 2007; 2011; 2013; Olsson and Isaksson 2008; Heron et al. 2013; Cramp and Evershed 2014; Taché and Craig 2015; Papakosta et al. 2019). Aquatic systems present wide variation in carbon isotope values based on their diversified habitats such as marine, freshwater and brackish. There are also species living in both ecosystems: anadromous, born in freshwater but live mostly in marine (e.g. salmon) and catadromous, born in marine but live in mostly fresh water (e.g. eel). Therefore, they may lead to an overlap in the process of identification. Nevertheless, it is possible to identify marine fats due to a gradual rise in $\delta^{13}C$ values in saline environments. In fact, marine fats appear to be isotopically more enriched in ^{13}C compared to the ^{13}C values of $C_{16:0}$ and $C_{18:0}$ obtained not only from freshwater organisms but also from terrestrial animals, apart from non-ruminant fats where there is often an overlap (Craig et al. 2007; Regert 2011; Cramp and Evershed 2014; Robson et al. 2016).

Unlike others discussed above, detecting modern plant oils through stable isotope analysis has been problematic as their $\delta^{13}C$ $C_{16:0}$ and $C_{18:0}$ values found to form a tight cluster while widely overlapping with the freshwater and ruminant adipose fats (Steele et al. 2010).

Calculation of $\Delta^{13}C$, the difference between the $\delta^{13}C$ values of the $C_{18:0}$ and $C_{16:0}$ fatty acids is another way to provide information on the origin of fat (Dudd and Evershed 1998; Dudd et al. 1998; Evershed et al 1999.; Copley et al. 2003; 2005a). Although $\delta^{13}C$ values are often affected by different environmental conditions and based on the animal diet (Evershed et al. 2002b), $\Delta^{13}C$ values do not change based on diet; therefore, provides reliable separation between origins of fats (Evershed 2009). While $\Delta^{13}C$ values that are higher than −1.1‰ indicate non-ruminant adipose fats, $\Delta^{13}C$ values that are between −1.1‰ and −3.3‰ are associated with ruminant adipose fats and $\Delta^{13}C$ values that are lower than −3.3‰ are with ruminant dairy products (Copley et al. 2005b; Evershed 2009; Craig et al. 2012). It is important to note here that these values come from domesticated animal tissues; therefore, might not match with wild ruminant adipose values. While wild ruminant carcass fats have a wide range of $\Delta^{13}C$ values, between −2.7‰ and −4.3‰, the minimum reported value for domesticated ruminant adipose fats is −3.0‰ (Craig et al. 2012). These are the values that are applied throughout this study.

Overall, $\delta^{13}C$ values allow to distinguish the ruminant and non-ruminant fats, dairy, and aquatic products. It is; however, important to note here that the $\delta^{13}C$ values of the $C_{18:0}$ and $C_{16:0}$ fatty acids collected from modern reference material may vary based on the specific diets of the animals and/or effects of different climates in different environments. Therefore, the selection for the modern reference material should be done with caution, being as similar as possible regarding the environmental and regional context of the studied archaeological material.

In this thesis, isotope values obtained from authentic modern tissue samples collected from Western Baltic was used to generate the freshwater fish, marine, porcine, ruminant adipose and ruminant dairy adipose ranges (Fig. 2.1). These ranges will be used to plot the isotopic results produced for this thesis. The reference data collection for each resource group was listed in Table 1 and presented at the end of this chapter.

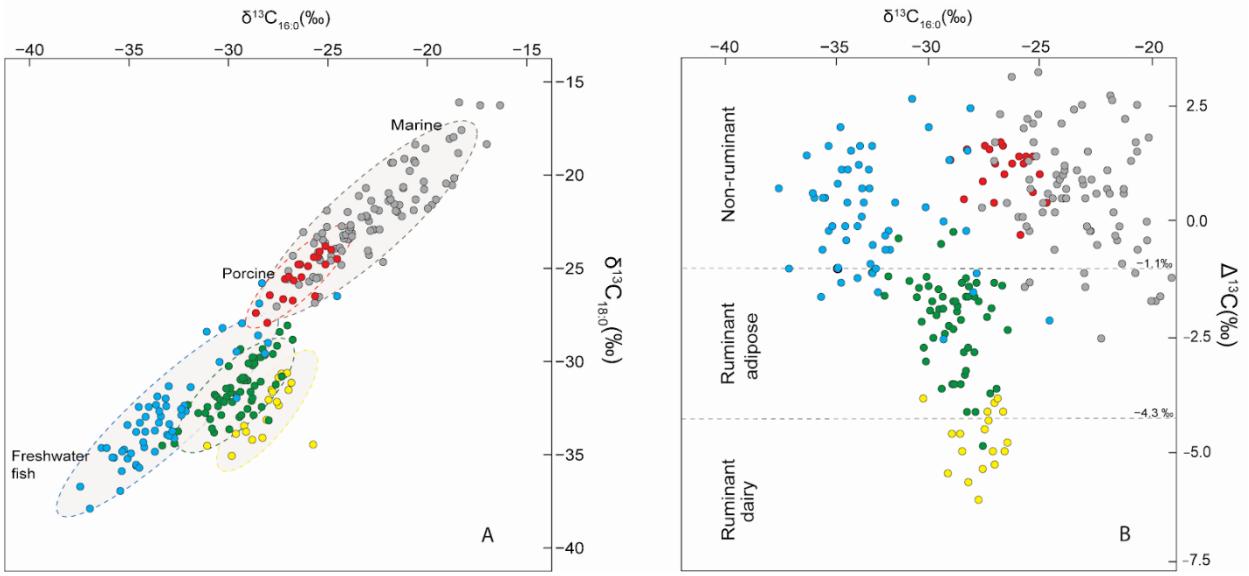


Fig. 2.1 (A) Compound specific isotope values of C16:0 and C18:0 fatty acids of modern tissue from Western Baltic plotted in 95% confidence ellipses; (B) compound specific isotope big data differentiating between non-ruminants, ruminant adipose and ruminant dairy fats (ref). Marine tissues are marked in grey, porcine in red, freshwater fish in blue, ruminant adipose fats in green, and ruminant dairy fats in yellow.

2.2.4.2. Bulk carbon nitrogen isotope ratio of carbonized surface residues (foodcrusts)

This method is used to determine isotopic composition of carbonized surface residues found on archaeological pottery. Carbonized surface residues can be formed as a result of some foodstuffs being exposed to high temperatures during the processing and/or cooking activities, either through direct contact with fire or when exposed to too much heat inside the cooking container (Heron and Craig 2015). They are found on the interior and/or exterior surface of the archaeological pottery and their analysis can provide valuable information concerning pottery use.

Bulk carbon and nitrogen isotope ratio mass spectrometry determines the isotopic ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of the bulk material and provides more quantitative (less qualitative) information on the composition of the foodcrust (Craig 2004). Experiments with modern reference samples collected from different foodstuff show that measurements of $\delta^{13}C$ and $\delta^{15}N$ and C and N concentrations in burnt

food crusts are reasonably consistent with values expected from those in the original uncooked foodstuff (Philippsen 2013), therefore, allowing us to identify them. The bulk $\delta^{13}C$ isotope values of food crusts are used to identify C_3 plants (and/or animals consuming C_3 plants) and C_4 plants as well as the differentiation between terrestrial and aquatic food stuff (Heron and Craig 2015). In contrast, nitrogen stable isotope ($\delta^{15}N$) values of protein that is available in the foodcrusts provides the information on the trophic level of different organisms processed in the pottery.

The C/N ratio is another dietary indicator which is commonly used to show the contribution of proteins versus lipids and/or other non-nitrogenous compounds such as carbohydrates. The C/N ratio is based on the total amount of carbon atoms divided by the total amount of nitrogen atoms in an organic sample, and it is known to vary greatly among different food groups based on their abundance in the analysed carbonised surface residue. While the foodcrusts that are formed by low lipid content and protein rich animal (both aquatic and terrestrial) tissues would give low C/N ratios, oily substances (e.g. rendering oil), having higher lipid content, would produce higher C/N ratios. Ertebølle 'blubber lamps' thought to have been used to burn marine mammal oil is a good example of this (Heron et al. 2013).

In addition, the offsets between $\delta^{13}C$ values ($\delta^{13}C_{16:0-18:0}$) and the corresponding bulk $\delta^{13}C$ values in foodcrusts from the same sherds ($\Delta^{13}C_{16:0-18:0}$–bulk $\delta^{13}C$) can be also used as a tool to understand the composition of the foodcrusts. Small offsets and high C/N ratios generally indicate that the foodcrusts are mainly formed from fatty adipose tissues or aquatic oils, as both analytic techniques are measuring the $\delta^{13}C$ value of the lipid component. In contrast, foodcrusts derived from a higher proportion of protein-rich tissues, such as muscle tissues, would be expected to have a higher $\Delta^{13}C_{16:0-18:0}$–bulk offset as a result of mixing carbon from protein and fat which have the different isotope values.

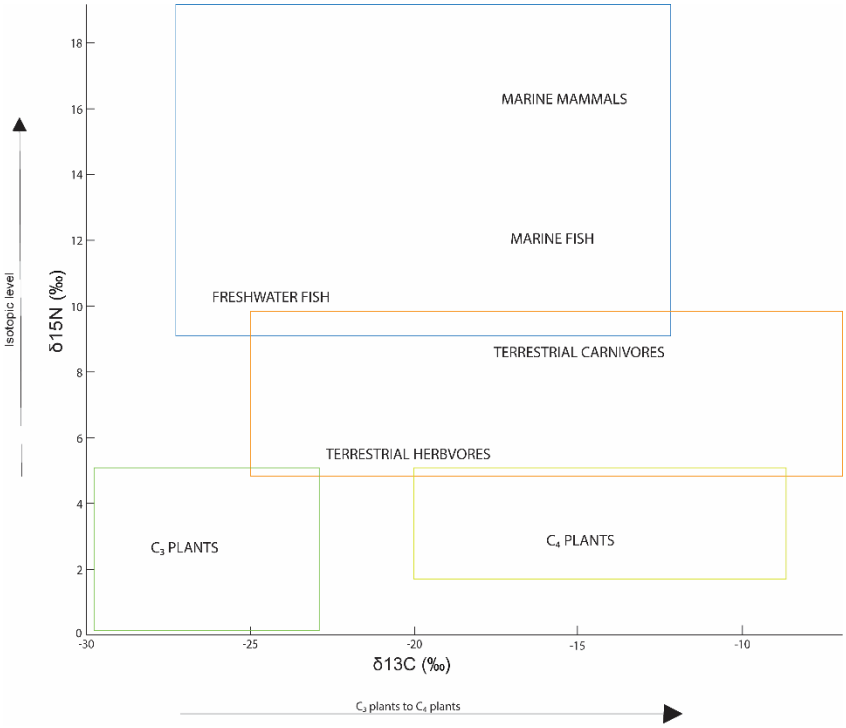


Fig. 2.2 General Carbon nitrogen reference ranges roughly plotted on a basic carbon nitrogen graph (based on Evershed 2009; Robson et al. 2016).

2.2.5. Lipid preservation and degradation

Preservation of different components coming from organic residues depends on the physico-chemical conditions such as pH, redox potential, temperature, wetness, and biomass present at the immediate depositional environment (Eglinton and Logan 1991; Heron and Evershed 1993; Debono-Spiteri 2012). It also depends on the functional groups that exist in the molecules which form the organic residues. Compared to the preservation of other biomolecules such as DNA, proteins, and carbohydrates, lipids tend to have higher preservation due to their hydrophobic nature (Evershed 1993; Heron and Evershed 1993; Cappellini et al. 2018). In addition to this, being absorbed and trapped into the clay matrix during the use of the pottery increases the survival of organic compounds since it limits the direct access of microorganisms deteriorating organic matters (Heron and Evershed 1993; Cappellini et al. 2018).

Preservation of lipids in archaeological pottery is also depended on the frequency and intensity of pottery use, porous structure of the vessel, the initial deposition and alterations and degradations that occurs in the chemical composition of the organic residues due to chemical or microbial decay (Evershed et al. 1992; Charters et al. 1993; Heron and Evershed 1993; Oudemans 2006). Fat and oil react differently to food processing and storage than other materials consisting of carbohydrates and proteins. This is because lipid molecules have less reactive sites compared to others (Debono-Spiteri

2012). Despite of that, cooking and storage activities and the deposition in the soil may increase the chemical and enzymatic hydrolysis (loss of water-soluble compounds) for the acyl lipids such as triacylglycerols and phospholipids (Evershed et al. 1992; Regert et al. 1998). Under hydrolysis conditions, degraded lipids such as diacids and hydroxy acids are removed from the pottery and lost to groundwater leaching due to their water-soluble compositions (Regert et al. 1998; Aillaud 2002).

Oxidation is another degradation process which is the most frequently observed degradation on lipids in food materials. Oxidation products in archaeological pottery were detected and identified by Regert and co-workers in 1998 for the first time (see Regert et al. 1998). These detected and identified oxidation products are defined as oxidative deterioration of lipids containing any number of carbon-carbon double bonds (Evershed et al. 1992; Cappellini et al. 2018). It affects the concentration of unsaturated fatty acid components observed in lipid extracts poorly and forms a range of oxidation products (such as mono-, and dihydroxy fatty acids, short-chain fatty acids) whose structures indicate the structural composition of the unsaturated component they were produced from. Polyunsaturated fatty acids (such as linoleic acid ($C_{18:2}$) are the most affected due to their rapid oxidation; therefore, rarely seen in archaeological materials (Evershed et al. 1992; Heron and Evershed 1993). Sterols are relatively more resistant to degradation compared to the fatty acids however a stronger subject to oxidation and reduction (Evershed et al. 1992; Evershed 1993).

2.2.5. Contamination in lipid residue analysis

Contamination is defined as the introduction of modern compounds and residues into the archaeological sample. The burial contamination and the contamination caused by archaeological processing are the two main contaminants in lipid residue analysis (Heron and Evershed 1993; Regert 2011; Malainey 2012). In the burial environment, the contamination is based on the possible migration of external lipids from the soil into the pottery (Evershed 1993; 2008b). This kind of contamination has shown to be negligible in lipid residue analysis (Heron et al. 1991) and often avoided by the established approach of removal of the sherd surface before sampling (Roffet-Salque et al, 2016), however, it may be tested by analysing the soil sediments in the burial environment of the pottery, where possible.

The contamination caused by archaeological processing includes handling the ceramic samples during various documentation processes and storing conditions afterwards. Improper handling of the ceramic sherds may cause human contamination which is described as transferring human fingerprint oils into the pottery (Evershed 1993; Malainey 2012). Squalene and cholesterol, both recognized by mass spectrometry analyses, can occur as a result of human contamination. Due to its specific structure with large number of double bonds and low resistance to degradation, squalene can be easily detected as a

post excavation contamination in archaeological residues (Evershed 1993). The presence of cholesterol with lower abundance than squalene could also be originated from human lipids; however due to its natural occurrence also in animal fats, it is accepted as a contamination when there is a co-occurrence with squalene in the lipid extracts of archaeological materials (Evershed 1993). This kind of human contamination can be prevented by handling the pottery only with clean tools or gloves.

Phthalates, which are industrial plasticizers are also commonly detected in archaeological residues and are caused by the storage of the archaeological samples in plastics (Evershed 1993; Pollard et al. 2007). Plasticizers can be easily recognized in mass spectrometry due to their specific retention times and their mass spectra dominated by *m/z* 149 ion (Evershed 1993) and can cause some identification failure of some molecules that are overwritten by them. Using gloves while handling the samples and wrapping them in aluminium foil before storing them in plastics may help to reduce this kind of contamination in archaeological residues.

Another contamination caused by storing conditions may also include the growth of bacteria or fungi on archaeological samples that are stored under environments where the temperature and the humidity is not controlled properly (Evershed 1993; Oudemans 2006). This can be prevented by storing the archaeological samples in dry or cold storage rooms and by applying microscopic inspections of residues before sampling (Oudemans 2006).

References

Ackman R. G. and Hooper S. N. (1970). Branched-chain fatty acids of four fresh-water fish oils. Comparative Biochemistry and Physiology 32(1):117-25.

Aillaud, S. (2002). *Field and laboratory studies of diagenetic reactions affecting lipid residues absorbed in unglazed archaeological pottery vessels,* University of Bristol.

Andersen, K. (1983). *Stenalderbebyggelsen i den Vestsjællandske Åmose*, Copenhagen: Fredningsstyrelsen

Andersen, S. H. (1975). Ringkloster, en jysk indland-sboplads med Ertebøllekultur. *Kulm* 1973-1974 (1975), 11-108.

Andersen, S. H. (1993). Bjornsholm. A Stratified Kakkenmodding on the Central Limfjord. *Journal Danish Arch.* 10, 59-96.

Andersen, S. H. (2009). *Ronæs Skov. Marinkæologiske undersøgelser af kystbiplads fra Ertebølletid* (Jysk Arkæologisk Selskabs Skrifter 64). Højberg: Jysk Arkæologisk Selskab.

Andersen, S. H. (2010). The first pottery in South Scandinavia. In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.), *Pots, Farmers and Foragers: How Pottery Traditions Shed a Light on Social Interaction in the Earliest Neolithic of the Lower Rhine Area,* Leiden University Press, pp. 167-176.

Andersen, S. H. (2011). Kitchen middens and the early pottery of Denmark. In: Hartz, S., Lüth,F.,und Terberger, T. (eds.), *Early Pottery in the Baltic - dating, origin and social context*. Bericht der Römisch-Germanischen Kommission 2008/89, pp. 193-215.

Andersen, S. H. and Malmros, C. (1985). "Madskorpe" pä Ertebollekar fra Tybrind Vig ("food crust" in Ertebølle Vessels from Tybrind Vig). *Aarbøger for Nordisk Oldkyndighed Og Historie*, 78-95.

Baeten, J., Jervis, B., De Vos, D., and Waelkens, M. (2013). Molecular evidence for the mixing of Meat, Fish and Vegetables in Anglo-Saxon courseware from Hamwic, UK. *Archaeometry*, *55*(6), 1150-1174.

Baker, E. A. (1982). Chemistry and morphology of plant epicuticular waxes. In: Cutler, D. F., Alvin, K. L. and Price, C. E. (eds), *The Plant Cuticle. Linn. Soc. Symp. Ser. 10*. Academic Press, London, pp. 139-165.

Barnard, H., Dooley, A. N. and Faull, K. F. (2007). An introduction to archaeological lipid analysis by combined gas chromatography mass spectrometry (GC/MS). In: Barnard H. and Eerkens, J. W. (eds), *Theory and Practice of Archaeological Residue Analysis*, 42-60.

Bianchi G. (1995). Plant waxes. In: Hamilton, R. J. (ed.), *Waxes: Chemistry, Molecular Biology and Functions.* The Oily Press, Dundee, pp. 175-222.

Bondetti, M., Scott, S., Lucquin, A., Meadows, J., Lozovskaya, O., Dolbunova, E., Jordan, P., and Craig, O. E. (2019). Fruits, fish and the introduction of pottery in the Eastern European plain: Lipid residue analysis of ceramic vessels from Zamostje 2. *Quaternary International: The Journal of the International Union for Quaternary Research*. https://doi.org/10.1016/j.quaint.2019.05.008.

Bondetti, M., Scott, E., Courel, B., Lucquin, A., Shoda, S., Lundy, J., Labra-Odde, C., Drieu, L., and Craig, O. E. (2020). Investigating the formation and diagnostic value of *ω*-(*o*-alkylphenyl) alkanoic acids in ancient pottery. *Archaeometry*. https://doi.org/10.1111/arcm.12631.

Brinch Petersen, E. (2011). Hundred and fifty years of Ertebølle ceramics in the western Baltic. In: Hartz, S., Lüth, F. and Terberger, T. (eds.), *Early Pottery in the Baltic - Dating, Origin and Social Context. International Workshop at Schleswig from 20th to 207 21st October 2006*. Bericht der Römish-Germanishen Kommission, Band 89, 2008. Frankfurt a. M.,Philipp von Zabern, pp. 217-239.

Brinkhuizen, D. C. (1979). Preliminary notes on fish remains from archaeological sites in the Netherlands. *Palaeohistoria*, 21(0), 83-90.

Brown, K.A. and Brown, T. A. (2013). Biomolecular archaeology. *Annu. Rev. Anthropol.* 42: 159-74.

Brown, L. and Heron, C. (2005). Presence or absence: A Preliminary study into the detection of fish oils in ceramics. In: Mulville, J. and Outram, A. K. (eds). *The Zooarchaeology of Fats, Oils, Milks and Dairying*. Oxbow Books, Oxford.

Bush, R. T. and McInerney, F. A. (2013). Leaf wax n-alkane distributions in and across modern plants: Implications for paleoecology and chemotaxonomy. *Geochimica et Cosmochimica Acta*, *117*, 161-179.

Cappellini, E., Prohaska, A., Racimo, F., Welker, F., Pedersen, M. W., Allentoft, M. E., de Barros Damgaard, P., Gutenbrunner, P., Dunne, J., Hammann, S., Roffet-Salque, M., Ilardo, M., Moreno-Mayar, J. V., Wang, Y., Sikora, M., Vinner, L., Cox, J., Evershed, R. P., and Willerslev, E. (2018). Ancient Biomolecules and Evolutionary Inference. *Annual Review of Biochemistry*, *87*, 1029-1060.

Cappers, R. T., and Raemaekers, D. C. M. (2008) Cereal cultivation at Swifterbant? Neolithic wetland farming on the north European plain. *Current Anthropology 49*(3), 385-402.

Charters, S., Evershed, R. P., Goad, L. J., Leyden, A., Blinkhorn, P. W., and Denham, V. (1993). Quantification and Distribution of Lipid in Archaeological Ceramics: Implications for Sampling Potsherds for Organic Residue Analysis and the Classification of Vessel Use. *Archaeometry*, *35*(2), 211-223.

Charters, S., Evershed, R. P., Blinkhorn, P. W., and Denham, V. (1995). Evidence for the mixing of fats and waxes in archaeological ceramics. *Archaeometry*, *37*(1), 113-127.

Christie, W. W. (2010). Lipid analysis: isolation, separation, identification and structural analysis of lipids, (4th edn) Bridgwater, The Oily Press.

Clason, A. T. (1978) Worked bone, antler and teeth. A preliminary report (Swifterbant contribution 9). *Helinium* 18:83-86.

Colonese, A. C., Lucquin, A., Guedes, E. P., Thomas, R., Best, J., Fothergill, B. T., Sykes, N., Foster, A., Miller, H., Poole, K., Maltby, M., Von Tersch, M., & Craig, O. E. (2017/2). The identification of poultry processing in archaeological ceramic vessels using in-situ isotope references for organic residue analysis. *Journal of Archaeological Science*, *78*, 179–192.

Connolly, J. D., and Hill, R. A. (1991). *Dictionary of Terpenoids*. CRC Press.

Copley, M. S., Berstan, R., Dudd, S. N., Docherty, G., Mukherjee, A. J., Straker, V., Payne, S., and Evershed, R. P. (2003). Direct chemical evidence for widespread dairying in prehistoric Britain. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(4), 1524-1529.

Copley, M. S., Hansel, F. A., Sadr, K., and Evershed, R. P. (2004). Organic residue evidence for the processing of marine animal products in pottery vessels from the pre-colonial archaeological site of Kasteelberg D east, South Africa: research article. *South African Journal of Science*, *100*(5-6), 279-283.

Copley, M. S., Berstan, R., Dudd, S. N., Aillaud, S., Mukherjee, A. J., Straker, V., Payne, S., and Evershed, R. P. (2005a). Processing of milk products in pottery vessels through British prehistory. *Antiquity*, *79*(306), 895-908.

Copley, M. S., Bland, H. A., Rose, P., Horton, M., and Evershed, R. P. (2005b). Gas chromatographic, mass spectrometric and stable carbon isotopic investigations of organic residues of plant oils and animal fats employed as illuminants in archaeological lamps from Egypt. *The Analyst*, *130*(6), 860-871.

Corr, L. T., Richards, M. P., Jim, S., Ambrose, S. H., Mackie, A., Beattie, O., and Evershed, R. P. (2008). Probing dietary change of the Kwädąy Dän Ts'ìnchį individual, an ancient glacier body from British Columbia: I. Complementary use of marine lipid biomarker and carbon isotope signatures as novel indicators of a marine diet. *Journal of Archaeological Science*, *35*(8), 2102-2110.

Correa-Ascencio, M., Robertson, I. G., Cabrera-Cortés, O., Cabrera-Castro, R., and Evershed, R. P. (2014). Pulque production from fermented agave sap as a dietary supplement in Prehispanic Mesoamerica. *PNAS* 11(39):14223-8.

Courel, B., Robson, H. K., Lucquin, A., Dolbunova1, E., Oras, E., Adamczak, K., Andersen, S. H., Astrup, P. M., Charniauski, M., Czekaj-Zastawny, A., Ezepenko, I., Hartz, S., Kabaciński, J., Kotula, A., Kukawka, S., Loze, I., Mazurkevich, A., Piezonka, H., Piličiauskas, Sørensen, A. S., Talbot, H. M., Tkachou, A., Tkachova, M., Wawrusiewicz, A., Meadows, J., Heron, C. P., and Craig, O . E. (2020). Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter-gatherers. *Royal Society Open Science*, *7*. https://doi.org/10.1098/rsos.192016.

Craig, O. E. (2004). Organic analysis of food crusts from sites in the Schelde valley, Belgium: a preliminary evaluation. *Notae Praehistoricae*, *24*, 209-217.

Craig, O. E., Love, G. D., Isaksson, S., Taylor, G., and Snape, C. E. (2004). Stable carbon isotopic characterisation of free and bound lipid constituents of archaeological ceramic vessels released by solvent extraction, alkaline hydrolysis and catalytic hydropyrolysis. *Journal of Analytical and Applied Pyrolysis*, *71*(2), 613-634.

Craig, O. E., Chapman, J., Heron, C., Willis, L. H., Bartosiewicz, L., Taylor, G., Whittle, A., and Collins, M. (2005). Did the first farmers of central and eastern Europe produce dairy foods? *Antiquity*, *79*(306), 882-894.

Craig, O. E., Forster, M., Andersen, S. H., Koch, E., Crombé, P., Milner, N. J., Stern, B., Bailey, G. N., and Heron, C. P. (2007). Molecular and Isotopic Demonstration of the Processing of Aquatic Products in Northern European Prehistoric Pottery. *Archaeometry*, *49*(1), 135-152.

Craig, O. E., Steele, V. J., Fischer, A., Hartz, S., Andersen, S. H., Donohoe, P., Glykou, A., Saul, H., Jones, D. M., Koch, E., and Heron, C. P. (2011). Ancient lipids reveal continuity in culinary practices across the transition to agriculture in Northern Europe. *Proceedings of the National Academy of Sciences of the United States of America*, 108(44), 17910-17915.

Craig, O. E., Allen, R. B., Thompson, A., Stevens, R. E., Steele, V. J., and Heron, C. (2012). Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry: RCM*, *26*(19), 2359-2364.

Cramp, L. and Evershed, R. P. (2014). Reconstructing Aquatic Resource Exploitation in Human Prehistory Using Lipid Biomarkers and Stable Isotopes. In: Holland, H. D. and Turekian, K. K. (eds.), Treatise on Geochemistry (Second Edition). Oxford: Elsevier, pp. 319-339.

Crombé, P. (2010). Contact and Interaction between Early Farmers and late Hunter-Gatherers in Belgium during the 6th and 5th millennium cal BC. In: Detlef Gronenborn, J. P. (ed.), *The Spread of the Neolithic to Central Europe, International Symposium, Mainz 24 June - 26 June 2005*.Verlag des Römisch-Germanischen Zentralmuseums Mainz, pp. 551-566.

Crombé, P., Perdaen, Y., and Sergant, J. (2005). Sergant, La néolithisation de la Belgique: quelques réflexions. In: Marchand, G. and Tresset, A. (eds.), *Unité et diversité des processus de néolithisation sur la façade atlantique de l'Europe (6e -4e millénaires avant J.-C.)*. Table ronde de Nantes, 26-27 Avril 2002. Mémoires de la Société Préhistorique Française 36, pp. 47-66.

Crombé, P., Boudin, M., and van Strydonck, M. (2008). Swifterbant pottery in the Scheldt Basin and the emergence of the earliest indigenous pottery in the sandy lowlands of Belgium. *Bericht Der Romisch-Germanischen Kommission*, *89*, 465–483.

Cubas, M., Lucquin, A., Robson, H. K., Colonese, A. C., Arias, P., Aubry, B., Billard, C., Jan, D., Diniz, M., Fernandes, R., Fábregas Valcarce, R., Germain-Vallée, C., Juhel, L., de Lombera-Hermida, A., Marcigny, C., Mazet, S., Marchand, G., Neves, C., Ontañón-Peredo, R., Rodriguez Alvarez X. P., Simoes, T., Zilhao, J., and Craig, O. E. (2020). Latitudinal gradient in dairy production with the introduction of farming in Atlantic Europe. *Nature Communications*, *11*(1), 2036.

Czekaj-Zastawny, A. and Kabaciński, J. (2015). The early Funnel Beaker culture in Dąbki. In: Kabaciński, J., Hartz, S., Raemaekers, D. C. M., and Terberger, T. (eds), *The Dąbki site in Pomerania and the neolithization of the North European Lowland (c. 5000-3000 cal BC),* (= Archaologie und Geschichte im Ostseeraum Archaeology and History of the Baltic 8). Rahden-Westf., pp. 203-217.

Czekaj-Zastawny, A., Kabaciński, J. and Terber, T. (2011). Cultural Relations between the Great Hungarian Plain and the Southern Baltic Coast. Imports from the Bodrog-Keresztúr Culture on the Site Dąbki 9. *Sprawozdania Archeologiczne* 63, 55-88.

Çakırlar, C., Breider, R., Koolstra, F., Cohen, K. M. and Raemaekers, D.C.M. (2020). Dealing with domestic animals in the fifth millennium cal BC Dutch wetlands: new insights from old Swifterbant assemblages. In: Gron, K. J., Sørensen, L., and Rowley-Conwy, P. (eds.), *Farmers at the Frontier: A Pan-European Perspective on Neolithisation.* Oxbow Books, pp. 263-287.

Debono Spiteri, C. (2012). *Pottery use at the transition to agriculture in the western Mediterranean. Evidence from biomolecular and isotopic characterisation of organic residues in Impressed/Cardial Ware vessels*. Dissertation, University of York.

DeMan, J. M. (1999). *Principles in food chemistry*, (3rd ed) Maryland, Aspen Publishers Inc.

Demirci, Ö., Lucquin, A., Craig, O. E., and Raemaekers, D. C. M. (2020). First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300-4000 BC). *Archaeological and Anthropological Sciences*, *12*(5), 105.

DeNiro, M. J. (1987). Stable Isotopy and Archaeology. *American Scientist, 75*(2), 182-191.

Dudd, S. N. (1999). *Molecular and isotopic characterisation of animal fats in archaeological pottery*. University of Bristol.

Dudd, S. N. and Evershed, R. P. (1998). Direct Demonstration of Milk as an Element of Archaeological Economies. *Science*, *282*, 1478-1481.

Dudd, S. N., Regert, M. and Evershed, R. P. (1998). Assessing microbial lipid contributions during laboratory degradation of fats and oils and pure triacylglycerols absorbed in ceramic potsherds. *Org. Geochem.*, *29*(5-7), 1345-1354.

Dudd, S. N., Evershed, R. P. and Gibson, A. M. (1999). Evidence for Varying Patterns of Exploitation of Animal Products in Different Prehistoric Pottery Traditions Based on Lipids Preserved in Surface and Absorbed Residues. *Journal of Archaeological Science*, *26*(12), 1473-1482.

Dunne, J., Evershed, R. P., Salque, M., Cramp, L., Bruni, S., Ryan, K., Biagetti, S., and di Lernia, S. (2012). First dairying in green Saharan Africa in the fifth millennium BC. *Nature*, *486*(7403), 390-394.

Eglinton, G., and Logan, G. A. (1991). Molecular preservation, *Philosophical Transactions of the Royal Society of London, Series B, 333*, 315-28.

Evershed, R. P. (1992a). Gas chromatography of lipids. In: Hamilton, R. J. and Hamilton, S. (eds.) *Lipid analysis: a practical approach*. Oxford, Oxford University Press, pp. 113-151.

Evershed, R. P. (1992b) Mass spectrometry of lipids. In: Hamilton R. J. and Hamilton, S. (eds.) *Lipid analysis: A practical approach*. Oxford, Oxford University Press, pp. 263-308.

Evershed, R. P. (1993). Biomolecular archaeology and lipids. *World Archaeology*, *25*(1), 74-93.

Evershed, R. P. (2008). Organic residue analysis in archaeology: the archaeological biomarker revolution. *Archaeometry*, *50*(6), 895-924.

Evershed, R. P. (2009). Compound-specific Stable Isotopes in Organic Residue Analysis in Archaeology. In: Colombini, M. P. and Modugno, F. (eds.), *Organic Mass Spectrometry in Art and Archaeology*. Chichester, UK: John Wiley & Sons, Ltd., pp. 389-432.

Evershed, R. P., Heron, C. and Goad, L. J. (1991). Epicuticular wax components preserved in potsherds as chemical indicators of leafy vegetables in ancient diets. *Antiquity*, *65*(248), 540.

Evershed, R. P., Arnot, K. I., Collister, J., Eglinton, G., and Charters, S. (1994). Application of isotope ratio monitoring gas chromatography-mass spectrometry to the analysis of organic residues of archaeological origin. *The Analyst*, *119*(5), 909-914.

Evershed, R. P., Charters, S. and Quye, A. (1995). Interpreting Lipid Residues in Archaeological Ceramics: Preliminary Results from Laboratory Simulations of Vessel Use and Burial. *MRS Online Proceedings Library Archive*, *352*. https://doi.org/10.1557/PROC-352-85.

Evershed, R. P., Mottram, H. R., Dudd, S. N., Charters, S., Stott, A. W., Lawrence, G. J., Gibson, A. M., Conner, A., Blinkhorn, P. W., and Reeves, V. (1997). New Criteria for the Identification of Animal Fats Preserved in Archaeological Pottery. *Die Naturwissenschaften*, *84*(9), 402-406.

Evershed, R. P., Dudd, S. N., Charters, S., Mottram, H., Stott, A. W., Raven, A., van Bergen, P. F., and Bland, H. A. (1999). Lipids as carriers of anthropogenic signals from prehistory. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *354*(1379), 19.

Evershed, R. P., Dudd, S. N., Copley, M. S., Berstan, R., Stott, A. W., Mottram, H., Buckley, S. A., and Crossman, Z. (2002a). Chemistry of archaeological animal fats. *Accounts of Chemical Research*, *35*(8), 660-668.

Evershed, R. P., Dudd, S. N., Copley, M. S., and Mukherjee, A. J. (2002b). Identification of animal fats via compound specific δ13C values of individual fatty acids: assessments of results for reference fats and lipid extracts of archaeological pottery vessels. *Documenta Praehistorica*, *21*, 73-96.

Evershed, R. P., Copley, M. S., Dickson, L., and Hansel, F. A. (2008a). Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. *Archaeometry*, *50* (1), 101-113.

Evershed, R. P., Payne, S., Sherratt, A. G., Copley, M. S., Coolidge, J., Urem-Kotsu, D., Kotsakis, K., Ozdoğan, M., Özdoğan, A. E., Nieuwenhuyse, O., Akkermans, P. M. M. G., Bailey, D., Andeescu, R.-R., Campbell, S., Farid, S., Hodder, I., Yalman, N., Özbaşaran, M., Bıçakçı, E., Garfinkel, Y., Levy, T., and Burton, M. M. (2008b). Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding. *Nature*, *455*(7212), 528-531.

Fernandes, R., Millard, A. R., Brabec, M., Nadeau, M.-J., and Grootes, P. (2014). Food reconstruction using isotopic transferred signals (FRUITS): a Bayesian model for diet reconstruction. *PloS One*, *9*(2), e87436.

Fernandes, R., Eley, Y., Brabec, M., Lucquin, A., Millard, A., and Craig, O. E. (2018). Reconstruction of prehistoric pottery use from fatty acid carbon isotope signatures using Bayesian inference. *Organic Geochemistry*, *117*, 31–42.

Fischer, A. (2002). Food for feasting? An evaluation of explanations of the neolithisation of Denmark and southern Sweden. In: Fischer, A., Kristiansen, K. (eds.) *The Neolithisation of Denmark: 150 Years of Debate*, Sheffield, J. R. Collis Publications, pp. 343-393.

Garnier, N.and Valamoti, S. M. (2016). Prehistoric wine-making at Dikili Tash (Northern Greece): Integrating residue analysis and archaeobotany. *Journal of Archaeological Science*, *74*, 195-206.

Gjessing, G. (1955) Veiding og sanking i førhistorisk tid i norden. In: Erixon, S. (ed) *Fångst, jakt och fiske*, Nordisk kultur. no. 11/12A, Stockholm, Oslo, København: Albert Bonniers Förlag, H. Aschehoug and Co.s Forlag, J.H. Schultz Forlag, pp 1-63.

Glykou, A. (2010). Technological and typological analysis of Ertebølle and early Funnel Beaker pottery from Neustadt LA 156 and contemporary sites in northern Germany. In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.), *Pots, Farmers and Foragers: How Pottery*

Traditions Shed a Light on Social Interaction in the Earliest Neolithic of the Lower Rhine Area, pp. 177-188.

Glykou, A. (2011). Neustadt LA 156: A submarine site from the Late Mesolithic-Ertebølle and earliest Neolithic-Funnel Beaker in northern Germany - First results of the typological and technological analysis of the ceramics. In Hartz, S., Lüth, F. und Terberger, T. (eds.), *Early Pottery in the Baltic - dating, origin and social context*. Bericht der Römisch-Germanischen Kommission 2008/89, pp. 277-286.

Gregg, M. W., Banning, E. B., Gibbs, K., and Slater, G. F. (2009). Subsistence practices and pottery use in Neolithic Jordan: molecular and isotopic evidence. *Journal of Archaeological Science*, *36*(4), 937-946.

Guasch-Jané, M. R., Ibern-Gómez, M., Andrés-Lacueva, C., Jáuregui, O., and Lamuela-Raventós, R. M (2004). Liquid chromatography with mass spectrometry in tandem mode applied for the identification of wine markers in residues from ancient Egyptian vessels. *Analytical Chemistry*, *76*(6), 1672-1677.

Gunstone, F. D. (2004). *The chemistry of oils and fats: sources, composition, properties and uses*, Oxford, Blackwell Publishing Ltd.

Gunstone, F. D., Harwood, J. L. and Dijkstra, A. J. (2007). *The lipid handbook*. CRC Press.

Gurr, M. I., Harwood, J. L. and Frayn, K. N. (2002). *Lipid biochemistry*, (5th ed.) Oxford, Blackwell Science Ltd.

Hallgren, F. (2008). *Identitet i praktik. Lokala, regionala och överregionala sociala sammanhang inom nordlig trattbägarkultur*. Coast to Coast-books 17. Doktorsavhandling i arkeologi, Uppsala Universitet.

Hallgren, F., (2011). The early 'Trichterbecher' of Mälardalen, eastern Central Sweden. In: Hartz, S., Lüth, F., Terberger, T. (eds.), *Early Pottery in the Baltic e Dating, Origin and Social Context, vol. 89*. Bericht der Römisch-Germanische Kommission, Frankfurt, pp. 111-134.

Hammann, S and Cramp, L. J. E. (2018). Towards the detection of dietary cereal processing through absorbed lipid biomarkers in archaeological pottery. *Journal of Archaeological Science,* 93, 74-81.

Hansel, F. A., Copley, M. S., Madureira, L. A. S., and Evershed, R. P. (2004). Thermally produced *ω*-(*o*-alkylphenyl) alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. *Tetrahedron Letters*, *14*(45), 2999-3002.

Harfoot, C. G. (1981). Anatomy, physiology and microbiology of the ruminant digestive tract. In W. W. Christie (Ed.), *Lipid Metabolism in Ruminant Animals,* Pergamon, pp. 1-19.

Hartz, S. (2011). From pointed bottom to round and flat bottom - tracking early pottery from Schleswig-Holstein. In: S. Hartz, F. Lüth und T. Terberger (eds), *Early Pottery in the Baltic - dating, origin and social context*. Bericht der Römisch-Germanischen Kommission 2008/89, pp. 241-276.

Hartz, S. and Lübke, H. (2006). New Evidence for a Chronostratigraphic Division of the Ertebølle Culture and the Earliest Funnel Beaker Culture on the Southern Mecklenburg Bay. In C. J. Kind (ed.), *After the ice age. Settlement, subsistence and social development in the Mesolithic of Central Europe.* Konrad Theiss Verlag, pp. 59-74.

Hartz, S., Heinrich, D. and Lübke, H. (2000). Frühe Bauern an der Küste. Neue 14C-Daten und aktuelle Aspekte zum Neolithisierungsprozeß im norddeutschen Ostseeküstengebiet, *Praehistorische Zeitschrift*, *75*(2), 129-152. doi: https://doi.org/10.1515/prhz.2000.75.2.129.

Hartz, S., Heinrich, D., Lübke, H. (2002). Coastal Farmers - the neolithisation of northern-most Germany. In: Anders Fischer K. K. (ed.), *The Neolithisation of Denmark. 150 years of debate.* Sheffield, J.R.Collins, pp. 319-340.

Harwood J. L. and Russell N. J. (1984). *Lipids in Plants and Microbes*. George Allen and Unwin, London.

Hastorf, C. A. and DeNiro, M. J. (1985). Reconstruction of prehistoric plant production and cooking practices by a new isotopic method. *Nature*, *315*(6019), 489-491.

Heron, C., Evershed, R. P. and Goad, L. J. (1991). Effects of migration of soil lipids on organic residues associated with buried potsherds. *Journal of Archaeological Science*, *18*(6), 641-659

Heron, C. and Evershed, R. P. (1993). The Analysis of Organic Residues and the Study of Pottery Use. *Archaeological Method and Theory*, *5*, 247-284.

Heron, C., and Craig, O. E. (2015). Aquatic Resources in Foodcrusts: Identification and Implication. *Radiocarbon*, *57*(4), 707-719.

Heron, C., Andersen, S., Fischer, A., Glykou, A., Hartz, S., Saul, H., Steele, V., and Craig, O. (2013). Illuminating the Late Mesolithic: residue analysis of "blubber" lamps from Northern Europe. *Antiquity*, 178-188.

Heron, C., Shoda, S., Breu Barcons, A., Czebreszuk, J., Eley, Y., Gorton, M., Kirleis, W., Kneisel, J., Lucquin, A., Müller, J., Nishida, Y., Son, J.-H., and Craig, O. E. (2016). First molecular and isotopic evidence of millet processing in prehistoric pottery vessels. *Scientific Reports*, *6*, 38767.

Hogestijn, J. W. H. (1991). Archeologische kroniek van Flevoland, *Cultuur Historisch Jaarboek van Flevoland 1*, 110-129.

Hogestijn, J. W. H. and Lauwerier, R. C. G. M. (1992). Zoelen Beldert, *Jaarverslag Rijksdienst voor het Oudheidkundig Bodemonderzoek 1991*, 108

Hoika, J. and Lübke, H. (2000). Allgemeine Angaben zum Fundplatz Bebensee LA 76. In: Lübke, H. (ed.). Die steinzeitlichen Fundplätze Bebensee LA 26 und LA 76, Kreis Segeberg. Teil I: Die Steinartefakte.

Hulthén, B. (1977). *On ceramic technology during the Scanian Neolithic and Bronze age*. Stockholm: Akademilitteratur.

Isaksson, S. and Hallgren, F. (2012) Lipid residue analyses of Early Neolithic Funnel-beaker pottery from Skogsmossen, eastern Central Sweden, and the earliest evidence of dairying in Sweden. *Journal of Archaeological Science* 39, 3600-3609.

Jacob, J., Disnar, J.-R., Arnaud, F., Chapron, E., Debret, M., Lallier-Vergès, E., Desmet, M., and Revel-Rolland, M. (2008). Millet cultivation history in the French Alps as evidenced by a sedimentary molecule. J*ournal of Archaeological Science.* 35(3):814-20.

Jansen, B., Nierop, K. G. J., Kotte, M. C., de Voogt, P., and Verstraten, J. M. (2006). The applicability of accelerated solvent extraction (ASE) to extract lipid biomarkers from soils. *Applied Geochemistry*, 21, 1006-1015.

Jansen, D., Mischka, D. and Nelle, O. (2013). Wood usage and its influence on the environment from the Neolithic until the Iron Age: a case study of the graves at Flintbek (Schleswig-Holstein, Northern Germany). *Vegetation History and Archaeology* 22, 335-349.

Jennbert, K. (2011). Ertebølle pottery in southern Sweden - a question of handicraft, networks and creolization in a period of Neolithisation. In: Hartz, S., Lüth, F. und Terberger T. (eds.), *Early Pottery in the Baltic - dating, origin and social context.*). Bericht der Römisch-Germanischen Kommission 2008/89, pp. 89-110.

Jensen, R. G. (2002). The composition of bovine milk lipids: January 1995 to December 2000. *Journal of Dairy Science*, *85*(2), 295-350.

Junno, A., Isaksson, S., Hirasawa, Y., Kato, H., and Jordan, P. D. (2020). Evidence of increasing functional differentiation in pottery use among Late Holocene maritime foragers in northern Japan. *Archaeological Research in Asia*, *22*, 100194.

Klassen, L. (1997). The debate on the Mesolithic-Neolithic transition in the western Baltic: a central European perspective. *J. Danish Archaeol.* 13 (1), 171-178. https://doi.org/ 10.1080/0108464X.1997.10590103.

Klassen, L. (2002). The Ertebølle Culture and Neolithic continental Europe: traces of contact and interaction. *The Neolithisation of Denmark*, *150*, 305-317.

Klassen, L. (2004). *Jade und Kupfer: Untersuchungen zum Neolithisierungsprozess im westlichen Ostseeraum unter besonderer Berücksichtigung der Kulturentwicklung Europas 5500-3500 BC* (Vol. 47). Aarhus Universitetsforlag.

Koch, E. (1998). *Neolithic Bog Pots: From Zealand, Møn, Lolland and Falster*. Det Kongelige Nordiske Oldskriftselskab 16, København.

Kotula, A., Piezonka, H. and Terberger, T. (2015). New pottery dates on the Mesolithic-Neolithic transition in the north-central European lowlands. In: Kabaciński, J., Hartz, S., Raemaekers, D. C. M., Terberger T. (eds.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000-3000 calBC)*, Leiford, Rahden/Westf, pp. 489-509.

Krause-Kyora, B., Makarewicz, C., Evin, A., Flink, L. G., Dobney, K., Larson, G., Hartz, S., Schreiber, S., von Carnap-Bornheim, C., von Wurmb-Schwark, N., and Nebel, A. (2013). Use of

domesticated pigs by Mesolithic hunter gatherers in northwestern Europe. *Nat. Commun* 4, 2348. https://doi.org/10.1038/ncomms3348.

Kriiska, A. (1996). The Neolithic pottery manufacturing technique of the lower course of the Narva river. In: Hackens, T. (ed). *Coastal Estonia. Recent Advances in Environmental and Cultural History*. (PACT, 51.) Rixensart, 373-384.

Kriiska, A., Oras, E., Lõugas, L., Meadows, J., Lucquin, A., and Craig, O. E (2017). Late Mesolithic Narva stage in Estonia: Pottery, settlement types and chronology. *Estonian Journal of Archaeology*, *21*(1), 52-86.

Kroezenga, P., Lanting, J. N., Kosters, R. J., Prummel, W. and de Roever, J. P. (1991). Vondsten van de Swifterbantcultuur uit het Voorste Diep bij Bronneger (Dr.), *Paleo-Aktueel 2*, 32-36.

Kubiak-Martens, L. (1999). The plant food component of the diet at the late Mesolithic (Ertebølle) settlement at Tybrind Vig, Denmark. *Veg. Hist. Archaeobotany* 8, 117-127. http://www.jstor.org/stable/23417650

Louwe Kooijmans, P. (1974). *The Rhine/Meuse delta. Four studies on its prehistoric occupation and Holocene geology*. Dissertation, Leiden University (Oudheidkundige Mededelingen uit het Rijksmuseum van Oudheden te Leiden 53-54 / Analecta Praehistorica Leidensia 7).

Louwe Kooijmans, P. (1976). Local developments in a borderland. A survey of the Neolithic at the Lower Rhine. *Oudheidkundige Mededelingen uit het Rijksmuseum van Oudhe¬den te Leiden 57*, 227-298.

Louwe Kooijmans, P. (2001a). *Hardinxveld-Giessendam Polderweg: Een Mesolithisch jachtkamp in het rivierengebied (5500-5000 v. Chr).* Amersfoort, Rapportage Archeologische Monumentenzorg, 83.

Louwe Kooijmans, P. (2001b). *Hardinxveld-Giessendam De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.)*. Amersfoort, Rapportage Archeologische Monumentenzorg, 83.

Louwe Kooijmans, P. (2003). The Hardinxveld sites in the Rhine/Meuse delta, the Netherlands, 5500-4500 cal BC. In: Larsson, L., Kindgren, H., Knutsson, K., Loeffler, D., Åkerlund, A. (eds.), *Mesolithic on the Move,* Oxbow Books*,* pp. 608-624.

Louwe Kooijmans, L. P. (2010). The ceramisation of the Low Countries, seen as the result of gender-specific processes of communication. In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.), *Pots, Farmers and Foragers: Pottery Traditions and Social Interaction in the Earliest Neolithic of the Lower Rhine Area*, Amsterdam University Press, pp. 27-40

Lucquin, A., Colonese, A. C., Farrell, T. F. G., and Craig, O. E (2016). Utilising phytanic acid diastereomers for the characterisation of archaeological lipid residues in pottery samples. *Tetrahedron Letters*, *57*(6), 703-707.

Malainey, M. E. (2012). *A Consumer's Guide to Archaeological Science*. Springer.

Malainey, M. E., Przybylski, R. and Sherriff, B. L. (1999). The Effects of Thermal and Oxidative Degradation on the Fatty Acid Composition of Food Plants and Animals of Western Canada: Implications for the Identification of Archaeological Vessel Residues. *Journal of Archaeological Science*, *26*(1), 95-103.

Mathiassen, T. (1935). Blubber Lamps in the Ertebølle Culture? *Acta Archaologica* 6, 139-151.
Matthews, D. E.and Hayes, J. M. (1978). Isotope-ratio-monitoring gas chromatography-mass spectrometry. *Analytical Chemistry*, *50*(11), 1465-1473.

Meurers-Balke, J. and Weninger, B. (1994). 14C-Chronologie der frühen Trichterbecher-Kultur im norddeutschen Tiefland und in Süd-Skandinavien. In: Hoika, J., Meurers-Balke, J. (eds.), *Beiträge zur frühneolithischen Trichterbecherkultur im westlichen Ostseegebiet*. Symposium Schleswig 4.-7. März 1985. Untersuchungen und Materialien zur Steinzeit in Schleswig-Holstein 1 (Schleswig), pp. 251-287.

Mottram, H. R., Dudd, S. N., Lawrence, G. J., Stott, A. W., and Evershed, R. P. (1999). New chromatographic, mass spectrometric and stable isotope approaches to the classification of degraded animal fats preserved in archaeological pottery. *Journal of Chromatography. A*, *833*(2), 209-221.

Mukherjee, A. J., Berstan, R., Copley, M. S., Gibson, A. M., and Evershed, R. P. (2007). Compound-specific stable carbon isotopic detection of pig product processing in British Late Neolithic pottery. *Antiquity*, *81*(313), 743-754.

Müller, J. (2011). *Megaliths and Funnel Beakers: societies in change 4100–2700 BC*. (Kroon-Vordaacht 13). Amsterdam, Amsterdams Archaeologisch Centrum van der Universiteit.

Nielsen, P. O. (1984). De første bønder. Nye fund fra den tidligste Tragtbægerkultur ved Sigersted. *Aarbøger for Nordisk Oldkyndighed og Historie*, 96-126.

Noe-Nygaard, N. (1983). 'The importance of aquatic resources to Mesolithic man at inland sites in Denmark. In: Grigson, C., Clutton-Brock, J. (eds), *Animals and Archaeology 2: Shell middens, fishes and birds*, Oxford: British Archaeol. Rep. Int. Ser. 183, pp. 125-142.

Olsson, M. and Isaksson, S. (2008). Molecular and isotopic traces of cooking and consumption of fish at an Early Medieval manor site in eastern middle Sweden. *Journal of Archaeological Science*, *35*(3), 773-780.

Oudemans, T. F. M. (2006). *Molecular studies of organic residues preserved in ancient vessels* (Faculty of Archaeology, Leiden University). Retrieved from https://openaccess.leidenuniv.nl/handle/1887/5418

Oudemans, T. F. M. (2007). Applying organic residue analysis in ceramic studies - a functional approach. *Leiden Journals of Pottery Studies*, *23*, 5-20.

Palarczyk, M. J. (1986). *Slootkantverkenningen in de Noordoostpolder,* internal rapport Amsterdam University.

Papakosta, V., Oras, E. and Isaksson, S. (2019). Early pottery use across the Baltic - A comparative lipid residue study on Ertebølle and Narva ceramics from coastal hunter-gatherer sites in southern Scandinavia, northern Germany and Estonia. *Journal of Archaeological Science: Reports*, *24*, 142-151.

Patrick, M., De Koning, A. J. and Smith, A. B. (1985). Gas liquid chromatographic analysis of fatty acids in food resides from ceramics found in the southwestern Cape, South Africa. *Archaeometry*, 27, 231-236.

Pecci, A., Giorgi, G., Salvini, L., and Cau Ontiveros, M. Á. (2013). Identifying wine markers in ceramics and plasters using gas chromatography-mass spectrometry. Experimental and archaeological materials. *Journal of Archaeological Science*, *40*(1), 109-115.

Peeters, F. J. C and Peeters, J. H. M. (2001). De opgraving van de mesolithische en neolithische vindplaats Urk-E4 (Domineesweg, gemeente Urk). Amersfoort, *Rapportage Archeologische Monumentenzorg 93*.

Peeters, J. H. M., Hanraets, E., Hogestijn, J. W. H. and Jansma, E. (2001). Dateringen: 14C-analyse en dendrochronologie. In:Hogestijn, J. W. H. and Peeters, J. H. M. (eds), *De mesolithische en vroeg-neolithische vindplaats Hoge Vaart-A27 (Flevoland)*, Amersfoort (Rapportage Archeologische Monumentenzorg 79), Deel 12.

Philippsen, B. (2013). Der Süßwasser-Reservoireffekt in der 14C-Datierung: neue Analysen und mesolithische Kochexperimente. *Experimentelle Archäologie in Europa*, 20-32.

Phillips, D. L., Newsome, S. D., and Gregg, J. W. (2005). Combining sources in stable isotope mixing models: alternative methods. *Oecologia*, *144*(4), 520–527.

Philippsen, B., Kjeldsen, H., Hartz, S., Paulsen, H., Clausen, I., and Heinemeier, J. (2010). The hardwater effect in AMS 14C dating of food crusts on pottery. *Nuclear Instruments & Methods in Physics Research. Section B, Beam Interactions with Materials and Atoms*, *268*(7), 995-998.

Piezonka, H., Hartz, S., Lüth, F. and Terberger, T. (2011). The earliest pottery east of the Baltic Sea. In: Hartz, S., Lüth, F. und Terberger, T. (eds), *Early Pottery in the Baltic - dating, origin and social context*. Bericht der Römisch-Germanischen Kommission 2008/89, pp. 301-346.

Pollard, A. M., Sterm, B., Young, S. M. M., and Batt, C. M. (2007). *Analytical chemistry in archaeology*, Cambridge, Cambridge University Press.

Povlsen, K. (2014). The introduction of ceramics in the Ertebølle Culture. *Danish Journal of Archaeology*, *2*(2), 146-163.

Prangsgaard, K. (1992) Introduktion af Keramik i den yngre Ertebolle-Kultur i Sydskandinavien, *LAG* 3, 29-52.

Raemaekers, D. C. M. (1999). *The articulation of a "New Neolithic"* (PhD; L. P. Louwe Kooijmans & A. L. van Gijn, Eds.). University of Leiden.

Raemaekers, D. C. M. (2001a). Aardewerk en verbrande klei. In: Louwe Kooijmans, L.P. (ed.), *Hardinxveld-Giessendam Polderweg. Een mesolithisch jachtkamp in het rivierengebied (5500-5000 v. Chr.)*, Amersfoort (Rapportage Archeologische Monumentenzorg 83), 105-118.

Raemaekers, D. C. M. (2001b). Aardewerk en verbrande klei. In: Louwe Kooijmans, L.P. (ed.), *Hardinxveld-Giessendam De Bruin. Een kampplaats uit het laatmesolithicum en het begin van de*

Swifterbant-cultuur (5500-4450 v. Chr.), Amersfoort (Rapportage Archeologische Monumentenzorg 88), 117-152.

Raemaekers, D. C. M. (2003). Cutting a long story short? The process of neolithization in the Dutch delta re-examined. *Antiquity*, *77*(298), 740-748.

Raemaekers, D. C. M. (2004). An outline of Late Swifterbant pottery in the Noordoostpolder (province of Flevoland, the Netherlands) and the chronological development of the pottery of the Swifterbant culture, *Palaeohistoria 45-46*, 11-36.

Raemaekers, D. C. M. (2011). Early Swifterbant pottery (5000-4600 BC): research history, age, characteristics and the introduction of pottery. *Berichte Römisch-Germanische Kommission 89*, 485-500.

Raemaekers, D. C. M. (2015). Rethinking Swifterbant S3 ceramic variability. Searching for the transition to TRB before 4000 cal BC. In: Kabaciński, J., Hartz, S., Raemaekers, D. C. M., and Terberger, T. (eds.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000-3000 calBC).* (pp. 321-334). Verlag Marie Leidorf GmbH.

Raemaekers, D. C. M., Bakels, C. C., Beerenhout, B., van Gijn, A. L., Hänninen, K., Molenaar, S., Paalman, D., Verbruggen, M., and Vermeeren, C. (1997). Wateringen 4. a coastal settlement of the Middle Neolithic Hazendonk 3 Group, *Analecta Praehistorica Leidensia 29*, 143-191.

Raemaekers, D. C. M. and de Roever, P. J. (2010). The Swifterbant pottery tradition (5000-3400 BC). In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.), *Pots, Farmers and Foragers. Pottery traditions and social interaction in the earliest Neolithic of the Lower Rhine Area*, Leiden University Press, pp. 135-149.

Raemaekers, D. C. M., Kubiak-Martens, L., and Oudemans, T. F. M. (2013). New food in old pots - charred organic residues in Early Neolithic ceramic vessels from Swifterbant, the Netherlands (4300-4000 cal BC). *Archäologisches Korrespondenzblatt*, *43*(3), 315-334.

Rageot, M., Mötsch, A., Schorer, B., Bardel, D., Winkler, A., Sacchetti, F., Chaume, B., Della Casa, P., Buckley, S., Cafisso, S., Fries-Knoblach, J., Krausse, D., Hoppe, T., Stockhammer, P., and Spiteri, C. (2019). New insights into Early Celtic consumption practices: Organic residue analyses of local and imported pottery from Vix-Mont Lassois. *PloS One*, *14*(6), e0218001.

Raven, A. M., van Bergen, P. F., Stott, A. W., Dudd, S. N., and Evershed, R. P. (1997). Formation of long-chain ketones in archaeological pottery vessels by pyrolysis of acyl lipids. *Journal of Analytical and Applied Pyrolysis*, *40-41*, 267-285.

Richter J. and Noe-Nygaard N. (2003). A late Mesolithic Hunting Station at Agernæs, Fyn, Denmark. *Acta Archaeologica* 74, 1-64.

Regert, M. (2011). Analytical strategies for discriminating archaeological fatty substances from animal origin. *Mass Spectrometry Reviews*, *30*(2), 177-220.

Regert, M., Bland, H. A., Dudd, S. N., Bergen, P. F. V., and Evershed, R. P. (1998). Free and bound fatty acid oxidation products in archaeological ceramic vessels. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *265*(1409), 2027-2032.

de Roever, J. P. (2004). *Swifterbant aardewerk: Een analyse van de neolithische nederzettingen bij Swifterbant 5e millennium voor Christus*, Dissertation, University of Groningen.

de Roever, J. P. (2009). The pottery of hunter-gatherers in transition to agriculture, illustrated by Swifterbant Culture, the Netherlands. In: Gheorghiu, D. (ed.), *Early Farmers, Late Foragers, and Ceramic Traditions: On the Beginning of Pottery in the Near East and Europe*. Cambridge Scholar Publishing, pp. 150-166.

Richards, M. P., and Hedges, R. E. M. (1999). Stable Isotope Evidence for Similarities in the Types of Marine Foods Used by Late Mesolithic Humans at Sites Along the Atlantic Coast of Europe. *Journal of Archaeological Science*, *26*(6), 717–722.

Robson, H. K., Andersen, S. H., Clarke, L., Craig, O. E., Gron, K. J., Jones, A. K. G., Karsten, P., Milner, N., Price, T. D., Ritchie, K., Zabilska-Kunek, M., and Heron, C. (2016). Carbon and nitrogen stable isotope values in freshwater, brackish and marine fish bone collagen from Mesolithic and Neolithic sites in central and northern Europe. *Environmental Archaeology*, *21*(2), 105-118.

Robson, H., Oras, E., Hartz, S., Kabaciński, J., Gumiński, W., Tielen, L., Akotula, A., Czekaj-Zastawny, A., Lucquin, A., Craig, O., and Heron, C. (2018). Illuminating the prehistory of Northern Europe: organic residue analysis of lamps. In: Berihuete-Azorín, M., Lozovskaya, O. (eds), *Subsistence strategies in the stone age, direct and indirect evidence of fishing and gathering*. Volume 54. 1Institute for the History of Material Culture Russian Academy of Science, pp. 214-217.

Robson, H. K., Skipitytė, R., Piličiauskienė, G., Lucquin, A. J. A., Heron, C., Craig, O. E., and Piličiauskas, G. (2019). Diet, cuisine and consumption practices of the first farmers in the south-eastern Baltic. *Archaeological and Anthropological Sciences*, 1-14.

Romanus, K., Poblome, J., Verbeke, K., Luypaerts, A., Jacobs, P., de Vos, D., and Waelkens, M. (2007). An evaluation of analytical and interpretative methodologies for the extraction and identification of Lipids Associated with pottery sherds from the site Sagalasos, Turkey. *Archaeometry*, *49*(4), 729-747.

Ross, A. B. (2012). Present status and perspectives on the use of alkylresorcinols as biomarkers of wholegrain wheat and rye intake. *Journal of Nutrition and Metabolism*, *2012*, 462967.

Ross, A. B., Shepherd, M. J., Schüpphaus, M., Sinclair, V., Alfaro, B., Kamal-Eldin, A., and Aman, P. (2003). Alkylresorcinols in cereals and cereal products. *Journal of Agricultural and Food Chemistry*, *51*(14), 4111-4118.

Rowley-Conwy, P. (1983). Sedentary hunters. The Ertebolle example, In: Bailey, G. (ed.), *Hunter-gatherer economy in prehistory*, Cambridge, pp. 111-126.

Rowley-Conwy, P. (2004) How the west was lost: A reconsideration of agricultural origins in Britain, Ireland, and Southern Scandinavia. *Curr Anthropol* 45(S4): S83- S113-S183-S113

Rowley-Conwy, P. and Zeder, M. (2014). Mesolithic domestic pigs at Rosenhof - or wild boar? A critical re-appraisal of ancient DNA and geometric morphometrics. *World Archaeol.* 46, 813-824. doi:10.1080/00438243.2014.953704.

Saul, H., Glykou, A. and Craig, O. E. (2014). Stewing on a Theme of Cuisine Biomolecular and Interpretive Approaches to Culinary Changes at the Transition to Agriculture. In: Whittle, A., Bickle**,** P. (eds.), *Early Farmers: The View from Archaeology and Science* Vol. 198, 197-213.

Schoeninger, M. J., DeNiro, M. J., & Tauber, H. (1983). Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science*, *220*(4604), 1381–1383.

Sergant, J., Crombé, P. H. and Perdaen, Y. (2006). The sites of Doel 'Deurganckdok' and the Mesolithic/Neolithic transition in the sandy lowlands of Belgium. In: Guilaine, J., van Berg, P.-L.

(eds), *The Neolithisation Process, Acts of the XIVth UISPP Congress, University of Liège, Belgium, 2-8 September 2001, Symposium 9.2*, Oxford (BAR International Series 1520), pp. 53-60.

Skousen, H. (2008) Arkæologi i lange baner. Undersøgelser forud for anlæggelsen af motorvejen nord om Århus. Moesgård Museum. Forlaget Moesgård, Højbjerg.

Skousen, H. (2008). *Arkæologi i lange baner.* Undersøgelser forud for anlæggelsen af motorvejen nord om Århus. Moesgård Museum. Højbjerg, Forlaget Moesgård.

Spangenberg, J. E., Jacomet, S. and Schibler, J. (2006). Chemical analyses of organic residues in archaeological pottery from Arbon Bleiche 3, Switzerland - evidence for dairying in the late Neolithic. *Journal of Archaeological Science*, *33*(1), 1-13.

Steele, V. J., Stern, B. and Stott, A. W. (2010). Olive oil or lard? distinguishing plant oils from animal fats in the archeological record of the eastern Mediterranean using gas chromatography/combustion/isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry: RCM*, *24*(23), 3478-3484.

Stern, B., Heron, C., Serpico, M., and Bourriau, J. (2000). A Comparison of Methods for Establishing Fatty Acid Concentration Gradients Across Potsherds. A Case Study Using Late Bronze Age Canaanite Amphorae. *Archaeometry* 42(2), 399-414.

Stilborg, O. and Bergenstråhle, I. (2000). Traditions in transition. A comparative study of the patterns of the Ertebølle lithic and pottery changes in the late Mesolithic ceramic phase at Skateholm I, III and Soldattorpet in Scania, Sweden. *Lund Archaeological Review* 6, 23-41.

Sørensen, L. (2014). The analysis of secondary evidence of agriculture in south Scandinavia during the 5th and 4th millennium BC. In: Sørensen, L. (ed.), *From Hunter to Farmer in Northern Europe: Migration and adaptation during the Neolithic and Bronze Age*. *Acta Archaeologica* 85, 1. Oxford, Wiley, pp. 109-126.

Taché, K. and Craig, O. E. (2015). Cooperative harvesting of aquatic resources and the beginning of pottery production in north-eastern North America. *Antiquity*, *89*(343), 177-190.

Teetaert, D. (2020). *Routes of technology: pottery production and mobility during the Mesolithic-Neolithic transition in the Scheldt river valley (Belgium)*. Dissertation, Ghent University.

ten Anscher, T. J. (2012). *Leven met de Vecht: Schokland-P14 en de Noordoostpolder in het neolithicum en de bronstijd*. Dissertation University of Amsterdam.

ten Anscher, T. J. (2015). Under the radar: Swifterbant and the origins of the Funnel Beaker culture. In: Kabaciński, J., Hartz, S., Raemaekers, D. C. M., and Terberger, T. (eds.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000-3000 cal BC)*. Verlag Marie Leidorf GmbH. Rahden/Westf, pp. 335-358.

Terberger, T., Hartz, S., and Kabaciński, J. (2009). Late hunter-gatherer and early farmer contacts in the southern Baltic - a discussion. In: Glørstad, H., Prescott, C. (eds). N*eolithisation as if history mattered: process of neolithisation in North-Western Europe,* Uddevalla, Sweden: Bricoleur Pres, pp. 257-298.

Vanhanen, S., Gustafsson, S., Ranheden, H., Björck, N., Kemell, M., and Heyd, V. (2019). Maritime Hunter-Gatherers Adopt Cultivation at the Farming Extreme of Northern Europe 5000 Years Ago. *Scientific Reports*, 9(1), 4756.

van Diest, H. (1981). Zur frage der 'lampen' nach den ausgrabungsfunden von Rosenhof (Ostholstein) *Archaologisches Korrespondenzblatt* 11, 301-14.

Verneau, S. M. J. P. (2001). Aardewerk. In F.J.C. Peters and J. H.M. Peeters (eds), *De opgraving van de mesolithische en neolithische vindplaats Urk-E4 (Domineesweg, gemeente Urk),* Amersfoort (Rapportage Archeologische Monumentenzorg 93), pp. 77-93.

Voet D. and Voet G. (2011) *Biochemistry*. Wiley, New York.

Weete, J. D., Abril, M. and Blackwell, M. (2010). Phylogenetic distribution of fungal sterols. *PloS One*, 5(5), e10899.

Wstępne, U. (2012). Sprawozdanie Z Badan Wykopaliskowych na Stanowisku 20 W Redczu krukowym, Pow. Włocławski, Woj. Kujawsko-Pomorskie. Prace I Materiały Muzeum Archeologicznego I Etnograficznego Łodzi, *Seria Archeologiczna 45*, 2010-2012, 195-238.

Zeiler, J. T. (1997) Hunting, fowling and stock-breeding in the Dutch Neolithic. *Archaeofauna* 6:97-113.

Zich, B. (1993). Die Ausgrabungen chronisch gefährdeter Hügelgräber der Stein- und Bronzezeit in Flintbek, Kreis RendsburgEckernförde. *Ein Vorbericht. Offa* 49/50, 1992/93, 15-31.

Ziegler, J. U., Steingass, C. B., Longin, C. F. H., Würschum, T., Carle, R., and Schweiggert, R. M. (2015). Alkylresorcinol composition allows the differentiation of Triticum spp. having different degrees of ploidy. *Journal of Cereal Science*, 65, 244-251.

Table 1. Corrected isotope values obtained from authentic modern tissue samples collected from Western Baltic

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Dairy	-31.15	-27.48	-3.7	goat	Capra hircus	Rumiant milk	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-32.53	-27.47	-5.1	goat	Capra hircus	Rumiant milk	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-31.76	-27.82	-3.9	goat	Capra hircus	Rumiant milk	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-30.95	-27.33	-3.6			Milk (Northern Finncattle)	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-30.92	-27.06	-3.9			Milk (Northern Finncattle)	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-31.77	-26.99	-4.8			Milk (Northern Finncattle)	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-31.41	-26.85	-4.6			Milk (Northern Finncattle)	Laitila	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-31.86	-27.77	-4.1			Milk (Northern Finncattle)	n/a	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Dairy	-34.5	-25.79	-8.7	cattle		Ruminant milk	Metsakivi, EST	Modern	2015	2015	Ester Oras (postdoc project, unpublished)
Dairy	-34.56	-30.96	-3.6	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-32.26	-27.96	-4.3	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-33.96	-29.56	-4.4	sheep	Ovis Aries	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-33.56	-29.16	-4.4	sheep	Ovis Aries	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-32.36	-27.56	-4.8	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-33.86	-29.06	-4.8	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-35.06	-29.76	-5.3	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-33.26	-28.06	-5.2	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-34.26	-28.76	-5.5	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis
Dairy	-34.16	-28.26	-5.9	cow	Bos Taurus	Ruminant milk	Southern UK	Modern	1990-1995	1992	Dudd thesis

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Freshwater	-36.2	-34.77	1.4	Bream	Abramis brama	Soft tissue	Lake Niinivesi, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-34.3	-34.73	-0.4	Bream	Abramis brama	Soft tissue	Lake Niinivesi, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-35.83	-35.29	0.5	Bream	Abramis brama	Soft tissue	Lake Niinivesi, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-34.07	-32.57	1.5	Bream	Abramis brama	Soft tissue	Lake Kellojärvi, Kuhmo	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-34.58	-32.57	2	Burbot	Lota lota	Soft tissue	Lake Kellojärvi, Kuhmo	Modern	Winter 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.06	-31.46	1.6	Ide	Leuciscus idus	Soft tissue	Lake Pajalampi, Kuhmo	Modern	Summer 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.64	-32.01	1.6	Ide	Leuciscus idus	Soft tissue	Lake Pajalampi, Kuhmo	Modern	Summer 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.46	-33.08	0.4	Northern pike	Esox lucius	Soft tissue	Lake Pönkälampi, Kuhmo	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-31.95	-31.51	0.4	Northern pike	Esox lucius	Soft tissue	Lake Niinivesi, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.7	-32.46	1.2	Northern pike	Esox lucius	Soft tissue	Lake Kellojärvi, Kuhmo	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-32.27	-32.5	-0.2	Perch	Perca fluviatilis	Soft tissue	Lake Murtojärvi, Kuhmo	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-35.32	-34.86	0.5	Perch	Perca fluviatilis	Soft tissue	Lake Pönkälampi, Kuhmo	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-34.52	-33.42	1.1	Perch	Perca fluviatilis	Soft tissue	Lake Niinivesi, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-35.15	-33.54	1.6	Perch	Perca fluviatilis	Soft tissue	Lake Valkea-Kotinen, Hämeenlinna	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.54	-32.8	0.7	Perch	Perca fluviatilis	Soft tissue	Lake Valkea-Kotinen, Hämeenlinna	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-33.19	-32.53	0.7	Perch	Perca fluviatilis	Soft tissue	Lake Valkea-Kotinen, Hämeenlinna	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-35.42	-34.96	0.5	Perch	Perca fluviatilis	Soft tissue	Lake Pajalampi, Kuhmo	Modern	Summer 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-32.2	-32.8	-0.6	Perch	Perca fluviatilis	Soft tissue	Lake Hujakko, Äänekoski	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-35.51	-37.07	-1.6	Perch	Perca fluviatilis	Soft tissue	Lake Pajalampi, Kuhmo	Modern	Summer 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-34.71	-33.91	0.8	Pike-Perch	Sander lucioperca	Soft tissue	Lake Kellojärvi, Kuhmo	Modern	Spring 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-30.49	-30.16	0.3	Pike-Perch	Sander lucioperca	Soft tissue	n/a	Modern	2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-29.63	-32.1	-2.5	Roach	Rutilus rutilus	Soft tissue	Lake Hujakko, Äänekoski	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Freshwater	-34.23	-33.1	1.1	Roach	Rutilus rutilus	Soft tissue	Lake Pajalampi, Kuhmo	Modern	Summer 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-29.63	-29.61	0	Roach	Rutilus rutilus	Soft tissue	Lake Peipus/Peipsi	Modern	Autumn 2015	2015	Ester Oras (postdoc project, unpublished)
Freshwater	-28.48	-27.03	1.5	Vendace	Coregonus albula	Soft tissue	Lake Vanajanselkä	Modern	Summer 2012	2012	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-37.05	-38.02	-1	Vendace	Coregonus albula	Soft tissue	Lake Lentua, Kuhmo	Modern	Summer 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-29.35	-28.09	1.3	Vendace	Coregonus albula	Soft tissue	Lake Puruvesi	Modern	Autumn 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-28.2	-29.71	-1.5	Vendace	Coregonus albula	Soft tissue	Lake Puruvesi	Modern	Autumn 2013	2013	Mirva Paakonen Pers. Comm. JONAS 2018
Freshwater	-28.54	-28.74	-0.2	Eel	Anguilla anguilla	Soft tissue	Denmark	Modern	2000 - 2005	2002	Craig et al. 2011
Freshwater	-35.14	-35.34	-0.2	Pike	Esox lucius	Soft tissue	Denmark	Modern	2000 - 2005	2002	Craig et al. 2011
Freshwater	-28.04	-29.14	-1.1	Tench	Tinca tinca	Soft tissue	Denmark	Modern	2000 - 2005	2002	Craig et al. 2011
Freshwater	-24.54	-26.64	-2.1	Tench	Tinca tinca	Soft tissue	Denmark	Modern	2000 - 2005	2002	Craig et al. 2011
Freshwater	-37.54	-36.84	0.7	Tench	Tinca tinca	Soft tissue	Denmark	Modern	2000 - 2005	2002	Craig et al. 2011
Freshwater	-33.22	-32.12	1.1			Soft tissue	Lake Constance	Modern	2000-2005	2002	Spangenberg et al. 2006
Freshwater	-30.34	-28.34	2	Carp	Carassius carassius		UK	Modern	2000-2005	2002	Unpublished
Freshwater	-28.34	-25.94	2.4	Pike	Esox lucius		UK	Modern	2000-2005	2002	Unpublished
Freshwater	-31.14	-28.54	2.6	Perch	Perca fluviatilis		UK	Modern	2000-2005	2002	Unpublished
Freshwater	-35.91	-35.28	0.6	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-35.44	-36.01	-0.6	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.97	-35.06	-0.1	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.71	-35.72	-1	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.71	-35.67	-1	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.55	-35.83	-1.3	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.25	-33.9	0.4	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Freshwater	-33.76	-33.84	-0.1	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-33.56	-33.42	0.1	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-33.14	-34.06	-0.9	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-32.78	-34.26	-1.5	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-32.42	-33.01	-0.6	Perch	Perca fluviatilis	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-34.35	-34.46	-0.1	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-33.76	-34.97	-1.2	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-33.04	-34.12	-1.1	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-32.88	-33.87	-1	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-33.03	-33.49	-0.5	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Freshwater	-32.43	-32.69	-0.3	Roach	Rutilus sp.	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Marine	-25.48	-26.78	-1.3	Atlantic cod	Gadus morhua	Fame	UK	Modern	1990-1995	1993	Dudd thesis
Marine	-26.78	-24.48	2.3	Haddock	Melanogrammus aeglefinus	fillet	UK	Modern	1990-1995	1993	Dudd thesis
Marine	-24.68	-24.08	0.6	Plaice	Pleuronectes platessa	fillet	UK	Modern	1990-1995	1993	Dudd thesis
Marine	-20.73	-21.33	-0.6	Eel	Anguilla anguilla	Soft tissue	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-20.83	-21.93	-1.1	Eel	Anguilla anguilla	Soft tissue	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-18.63	-18.73	-0.1	Eel	Anguilla anguilla	Soft tissue	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-19.93	-21.63	-1.7	Eel	Anguilla anguilla	Soft tissue	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-23.03	-22.53	0.5	Atlantic cod	Gadus morhua	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-23.03	-24.43	-1.4	Atlantic cod	Gadus morhua	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-22.33	-24.83	-2.5	Atlantic cod	Gadus morhua	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Marine	-20.33	-20.33	0	Spotted seal	Phoca largha	Blubber	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-13.13	-14.63	-1.5	Spotted seal	Phoca largha	Blubber	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-18.93	-20.53	-1.6	Harbour seal	Phoca vitulina	Blubber	Germany	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-18.83	-20.13	-1.3	European flounder	Platichthys flesus	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-20.13	-21.83	-1.7	Plaice	Pleuronectes platessa	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-19.23	-20.43	-1.2	Plaice	Pleuronectes platessa	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-19.73	-21.33	-1.6	Eelpout	Zoarces viviparus	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-17.23	-18.23	-1	Eelpout	Zoarces viviparus	Flesh	Denmark	Modern	2000 - 2005	2003	Craig et al. 2011
Marine	-23.53	-21.13	2.4	Atlantic herring	Clupea harengus	Soft tissue	Germany	Modern	2000 - 2005	2003	Craig et al. 2011?
Marine	-21.63	-22.03	-0.4	Atlantic cod	Gadus morhua	Soft tissue	Germany	Modern	2000 - 2005	2003	Craig et al. 2011?
Marine	-18.59	-15.89	2.7	Eel	Anguilla anguilla		UK	Modern	2000-2005	2003	Unpublished
Marine	-24.89	-24.49	0.4	Atlantic cod	Gadus morhua		UK	Modern	2000-2005	2003	Unpublished
Marine	-21.53	-21.63	-0.1	Bull trout	Myoxocephalus scorpius	Flesh	Denmark	Modern	2000-2005	2003	Unpublished
Marine	-24.39	-24.99	-0.6	oyster	Ostrea edulis		UK	Modern	2000-2005	2003	Unpublished
Marine	-19.23	-20.43	-1.2	European flounder	Platichthys flesus	Flesh	Denmark	Modern	2000-2005	2003	Unpublished
Marine	-25.49	-25.69	-0.2	Atlantic mackerel	Scomber scombrus		UK	Modern	2000-2005	2003	Unpublished
Marine	-25.98	-25.93	0.1	sea salmon	Salmonidae sp.	tissue	UK	Modern	2000-2005	2003	Unpublished,YE 20150924
Marine	-25.78	-25.66	0.1	sea salmon	Salmonidae sp.	experimental sherd	UK	Modern	2000-2005	2003	Unpublished,YE 20150928
Marine	-27.58	-27.32	0.3	Atlantic herring	Clupea harengus	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-27.04	-25.79	1.3	Atlantic herring	Clupea harengus	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-27	-25.33	1.7	Atlantic herring	Clupea harengus	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-26.48	-26.1	0.4	Atlantic herring	Clupea harengus	Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Marine	-25.7	-27.12	-1.4	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.91	-24.76	0.2	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.47	-24.02	0.5	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.01	-23.54	0.5	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.19	-23.75	1.4	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.31	-23.58	1.7	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.74	-23.79	2	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.58	-23.42	2.2	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.33	-23.22	2.1	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.1	-22.86	2.3	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-26.27	-23.16	3.1	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.1	-21.95	3.2	Bivalves		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.07	-23.56	0.5	marines mammals		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.53	-24.28	1.3	marines mammals		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.62	-25.75	-0.1	marines mammals		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.49	-24.62	0.9	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-25.44	-24.74	0.7	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.37	-24.2	0.2	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.27	-23.51	0.8	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.3	-23.33	1	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.16	-23.29	0.9	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.87	-23.21	0.7	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Marine	-24.01	-23.04	1	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.94	-22.88	1.1	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.94	-22.76	1.2	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.37	-22.83	1.5	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-24.08	-22.03	2.1	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.12	-22.3	0.8	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.17	-22.24	0.9	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.8	-23.02	-0.2	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.83	-23.02	-0.2	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.96	-23.08	-0.1	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.92	-21.4	1.5	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.71	-21.97	-0.3	Marine fish		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.51	-23.01	-0.5	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.54	-21.95	0.6	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.18	-20.69	2.5	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.79	-21.58	0.2	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.07	-21.41	0.7	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.96	-21.32	0.6	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.06	-20.97	1.1	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-20.31	-20.76	-0.4	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.02	-19.73	1.3	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.93	-19.27	2.7	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.85	-19.26	2.6	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Marine	-21.28	-19.05	2.2	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-20.81	-19.15	1.7	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-20.75	-19.26	1.5	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-20.75	-18.25	2.5	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-19.06	-17.93	1.1	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-18.86	-17.83	1	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-18.47	-17.44	1	Gastropods		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.87	-23.39	0.5	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.4	-22.32	1.1	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-22.76	-21.85	0.9	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.41	-22.27	-0.9	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.34	-20.7	0.6	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-21.34	-20.63	0.7	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-20.24	-18.47	1.8	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-17.55	-16.05	1.5	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-16.57	-16.05	0.5	Crustaceans		Soft tissue	UK	Modern	2010-2014	2012	Cramp et al 2014
Marine	-23.08	-24.19	-1.1	see bass	Dicentrarchus labrax	tissue	UK	Modern	2004	2004	Bell et al, J. Agric. Food Chem.,

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Porcine	-27.35	-25.76	1.6	Pig	Sus scrofa domesticus		n/a	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Porcine	-28.13	-26.65	1.5	Pig	Sus scrofa domesticus		n/a	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Porcine	-27.44	-26.86	0.6	Pig	Sus scrofa domesticus		n/a	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Porcine	-27.15	-25.63	1.5	Pig	Sus scrofa domesticus		n/a	Modern	2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Porcine	-26.5	-25.66	0.8	Wild boar	Sus scrofa ferus		Ilomantsi	Modern	1991	1991	Mirva Paakonen Pers. Comm. JONAS 2018

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Porcine	-26.95	-26.94	0	Wild boar	Sus scrofa ferus		Ilomantsi	Modern	1986	1986	Mirva Paakonen Pers. Comm. JONAS 2018
Porcine	-26.9	-25.84	1.1	Wild boar	Sus scrofa ferus		Alatskivi, EST	Modern	Sep-15	2015	Ester Oras (postdoc project, unpublished)
Domestic porcine adipose	-24.96	-24.16	0.8	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-26.56	-24.96	1.6	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-26.66	-24.96	1.7	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-25.66	-24.56	1.1	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-26.16	-25.06	1.1	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-25.26	-23.96	1.3	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-25.86	-24.56	1.3	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-25.56	-24.26	1.3	Pig	Sus scrofa domesticus		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic porcine adipose	-28.85	-27.62	1.2	Pig	Sus scrofa domesticus		Local farm (Langerbruck, CH)	Modern	2000-2005	2002	Spangenberg et al. 2006
Domestic porcine adipose	-25.8	-26.7	-0.9	Pig	Sus scrofa domesticus		Local farm (Langerbruck, CH)	Modern	2000-2005	2002	Spangenberg et al. 2006
Wild non-ruminant	-24.66	-24.66	0				switzerland	Modern	2000-2005	2002	Spangenberg et al. 2010
Wild porcine	-25.26	-24.96	0.3	Wild boar	Sus scrofa ferus		Germany	Modern	2010	2010	Spiteri 2012
Wild porcine	-28.26	-28.16	0.1	Wild boar	Sus scrofa ferus		Germany	Modern	2010	2010	Spiteri 2012

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Wild Ruminant adipose	-30.23	-32.2	-1.97	Eurasian elk	Alces alces		Kuhmo	Modern	2012	2012	Mirva Paakonen Pers. Comm. JONAS 2018
Wild Ruminant adipose	-28.82	-30.3	-1.48	Eurasian elk	Alces alces		Kuhmo	Modern	2012	2012	Mirva Paakonen Pers. Comm. JONAS 2018
Wild Ruminant adipose	-29.77	-32.1	-2.33	Eurasian elk	Alces alces		Oripää	Modern	2003	2003	Mirva Paakonen Pers. Comm. JONAS 2018
Wild Ruminant adipose	-29.2	-31.4	-2.2	Eurasian elk	Alces alces		Kuhmo	Modern	1984	1984	Mirva Paakonen Pers. Comm. JONAS 2018
Wild Ruminant adipose	-30.04	-32	-1.96	Eurasian elk	Alces alces		Alatskivi, EST	Modern	2015	2015	Ester Oras (postdoc project, unpublished)
Wild Ruminant adipose	-31.19	-32.7	-1.51	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Wild Ruminant adipose	-31.29	-33	-1.71	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-31.64	-33	-1.36	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-33.42	-34.6	-1.18	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-31.06	-33.3	-2.24	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-30.14	-30.7	-0.56	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-32.82	-34.5	-1.68	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-29.38	-31.4	-2.02	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-32.16	-32.6	-0.44	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-30.83	-32.1	-1.27	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-30.73	-32.2	-1.47	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-32.64	-33.9	-1.26	Eurasian elk	Alces alces		Alatskivi/Metsakivi, EST	Modern	2016	2016	Oras, Lucquin, Clayton, Craig (unpublished)
Wild Ruminant adipose	-27.81	-31.6	-3.79	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-27.51	-31.2	-3.69	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-28.51	-32.7	-4.19	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-30.11	-33.8	-3.69	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-29.21	-32.8	-3.59	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-28.91	-33.1	-4.19	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-30.51	-33.1	-2.59	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-29.61	-33.2	-3.59	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-29.01	-32.4	-3.39	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-29.51	-33.1	-3.59	Deer	Cervus elaphus		Poland, Slowinski National Park	Modern		1994	Craig et al 2012 RCMS
Wild Ruminant adipose	-28.46	-29.86	-1.4	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Wild Ruminant adipose	-28.96	-30.66	-1.7	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Wild Ruminant adipose	-29.56	-29.86	-0.3	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Wild Ruminant adipose	-28.96	-32.26	-3.3	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Wild Ruminant adipose	-28.16	-33.36	-5.2	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Wild Ruminant adipose	-30.86	-33.96	-3.1	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Wild Ruminant adipose	-30.96	-33.76	-2.8	Deer	Cervus elaphus	adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.56	-31.36	-1.8	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.56	-30.26	-1.7	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.86	-30.56	-1.7	Sheep	Ovis Aries	Ram lamb 2	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.36	-31.26	-1.9	Sheep	Ovis Aries	Ram lamb 1	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.46	-31.26	-1.8	Sheep	Ovis Aries	Mutton shoulder	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.56	-31.46	-2.9	Sheep	Ovis Aries	Mutton leg fat	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.96	-30.26	-1.3	Sheep	Ovis Aries	Hebridean lamb	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.36	-30.16	-1.8	Sheep	Ovis Aries	sheep (MUTTON FAT)	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-30.56	-32.36	-1.8	Sheep	Ovis Aries	E8B91 (EWE ORIG)	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-30.36	-32.46	-2.1	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-30.66	-32.66	-2	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.56	-31.96	-2.4	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.16	-30.56	-1.4	Sheep	Ovis Aries		Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.06	-31.96	-2.9	Cow	Bos Taurus	Ruminant Adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-29.96	-32.46	-2.5	Cow	Bos Taurus	Ruminant Adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-28.86	-31.66	-2.8	Cow	Bos Taurus	Ruminant Adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis

Class	d13C18	d13C16	Δ13C (C18:0-C16:0)	Common name	Taxa	Sample type	Place of catchment	Period	date collected (death)	mean date of collection	Reference
Domestic ruminant adipose	-30.06	-31.76	-1.7	Cow	Bos Taurus	Ruminant Adipose	Southern UK	Modern	1990-1995	1992	Dudd thesis
Domestic ruminant adipose	-27.62	-29.02	-1.4	Cattle	Bos taurus		Kärkölä	Modern	Autumn 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Domestic ruminant adipose	-27.24	-28.7	-1.46	Cattle	Bos taurus		n/a	Modern	Autumn 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Domestic ruminant adipose	-26.98	-29.4	-2.42	Cattle	Bos taurus		Koski as.	Modern	Autumn 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Domestic ruminant adipose	-27.75	-29.7	-1.95	Cattle	Bos taurus		n/a	Modern	Autumn 2014	2014	Mirva Paakonen Pers. Comm. JONAS 2018
Domestic ruminant adipose	-27.96	-30.1	-2.14	Cattle	Bos taurus		Võru county, EST	Modern	Autumn 2016	2016	Ester Oras (postdoc project, unpublished)
Domestic ruminant adipose	-30.26	-31.8	-1.54	Sheep	Ovis aries		Metsakivi, EST	Modern	2015	2015	Ester Oras (postdoc project, unpublished)

CHAPTER 3

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

Özge Demirci, Alexandre Lucquin, Oliver E. Craig, Daan C.M. Raemaekers

Published in: *Archaeological and Anthropological Sciences* (2020) 12:105

doi: 10.1007/s12520-020-01062-w

Archaeological and Anthropological Sciences (2020) 12:105
https://doi.org/10.1007/s12520-020-01062-w

ORIGINAL PAPER

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

Özge Demirci[1,2] · Alexandre Lucquin[2] · Oliver E. Craig[2] · Daan C.M. Raemaekers[1]

Received: 3 December 2019 / Accepted: 5 April 2020

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 Anscher 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

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12520-020-01062-w) contains supplementary material, which is available to authorized users.

✉ Özge Demirci
odemirci@palaeome.org

[1] Groningen Institute of Archaeology, Poststraat 6, 9712 ER Groningen, the Netherlands

[2] BioArch, Department of Archaeology, University of York, York YO10 5YW, UK

Published online: 26 April 2020

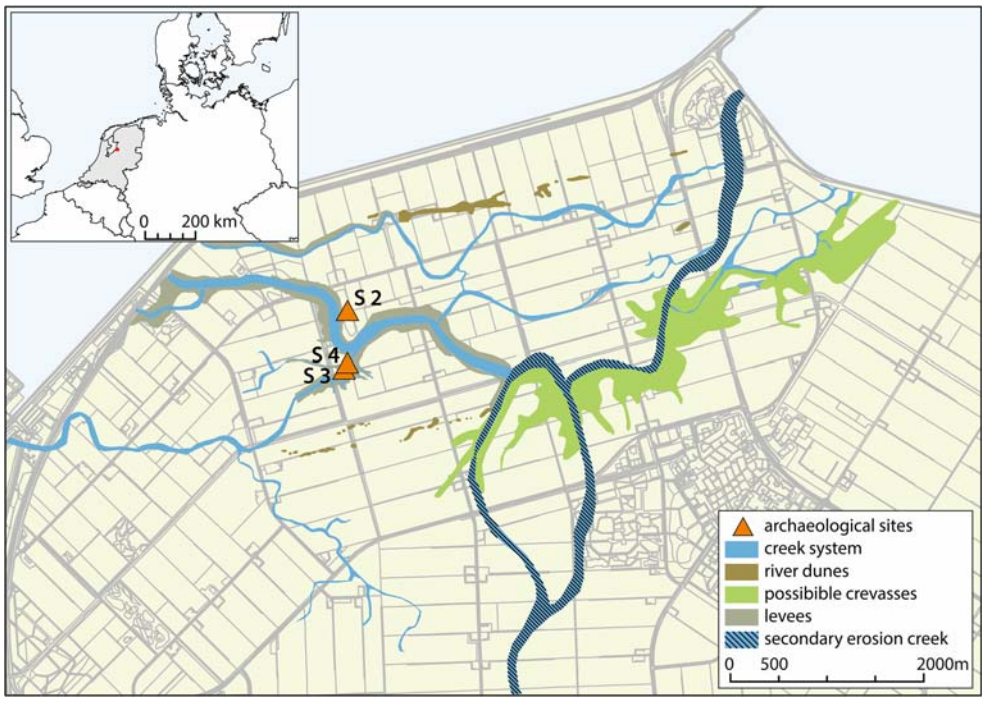


Fig. 1 Map showing the location of the Swifterbant cluster sites along the freshwater creek system (Devriendt 2014, Fig. 2), overlain on a modern map. Insert map showing the location of the Netherlands in relation to Northern Europe and the location of the Swifterbant cluster within the Netherlands

'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

[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

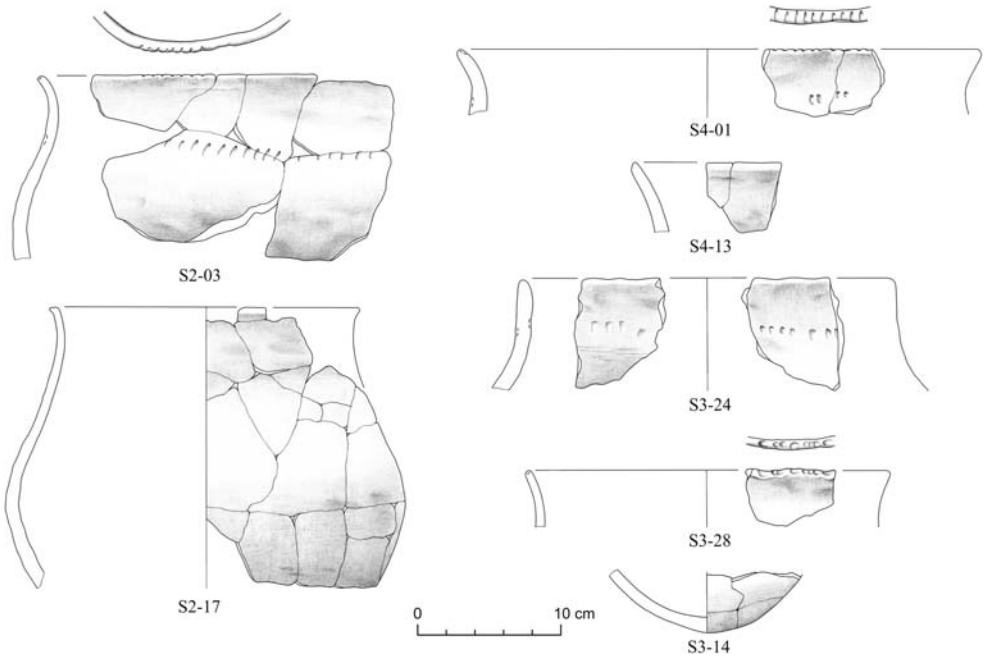


Fig. 2 Illustrations of selected sherds from Swifterbant S2, S3 and S4 (scale 1:3)

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 ± SD values of *n*-alkanoic acid esters were − 31.65 ± 0.27‰ for the methyl ester of $C_{16:0}$ and − 26.01 ± 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

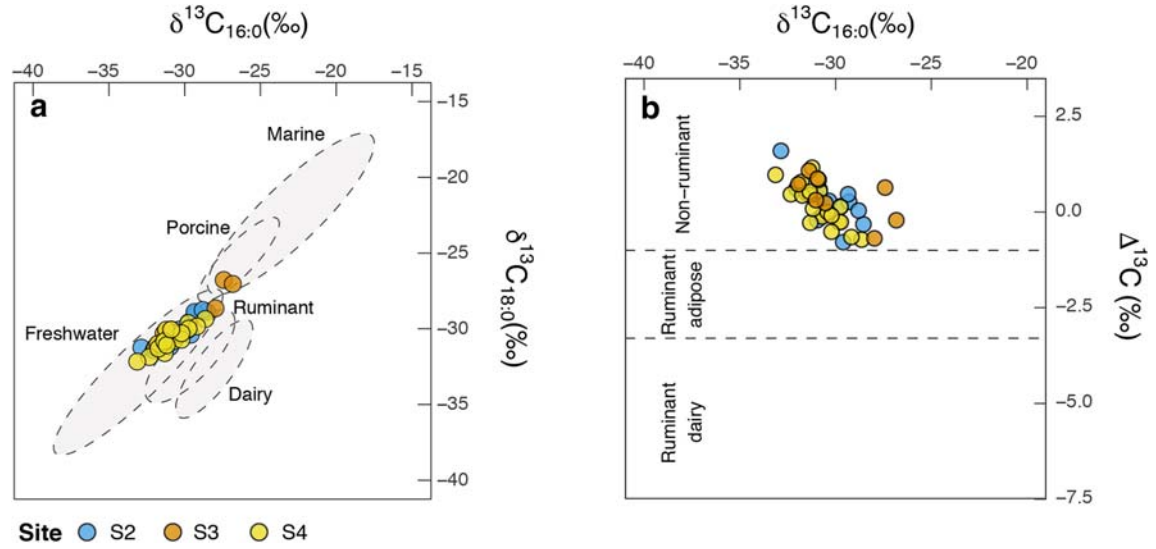


Fig. 3 Stable carbon isotope measurements of $C_{16:0}$ and $C_{18:0}$ fatty acids obtained from ceramic matrices of Swifterbant pottery by site. **a** Plot of $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values against ranges of authentic reference fats and oils. Ellipses indicate the 95% confidence 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.

Acknowledgements We thank Erwin Bolhuis (Groningen Institute of Archaeology) who produced the map for Fig. 1 and Frits Steenhuisen (Arctic Centre, Groningen) for his additional help on it. We also thank M.A. Los-Weijns (Groningen Institute of Archaeology) for the pottery illustrations in Fig. 2. We thank Helen Talbot and Matthew Von Tersch for their assistance with aspects of laboratory work.

Funding information This project is part of a Marie Sklodowska-Curie European Joint Doctoral Training Program, funded by the European Union's EU Framework program for Research and Innovation Horizon 2020 under the Grant Agreement No. 676154 (ArchSci2020 program).

References

Admiraal M, Lucquin A, von Tersch M, Jordan PD, Craig OE (2018) Investigating the function of prehistoric stone bowls and griddle stones in the Aleutian Islands by lipid residue analysis. Quat Res 91(3):1–13

Amkreutz, L. W. S. W. (2013). Persistent traditions: a long-term perspective on communities in the process of Neolithisation in the lower Rhine area (5500–2500 cal BC. Dissertation Leiden University

Andersen, S. H. (2010). The first pottery in South Scandinavia. In B. Vanmontfort, L. Louwe Kooijman, L. Amkreutz, L. Verhart (eds.), Pots, farmers and foragers: how pottery traditions shed a light on social interaction in the earliest Neolithic of the lower Rhine area (pp. 167–176). Leiden University Press

Bailey G, Spikins P (eds) (2008) Mesolithic Europe. Cambridge University Press, Cambridge

Ballin, T. B. (2014). The culture concept and the Ertebølle-Swifterbant dispute a spin-off from the debate between Raemaekers and Stilborg (or: the basic elements of prehistoric territorial studies)

Barker G (2006) The agricultural revolution in prehistory: why did foragers become farmers? Oxford University Press, Oxford

Brinkhuizen, D. C. (1976). Preliminary notes on fish remains from archaeological sites in the Netherlands. Palaeohistoria, 21(0), 83–90

Cappers RTJ, Raemaekers DCM (2008) Cereal cultivation at Swifterbant? Neolithic wetland farming on the North European Plain. Curr Anthropol 49(3):385–402

Clason AT (1978) Worked bone, antler and teeth. A preliminary report (Swifterbant contribution 9). Helinium 18:83–86

Clason AT, Brinkhuizen DC (1978) Swifterbant, mammals, birds, fishes. Preliminary report. Swifterbant contribution 8. Helinium 18:69–82

Colonese AC, Hendy J, Lucquin A, Speller CF, Collins MJ, Carrer F, Gubler R, Kühn M, Fischer R, Craig OE (2017) New criteria for the molecular identification of cereal grains associated with archaeological artefacts. Sci Rep 7(1):6633

Copley MS, Berstan R, Dudd SN, Docherty G, Mukherjee AJ, Straker V, Evershed RP (2003) Direct chemical evidence for widespread dairying in prehistoric Britain. Proc Natl Acad Sci U S A 100(4):1524–1529

Correa-Ascencio M, Evershed RP (2014) High throughput screening of organic residues in archaeological potsherds using direct acidified methanol extraction. Anal Methods 6(5):1330–1340

Craig OE, Forster M, Andersen SH, Koch E, Crombé P, Milner NJ, Heron CP (2007) Molecular and isotopic demonstration of the aquatic products in northern European prehistoric pottery. Archaeometry 49(1):135–152

Craig OE, Steele VJ, Fischer A, Hartz S, Andersen SH, Donohoe P, Heron CP (2011) Ancient lipids reveal continuity in culinary practices across the transition to agriculture in Northern Europe. Proc Natl Acad Sci U S A 108(44):17910–17915

Craig OE, Allen RB, Thompson A, Stevens RE, Steele VJ, Heron C (2012) Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. Rapid Commun Mass Spectrom 26(19):2359–2364

Craig OE, Saul H, Lucquin A, Nishida Y, Taché K, Clarke L, Jordan P (2013) Earliest evidence for the use of pottery. Nature 496(7445): 351–354

Cramp LJE, Evershed RP (2014) Reconstructing aquatic resource exploitation in human prehistory using lipid biomarkers and stable isotopes. In: Holland HD, Turekian KK (eds) Treatise on geochemistry, second edn. Elsevier, Oxford, pp 319–339

Cramp LJE, Evershed RP, Lavento M, Halinen P, Mannermaa K, Oinonen M, Heyd V (2014) Neolithic dairy farming at the extreme of agriculture in Northern Europe. Proc R Soc Lond B Biol Sci 281(1791):20140819

Cramp LJE, Ethier J, Urem-Kotsou D, Bonsall C, Borić D, Boroneanț A, Evershed RP, Perić S, Roffet-Salque M, Whelton HL, Ivanova M (2019) Regional diversity in subsistence among early farmers in Southeast Europe revealed by archaeological organic residues. *Proceedings Biological Sciences / The Royal Society 286*(1894): 20182347

De Roever JP (1979) The pottery from Swifterbant-Dutch Ertebølle? (Swifterbant contribution 9). Helinium 19:13–39

De Roever, J. P. (2004). Swifterbant aardewerk: Een analyse van de neolithische nederzettingen bij Swifterbant 5e millennium voor Christus. Dissertation, University of Groningen

Deckers PH (1982) Preliminary notes on the neolithic flint material from Swifterbant (Swifterbant contribution 13). Helinium 22:33–39

Devriendt, I. (2014). Swifterbant stones: the Neolithic stone and flint industry at Swifterbant (the Netherlands): from stone typology and flint technology to site function. Dissertation, University of Groningen

Evershed RP (1993) Biomolecular archaeology and lipids. World Archaeol 25(1):74–93

Evershed RP (2008) Organic residue analysis in archaeology: the archaeological biomarker revolution. Archaeometry 50(6):895–924

Evershed RP, Dudd SN, Copley MS, Berstan R, Stott AW, Mottram H, Crossman Z (2002) Chemistry of archaeological animal fats. Acc Chem Res 35(8):660–668

Evershed RP, Copley MS, Dickson L, Hansel FA (2008) Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. Archaeometry 50(1):101–113

Geuverink, J. (2020). *Features and spatial analysis*. In D.C.M. Raemaekers and J.P. de Roever (eds)., Swifterbant S4 (the Netherlands) Occupation and exploitation of a neolithic levee seite (c. 4300–4000 cal. BC). Barkhuis Publishing, p. 98–106

Gronenborn D (2007) Beyond the models: "Neolithisation" in Central Europe. In: Gronenborn D (ed) Going over: the Mesolithic-Neolithic transition in North-West Europe. British Academy, London, pp 73–98

Hammann S, Cramp LJE (2018) Towards the detection of dietary cereal processing through absorbed lipid biomarkers in archaeological pottery. J Archaeol Sci 93:74–81

Hansel FA, Copley MS, Madureira LAS, Evershed RP (2004) Thermally produced ω-(o-alkyl phenyl) alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. Tetrahedron Lett 45(14):2999–3002

Heron C, Andersen S, Fischer A, Glykou A, Hartz S, Saul H, Craig O (2013) Illuminating the Late Mesolithic: residue analysis of "blubber" lamps from Northern Europe. Antiquity 87:178–188

Heron C, Craig OE, Luquin A, Steele VJ, Thompson A, Piličiauskas G (2015) Cooking fish and drinking milk? Patterns in pottery use in the southeastern Baltic, 3300–2400 cal BC. J Archaeol Sci 63:33–43

Huisman DJ, Raemaekers DCM (2014) Systematic cultivation of the Swifterbant wetlands (the Netherlands). Evidence from Neolithic tillage marks (c. 4300–4000 cal. BC). J Archaeol Sci 49:572–584

Huisman DJ, Jongmans AG, Raemaekers DCM (2009) Investigating Neolithic land use in Swifterbant (NL) using micromorphological techniques. Catena 78(3):185–197

Krause-Kyora B, Makarewicz C, Evin A, Flink LG, Dobney K, Larson G, Hartz S, Schreiber S, von Carnap-Bornheim C, von Wurmb-Schwark N, Nebel A (2013) Use of domesticated pigs by Mesolithic hunter-gatherers in northwestern Europe. Nat Commun 4:2348

Louwe Kooijmans LP (1993) Wetland exploitation and upland relations of prehistoric communities in the Netherlands. East Anglian Archaeology 50:71–116

Louwe Kooijmans, L. P. (2003). The Hardinxveld sites in the Rhine/Meuse Delta, the Netherlands, 5500-4500 cal BC, in: L. Larsson, H. Kindgren, K. Knutsson, D. Loeffler a. Åkerlund (eds): Mesolithic on the move. Papers presented at the sixth international conference on the Mesolithic in Europe, Stockholm 2000. Oxford: oxbow books, pp. 608–624

Louwe Kooijmans LP (2010) The ceramisation of the Low Countries, seen as the result of gender-specific processes of communication. In: Vanmontfort B, Louwe Kooijmans L, Amkreutz L, Verhart L (eds) Pots, farmers and foragers: pottery traditions and social interaction in the earliest Neolithic of the Lower Rhine Area. Leiden University Press, Leiden, pp 27–40

Papakosta V, Smittenberg RH, Gibbs K, Jordan P, Isaksson S (2015) Extraction and derivatization of absorbed lipid residues from very small and very old samples of ceramic potsherds for molecular analysis by gas chromatography–mass spectrometry (GC–MS) and single compound stable carbon isotope analysis by gas chromatography–combustion–isotope ratio mass spectrometry (GC–C–IRMS). Microchem J 123:196–200

Papakosta V, Oras E, Isaksson S (2019) Early pottery use across the Baltic – a comparative lipid residue study on Ertebølle and Narva ceramics from coastal hunter-gatherer sites in southern Scandinavia, northern Germany and Estonia. J Archaeol Sci Rep 24:142–151

Peeters, J. H. M. (2007). Hoge Vaart-A27 in context: towards a model of mesolithic - neolithic land use dynamics as a framework for archaeological heritage management. Amersfoort Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten

Philippsen, B., Meadows, J. (2014), Inland Ertebølle culture: the importance of aquatic resources and the freshwater reservoir effect in radiocarbon dates from pottery food crusts. Internet Archaeology 37

Philippsen B, Kjeldsen H, Hartz S, Paulsen H, Clausen I, Heinemeier J (2010) The hardwater effect in AMS 14C dating of food crusts on pottery. Nuclear instruments & methods in physics research. Section B, Beam Interactions with Materials and Atoms 268(7): 995–998

Raemaekers DCM (1997) The history of the Ertebølle parallel in Dutch Neolithic studies and the spell of the point-based Pottery1. Archaeological Dialogues 4(2):220–234

Raemaekers DCM (1998) Ertebølle and Swifterbant: a comparison of attitudes. Anthropologie et Préhistoire 109:155–161

Raemaekers, D. C. M. (1999). *The articulation of a "New Neolithic"* dissertation Leiden University

Raemaekers D (2003) Cutting a long story short? The process of neolithization in the Dutch delta re-examined. Antiquity 77(298): 740–748

Raemaekers, D. C. M. (2012). Rethinking Swifterbant S3 ceramic variability. Searching for the transition to TRB before 4000 calBC. In J. Kabaciński, S. Hartz, D. Raemaekers, T. Terberger (eds.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000–3000 calBC).* Rahden: Verlag Marie Leidorf, pp. 321–334

Raemaekers, D. C. M. and de Roever, J. P. (2010). The Swifterbant pottery tradition (5000-3400 BC). In B. L. L. Vanmontfort, K. L. P. Louwe, L. W. S. W. Amkreutz, & L. B. M. Verhart (Eds.), *Pots, Farmers and Foragers. Pottery traditions and social interaction in the earliest Neolithic of the Lower Rhine Area* Leiden University press, pp. 135–149

Raemaekers DCM, Molthof HM, Smits E (2009) The textbook `dealing with death' from the Neolithic Swifterbant culture (5000-3400 BC), the Netherlands. Berichte Römisch-Germanische Kommission 88: 479–500

Raemaekers DCM, Kubiak-Martens L, Oudemans TFM (2013) New food in old pots - charred organic residues in early Neolithic ceramic vessels from Swifterbant, the Netherlands (4300-4000 cal BC). Archäologisches Korrespondenzblatt 43(3):315–334

Robson H, Oras E, Hartz S et al (2018) Illuminating the prehistory of northern Europe: organic residue analysis of lamps. In: Lozovskaya O, Vybornov A, Dolbunova E (eds) Subsistence strategies in the stone age, direct and indirect evidence of fishing and gathering. Saint Petersburg, Institute for the History of Material Culture Russian Academy of Science, pp 214–217

Rowley-Conwy P (2013) North of the frontier: early domestic animals in northern Europe. In: Colledge S, Connoly J, Dobney K, Manning K, Shennan S (eds) The origins and spread of domestic animals in Southwest Asia and Europe. Left Coast Press, Walnut Creek, pp 283–312

Saul H, Madella M, Fischer A, Glykou A, Hartz S, Craig OE (2013) Phytoliths in pottery reveal the use of spice in European prehistoric cuisine. PLoS One 8(8):e70583

Smits L, van der Plicht H (2009) Mesolithic and Neolithic human remains in the Netherlands: physical anthropological and stable isotope investigations. Journal of Archaeology in the Low Countries 1(1):55–85

Smits E, Millard RA, Nowell G, Pearson DG (2010) Isotopic investigation of diet and residential mobility in the Neolithic of the lower Rhine Basin. Eur J Archaeol 13(1):5–31

Stilborg O (1999) Dutch Swifterbant and Swedish Ertebølle: a debate on regionality and ceramic analysis. Archaeological Dialogues 6(1): 47–54

Taché K, Craig OE (2015) Cooperative harvesting of aquatic resources and the beginning of pottery production in North-Eastern North America. Antiquity 89(343):177–190

ten Anscher, T. J. (2012). Leven met de Vecht: Schokland-P14 en de Noordoostpolder in het neolithicum en de bronstijd. Dissertation University of Amsterdam

van Zeist W, Palfenier-Vegter RM (1981) Seeds and fruits from the Swifterbant S3 site. Final Reports on Swifterbant IV. Palaeohistoria 23:105–168

Zeiler JT (1997a) Hunting, fowling and stock-breeding in the Dutch Neolithic. Archaeofauna 6:97–113

Zeiler, J. T. (1997b). *Hunting, fowling and stock-breeding at Neolithic sites in the western and central Netherlands* dissertation Groningen University

Authors' contributions (%)

Özge Demirci:

Conceptualization	95%
Formal analysis (lab work)	100%
Investigation (data analysis)	95%
Visualization of data	100% (also see Acknowledgements)
Writing - original draft	96%
Writing - review & editing	89%

Alexandre Lucquin:

Investigation (data analysis)	5%
Writing - review & editing	1%

Oliver E. Craig:

Conceptualization	2%
Methodology	100%
Resources (lab access)	50%
Validation	50%
Supervision	40%
Project administration	50%
Funding acquisition	50%
Writing - original draft	2%
Writing - review & editing	5%

Daan C. M. Raemaekers:

Conceptualization	3%
Resources (material access)	50%
Validation	50%
Supervision	60%
Project administration	50%
Funding acquisition	50%
Writing - original draft	2%
Writing - review & editing	5%

All authors gave their final approval for publication.

SUPPLEMENTARY MATERIAL

(ONLINE RESOURCE-1)

for

First lipid residue analysis of Early Neolithic pottery from Swifterbant

(the Netherlands, ca. 4300–4000 BC)

Özge Demirci, Alexandre Lucquin, Oliver E. Craig, Daan C.M. Raemaekers

Supplementary Material (Online Resource -1): Sampled pottery information

sample ID	Pre-treatment	Site	Location	Site type	Cultural group	Cultural phase	Vessel type	Vessel part	Decoration	Rim diameter (cm)	Weight (gr)	Wall thickness (mm)	Main tempering material
S2-01	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	14	66.3	11	plant material
S2-03	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	24	328.5	13	plant material
S2-06	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	27	44.6	9	plant material
S2-08	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	25		6	grit
S2-10	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	yes		31.3	6	grit
S2-12	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		76.7	12	plant material
S2-15	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	32	336.3	9	grit
S2-17	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	30	87.1	9	grit
S2-19	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		31.5	10	grit
S2-20	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		24.4	8	plant material
S2-21	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		35.1	8	plant material
S2-22	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		23.7	10	grit
S2-23	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		40	10	plant material
S2-24	AE	Swifterbant S2	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		7	9	grit
S3-01	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		25.3	9	plant material
S3-03	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		27.1	8	plant material
S3-05	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		92.1	10	plant material
S3-08	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		57.6	9	plant material
S3-10	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		50.9	11	plant material
S3-12	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		168.2	10	plant material
S3-14	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		205.6	9	plant material
S3-16	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		141	9	plant material
S3-18	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		29.9	10	plant material
S3-20	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		80.6	11	plant material
S3-22	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes		52.9	10	sand
S3-24	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	20	65.1	11	mica
S3-26	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes		33.6	10	mica
S3-28	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	28	28.8	8	plant material
S3-30	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	26	44	7	plant material
S3-32	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		32.7	9	plant material
S3-34	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	20	35.2	9	plant material
S3-36	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	20	14.9	9	grit
S3-38	AE	Swifterbant S3	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	15	67.4	12	grit
S4-01	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	45	45.1	11	plant material
S4-02	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	yes		22.9	14	plant material
S4-03	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		41.4	11	plant material
S4-04	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	15	30.2	8	mica
S4-05	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	17	84.4	10	plant material
S4-06	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes		6	10	plant material
S4-07	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	12	5.9	9	plant material
S4-08	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	base	no		26.2	7	plant material
S4-09	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	40	95.4	12	plant material
S4-10	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	23	70.5	7	plant material

Supplementary Material (Online Resource -1): Sampled pottery information (continues)

sample ID	Pre-treatment	Site	Location	Site type	Cultural group	Cultural phase	Vessel type	Vessel part	Decoration	Rim diameter (cm)	Weight (gr)	Wall thickness (mm)	Main tempering material
S4-11	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes		23.7	6	plant material
S4-12	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	20	13.8	9	plant material
S4-13	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	27	30.3	9	plant material
S4-14	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	yes	20 ?	23.8	10	plant material
S4-15	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	yes		68.2	12	plant material
S4-16	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		16.9	11	plant material
S4-17	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	yes		10. 3	6	plant material
S4-18	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		16.7	9	plant material
S4-19	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		17.8	13	mica
S4-20	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	yes		11.8	7	plant material
S4-21	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		21.7	10	plant material
S4-22	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		65.8	11	plant material
S4-23	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	35	49.1	10	plant material
S4-24	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		31. 5	9	plant material
S4-25	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	25	10.8	9	plant material
S4-26	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	yes		17.1	14	plant material
S4-27	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		10.5	9	plant material
S4-28	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	rim	no	14	4	6	mica
S4-29	AE	Swifterbant S4	Inland	Waterlogged settlement site	Swifterbant	Late Swifterbant	Cooking pot	body	no		18.8	8	plant material

Supplementary Material (Online Resource -1): Results of organic residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers
S2-01	Potsherd	Internal	105	2.32	-29.74	-29.59	0.15	APAA(C_{16-22}), tmtd, phy	79.1	x	SFA($C_{13:0-22:0}$), UFA($C_{18:01}$), DC($C_{9:0}$), br
S2-03	Potsherd	Internal	343	1.73	-31.02	-30.61	0.41	APAA(C_{18-20}), tmtd, phy	92.2	x	SFA($C_{11:0-19:0}$), UFA($C_{18:01}$), DC($C_{9:0}$), br
S2-06	Potsherd	Internal	295	1.54	-29.29	-29.03	0.26	APAA(C_{16}), phy	65.1	-	SFA($C_{14:0-18:0}$)
S2-08	Potsherd	Internal	33	1.59	-28.55	-28.87	-0.32	APAA(C_{18-20}), tmtd, phy	86.2	x	SFA($C_{14:0-20:0}$), UFA($C_{17:01}$), br
S2-10	Potsherd	Internal	36	1.07	-29.6	-30.39	-0.79	APAA(C_{18}), tmtd, phy	84.1	-	SFA($C_{14:0-19:0}$), UFA($C_{18:01}$), br
S2-12	Potsherd	Internal	121	1.59				APAA(C_{16-20})	n/a	x	SFA($C_{12:0-28:0}$), UFA($C_{18:01}$), br
S2-15	Potsherd	Internal	31	1.17	-32.85	-31.25	1.6	APAA(C_{16-18})	n/a	-	SFA($C_{14:0-24:0}$), br
S2-17	Potsherd	Internal	88	0.87	-29.35	-28.89	0.46	APAA(C_{16-18})	n/a	-	SFA($C_{14:0-20:0}$), br
S2-19	Potsherd	Internal	266	1.8	-32.04	-31.42	0.61	APAA(C_{16-22}), tmtd, phy	91.6	x	SFA($C_{10:0-19:0}$), UFA($C_{16:1,\ 18:1}$), DC($C_{9:0}$)
S2-20	Potsherd	Internal	127	1.18	-28.81	-28.77	0.04	phy	67.7	-	SFA($C_{12:0-21:0}$), UFA($C_{18:01}$), br
S2-21	Potsherd	Internal	469	1.66	-30.97	-31.18	-0.22	APAA(C_{16-22})	n/a	-	SFA($C_{13:0-28:0}$), UFA($C_{18:1,\ 20:1}$), br
S2-22	Potsherd	Internal	83	1.03	-30.35	-30.05	0.29	APAA(C_{18-20}), tmtd, phy	n/a	x	SFA($C_{14:0-20:0}$), UFA($C_{18:1}$), br
S2-23	Potsherd	Internal	160	1.71	-30.84	-30.25	0.59	APAA(C_{18-20}), tmtd	n/a	x	SFA($C_{12:0-18:0}$), UFA($C_{16:1,\ 18:1}$), br
S2-24	Potsherd	Internal	286	1.35				APAA(C_{18})	n/a	-	SFA($C_{11:0-22:0}$), UFA($C_{16:1,\ 18:1}$), br
S3-01	Potsherd	Internal	14	1.92				tmtd, pri, phy	76.9	-	SFA($C_{14:0-18:0}$)
S3-03	Potsherd	Internal	194	2.68	-30.53	-30.3	0.23	APAA(C_{16-20}), phy	81.4	x	SFA($C_{13:0-18:0}$), UFA($C_{16:1,\ 18:1}$), br, chol
S3-05	Potsherd	Internal	30	1.85	-27.42	-26.78	0.64	tmtd, pri	n/a	-	SFA($C_{14:0-26:0}$), br, chol
S3-08	Potsherd	Internal	10	2.09				APAA(C_{16-20}), tmtd, pri, phy	n/a	x	SFA($C_{15:0-18:0}$)
S3-10	Potsherd	Internal	12	2.23				APAA(C_{16-18}), tmtd, pri, phy	17.6	x	SFA($C_{16:0-18:0}$)
S3-12	Potsherd	Internal	75	1.36	-31.39	-30.32	1.08	APAA(C_{16-20}), tmtd, pri, phy	n/a	x	SFA($C_{14:0-20:0}$), UFA($C_{18:01}$)
S3-14	Potsherd	Internal	54	1.52	-31.02	-30.71	0.31	APAA(C_{16-20}), tmtd, phy	53.8	x	SFA($C_{14:0-24:0}$)
S3-16	Potsherd	Internal	30	2.28	-31.95	-31.22	0.73	APAA(C_{16-18}), tmtd, pri, phy	18.4	x	SFA($C_{14:0-18:0}$), UFA($C_{18:01}$)
S3-18	Potsherd	Internal	22	1.91				APAA($_{16-22}$), tmtd, pri, phy	n/a	x	SFA($C_{14:0-18:0}$)
S3-20	Potsherd	Internal	12	2.06				APAA(C_{16}), tmtd, phy	23.4	-	SFA($C_{14:0-18:0}$)
S3-22	Potsherd	Internal	620	1.03					n/a	-	SFA($C_{14:0-18:0}$)
S3-24	Potsherd	Internal	6186	1.87					n/a	-	SFA($C_{14:0-24:0}$), UFA($C_{18:01}$)
S3-26	Potsherd	Internal						APAA(C_{16-22})	n/a	x	SFA($C_{14:0-20:0}$)
S3-28	Potsherd	Internal	33	1.34	-27.97	-28.66	-0.68	APAA(C_{18-20}), pri, phy	49.8	x	SFA($C_{14:0-24:0}$), UFA($C_{18:01}$)
S3-30	Potsherd	Internal	63	2.6	-30.93	-30.06	0.87	APAA(C_{16-20}), tmtd, pri, phy	27.3	x	SFA($C_{13:0-26:0}$), UFA($C_{16:1,18:1}$)
S3-32	Potsherd	Internal	38					APAA(C_{18}), tmtd, phy	33.5	-	SFA($C_{14:0-18:0}$), br, chol
S3-34	Potsherd	Internal	483	1.35	-26.82	-27.03	-0.21	APAA(C_{16-20}), pri, phy	n/a	x	SFA($C_{12:0-24:0}$), UFA($C_{18:01}$)
S3-36	Potsherd	Internal	3	1.16				pri, phy	n/a	-	SFA($C_{14:0-18:0}$)
S3-38	Potsherd	Internal	4	0.94					n/a	-	SFA($C_{14:0-18:0}$)
S4-01	Potsherd	Internal	524	2.18	-29.83	-30.09	-0.26	APAA(C_{16-22}), phy	74.9	-	SFA($C_{12:0-24:0}$), UFA($C_{18:01}$), br, chol
S4-02	Potsherd	Internal	31	2.04	-28.65	-29.37	-0.72	APAA(C_{16-20}), tmtd	n/a	x	SFA($C_{14:0-20:0}$), UFA($C_{18:1,22:1}$), br
S4-03	Potsherd	Internal	39	1.65	-31.48	-31	0.48	APAA(C_{16-20}), tmtd, phy	n/a	x	SFA($C_{13:0-18:0}$), UFA($_{16:1,\ 18:1}$), br, chol
S4-04	Potsherd	Internal	35	1.79				tmtd, phy	64	-	SFA($C_{12:0-18:0}$), br
S4-05	Potsherd	Internal	334	1.71				APAA(C_{16-22}), tmtd	n/a	x	SFA($C_{12:0-22:0}$), UFA($C_{18:1}$), br
S4-06	Potsherd	Internal	148	1.32	-30.64	-30.7	-0.06	APAA(C_{16-20}), tmtd, phy	n/a	x	SFA($C_{14:0-20:0}$), UFA($_{18:1}$), br
S4-07	Potsherd	Internal	26	1.19	-29.75	-29.62	0.13	APAA(C_{18}), tmtd	n/a	-	SFA($C_{14:0-18:0}$), UFA($_{18:1,\ 22:1}$), br

Supplementary Material (Online Resource -1): Results of organic residue analysis (continues)

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers
S4-08	Potsherd	Internal	110	0.74	-29.18	-29.84	-0.66	APAA(C_{16-22}), tmtd, pri, phy	49.2	x	SFA($C_{12:0-24:0}$), UFA($C_{18:01}$), br
S4-09	Potsherd	Internal	16	0.79	-30.7	-30.82	-0.12	tmtd	n/a	-	SFA($C_{14:0-18:0}$), UFA($C_{22:01}$), br
S4-10	Potsherd	Internal	50	1.3				APAA(C_{16-20}), tmtd, phy	74.9	x	SFA($C_{14:0-25:0}$), UFA($C_{18:1, 22:1}$), br, chol
S4-11	Potsherd	Internal	68	0.99	-30.41	-30.41	0	APAA(C_{16}), tmtd, phy	n/a	-	SFA($C_{12:0-18:0}$), UFA($C_{16:1,18:1}$), br
S4-12	Potsherd	Internal	203	1.11	-30.82	-30.28	0.54	APAA(C_{16-22}), tmtd, phy	90.4	x	SFA($C_{12:0-20:0}$), UFA($C_{18:1}$), br
S4-13	Potsherd	Internal	15	1.24	-31.23	-30.07	1.16	APAA(C_{16-18}), tmtd phy	2.9	-	SFA($C_{14:0-24:0}$), UFA($C_{18:1}$), br
S4-14	Potsherd	Internal	579	2.4	-31.32	-31.61	-0.29	APAA(C_{16-22}), tmtd, phy	n/a	x	SFA($C_{14:0-28:0}$), UFA($C_{18:1,22:1}$), br
S4-15	Potsherd	Internal	96	1.75	-31.8	-31.01	0.79	APAA(C_{16-18}), phy	83.6	-	SFA($C_{12:0-18:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), chol
S4-16	Potsherd	Internal	18	1.03	-29.74	-30	-0.26	tmtd, phy	15.2	-	SFA($C_{14:0-20:0}$), UFA($C_{18:01}$)
S4-17	Potsherd	Internal	193	1.6	-31.34	-30.89	0.45	tmtd	n/a	-	SFA($C_{12:0-18:0}$), UFA($C_{16:1,18:1}$)
S4-18	Potsherd	Internal	163	2.24	-32.34	-31.87	0.46	APAA(C_{16-20}), tmtd, phy	91.4	x	SFA($C_{13:0-18:0}$), UFA($C_{16:1,18:1}$)
S4-19	Potsherd	Internal	140	1.64	-31.73	-31.3	0.43	APAA(C_{16-22}), tmtd, phy	91.7	x	SFA($C_{12:0-22:0}$), UFA($C_{16:1,18:1}$)
S4-20	Potsherd	Internal	93	0.83	-30.21	-30.72	-0.52	tmtd	n/a	-	SFA($C_{14:0-20:0}$), UFA($C_{18:01}$)
S4-21	Potsherd	Internal	34	1.49	-31.35	-30.82	0.53	APAA(C_{18-20}), phy	n/a	-	SFA($C_{13:0-22:0}$), UFA($C_{16:1, 18:1}$), DC($C_{9:0}$), br
S4-22	Potsherd	Internal	83	1.65				APAA(C_{16-22}), tmtd	n/a	x	SFA($C_{13:0-24:0}$), UFA($C_{16:1, 18:1}$), chol
S4-23	Potsherd	Internal	17	0.89	-30.21	-30.3	-0.09	APAA(C_{16}), tmtd, phy	19.8	-	SFA($C_{14:0-26:0}$), UFA($C_{18:01}$), br
S4-24	Potsherd	Internal	590	1.47	-33.13	-32.16	0.97	APAA(C_{16-22}), tmtd	n/a	x	SFA($C_{12:0-18:0}$), UFA($C_{18:1}$), br
S4-25	Potsherd	Internal	164	1.22	-31.18	-31.09	0.09	APAA(C_{16-22}), tmtd, phy	n/a	x	SFA($C_{14:0-24:0}$), UFA($C_{16:1,18:1}$), br
S4-26	Potsherd	Internal	132	1.42	-30.89	-30.05	0.84	APAA(C_{16-20}), tmtd, phy	90.4	x	SFA($C_{14:0-20:0}$), chol
S4-27	Potsherd	Internal	116	0.91					n/a	-	SFA($C_{12:0-20:0}$), UFA($C_{18:1}$)
S4-28	Potsherd	Internal	490	1.44				APAA(C_{18-22}), tmtd, phy	n/a	x	SFA($C_{12:0-18:0}$),UFA($C_{18:1}$)
S4-29	Potsherd	Internal	6	0.19				tmtd, phy	n/a	-	SFA($C_{14:0-18:0}$), UFA($C_{16:1, 18:1}$), DC($C_{9:0}$), br, chol

(Cn:x) - carboxilic acids with carbon length n and number of unsaturations x, SFA – saturated fatty acid, UFA – unsaturated fatty acids, DC - α,ω-dicarboxylic acids, APAA - ω-(o-alkylphenyl) alkanoic acids, br -branched chain acids, tmtd - 4,8,12-trimethyltridecanoic acid, pri – pristanic acid, phy – phytanic acid with the percentage contribution of SRR diastereomer in total phytanic acid, chol - cholesterol or derivatives

CHAPTER 4

Lipid residue analysis on Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process

Özge Demirci, Alexandre Lucquin, Canan Çakırlar, Oliver E. Craig, Daan C.M. Raemaekers

Published in: *Journal of Archaeological Science: Reports* 36 (2021) 102812

doi: 10.1016/j.jasrep.2021.102812

Journal of Archaeological Science: Reports 36 (2021) 102812

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Lipid residue analysis on Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process

Özge Demirci [a,b,*], Alexandre Lucquin [b], Canan Çakırlar [a], Oliver E. Craig [b], Daan C. M. Raemaekers [a]

[a] Groningen Institute of Archaeology, Poststraat 6, 9712 ER Groningen, The Netherlands
[b] BioArch, Department of Archaeology, University of York, York YO10 5YW, UK

ARTICLE INFO

Keywords:
Lipid residue analysis
Hunter-gatherers
Early pottery use
Neolithisation process
Lower Rhine-Meuse area
Swifterbant culture
Human animal relations

ABSTRACT

This paper focuses on the functional analysis of Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands). It examines pottery use across the transition to agriculture and aims to assess temporal changes in human-animal relations during the 5th millennium BC in the Lower Rhine-Meuse area through lipid residue analysis. We conducted lipid residue analysis of 49 samples from four Swifterbant sites: Hardinxveld-Giessendam Polderweg, Hardinxveld-Giessendam De Bruin, Brandwijk-het Kerkhof, and Hazendonk. A combined approach using both GC-MS and GC-C-IRMS of residues absorbed into the ceramic was employed to identify their context. Their context was then compared to published faunal datasets to present the relative abundance of taxa detected in the lipid residues. Evidence of processing freshwater fish was found in all sites, presenting that it was a continuous and primary function of Swifterbant pottery in the Lower Rhine-Meuse area starting from its first appearance at c. 5000 cal BC till the end of 5th millennium BC regardless of vessel form, size, decoration or temper. The results of our analysis also present temporal changes in the exploitation of food resources from the early to the late 5th millennium BC. From the mid 5th millennium BC onwards, vessels were also used to process different ranges of foodstuffs such as terrestrial resources and dairy products. The identification of dairy residue is the first direct evidence so far from Swifterbant pottery. We tentatively explain these results as an indication of presence of different culinary practices that had developed through the 5th millennium in the Lower Rhine-Meuse area and that the use of Swifterbant pottery is a direct reflection of changing cultural preferences on food preparation and consumption.

1. Introduction

The term Neolithisation usually describes the transitional stages from the last hunter-gatherer communities to the first farming societies. The Neolithisation process, its timing and tempo, have traditionally been studied through observing changes in the subsistence economy, i.e. the inception of domesticated animal and plant remains, and through associated changes in material culture, such as pottery and stone tools. More recently, organic residue analysis has been used to examine both hunter-gatherer and early agricultural pottery use to look at economic change and offer new perspectives regarding culinary change and cooking practices at this important transition in prehistory. A clear pattern emerging from this growing body of research is the discrepancy between the use of hunter-gatherer pottery, entirely from northern Europe, and early farmer pottery from southern, central and Atlantic Europe. Hunter-gatherer pots were frequently used for cooking both marine and freshwater aquatic resources, as observed in the earliest vessels to appear in mid-6th millennium cal BC in north-eastern Europe (i.e. Narva-type pottery in southeastern Baltic) (Oras et al., 2017; Robson et al., 2019) and 5th millennium cal BC in northern Europe (i.e. Ertebølle pottery (EBK) in southwest Baltic, although Ertebølle ceramics were also used for processing of terrestrial animal and plant resources; Courel et al., 2020; Craig, 2007, 2011; Heron et al., 2013; Papakosta, 2019; Philippsen and Meadows, 2014). This contrasts markedly with the early farming pottery outside of northern Europe where, with a few notable exceptions (Cramp et al., 2019), aquatic resources are virtually

* Corresponding author at: Groningen Institute of Archaeology, Poststraat 6, 9712 ER Groningen, The Netherlands.
E-mail address: odemirci@palaeome.org (Ö. Demirci).

https://doi.org/10.1016/j.jasrep.2021.102812
Received 25 September 2020; Received in revised form 8 January 2021; Accepted 12 January 2021

absent and ruminant meat and dairy products are frequently found (Guiry et al., 2016; Cramp et al., 2014, 2019; Smyth and Evershed, 2015; Debono-Spiteri et al., 2016; Cubas et al., 2019, 2020).

Although both hunter-gatherer pottery and early agricultural pottery have been studied in some detail (Craig et al., 2007; Dolukhanov et al., 2010; Povlsen, 2014; Kriiska et al., 2017; Oras et al., 2017; Hommel, 2018; Bondetti et al., 2019; Courel et al., 2020; Cubas, 2019), there have been relatively fewer comparisons of pottery use across the transition to agriculture. Such comparisons are only possible in northern Europe, where the tradition of pottery use by hunter–gatherer communities was already established prior to the arrival of farming. In some regions, the arrival of agriculture is accompanied by marked changes in pottery forms and manufacturing techniques. Residue analysis of pottery sequences that span the arrival of agriculture, such as the EBK to Funnel Beaker (TRB) in southern Scandinavia (c. 4000 cal BC) (Craig et al., 2011; Isaksson and Hallgren, 2012; Sørensen and Karg, 2014; Sørensen, 2017) and 'subneolithic' to Corded Ware (CWC) in southeastern Baltic (c. 2900/2800 cal BC) (Piličiauskas et al., 2017; Cramp et al., 2014; Heron et al., 2015; Robson et al., 2019) show a mixture of traditional hunter-gatherer subsistence strategies, including exploitation of aquatic resources, and the early farming subsistence economies, often including dairy products. Unlike other early European farmers, in northern Europe aquatic products continued to be processed in pottery beyond the arrival of farming and perhaps were influenced by pre-existing indigenous culinary practices.

Here we examine pottery use across the transition to agriculture in the Lower Rhine-Meuse area. In this region pottery began to be produced at c. 5000 cal BC by hunter-gatherers, known as the Swifterbant tradition. At around 4500–4400 cal BC, there is some evidence that domesticated animals were incorporated into the Swifterbant economy followed by cereal cultivation at around 4300–4000 cal BC (Cappers and Raemaekers, 2008; Çakırlar et al., 2020). Unlike other regions of northern Europe, these introductions were not accompanied by major changes in pottery forms or manufacturing techniques. Nevertheless, it is not known whether the use of pottery changed in this region with the arrival of domesticated animals and plants. Previous organic residue analysis of pottery from three of the Swifterbant type sites (Swifterbant S2, S3, S4), dating to the end of the sequence (c. 4300–4000 cal BC), show no evidence of domesticated animal products (Demirci et al., 2020) although domesticated cereals have been morphologically identified in the charred surface deposits of some vessels (Raemaekers et al., 2013). In this study, we examine a unique chronological transect of Swifterbant activity in the Lower Rhine-Meuse area. By comparing pottery use and faunal assemblages, we aimed to assess temporal changes in human-animal relations during the 5th millennium BC.

2. Archaeological sites

The lipid analysis was carried out on four Swifterbant sites in the Lower Rhine-Meuse area: Hardinxveld-Giessendam Polderweg (hereafter Polderweg), Hardinxveld-Giessendam De Bruin (hereafter De Bruin), Brandwijk-het Kerkhof (hereafter Brandwijk) and Hazendonk (Fig. 1). These sites provide the best sequence of Swifterbant pottery in the Lower Rhine-Meuse area, therefore allowing us to study the use of ceramics while across the transition to farming in the area. The Lower Rhine-Meuse area is a river delta in the Netherlands formed by the confluence of the Rhine and the Meuse rivers. At the end of the Late Pleistocene, the large riverbeds held relatively small rivers and the lack of vegetation cover allowed the sand at the surface to be transported by wind. As a result, a large number of river dunes were formed. From ca. 6000 BCE onwards, the sea level rise resulted in a rise of the groundwater in the area. In its turn, this caused sedimentation of peat and clay. As a result, the archaeological sites discussed here are located in a riverine landscape, where the river dunes provided sparse dry spots for occupation and exploitation (Louwe Kooijmans, 1974, 1993, 2003).

The occupation history of the four sites covers a period from c. 5500 to 3700 cal BC. All four sites were inhabited repeatedly. In this article we focus on the period c. 5000–3820 cal BC, from the oldest ceramics in Swifterbant style (Polderweg phase 2/ De Bruin phase 2; Raemaekers, 2011) to the end of the Swifterbant ceramic tradition (Brandwijk L60; Raemaekers, 1999: 52–53) in the area.

Overall, the pottery from the Lower Rhine-Meuse area sites fits the general description of Swifterbant pottery (Raemaekers: 30–31, 45–55, 63–65, 1999; Raemaekers, 2011; Raemaekers and de Roever, 2010; Louwe Kooijmans, 2010). The pottery from the four sites is characterised by S-shaped, mostly open forms with slightly pointed or rounded bases.

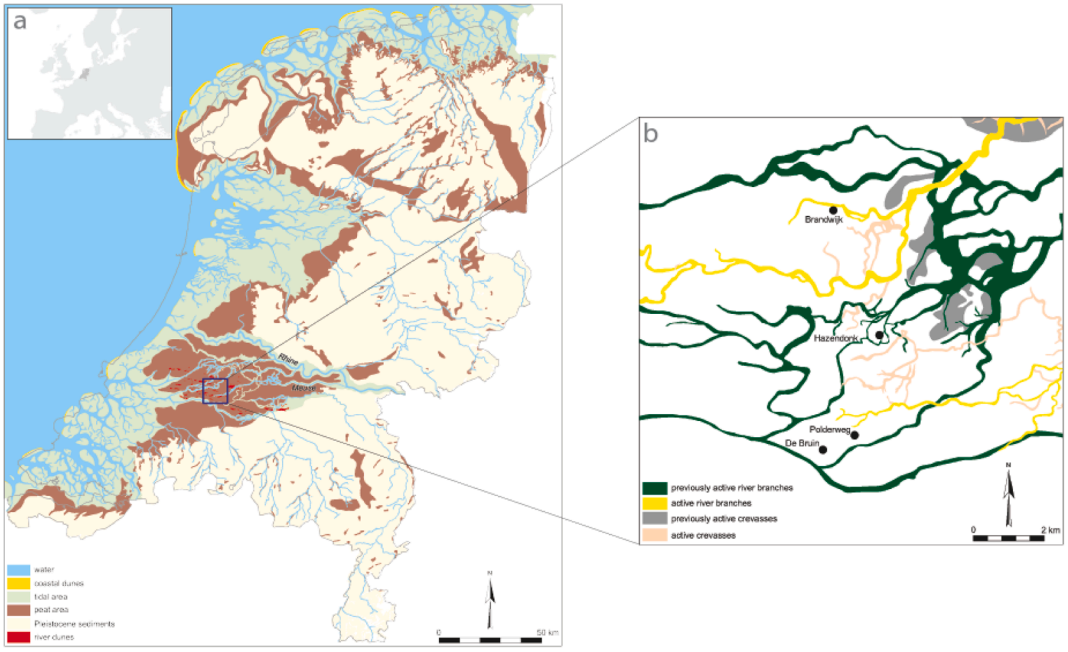


Fig. 1. Maps (a) showing the location of the Netherlands in relation to Europe and the location of the mentioned sites on a palaeogeographic map (3850 cal. BC) of the Netherlands (box), (b) showing the location of the four studied sites in relation to the various river branches. The white area consisted of marshes and lakes (Vos and de Vries, 2013; Vos, in prep.).

It was constructed using the coiling technique, with rim diameters varying from 15 to 40 cm (with the median diameter of 20 cm) and wall thicknesses from 5 to 12 mm (with the median thickness of 10 mm). In terms of fabric, all four sites produce extremely coarse pottery with mostly uneven surfaces. The surface treatment is rare and when present, varies between smoothing, smearing, roughening, and polishing. The most common inclusion for the Polderweg and De Bruin sherds is grit, although some grog and plant material appear as well. Almost all the sherds from Brandwijk and Hazendonk indicate plant material and/or grit as the main temper materials along with rare appearance of grog, sand, and mica. In terms of decoration, there is a temporal variation between the characteristics of the earlier Swifterbant pottery from Polderweg and De Bruin and later assemblages from Brandwijk and Hazendonk. In the earlier pottery assemblages, the decoration is uncommon and when present, it only appears as a series of spatula impressions on the top of the rim. In contrast, later assemblages present a higher distribution of vessels with wall and surface-covering decoration. Wall decorations vary between spatula impressions, thumb impressions, and hollow-circular impressions, while surface-covering decorations consist of either fingertip/nail or hollow spatula impressions. This temporal variation in decoration between earlier and later Swifterbant pottery is well illustrated in the sherds that have been subjected to lipid residue analysis (Supplementary Dataset-1).

All four sites used a broad range of subsistence strategies, exploiting a wide range of animal and plant taxa, including large and small game, terrestrial and aquatic, fowl and fish, nuts and berries. This wide scope remained consistent throughout the period under study (Brinkhuizen, 1979; Zeiler, 1997; Raemaekers, 1999; Louwe Kooijmans, 2003, 2001a, 2001b, 2007; Oversteegen et al., 2001). Deer (Cervidae), *Sus* sp., otter (*Lutra lutra*) and beaver (*Castor fiber*) are the most abundant mammals recovered at all sites. Otter and beaver were hunted in large numbers, and their meat as well as fur were exploited (Zeiler, 1997). It is difficult to assess the role of domestic animals in subsistence during this period (Rowley-Conwy, 2013; Çakırlar et al., 2020; Dusseldorp and Amkreutz, 2020). Analysis of mitochondrial aDNA of four *Sus* teeth of unclear phenotype from the late 5th millennium BC Swifterbant site S4 shows the prevalence of European maternal lineages in *Sus* there (Krause--Kyora, 2011; Kranenburg and Prummel, 2020). However, since intermixing between local wild boar and domestic pigs with origins in the Near East was very common (Frantz et al., 2019), information about maternal lineages alone adds little to the understanding of the nature of pig/boar use at this juncture. *Bos* sp. first appear in the younger phases of De Bruin, and always remain in low numbers (Çakırlar et al., 2020). Although small sample sizes do not allow reconstructing population-wide patterns in morphology and mortality, the absence of aurochs (*Bos primigenius*) in Polderweg and De Bruin phase 1, and the size and age-at-death variation represented by *Bos* specimens may suggest the presence of domesticated cattle herds possibly in De Bruin phase 3 and Brandwijk, and more probably in Hazendonk.

The most secure indication for the presence of domesticated animals in the archaeological record of the Lower Rhine-Meuse area in the Swifterbant period is the few remains of sheep or goat bones at De Bruin and Brandwijk. The earliest directly dated domesticated animal specimen in the region comes from De Bruin and is dated to 4520–4356 cal BC (Çakırlar et al., 2020: Table 13.5). Since sheep and goat are not native to Europe, it is certain that these animals must have been introduced to the area from regions to the south or east where farming was already established at this time. Albeit osteomorphological analyses suggest that some remains might belong to the same individual, decreasing the total number of identified sheep/goat specimens while increasing the uncertainties in their interpretation (Çakırlar et al., 2020). Future studies amalgamating zooarchaeology with high-resolution radiocarbon, stable isotope, and palaeogenomic analyses is needed to resolve this issue.

Given the ambiguity in the identification of wild vs. domesticated suids and bovids, '*Sus* sp.' '*Bos* sp.' are referred to hitherto. This classification also reflects the specificity that can be achieved by lipid residue analysis, which is unable to distinguish wild from domesticated ruminant and porcine fats.

From the high frequency of fish bone remains, it is clear that fishing was a key activity at all sites. All sites provide clear evidence for freshwater (i.e. pike [*Esox lucius*], perch [*Perca fluviatilis*], catfish [*Silurus glanis*], carp family (Cyprinidae)), anadromous (i.e. sturgeon [*Acipenser sturio*], eel [*Anguilla anguilla*], salmon/sea trout [*Salmo salar* cf. *trutta*], allis shad [*Alosa alosa* L.]) and occasional appearance of marine (mullet family (Mugilidae)) species (Brinkhuizen, 1979; Zeiler, 1997). Bird bones are relatively less common compared to mammal and fish remains in all four sites and mainly comprise duck (Anatidae), especially mallard (*Anas platyrhynchos*).

The archaeobotanical remains indicate that gathering remained an important subsistence strategy throughout the 5th millennium BC. All sites show evidence of numerous remains of wild plant species including acorn, hazelnut, water caltrop, wild apple and various berries. Archaeobotanical analyses also present the introduction of possible small-scale crop cultivation in the Lower Rhine-Meuse area. Brandwijk phases L50 and L60 and Hazendonk phase 1 yielded emmer wheat (*Triticum turgidum* ssp. *dicoccum*) and naked barley (*Hordeum vulgare* var. *nudum*) from 4220 to 3820 cal BC and 4020–3960 cal BC onwards respectively (Fig. 6) (Bakels, 1981; Out, 2008, 2009). Moreover, the study of anthropogenic influence on the vegetation indicates a restricted clearance of woodland (i.e. *Tilia* sp., *Quercus* sp.and *Alnus glutinosa)* and development of open patches at Brandwijk and Hazendonk. This may imply small-scale local cultivation at these sites (Out, 2009). The same cereals were found at other sites of the Swifterbant culture (Out, 2009; Schepers and Bottema-Mac Gillavry, 2020), while several cultivated field were recovered at the sites at Swifterbant (Huisman et al., 2009; Huisman and Raemaekers, 2014; Raemaekers and De Roever, 2020), strengthening the interpretation of local cultivation instead of imported crops. We consider the period of c. 4300–4000 cal BC the introduction date of cereal cultivation in the Swifterbant culture.

All four sites are considered to be seasonally occupied, where the function did not change over time, but occasional year-round occupation cannot be excluded either (Louwe Kooijmans, 1993, 2001a, 2001b; Raemaekers: 59–61, 1999).

3. Material and methods

3.1. Sampling strategy

A total of 49 samples (Polderweg, n = 9; De Bruin, n = 17; Brandwijk, n = 14; and Hazendonk, n = 9) were subjected to lipid residue analysis, all representing individual vessels. Of all samples, 17 (4 from Polderweg, 3 from De Bruin, and 10 from Brandwijk) have traces of carbonised remains (foodcrust) on interior and/or exterior surfaces, indicating that they had been used for cooking. Samples were selected from the Swifterbant pottery phases of each site (see Table 1). Pottery from all four Swifterbant sites, Polderweg, De Bruin, Brandwijk, and Hazendonk,

Table 1
Dates and archaeological phases associated with the samples from the four sites in the Lower Rhine-Meuse area (in chronological order).

Site	Phase/ Layer	Number of vessels sampled	Age /cal B. C.	Reference
De Bruin	Phase 2	2	5100–4800	Mol and Louvre Kooijmans, 2001
Polderweg	Phase 2	9	5050–4950	Louwe Kooijmans and Mol, 2001
De Bruin	Phase 3	15	4700–4450	Mol and Louvre Kooijmans, 2001
Brandwijk	L50	15	4220–3940	Verbruggen, 1992
Hazendonk	1	9	4020–3960	Verbruggen, 1992
Brandwijk	L60	1	3940–3820	Verbruggen, 1992

were highly fragmented courseware. Therefore, the sample size of each site is constrained to individual vessel fragments that provided different typological and morphological features and are large enough to be sampled. When available, rim fragments were preferentially selected as experimental studies suggest that lipids tend to accumulate on the rim due to the boiling of food products in the ceramic vessels (Charters et al., 1993). However, base fragments and decorated body sherds were also analysed as they are also diagnostic fragments providing information on the typology and the morphology of the pot. During the process of selecting samples, the form, size, decoration, rim diameter, wall thickness, and temper were recorded (Supplementary Dataset-1).

3.2. Lipid residue extraction

Samples were drilled from the interior surface of each vessel and were subjected to lipid extraction by established standard one step acidified methanol protocol (Craig et al., 2013; Papakosta et al., 2015). All extractions were analysed by Gas Chromatography-Mass Spectrometry (GC-MS), using different columns and modes for identification of different biomarkers (i.e. aquatic biomarkers) (Hansel et al., 2004; Regert, 2011; Cramp and Evershed, 2014; Lucquin et al., 2018), and Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry (GC-C-IRMS) for the measurement of compound-specific carbon stable isotopic ratios of the two most abundant fatty acids; $C_{16:0}$ and $C_{18:0}$, according to previously described protocols (Craig et al., 2012). To assess the corresponding zooarchaeological evidence, published faunal datasets were re-evaluated to quantify the relative abundance of taxa detected in the lipid residues and the taxonomic identification of relevant specimens were checked. The zooarchaeological data were further assessed to reconstruct patterns in body part representation, fragmentation, and mortality, but either sample size or data inaccessibility due to deficiencies in records and their metadata, or both hampered data re-use. Further detailed information on the methods can be found in the Supplementary Materials-Methods.

4. Results and interpretations

4.1. Results of molecular analysis (GC-MS)

All samples (n = 49) yielded sufficient quantities of lipids required for interpretation (>5 μg g^{-1}) with a mean value of 122 μg g^{-1} (ranging from 8 μg g^{-1} to 1,343 μg g^{-1}) (Supplementary Dataset-1).

In general, the lipid profiles obtained from each sample contained saturated fatty acids, ranging from $C_{10:0}$ to $C_{28:0}$, dominated by mid-chain saturated acids, palmitic acid ($C_{16:0}$) and stearic acid ($C_{18:0}$), respectively. The $C_{16:0}$ and $C_{18:0}$ ratios (P/S ratios) of all the samples are listed in the Supplementary Dataset-1. Thirty-four of all the samples yielded unsaturated fatty acids from $C_{15:1}$ to $C_{24:1}$, dominated by oleic acid ($C_{18:1}$). Branched fatty acids ($C_{12} - C_{25}$) were also identified in 43 of all the samples. Dicarboxylic acids are present in 28 samples (58%), all with C_9 (azelaic acid), of which two also have C_{10}. A total of 16 samples yielded cholesterol and its derivatives, indicating the presence of animal fats.

In addition, biomarkers for aquatic products were identified in 31 of all 49 samples (Supplementary Dataset-1). Co-occurrence of *ω*-(*o*-alkylphenyl) alkanoic acids (APAAs), with carbon atoms ranging from 18 to 22, and isoprenoid fatty acids which are TMTD (4,8,12-trimethyltridecanoic acid), pristanic acid (2,6,10,14-tetramethylpentadecanoic acid), and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid) is accepted as the established criteria for identifying aquatic lipids in the ancient pottery (Evershed et al., 2008a; Hansel et al., 2004; Craig et al., 2007; Cramp and Evershed, 2014; Heron et al., 2015). As APAAs are formed by heating (⩾200°, >5h; Bondetti et al., 2020) of mono and polyunsaturated fatty acids, their presence shows that these pots were used for cooking.

While TMTD is considered more of a characteristic of aquatic oils, pristanic and phytanic acids are found in both aquatic and ruminant resources (Ackman and Hooper, 1968; Heron and Craig, 2015). To investigate the origin of phytanic acid found in the samples, we study the ratio of the two diastereomers of phytanic acid (3S,7R,11R,15-phytanic acid (SRR) and 3R,7R,11R,15-phytanic acid (RRR)) as the SRR isomer tends to predominate in aquatic oils (>75.5% relative abundance) compared to ruminant fats (Lucquin et al., 2016). In total, 61% of the samples with phytanic acid meet this criterion. For the remaining samples, the SRR/RRR ratio is either not available or falls within both the aquatic and ruminant range. Further 16 samples yielded partial aquatic biomarkers, containing C_{18} APAA and at least one isoprenoid acid which is also an indication of possible process of aquatic resources in these vessels (Evershed et al., 2008a; Heron and Craig, 2015), although not definitive.

Although the presence of C_{20} APAA has been widely used to identify aquatic products in ancient pottery (Hansel et al., 2004; Cramp and Evershed, 2014), an experimental study undertaken by Bondetti et al. (2020) demonstrates that these compounds can also be formed by heating mammalian tissues. Nevertheless, this study found that the C_{20} APAAs in heated aquatic products are at much greater relative abundance compared to C_{18} components whereas the APAA C_{20}/C_{18} ratio was substantially lower in mammalian tissues. Based on their results, Bondetti et al. assign an APAA C_{20}/C_{18} ratio of 0.06 as the lower limit for the identification of aquatic products. Here, all four sites provide a significantly large number of beaver bone remains (Fig. 6) hence beaver may have been a commodity processed in pottery, particularly for rendering the fatty tail meat (Coles, 2006). To investigate, we measured the APAA C_{20}/C_{18} in 12 Swifterbant vessels and found that in all cases the values were above 0.06 (varying between 0.16 and 0.76; Supplementary Dataset-1) and therefore corresponding to reference fish samples rather than the mammalian dataset that included beaver (Bondetti et al., 2020). For the remaining samples, the APAA C_{20}/C_{18} ratio was not possible to measure accurately.

As further evidence for distinguishing aquatic products from beaver as well as dairy products, we also looked at the branched fatty acids (C_{15br} and C_{17br}) in samples with fully aquatic biomarkers (n = 31). Iso-branched fatty acids predominant in fish oils (Hauff and Vetter, 2010; Garnier et al., 2018), while anteiso- branched fatty acids are more predominant in beaver fat (Käkelä et al., 1996) and also in dairy products (Hauff and Vetter, 2010); the iso- branched fatty acids account for 59 ± 16% of the C_{15} and 59 ± 5% of the C_{17} branched fatty acids in fish oils, 38 ± 6% of the C_{15} and 34 ± 2% of the C_{17} branched fatty acids in dairy products and 19 ± 4% of the C_{15} and 35 ± 12% of the C_{17} branched fatty acids in beaver adipose and flesh tissue fats, the latter from Estonia, Russia and Canada (*Castor fiber* and *Castor canadensis*, n = 10; Supplementary Dataset-3). Of the samples from the Lower Rhine-Meuse Swifterbant samples with fully aquatic biomarkers (n = 31), 61 ± 0.8% of the C_{15} and 53 ± 10% of the C_{17} branched fatty acids (Supplementary Dataset-1) are present as *iso*-fatty acids and therefore are comparable with fish oils rather than beaver fats or dairy products. It is important to note here that the potential effect of the burial environment on this ratio is not known and needs to be tested in further studies.

Finally, none of the samples yielded plant derived lipids (e.g. phytosterols) (Supplementary Dataset-1). It is important to mention here that these results are based on acid extraction and none of the samples have been subjected to solvent extraction to identify cereal derived lipids. Interestingly, the clear presence of carbonized macro remains of numerous food plants found at all four sites suggest that they were processed as part of the food preparation (Out, 2009). In addition, archaeobotanical studies at Brandwijk and Hazendonk indicate the presence of micro remains (i.e. pollen) of crop plants in high amounts (Out, 2009). As naked barley and emmer wheat release the highest amount of pollen during threshing, its presence clearly indicates processing of cereal products at these two sites (Out, 2008, 2009). Although this can be explained by the application of other techniques not requiring ceramics to process food plants, we know that food plants have

a low lipid content and may be masked by other animal fats processed in pots (Colonese et al., 2017; Hammann and Cramp, 2018). This, therefore, makes it very difficult to identify the presence of food plants through lipid residue analysis. We also know that the scanning electron microscope (SEM) analysis on the carbonized surface deposits (foodcrust) collected from another Swifterbant site, Swifterbant S3, has shown that the pots were also used for processing plant materials (Raemaekers et al., 2013). Given that, the absence of plant biomarkers in Swifterbant pottery through lipid residue analysis should be approached cautiously.

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

In order to provide more information on the origin of the lipid residues, the carbon stable isotope values of palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids were analysed by GC-C-IRMS. Analyses included 48 samples which yielded sufficient fatty acids (>5 μg g^{-1}). The data from the samples are listed in and Supplementary Dataset-1. They are plotted in Fig. 3 against the reference ranges of authentic modern animal fats collected from the western Baltic, except for modern beaver fat which was collected from eastern Baltic.

Overall, the majority of the $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids from all four sites are consistent with freshwater organisms (Fig. 3). Of 31 samples with fully aquatic biomarkers, 27 plots in this range. Although beaver also plots within the freshwater range (Fig. 3), both APAA C_{20}/C_{18} ratios and iso to anteiso ratio of C_{15} and C_{17} branched fatty acids refute the possible presence of beaver in these pots. Therefore, there is compelling evidence that these vessels were regularly used for processing freshwater fish.

Three samples from Brandwijk and five samples from Hazendonk plot within the range of modern porcine and marine fats (Fig. 3c and d). *Sus* sp. is abundant at Brandwijk (30% of all identified mammal fragments in L50, Number of Fragments (NF) = 73; 22% of all identified mammal fragments in L60, NF = 99; See Supplementary Dataset-2). *Sus* sp. is also present at Hazendonk (10% of all identified mammal fragments in Hazendonk 1/2; NF = 167, and 11% of all identified mammals in Hazendonk 3; NF = 490) (Zeiler, 1997; Çakırlar et al., 2019). While marine taxa are virtually absent from the zooarchaeological record of both sites, anadromous fish species are present in Brandwijk and Hazendonk. The species include sturgeon, salmon/sea trout, and allis shad (the latter only in Hazendonk) (Brinkhuizen, 1979). It is important to mention here that sturgeon represents a relatively large portion (3.1%, NF = 991 in L50; 3.8%, NF = 415 in L60) of the total fish bone remains at Brandwijk (Raemaekers, 1999: Table 3.27). Although it is

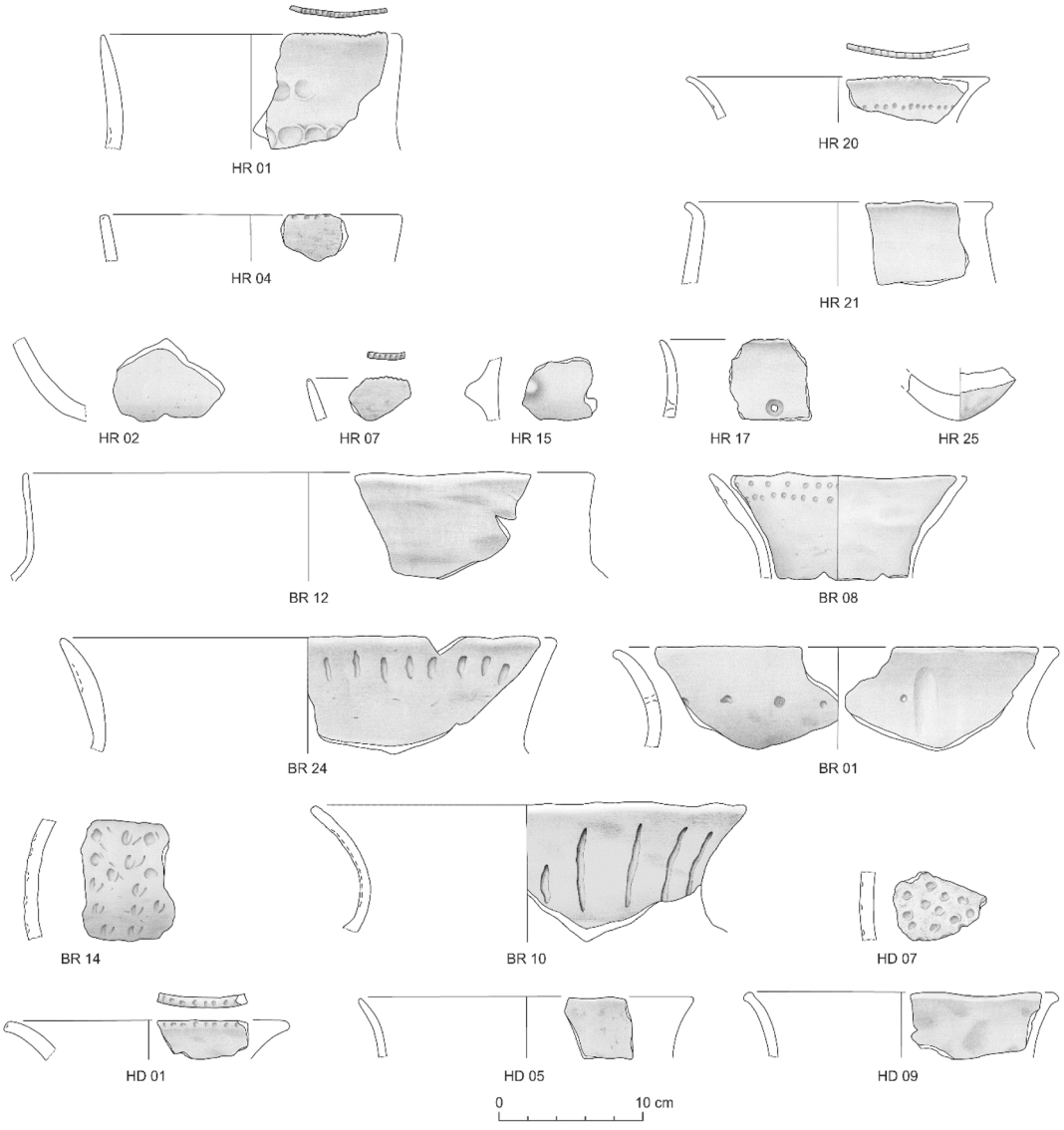


Fig. 2. Illustrations of selected sherds from Polderweg (HR01-HR07), De Bruin (HR15-HR25), Brandwijk (BR) and Hazendonk (HD).

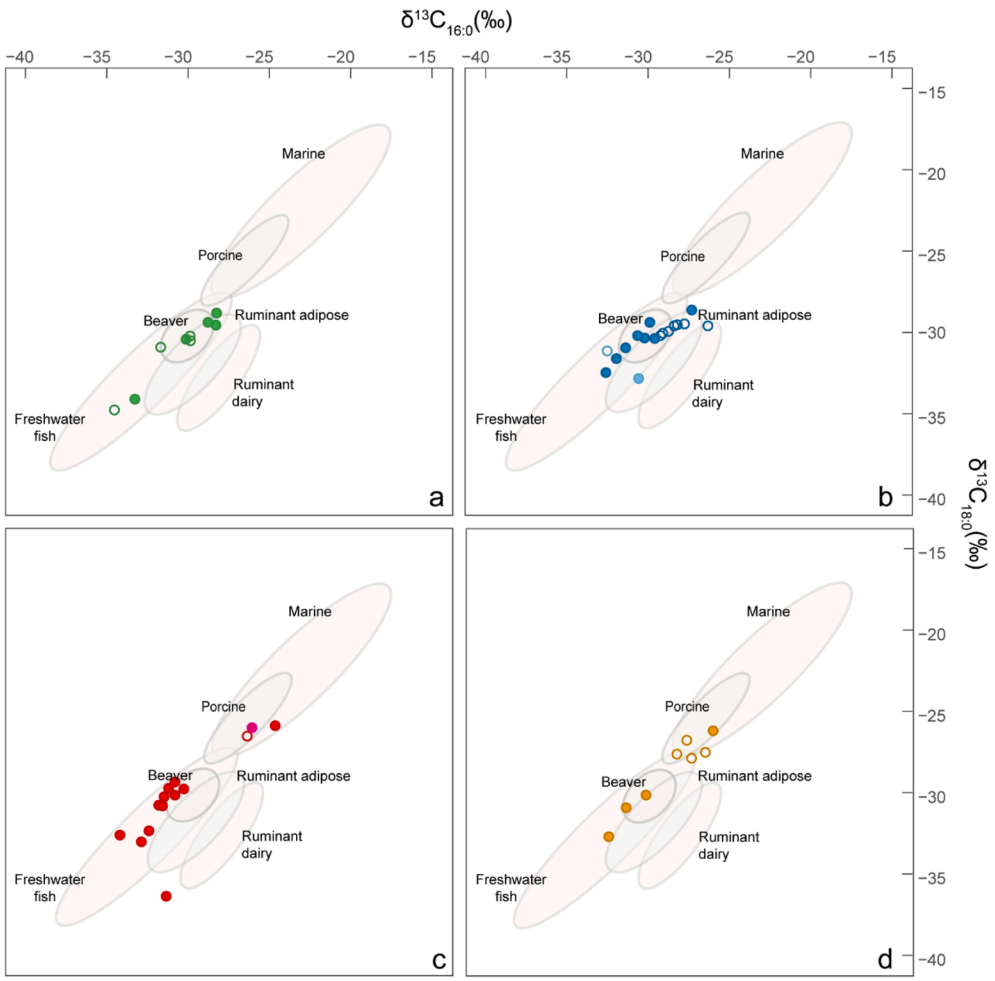


Fig. 3. GC-C-IRMS results showing isotopic values of $C_{16:0}$ and $C_{18:0}$ fatty acids of (a) Polderweg phase 2 (n = 9) in green, (b) De Bruin phase 3 (n = 15) in blue and phase 2 (n = 2) in light blue, (c) Brandwijk L50 (n = 13) in red and L60 (n = 1) in pink, and (d) Hazendonk 1 (n = 9) in orange. Samples with the full set of aquatic biomarkers are shown by filled circles. 95% confidence ellipses indicate areas of authentic reference values for each group of origins from western Baltic, and for beaver from eastern Baltic.

difficult to know the exact isotope values of sturgeon without its collagen analysis, the possibility of it being processed in the vessels cannot be ruled out for this site. Based on the faunal remains and on the fact that one of the three Brandwijk samples and all five of Hazendonk samples contain partial aquatic biomarkers (Supplementary Dataset-1), we can conclude that these samples contain a mixture of aquatic (mainly freshwater) and porcine derived lipids.

In Fig. 4, the $\delta^{13}C$ values of the $C_{16:0}$ acid are also plotted against the difference between the two major fatty acids ($\Delta^{13}C = \delta^{13}C_{18:0} - \delta^{13}C_{16:0}$) (Supplementary Dataset-1). This enables us to differentiate ruminant adipose, non-ruminant, and dairy fats (Dudd, 1999; Craig et al., 2012, 2013; Cramp and Evershed, 2014; Taché and Craig, 2015). $\Delta^{13}C$ values lower than −1‰ are typical of ruminant fats (Dudd et al., 1998; Evershed et al., 2002; Copley et al., 2003; Craig et al., 2012). Seven samples from De Bruin plotted in the ruminant adipose fat range and another two in between non-ruminant and ruminant adipose fat ranges (Fig. 4b). Faunal material from De Bruin shows the presence of *Bos* sp. and sheep/goat (0.2% and 0.1% of identified mammal bones in Phase 2, NF = 1728; 4% and 1.8% in Phase 3, NF = 591, respectively) as well as red deer remains (~3.2% of identified mammal bones in Phase 2, NF = 1728; and in Phase 3, NF = 591) (Fig. 6B; Supplementary Dataset-2) (Louwe Kooijmans, 2007; Oversteegen et al., 2001; Amkreutz, 2013; Çakırlar et al., 2019, 2020). The presence of a series of cut and chop marks on these remains also indicates that they were processed for consumption (Clason, 1978). As three of these vessels have fully aquatic biomarkers and four of the remaining five are partially aquatic, we conclude that the residue is derived from a mixture of freshwater and ruminant fats.

One sample from Polderweg is in the ruminant adipose fat range (Fig. 4a). In terms of the presence of ruminant animals at Polderweg, faunal records indicate a total absence of domesticated animals and red deer covers only 0.8% of identified mammal bones (in Phase 2, excluding antlers, NF = 233) (Fig. 6B; Supplementary Dataset-2) (Van Wijngaarden-Bakker et al., 2001; Çakırlar et al., 2019). In addition, this sample has fully aquatic biomarkers. However, it is known that even a minor contribution of ruminant fat can be detected given there is a strong bias against aquatic oils when mixed with ruminant fats due to the difference in fatty acid concentration between these products (Cramp et al., 2019). Based on these, we conclude that this residue may also be a possible mixture of lipids derived from aquatic and ruminant fats.

Finally, one sample from Brandwijk L50 (BR08) clearly plots below the limit for wild ruminant carcass fats (−4.3‰; Craig et al., 2012) (Fig. 4c), meeting widely accepted criteria for ruminant dairy fats (Copley et al., 2003; Evershed et al., 2008b; Debono-Spiteri et al., 2016). As this sample (BR08) has fully aquatic biomarkers, this residue likely contains a mixture of lipids derived from both aquatic and dairy sources. Although no other sample plot in the dairy range, it is important to mention that low quantities for dairy fats would not be detected using these criteria when mixed with relatively high quantities of non-ruminant lipids (including aquatic) (Debono-Spiteri et al., 2016; Cramp et al., 2019).

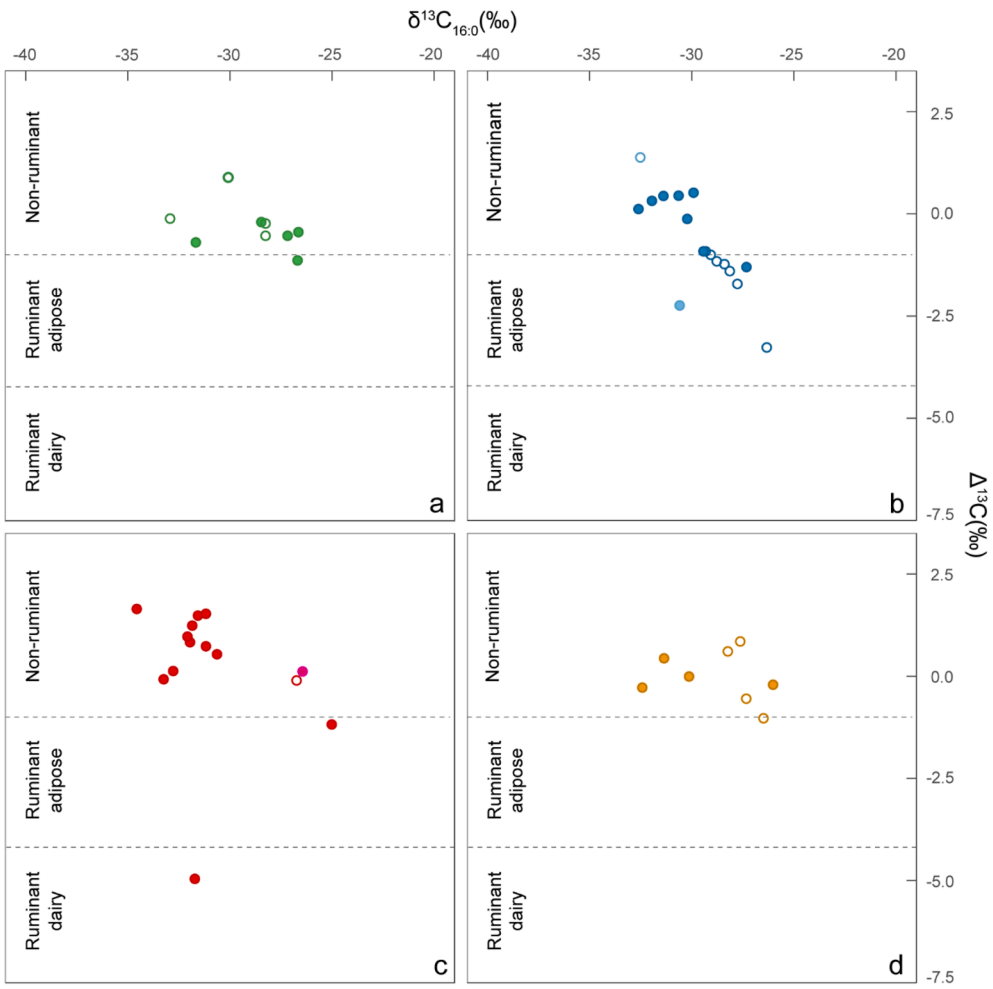


Fig. 4. $\Delta^{13}C$ ($\delta^{13}C_{18:0}$ - $\delta^{13}C_{16:0}$ values) against $\delta^{13}C_{16:0}$ values of Swifterbant pottery from only ceramic matrices. (a) Polderweg phase 2 (n = 9) in green, (b) De Bruin phase 3 (n = 15) in blue and phase 2 (n = 2) in light blue, c) Brandwijk L50 (n = 13) in red and L60 (n = 1) in pink, and (d) Hazendonk 1 (n = 9) in orange. Samples with the full set of aquatic biomarkers are shown by filled circles. Dotted lines indicate designated areas of authentic modern reference values for each group of origins from Western Baltic.

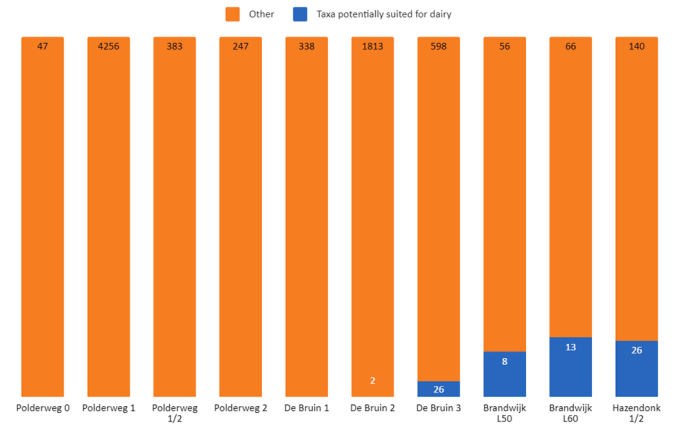


Fig. 5. The proportion of potentially dairy producing species to other food mammals in Number of Fragments (=NF) identified in the different phases of Polderweg, De Bruin, Brandwijk and Hazendonk. Data labels = NF.

5. Discussion

5.1. Functional continuity of the Swifterbant pottery for freshwater fish processing

Our research provides new insight into the function of Swifterbant pottery, starting from its first appearance at c. 5000 cal BC, throughout the 5th millennium in the Lower Rhine-Meuse area. The molecular and isotopic evidence show that this pottery was heavily used for processing freshwater resources regardless of vessel form, size, decoration (Fig. 2) or temper (Supplementary Dataset-1). Processing of freshwater resources seems to have been the primary function of Swifterbant pottery, for over 1000 years, despite the introduction of domesticated animals and plants.

Similarly, previous studies have shown that aquatic resources were extensively processed in hunter-gatherer ceramics throughout northern Europe (Craig et al., 2007; Heron et al., 2015; Oras et al., 2017), although in some cases they were mixed with terrestrial products and foodplants (i.e. Ertebølle pottery; Courel et al., 2020; Papakosta, 2019). This practice continued beyond the arrival of agriculture. Recent residue analysis of vessels from three other Swifterbant sites, Swifterbant S2, S3 and S4 (ca. 4300–4000 cal BC) (Demirci et al., 2020) also shows a dominance of freshwater fish.

5.2. Economic importance of pig

Unlike Polderweg and De Bruin, Brandwijk and Hazendonk yielded evidence for porcine fats in the vessels. The vessels with porcine fats did not show any specific morphological or technological differences compared to the pottery assemblages as a whole. We conclude that the processing of *Sus* sp. changed from Brandwijk L50 onward. Although it is difficult to assess the importance of the *Sus* sp. in subsistence through lipid residue analysis, the combination of our results and the zooarchaeological record provides some clues about what might lie behind this change. Suid remains are abundant in the zooarchaeological assemblages of the Lower Rhine-Meuse area dating to the 6th millennium BC

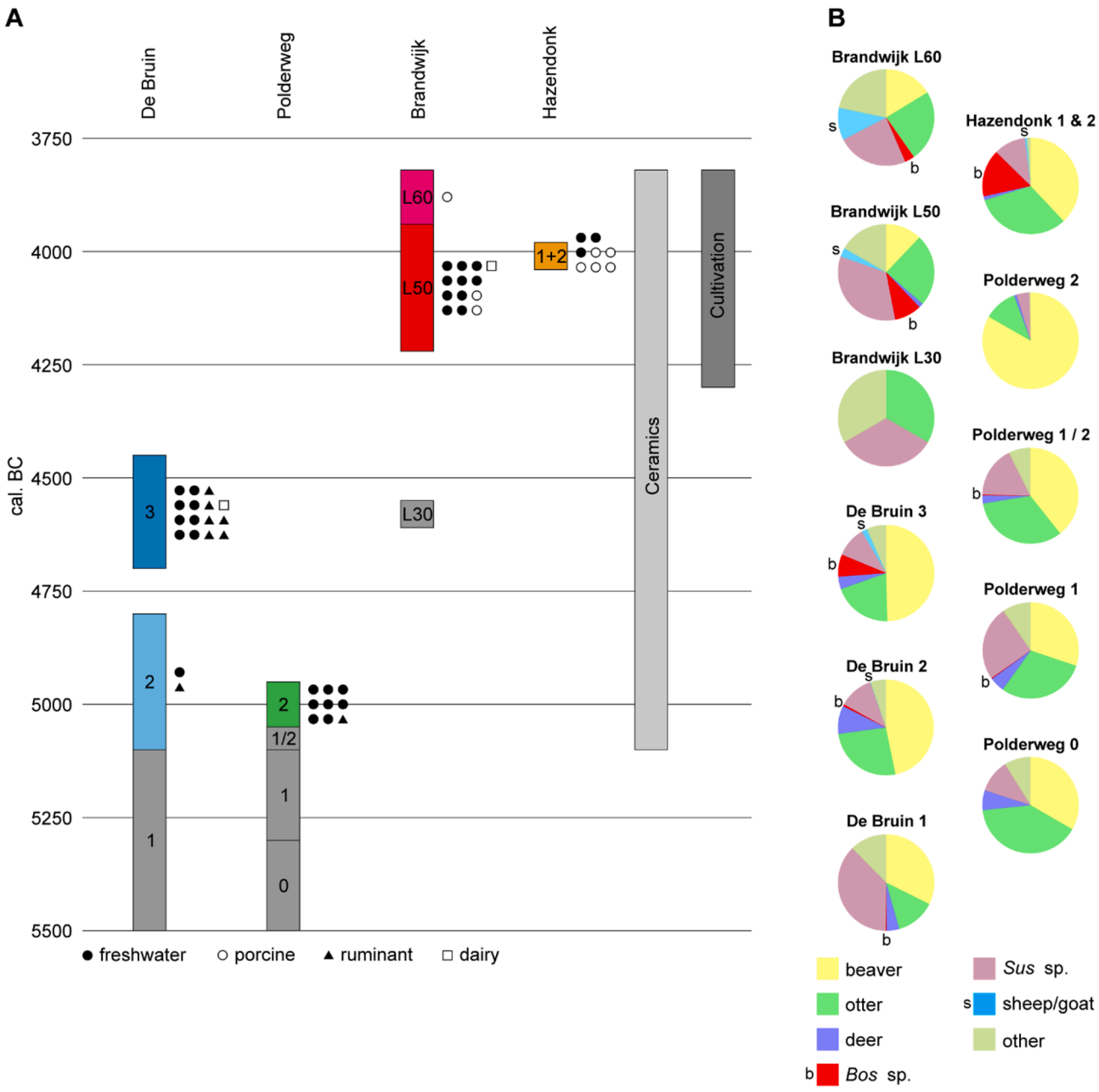


Fig. 6. (A) Figure showing dating, arrival pottery and starting date of cultivation of four Lower Rhine-Meuse area sites discussed in this study. Polderweg phase 2 (n = 9) in green, De Bruin phase 2 (n = 2) in light blue and phase 3 (n = 15) in blue, Brandwijk L50 (n = 13) in red and L60 (n = 1) in pink, and Hazendonk 1 (n = 9) in orange. (B) Pie charts showing the distribution of identified (wild and/or domestic) mammal bone remains (=NF). Based on the references listed in Supplementary Dataset-2.

and they remain so in the 5th millennium BC (Fig. 6B). A recent study on the bone remains show that small-sized *Sus* sp., possibly representing domesticated pigs, are absent in Polderweg and De Bruin, while they appear in Brandwijk L60 (Çakırlar et al., 2020). The pig population at Brandwijk seems to have been culled at younger ages than the individuals exploited in Polderweg and De Bruin. Size and age-at-death data suggest a change in pig management, possibly with the appearance of smaller, domesticated pigs interbreeding with wild boar.

This change in pig management seems to correlate to the presence of porcine fat in the Brandwijk and Hazendonk vessels. Interestingly, the *Sus* sp. is represented almost exclusively by cranial and distal extremity elements (i.e. head and feet) in Brandwijk. While this pattern of body part representation is markedly different from Polderweg, De Bruin, and Hazendonk, the Brandwijk sample is relatively small (NF = 22 in both L50 and L60) and it is difficult to pinpoint what the differential body part representations mean. One possibility is that the Brandwijk inhabitants received only parts of the carcass, another is that the inhabitants of Brandwijk processed pork off site, with a cooking tradition that favoured heads and feet. Reported data allow us to calculate average *Sus* sp. fragment weight per assemblage (see Supplementary Dataset-2: Table 1), which shows a decreasing trend from Polderweg to De Bruin. Although bone weight can be influenced by post-depositional factors such as leaching and burning, and excavation methods such as sieving, it is considered a good index of carcass processing techniques because it can decrease when pot-sizing and grease extraction become more common in culinary practices (Gifford-Gonzalez, 2018). The reduced weight of *Sus* sp. fragments in the younger phases of De Bruin, Brandwijk, and Hazendonk may be associated with a new practice of

cooking pork in pots.

5.3. Evidence of ruminant fats

Lipid residue analysis indicates a changing approach to processing ruminant resources in the pots from these four Swifterbant sites. It is only in De Bruin phase 3 that we see clear evidence of processing ruminant resources in the pots. While Polderweg has only one sample yielding ruminant fats, ruminant carcass fats are completely absent in Brandwijk and Hazendonk samples. The pots with ruminant fats do not deviate from the other pots in terms of their morphological or technological features. Therefore, processing ruminant resources in the pots may be explained with specific local cultural preferences in culinary practices and/or changing human-animal relations rather than any gross changes in subsistence strategies.

Zooarchaeological records show the presence of ruminant in all four sites (Supplementary Dataset-2) and various species of deer, *Bos* sp. and sheep/goat could be the source of these ruminant fats in the pots. There is one sample from Polderweg that yielded $\Delta^{13}C$ values matching to ruminant adipose (see Fig. 4a, Supplementary Dataset-1). As domesticated ruminants seem absent from Polderweg, it is most likely that the vessel with adipose fat is derived from wild ruminants, such as deer or aurochs. If that is the case, although the combination of our results and the faunal data suggest that the samples from De Bruin with ruminant fats may indicate processing domesticated animals, processing wild ruminant food resources, possibly deer, in these pots is equally possible.

5.4. Dairy products in the Swifterbant pottery

Dairy is readily identifiable in prehistoric pottery throughout Europe (Craig et al., 2005, 2011; Spangenberg et al., 2008; Isaksson and Hallgren, 2012; Salque et al., 2012; Heron et al., 2015; Cramp et al., 2019; Stojanovski et al., 2020) and it is considered to be one of the main drives of the introduction of domesticated animals into the subsistence economy (Copley et al., 2003; Dunne et al., 2012). However, direct chemical evidence for the presence of dairy in the Swifterbant culture has been lacking until now. In this study, we present the first evidence for dairy products in two Swifterbant vessels, one from Brandwijk L50 (Fig. 4c) and one possibly from De Bruin phase 3 (Fig. 4b).

One of the biggest challenges now, however, is to understand whether these one or two pots with dairy lipids are an underrepresentation of the wider use of dairy products in the Swifterbant culture or if they are the results of interactions with neighbouring farmer communities. Traditionally, one of the ways to study dairying is to reconstruct slaughter age and sex profiles based on the animal bones. High abundances of mature females, low numbers of mature males and high abundances of very young animals are seen as evidence for dairying (Payne, 1973). While *Bos* sp. and sheep/goat are present at both De Bruin and Brandwijk (Fig. 5, Fig. 6B; Çakırlar et al., 2019, 2020), the high fragmentation of the remains and the small size of the assemblages prevent us from profiling the age and sex of these animals. As a result, it remains uncertain whether these animals were kept for their meat or were also exploited for secondary products such as milk, butter and cheese.

Another type of analysis focuses on the ceramic characteristics of the vessels directly associated with dairy processing. Both Swifterbant vessel fragments containing dairy products are flask-like, have small diameters and are decorated with bird bone impressions around the neck (Supplementary Dataset-1; Fig. 2, BR08 and HR20). All the other pots from these assemblages have beaker shapes, larger diameters and are never decorated with bird bone impressions. The similarities between these two vessels further strengthens the interpretation of the De Bruin vessel as one involved in dairy processing and the shared notion about the characteristics of 'dairy vessels' between the potters of De Bruin and Brandwijk. This is consistent with the Funnel Beaker flasks from submerged coastal site Neustadt in Schleswig-Holstein, Northern Germany which were used for processing dairy (Saul et al., 2014). Our findings make further lipid analysis on more Swifterbant flask-like vessels as well as petrographic analysis of these assemblages the logical next step in order to test our results with a bigger data set and also to distinguish whether the 'dairy vessels' were produced on site or are vessels that were brought to the site, with their specific content.

6. Conclusion

The new data presented here clearly shows that processing freshwater fish was a continuous and primary function of Swifterbant pottery in the Lower Rhine-Meuse area, starting from its first appearance at c. 5000 cal BC till the end of 5th millennium BC. We argue that the main use of the pottery for processing freshwater fish among Swifterbant sites was a consistent and deliberate choice which was also maintained while the two main aspects of the Neolithization process (i.e. cereal cultivation and possibly animal husbandry) were introduced to the area. In this regard, our research contributes to the discussion of the pottery production in the hunter-gatherer societies and the function of the pottery through the Mesolithic-Neolithic transition in northern Europe. From our data, we suggest that the Mesolithic-Neolithic transition in the Lower Rhine-Meuse area was not a sudden event but more of a gradual process which was certainly influenced in part by the dynamics of intercultural encounters with neighbouring farming communities.

The results of our analysis also present temporal changes in the exploitation of food resources from the early to the late 5th millennium BC. In addition to the continuous exploitation of freshwater resources, we see that processing ruminant foodstuff becomes an important part of pottery use in the mid-5th millennium BC. Whether this is a result of the arrival of domesticated animals around the same time into the Lower Rhine-Meuse area or is evidence for the continuous exploitation of wild ruminant fauna, it presents a change in the ways of processing ruminant food resources and the use of pottery. This is followed by the first appearance of dairy products in the Swifterbant pottery. Although, at this point, we are not able to fully grasp the scale of dairy production, our study is important in terms of showing the first evidence of processing dairy in the Swifterbant pottery. It also allows us to propose that the De Bruin phase 3 is where we start to see a change in human-animal relations to such extent that we might talk about the start of the Mesolithic-Neolithic transition in the Lower Rhine-Meuse area.

By the late 5th millennium BC, we witness another change in the use of Swifterbant pottery in the Lower Rhine-Meuse area as the ruminant animal carcass fats completely disappear from the pots and get replaced by porcine fats. This kind of a shift in the use of pottery raises questions about changing human-animal relations in terms of animal management and culinary practices in Swifterbant culture. In view of the limited understanding of the animal bones present, lipid residue analysis provides a strong method to gain insights into human-animal relations during the 5th millennium BC.

Another outcome of our study relates the functional variation to the ceramic characteristics of the Swifterbant pottery. It appears that beaker-shaped vessels were used for processing freshwater and terrestrial resources, while processing dairy products was associated with flasks - a pottery shape associated with dairy products in other areas as well (Saul et al., 2014). This is the first time we are able to present functional variation in the Swifterbant pottery through lipid residue analysis. Therefore, this needs to be examined with further research such as petrographic analysis to determine the origin of these "dairy vessels" which would help us to gain insight into the origin of the content of the pots, contributing to the discussion of cultural preferences on culinary practices, human mobility and/or interaction between different groups in the Lower Rhine-Meuse area.

Differences in pottery use between these four Swifterbant sites cannot be explained only by the differences in availability or accessibility of the resources in their immediate or surrounding environment. It is known that diet can relate to different subsistence economies

determined by both local environment and cultural change. However, zooarchaeological and archaeobotanical records present a continuous exploitation of similar and diversified faunal/floral resources in all four sites. Therefore, we argue that different culinary practices developed through the 5th millennium in the Lower Rhine-Meuse area and that the use of Swifterbant pottery may be a direct reflection of changing cultural preferences on food preparation and consumption which requires further research.

Overall, our current study provides an important insight into the function of the hunter-gatherer pottery, broadening our knowledge about the Swifterbant culture north-western Europe. It also shows that additional analysis on the bone material is needed to contribute to the debate of changing human-animal relations and Mesolithic-Neolithic transition in the Swifterbant culture.

Funding

This project is part of a Marie Sklodowska-Curie European Joint Doctoral Training Program, funded by the European Union's EU Framework program for Research and Innovation Horizon 2020 under the Grant Agreement No 676154 (ArchSci2020 program).

CRediT authorship contribution statement

Özge Demirci: Conceptualization, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Alexandre Lucquin:** Investigation, Writing - review & editing. **Canan Çakırlar:** Validation, Investigation, Writing - original draft, Writing - review & editing. **Oliver E. Craig:** Methodology, Resources, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **Daan C.M. Raemaekers:** Conceptualization, Resources, Validation, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing.

Acknowledgements

We thank Erwin Bolhuis (Groningen Institute of Archaeology) who produced the map for Fig.1 and the diagram for Fig. 7. We also thank Miriam A. Los-Weijns (Groningen Institute of Archaeology) for the pottery illustrations in Fig. 2. Special thanks to Dr. Youri van den Hurk (Groningen Institute of Archaeology) for his assistance with the zooarchaeological records. We thank Helen Talbot (University of York) and Matthew Von Tersch (University of York) for their assistance with aspects of laboratory work.

We also would like to thank Roman Smolianinov (Lipetsk State Pedagogical University), Olga Lozovskaya (Institute for the History of Material Culture, Russian Academy of Sciences), Ester Oras (University of Tartu), and Karine Taché (University of Laval) for providing us with the modern beaver reference data that was used in section 4.1. Finally, we would like to thank the two anonymous reviewers, whose constructive comments and suggestions helped substantially improve this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2021.102812.

References

Ackman, R.G., Hooper, S.N., 1968. Examination of isoprenoid fatty acids as distinguishing characteristics of specific marine oils with particular reference to whale oils. Comp. Biochem. Physiol. 24, 549–565.

Amkreutz, L.W.S.W., 2013. Persistent traditions: a long-term perspective on communities in the process of Neolithisation in the Lower Rhine Area (5500-2500 cal BC. Dissertation Leiden University.

Bakels, C.C., 1981. Neolithic plant remains from the Hazendonk, Province of Zuid-Holland, The Netherlands. Zeitschrift für Archäologie 15, 141–148.

Bondetti, M., et al., 2019. Fruits, fish and the introduction of pottery in the Eastern European plain: Lipid residue analysis of ceramic vessels from Zamostje 2. Quat. Int.: J. Int. Union Quat. Res. https://doi.org/10.1016/j.quaint.2019.05.008.

Bondetti, M., et al., 2020. Investigating the formation and diagnostic value of ω-(o-alkylphenyl)alkanoic acids in ancient pottery. Archaeometry. https://doi.org/10.1111/arcm.12631.

Brinkhuizen, D.C., 1979. Preliminary notes on fish remains from archaeological sites in the Netherlands. Palaeohistoria 21, 83–90.

Cappers, R.T.J., Raemaekers, D.C.M., 2008. Cereal cultivation at Swifterbant? Neolithic wetland farming on the North European Plain. Curr. Anthropol. 49 (3), 385–402.

Charters, S., et al., 1993. Quantification A and distribution of lipid in archaeological ceramics: implications for sampling potsherds for organic residue analysis and the classification of vessel use. Archaeometry 35 (2), 211–223.

Clason, A.T., 1978. Worked bone, antler and teeth. A preliminary report (Swifterbant Contribution 9). Helinium 18, 83–86.

Coles, B., 2006. Beavers in Britain's Past. Oxbow Books, Oxford.

Colonese, A.C., et al., 2017. New criteria for the molecular identification of cereal grains associated with archaeological artefacts. Sci. Rep. 7 (1), 6633.

Copley, M.S., et al., 2003. Direct chemical evidence for widespread dairying in prehistoric Britain. PNAS 100 (4), 1524–1529.

Courel, B., et al., 2020. Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter–gatherers. R. Soc. Open Sci. 7 (4), 192016. https://doi.org/10.1098/rsos.192016.

Craig, O.E., et al., 2005. Did the first farmers of central and eastern Europe produce dairy foods? Antiquity 79 (306), 882–894.

Craig, O.E., et al., 2007. Molecular and isotopic demonstration of the aquatic products in Northern European prehistoric pottery. Archaeometry 49 (1), 135–152.

Craig, O.E., et al., 2011. Ancient lipids reveal continuity in culinary practices across the transition to agriculture in Northern Europe. PNAS 108 (44), 17910–17915.

Craig, O.E., et al., 2012. Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. Rapid Commun. Mass Spectrom. 26 (19), 2359–2364.

Craig, O.E., et al., 2013. Earliest evidence for the use of pottery. Nature 496 (7445), 351–354.

Cramp, L.J.E., Evershed, R.P., 2014. Reconstructing aquatic resource exploitation in human prehistory using lipid biomarkers and stable isotopes. In: Holland, H.D. Turekian, K.K. (Eds.), Treatise on Geochemistry, 2nd ed. Oxford: Elsevier, pp. 319–339.

Cramp, L.J.E., et al., 2014. Immediate replacement of fishing with dairying by the earliest farmers of the Northeast Atlantic archipelagos. Proc. Biol. Sci. Royal Soc. 281 (1780), 20132372. https://doi.org/10.1098/rspb.2013.2372.

Cramp, L.J.E., et al., 2019. Regional diversity in subsistence among early farmers in Southeast Europe revealed by archaeological organic residues. Proc. Biol. Sci. Royal Soc. 286 (1894), 20182347.

Cubas, M., et al., 2019. Long-term dietary change in Atlantic and Mediterranean Iberia with the introduction of agriculture: a stable isotope perspective. Archaeol. Anthropol. Sci. 11 (8), 3825–3836.

Cubas, M., et al., 2020. Latitudinal gradient in dairy production with the introduction of farming in Atlantic Europe. Nat. Commun. 11 (1), 2036.

Çakırlar, C., et al., 2019. Animals and people in the Netherlands' Past: >50 years of Archaeozoology in the Netherlands. Open Quarter. 5 (1), 13.

Çakırlar, C., et al., 2020. Dealing with domestic animals in the 5th millennium cal BC Dutch wetlands: new insights from old Swifterbant assemblages. In: Gron, K.J., Sørensen, L., Rowley-Conwy, P. (Eds.), Farmers at the Frontier: A Pan-European Perspective on Neolithisation. Oxford: Oxbow Books, pp. 263–287.

Debono-Spiteri, et al., 2016. Regional asynchronicity in dairy production and processing in early farming communities of the northern Mediterranean. Proc. Natl. Acad. Sci. 113 (48), 13594–13599.

Demirci, Ö., et al., 2020. First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300–4000 BC). Archaeol. Anthropol. Sci. 12 (5), 105. https://doi.org/10.1007/s12520-020-01062-w.

Dolukhanov, P.M., et al., 2010. Early pottery makers in Eastern Europe: centres of origins, subsistence and dispersal. In: Jordan, P., Zvelebil, M. (Eds.), Ceramics Before Farming. Walnut Creek, CA: Left Coast Press, pp. 237–254.

Dudd, S.N., 1999. Molecular and Isotopic Characterisation of Animal Fats in Archaeological Pottery. University of Bristol.

Dudd, S.N., et al., 1998. Assessing microbial lipid contributions during laboratory degradations of fats and oils and pure triacylglycerols absorbed in ceramic potsherds. Org. Geochem. 29 (5–7), 1345–1354.

Dunne, J., et al., 2012. First dairying in green Saharan Africa in the fifth millennium BC. Nature 486 (7403), 390–394.

Dusseldorp, G.L., Amkreutz, L.W.S.W., 2020. A long slow goodbye – re-examining the Mesolithic – Neolithic transition (5500–2500 BCE) in the Dutch delta. Analecta Praehistorica Leidensia 50, 121–142.

Evershed, R.P., et al., 2002. Chemistry of archaeological animal fats. Acc. Chem. Res. 35 (8), 660–668.

Evershed, R.P., et al., 2008a. Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. Archaeometry 50 (1), 101–113.

Evershed, R.P., et al., 2008b. Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding. Nature 455 (7212), 528–531.

Frantz, L.A.F., et al., 2019. Ancient pigs reveal a near-complete genomic turnover following their introduction to Europe. PNAS 116 (35), 17231–17238. https://doi.org/10.1073/pnas.1901169116.

Garnier, N., et al., 2018. Looking for ancient fish products through invisible biomolecular residues in the roman production vats from the Atlantic Coast. J. Maritime Archaeol. 13 (3), 285–328.
Gifford-Gonzalez, D., 2018. Culinary processing and preservational effects on bone. In: An Introduction to Zooarchaeology. Springer, Cham, pp. 305–337. https://doi.org/10.1007/978-3-319-65682-3_15.
Guiry, E.J., et al., 2016. The transition to agriculture in south-western Europe: new isotopic insights from Portugal's Atlantic coast. Antiquity 90 (351), 604–616.
Hammann, S., Cramp, L.J.E., 2018. Towards the detection of dietary cereal processing through absorbed lipid biomarkers in archaeological pottery. J. Archaeol. Sci. 93, 74–81.
Hansel, F.A., et al., 2004. Thermally produced ω-(o-alkyl phenyl)alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. Tetrahedron Lett. 45 (14), 2999–3002.
Hauff, S., Vetter, W., 2010. Quantification of branched chain fatty acids in polar and neutral lipids of cheese and fish samples. J. Agric. Food. Chem. 58 (2), 707–712.
Heron, C., et al., 2013. Illuminating the Late Mesolithic: residue analysis of "blubber" lamps from Northern Europe. Antiquity 87 (335), 178–188.
Heron, C., Craig, O.E., 2015. Aquatic resources in foodcrusts: identification and implication. Radiocarbon 57 (4), 707–719.
Heron, C., et al., 2015. Cooking fish and drinking milk? Patterns in pottery use in the southeastern Baltic, 3300–2400 cal BC. J. Archaeol. Sci. 63, 33–43.
Hommel, P., 2018. What's the point? Globalization and the emergence of ceramic using hunter-gatherers in Northern Eurasia. In: Boivin, N., Frachetti, M.D. (Eds.), Globalization in Prehistory: Contact, Exchange, and the 'People Without History'. Cambridge, UK: Cambridge University Press, pp.15–42.
Huisman, D.J., et al., 2009. Investigating Neolithic land use in Swifterbant (NL) using micromorphological techniques. Catena 78 (3), 185–197.
Huisman, D.J., Raemaekers, D.C.M., 2014. Systematic cultivation of the Swifterbant wetlands (The Netherlands). evidence from Neolithic tillage marks (c. 4300–4000 cal. BC). J. Archaeol. Sci. 49, 572–584.
Isaksson, S., Hallgren, F., 2012. Lipid residue analyses of Early Neolithic funnel-beaker pottery from Skogsmossen, eastern Central Sweden, and the earliest evidence of dairying in Sweden. J. Archaeol. Sci. 39 (12), 3600–3609.
Kranenburg, H., Prummel, W., 2020. The use of domestic and wild animals. In: Raemaekers, D.C.M., de Roever, J.P. (Eds.), Swifterbant S4 (the Netherlands) Occupation and exploitation of a neolithic levee seite (c. 4300-4000 cal. BC). Barkhuis Publishing, pp. 76–94.
Krause-Kyora, B., 2011. Molekulargenetische und archäologische Untersuchungen zur Domestikation und Züchtung des Schweins (Sus scrofa). Dissertation Christian-Albrechts-Universität Kiel.
Kriiska, A., et al., 2017. Late Mesolithic Narva stage in Estonia: pottery, settlement types and chronology. Estonian J. Archaeol. 21, 52. (doi:10.3176/arch.2017.1.03).
Käkelä, R., et al., 1996. Unusual fatty acids in the depot fat of the canadian beaver (Castor canadensis). Plann. Perspect: PP, 625, 629.
Louwe Kooijmans, P., 1974. The Rhine/Meuse Delta: four studies on its Prehistoric Occupation and Holocene geology. Analecta Praehistorica Leidensia VII 7, 52–54.
Louwe Kooijmans, P., 1993. The mesolithic/neolithic transformation in the lower Rhine Basin. In: Peter Bogucki (Ed.), Case Studies in European Prehistory. CRC Press, pp. 95–145.
Louwe Kooijmans, P., 2001a. Hardinxveld-Giessendam Polderweg: Een Mesolithisch jachtkamp in het rivierengebied (5500–5000 v. Amersfoort, Rapportage Archeologische Monumentenzorg, Chr), p. 83.
Louwe Kooijmans, P., 2001b. Hardinxveld-Giessendam De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.). Amersfoort, Rapportage Archeologische Monumentenzorg, 83.
Louwe Kooijmans, P., 2003. The Hardinxveld sites in the Rhine/Meuse delta, the Netherlands, 5500-4500 cal BC. In: Larsson, L., Kindgren, H., Knutsson, K., Loeffler, D., Åkerlund, A. (Eds.), Mesolithic on the Move, Oxbow Books, pp. 608–624.
Louwe, Kooijman, P., 2007. The gradual transition to farming in the Lower Rhine Basin. In: Whittle, A., Cummings, V., (Eds.), Going Over: The Mesolithic-Neolithic transition in North-West Europe. Oxford University Press, Oxford, pp. 287–309.
Louwe Kooijmans, P., 2010. The ceramisation of the Low Countries, seen as the result of gender-specific processes of communication. In: Vanmontfort, B., Louwe Kooijmans, L.P., Amkreutz, L.V., Verhart, L. (Eds.), Pots, Farmers and Foragers: Pottery Traditions and Social Interaction in the Earliest Neolithic of the Lower Rhine Area. Amsterdam University Press, pp. 27–40.
Louwe Kooijmans, P., Mol, J., 2001. Stratigrafie, chronologie en fasering. In: Louwe Kooijmans, L.P. (Ed.), Hardinxveld-Giessendam Polderweg: Een Mesolithisch jachtkamp in het rivierengebied (5500–5000 v. Chr), Amersfoort (Rapportage Archeologische Monumentenzorg, 83), pp. 55–72.
Lucquin, A., et al., 2016. Utilising phytanic acid diastereomers for the characterisation of archaeological lipid residues in pottery samples. Tetrahedron Lett. 57 (6), 703–707.
Lucquin, A., et al., 2018. The impact of environmental change on the use of early pottery by East Asian hunter-gatherers. PNAS 115 (31), 7931–7936.
Mol, J., Louwe Kooijmans, P., 2001. Stratigrafie, chronologie en fasering. In: L.P. Louwe Kooijmans (Ed.), Archeologie in de Betuweroute Hardinxveld-De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500–4450 v. Chr). Amersfoort (Rapportage Archeologische Monumentenzorg, 83) pp. 57–73.
Oras, E., et al., 2017. The adoption of pottery by north-east European hunter-gatherers: evidence from lipid residue analysis. J. Archaeol. Sci. 78, 112–119.
Out, W.A., 2008. Neolithisation at the site Brandwijk-Kerkhof, the Netherlands: natural vegetation, human impact and plant food subsistence. Vegetation History Archaeobotany 17 (1), 25–39.
Out, W.A., 2009. Sowing the Seed: Human impact and plant subsistence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC) Dissertation Leiden University.
Oversteegen, J.F., et al., 2001. Zoogdieren, vogels, reptielen. In: Louwe-Kooijmans, L.P. (Ed.), Hardinxveld-Giessendam De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.). Amersfoort, pp. 209–298.
Papakosta, V., et al., 2015. Extraction and derivatization of absorbed lipid residues from very small and very old samples of ceramic potsherds for molecular analysis by gas chromatography–mass spectrometry (GC–MS) and single compound stable carbon isotope analysis by gas chromatography–combustion–isotope ratio mass spectrometry (GC–C–IRMS). Microchem. J. 123, 196–200.
Papakosta, V., et al., 2019. Early pottery use across the Baltic – A comparative lipid residue study on Ertebølle and Narva ceramics from coastal hunter-gatherer sites in southern Scandinavia, northern Germany and Estonia. J. Archaeolog. Sci.: Rep. 24, 142–151.
Payne, S., 1973. Kill-off patterns in sheep and goats: the mandibles from Aşvan Kale. Anatolian Stud. 23, 281–303.
Philippsen, Bente, Meadows, John, 2014. Inland Ertebølle Culture: the importance of aquatic resources and the freshwater reservoir effect in radiocarbon dates from pottery food crusts. *Internet*. Archaeology (37). https://doi.org/10.11141/issn.1363-538710.11141/ia.37.9.
Piličiauskas, G., et al., 2017. The transition from foraging to farming (7000–500calBC) in the SE Baltic: a re-evaluation of chronological and palaeodietary evidence from human remains. J. Archaeolog. Sci.: Rep. 14, 530–542.
Povlsen, K., 2014. The introduction of ceramics in the Ertebølle Culture. Danish J. Archaeol. 2 (2), 146–163.
Raemaekers, D.C.M., 1999. The Articulation of a "New Neolithic". Dissertation Leiden University.
Raemaekers, D.C.M., 2011. Early Swifterbant pottery (5000–4600 BC): research history, age, characteristics and the introduction of pottery. Berichte Römisch-Germanische Kommission 89, 485–500.
Raemaekers, D.C.M., de Roever, J.P., 2010. The Swifterbant pottery tradition (5000-3400 BC). In: Vanmontfort, B., Louwe Kooijmans, L.P., Amkreutz, L.V., Verhart, L. (Eds.), Pots, Farmers and Foragers. Pottery Traditions and Social Interaction in the Earliest Neolithic of the Lower Rhine Area. Leiden University Press, pp. 135–149.
Raemaekers, D.C.M., de Roever, J.P., 2020. Swifterbant S4 (the Netherlands) Occupation and exploitation of a neolithic levee seite (c. 4300–4000 cal. BC). Barkhuis Publishing, Groningen.
Raemaekers, D.C.M., et al., 2013. New food in old pots - charred organic residues in Early Neolithic ceramic vessels from Swifterbant, the Netherlands (4300–4000 cal BC). Archäologisches Korrespondenzblatt 43 (3), 315–334.
Regert, M., 2011. Analytical strategies for discriminating archaeological fatty substances from animal origin. Mass Spectrom. Rev. 30 (2), 177–220.
Robson, H.K., et al., 2019. Diet, cuisine and consumption practices of the first farmers in the south-eastern Baltic. Archaeol. Anthropol. Sci. 1–14.
Rowley-Conwy, P., 2013. The origins and spread of domestic animals in southwest Asia and Europe. In: Colledge, S., Connoly, J., Dobney, K., Manning, K., Shennan, S. (Eds.), Walnut Creek: Left Coast Press.
Salque, M., et al., 2012. New insights into the Early Neolithic economy and management of animals in Southern and Central Europe revealed using lipid residue analyses of pottery vessels. Anthropozoologica 47 (2), 45–62. https://doi.org/10.5252/az2012n2a4.
Saul, H., et al., 2014. Stewing on a theme of cuisine biomolecular and interpretive approaches to culinary changes at the transition to agriculture. In: Alasdair Whittle, Penny Bickle (Eds.), Early Farmers: The View from Archaeology and Science, Vol. 198, pp. 197–213.
Schepers, M., Bottema-Mac Gillavry, N., 2020. The vegetation and exploitation of plant resources. In: Raemaekers, D.C.M., de Roever, J.P. (Eds.), Swifterbant S4 (the Netherlands) Occupation and exploitation of a neolithic levee seite (c. 4300-4000 cal. BC). Barkhuis Publishing, pp. 51–75.
Smyth, J., Evershed, R.P., 2015. The molecules of meals: new insight into Neolithic foodways. Proceedings of the Royal Irish Academy: Archaeology.
Spangenberg, J.E., et al., 2008. Direct evidence for the existence of dairying farms in prehistoric Central Europe (4th millennium BC). Isot. Environ. Health Stud. 44 (2), 189–200.
Stojanovski, D., et al., 2020. Living off the land: terrestrial-based diet and dairying in the farming communities of the Neolithic Balkans. PLoS ONE 15 (8), e0237608.
Sørensen, L., 2017. Hunters and farmers in the North – the transformation of pottery traditions and distribution patterns of key artefacts during the Mesolithic and Neolithic transition in southern Scandinavia. Acta Archaeologica Lodziensia 63, 59–78.
Sørensen, L., Karg, S., 2014. The expansion of agrarian societies towards the north – new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. J. Archaeol. Sci. 51, 98–114.
Taché, K., Craig, O.E., 2015. Cooperative harvesting of aquatic resources and the beginning of pottery production in north-eastern North America. Antiquity 89 (343), 177–190.
Van Wijngaarden-Bakker, L.H., et al., 2001. Zoogdieren, vogels, reptielen. In: Louwe-Kooijmans, L.P., (Ed.), Hardinxveld-Giessendam Polderweg: Een mesolithisch jachtkamp in het rivierengebied (5500-5000 v. Chr.). Amersfoort, pp. 181–242.
Verbruggen, M., 1992. Geoarchaeological prospection of the Rommertsdonk. Analecta Praehistorica Leidensia 25, 117–128.

Vos, P., de Vries, S., 2013. 2nd generation of paleo-geographical maps of Netherlands (version 2.0). Deltares, Utrecht. Downloaded in April 2020, from www.archeologieinnederland.nl.

Vos, P., in prep. Palaeogeographical maps of the Netherlands: compilation of the Holocene palaeogeographical maps of the Netherlands. In: Origin of the Dutch coastal landscape Long-term landscape evolution of the Netherlands during the Holocene. Utrecht. Downloaded in April 2020, from www.archeologieinnederland.nl.

Zeiler, J.T., 1997. Hunting, fowling and stockbreeding in the Dutch Neolithic. Archaeofauna 6, 97–113.

Authors' contributions (%)

Özge Demirci:

Conceptualization	95%
Formal analysis (lab work)	100%
Investigation (data analysis)	90%
Visualization of data	100% (also see Acknowledgements)
Writing - original draft	95%
Writing - review & editing	90%

Alexandre Lucquin:

Investigation (data analysis)	5%
Writing - review & editing	1%

Canan Çakırlar:

Validation	50%
Investigation (data analysis)	5%
Writing - original draft	2%
Writing - review & editing	1%

Oliver E. Craig:

Methodology	100%
Resources (lab access)	50%
Supervision	40%
Project administration	50%
Funding acquisition	50%
Writing - original draft	1%
Writing - review & editing	4%

Daan C. M. Raemaekers:

Conceptualization	5%
Resources (material access)	50%
Validation	50%
Supervision	60%
Project administration	50%
Funding acquisition	50%

Writing - original draft	3%
Writing - review & editing	4%

All authors gave their final approval for publication.

SUPPLEMENTARY MATERIALS

(METHODS and SUPPLEMENTARY DATASETS 1, 2, 3)

for

Lipid residue analysis on Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process

Özge Demirci, Alexandre Lucquin, Canan Çakırlar, Oliver E. Craig, Daan C.M. Raemaekers

Supplementary Material – Methods for: Lipid residue analysis on Swifterbant pottery (c. 5000-3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process

Özge Demirci[1,2*], Alexander Lucquin[2], Canan Çakırlar[1], Oliver E. Craig[2], Daan C.M. Raemaekers[1]

[1]Groningen Institute of Archaeology, Poststraat 6, 9712 ER, Groningen, the Netherlands
[2]BioArch, Department of Archaeology, University of York, York, YO10 5YW, UK

Methods

Acidified methanol extraction of lipids

Ceramic was drilled from the interior portion of each vessel (n = 49) and analysed using the established acidified methanol protocol (Craig et al. 2013; Correa-Ascencio and Evershed 2014; Papakosta et al. 2015). In order to eliminate the external contamination to a bare minimum, the outer surface (~0.1 mm) of the sampling area was first removed, using a Dremel drill. Then, the sherds were drilled to a depth of up to 5 mm on the interior surface to produce 1g of pottery powder. An internal standard (alkane $C_{34:0}$, 10 µL) was added to 1 g of powdered pottery followed by 4mL methanol. The suspension was sonicated for 15 minutes, then acidified with concentrated sulphuric acid (H_2SO_4, 800 µL) and heated for 4 hours at 70ºC. Lipids were sequentially extracted with *n*-hexane (2mL × 3). The extracts were combined and dried under nitrogen. Finally, an additional internal standard (n-hexatriacontane $C_{36:0}$, 10 µg) was added to each sample. All samples were analysed 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 connected to an Agilent 5975C Inert XL mass-selective detector (Agilent technologies, Cheadle, Cheshire, UK). Splitless injector at 300 ºC (1 µL) was used to inject the samples using helium as the carried gas with a constant flow rate at 3 mL/min. The column was inserted into the ion source of the mass spectrometry directly. The MS ionisation energy was 70 eV and spectra scanning window was between *m*/z 50 and 800. Samples (n = 49) were analysed by using an Agilent DB-5ms (5%phenyl) methylpolysiloxane column (30m × 0.25 mm × 0.25 µm; J&W Scientific, Folsom, CA, USA). The temperature was set to 50 ºC for 2 minutes, followed by a rise of 10 ºC per minute up to 350 ºC. The temperature was then held at 350 ºC for 15

minutes. Compounds were identified by comparing them with the library of mass spectral data and published data.

All samples (n = 49) were also analysed by using a DB-23ms (50%-cyanopropyl)-methylpolysiloxane column (60m x 0.25 mm × 0.25 μm; J&W Scientific, Folsom, CA, USA) in Single Ion Monitoring (SIM) mode to increase the sensitivity for the identification of isoprenoid fatty acids and ω-(*o*-alkylphenyl) alkanoic acids (APAAs) (Hansel et al. 2004; Cramp et al. 2014). Briefly, the initial temperature profile was 50 ºC for 2 minutes. It was followed by a rise of 4 ºC per minute up to 140 ºC, then 0.5 ºC per minute up to 160 ºC, and then 20 ºC per minute up to 250 ºC. The temperature was then held at 250 ºC for 10 minutes. 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, 87, 88, 101, 312), equivalent to pristanic acid; the third group of ions (m/z 74, 87, 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 C_{16} and C_{22}. 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-eight samples which had a lipid concentration over 5 μg g^{-1} were analysed by GC-C-IRMS in duplicates, following the existing protocol (Craig et al. 2012), in order to measure stable carbon isotope values of methyl palmitate ($C_{16:0}$) and methyl stearate ($C_{18:0}$), derived from precursor fatty acids. 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 ºC; Thermo Fisher). All samples were diluted with hexane. Then 1 μL of each sample was injected into a DB5ms fused-silica column (60m × 0.25mm × 0.25μm; J&W Scientific, Folsom, CA, USA). The temperature was fixed at 50 ºC for 0.5 minutes. This was followed by a rise of 25 ºC per minute up to 175 ºC, then 8 ºC per minute up to 325 ºC. The temperature was then held at 325 ºC for 20 minutes. Ultrahigh-purity-grade helium was used as the carrier gas with a constant flow rate at 2 mL/min. Eluted products were ionised in the mass spectrometer by electron ionisation 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±SD values of n-alkanoic acid esters were -31.65±0.27‰ for the methyl ester of $C_{16:0}$ and -26.01±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.

Zooarchaeological methods

Published online datasets (Kooijmans 2001; Kooijmans et al. 2001, and the unpublished Brandwijk dataset provided by DCM Raemaekers) were re-analysed in light of published records (e.g. Zeiler 1997). Primary data from Hazendonk was inaccessible at the time of writing. Relevant specimens in the De Bruin and Brandwijk assemblages were physically re-analysed using the zooarchaeological reference collections at the Groningen Institute of Archaeology (see Çakırlar *et al.* 2020 for further details). Smallest unit of quantification used in the zooarchaeological datasets and publications is the number of fragments (NF) and corresponding weights in grams. The use of NF calls for caution. In Dutch zooarchaeology, NF equals to the numbers of fragments in an assemblage, regardless of whether they belong to the same specimen or not (specimen *sensu* Stiner 2010). To quantify derived data from NF to estimate the relative taxonomic abundance might lead to even more erroneous results than doing it with NISP (=Number of Identified Specimens), which is usually controlled by predetermined diagnostic portions (*sensu* Davis 1987: 35 or Payne 1972).

Branched chain fatty acids C_{15} and C_{17}

The relative abundance of branched chain fatty acids (iso- and anteiso-fatty acids) C_{15br} and C_{17br} (i15:0, a15:0, i17:0 and a17:0) were separately calculated for all samples with fully aquatic biomarkers (n = 31). This was done based on the results of single ion monitoring (SIM) mode and from ion m/z 87. Then, the ratios of iso- branched chain fatty acids C_{15} and C_{17} were calculated based on the formulas below:

$$C15ivstot = i15:0 / i15:0 + a15:0$$

$$C17ivstot = i17:0 / i17:0 + a17:0$$

Each sample with fully aquatic biomarkers was compared to the average and standard deviation values of iso ratios of branched chain fatty acids C_{15} and C_{17} of modern reference data coming from fish and beaver. The values from modern fish are 59 ± 16% for the C_{15} and 59 ± 5% for the C_{17} branched fatty acids (Hauff and Vetter 2010). As no values for modern beaver adipose or flesh tissue fats were available, novel or previously published modern lipid extracts (Taché and Craig 2015; Courel et al. 2020) from Estonia, Russia and Canada (*Castor fiber* and *Castor canadensis*, n = 10) were analysed according the same procedure that archaeological samples. Values are 19 ± 4% for the C_{15} and 35 ± 12% for the C_{17} branched fatty acids.

References

Correa-Ascencio, M. and Evershed, R.P. 2014. High throughput screening of organic residues in archaeological potsherds using direct acidified methanol extraction. *Analytical Methods*, *6*(5), 1330-1340.

Courel B. et al. 2020. Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter–gatherers. *R. Soc. Open Sci. 7*: 192016. http://dx.doi.org/10.1098/rsos.192016.

Craig, O. E. et al. 2012. Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry*, *26*(19), 2359-2364.

Craig, O. E. et al. 2013. Earliest evidence for the use of pottery. *Nature*, *496*(7445), 351-354.

Cramp, L. and Evershed, R. P. 2014. Reconstructing Aquatic Resource Exploitation in Human Prehistory Using Lipid Biomarkers and Stable Isotopes. In: H. D. Holland and K. K. Turekian (eds.), *Treatise on Geochemistry (Second Edition)*, Elsevier, pp. 319-339.

Davis, S.J. 1987. *The archaeology of animals*. Psychology Press.

Fernandes, R. et al. 2014. Food reconstruction using isotopic transferred signals (FRUITS): a Bayesian model for diet reconstruction. *PloS One*, *9*(2), e87436.

Hansel, F. A. et al. 2004. Thermally produced ω- (o-alkyl phenyl)alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. *Tetrahedron Letters*, 45(14), 2999-3002

Hauff, S. and Vetter, W. 2010. Quantification of branched chain fatty acids in polar and neutral lipids of cheese and fish samples. *Journal of Agricultural and Food Chemistry*, *58*(2), 707-712.

Heron, C. et al. 2015. Cooking fish and drinking milk? Patterns in pottery use in the southeastern Baltic, 3300–2400 cal BC. *Journal of Archaeological Science*, 63, 33-43.

Louwe Kooijmans, L.P., Koot, C.W., Anscher, T.J. ten, Wijngaarden, G.J. van, Goudswaard, B. 2001. *Hardinxveld-Giessendam - De Bruin*. DANS. https://doi.org/10.17026/dans-zq3-qnhx .

Louwe Kooijmans, L.P. 2001. *Archeologie in de Betuweroute. Hardinxveld-Giessendam Polderweg. Een mesolithisch jachtkamp in het rivierengebied (5500-5000vChr.)*. DANS. https://doi.org/10.17026/dans-zpk-4g4a.

Papakosta, V. et al. 2015. Extraction and derivatization of absorbed lipid residues from very small and very old samples of ceramic potsherds for molecular analysis by gas chromatography--mass spectrometry (GC--MS) and single compound stable carbon isotope analysis by gas chromatography--combustion--isotope ratio mass spectrometry (GC-C-IRMS). *Microchemical Journal, Devoted to the Application of Microtechniques in All Branches of Science*, *123*, 196-200.

Payne, S. I972. On the interpretation of bone samples from archaeological sites. In: E. S. Higgs (ed), *Papers in Economic Prehistory*, Cambridge: Cambridge University, pp. 65-81.

Stiner, M.C. 2010. Taphonomy. In *Encyclopaedia of Archaeology*, Elsevier Inc., pp. 2113-2119.

Taché, K. and Craig, O. E. 2015. Cooperative harvesting of aquatic resources and the beginning of pottery production in north-eastern North America. *Antiquity 89(343)*, 177-190.

Supplementary Dataset -1: Sampled pottery information

sample ID	Pre-treatment	Site	Phase	Location	Site type	Culture	Vessel type	Vessel part **	Decoration	Rim diameter (cm)	Weight (gr)	Wall thickness (mm)	Main tempering material	Surface deposit (foodcrust)
HR-01	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	23	79.23	10	grit/grog	
HR-02	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	base	no	-	54.7	11	grit	
HR-03	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	57.54	10	grit	yes
HR-04	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	25-30	16.09	8	grit	yes
HR-05	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	31.63	11	grit	yes
HR-06	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	n/a	13.83	9	grog	
HR-07	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	n/a	11.47	9	grit	
HR-08	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	37.58	11	grit/sand?	yes
HR-09	AE	Polderweg	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	7.27	10	grog	
HR-10	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	135.31	12	grog	yes
HR-11	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	42.86	8	grog/sand	yes
HR-12	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	34.20	10	grog/sand	
HR-13	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	30	19.97	9	sand	
HR-14	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	20-25	14.56	7	grit	
HR-15	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body / knob	no	-	35.68	11	grit	
HR-16	AE	De Bruin	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	25-26	28.19	9	grog	
HR-17	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	n/a	36.51	8	grit	
HR-18	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	18	40.06	7	grog	
HR-19	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	20	58.37	9	grit/grog	
HR-20	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	15	29.03	7	grog	
HR-21	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	~25	53.52	11	plant material/sand	
HR-22	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	20	37.53	10	grog	
HR-23	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	base	no	-	57.44	10	grit/grog	
HR-25	AE	De Bruin	Phase 2	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	base	no	-	115.72	10	grit/grog	
HR-26	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	base	no	-	70.63	8	plant material	
HR-27	AE	De Bruin	Phase 3	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	17-20	68.01	10	grit	yes
BR-01	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	33	201.9	9	grit	yes
BR-03	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	36	251.7	11	grit	yes
BR-06	AE	Brandwijk	L60	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	23	151.8	9	grit	yes
BR-08	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	19	55.3	6	plant material/grit	
BR-10	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	32	214.7	10	plant material/grit	yes
BR-12	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	40	59.9	5	grit/plant material	yes
BR-14	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	57.7	10	grit	yes
BR-16	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	34.6	11	grit/plant material	yes
BR-18	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	base	no	-	56.1	7	grit	
BR-20	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	21.7	8	plant material	
BR-22	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	20	36	10	mica	yes
BR-24	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	30	108.7	9	grit	yes
BR-26	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	40	57	10	grit/plant material	yes
BR-28	AE	Brandwijk	L50	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	57.7	10	plant material/grit	

Supplementary Dataset -1: Sampled pottery information (continues)

sample ID	Pre-treatment	Site	Phase	Location	Site type	Culture	Vessel type	Vessel part **	Decoration	Rim diameter (cm)	Weight (gr)	Wall thickness (mm)	Main tempering material	Surface deposit (foodcrust)
HD-01	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	18	29.1	11	grit	
HD-03	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	35.1	10	plant material	
HD-05	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	14	5	plant material	
HD-07	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	yes	-	27	10	grit	
HD-09	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	>40	20.5	8	grit	
HD-11	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	body	no	-	44.4	11	sand	
HD-13	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	17	35.3	6	grit	
HD-15	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	yes	30	100.5	9	grog	
HD-17	AE	Hazendonk	1	Inland	Waterlogged settlement site	Swifterbant	Cooking pot	rim	no	25-30	6.7	5	plant material	

Supplementary Dataset -1: Results of organic residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	APAA C_{20}/C_{18} ratio	Fully aquatic	Partially aquatic	Other identified lipid markers	C15iso (%)	C17iso (%)
HR-01	Potsherd	Internal	203	1.39	-28.18	-28.66	-0.48	APAA($C_{16\text{-}22}$), tmtd, pri, phy	94.9	0.76	x	-	SFA($C_{13:0\text{-}22:0}$), UFA($C_{16:1,17:1,18:1}$), DC($C_{9:0}$), br	0.47	0.43
HR-02	Potsherd	Internal	594	1.03	-33.2	-33.94	-0.74	APAA($C_{16\text{-}20}$), phy	68.6		x	-		0.66	0.46
HR-03	Potsherd	Internal	58	1.14	-30.03	-30.27	-0.24	APAA($C_{16\text{-}20}$), tmtd, phy	93.6		x	-	SFA($C_{14:0\text{-}20:0}$), UFA($C_{18:1,22:1}$), br, chol	0.59	0.56
HR-04	Potsherd	Internal	45	0.98	-29.79	-30.36	-0.57	APAA($C_{16\text{-}18}$), tmtd, phy	69.2		-	x	SFA(C14:0-20:0), UFA($C_{18:1}$), br		
HR-05	Potsherd	Internal	791	1.67	-34.46	-34.62	-0.15	APAA($C_{16\text{-}18}$)	n/a		-	x	SFA($C_{11:0\text{-}24:0}$), UFA($C_{18:1}$), DC($C_{9:0,10:0}$), br		
HR-06	Potsherd	Internal	117	1.24	-28.71	-29.28	-0.57	APAA($C_{16\text{-}22}$), tmtd, pri, phy	86.7		x	-	SFA($C_{12:0\text{-}22:0}$), UFA($C_{16:1,18:1,20:1,22:1}$), DC($C_{9:0}$), br	0.62	0.42
HR-07	Potsherd	Internal	101	1.37	-28.22	-29.4	-1.18	APAA($C_{16\text{-}22}$), phy	n/a		x	-	SFA($C_{13:0\text{-}20:0}$), UFA($C_{16:1,18:1,22:1}$), DC($C_{9:0}$), br	0.53	0.38
HR-08	Potsherd	Internal	14	1.3	-31.61	-30.76	0.85	phy	89.8		-	x			
HR-09	Potsherd	Internal	13	1.02	-29.8	-30.07	-0.27	tmtd	n/a		-	-	SFA($C_{14:0\text{-}24:0}$), UFA($C_{16:1,18:1}$), br		
HR-10	Potsherd	Internal	186	1.28	-30.65	-30.2	0.45	APAA($C_{16\text{-}22}$), phy	72.4		x	-	SFA($C_{12:0\text{-}24:0}$), UFA($C_{16:1,\ 18:1}$), DC($C_{9:0}$), br	0.67	0.56
HR-11	Potsherd	Internal	8	0.81	-29.1	-30.1	-1	tmtd, phy	76.8		-	x	SFA($C_{14:0\text{-}20:0}$), br		
HR-12	Potsherd	Internal	22	1.22	-28.14	-29.54	-1.4	tmtd, pri, phy	31.7		-	-	SFA($C_{14:0\text{-}20:0}$), br		
HR-13	Potsherd	Internal	26	1	-28.78	-29.94	-1.16	tmtd, phy	51.2		-	x	SFA($C_{14:0\text{-}24:0}$), br		
HR-14	Potsherd	Internal	15	1.25	-27.76	-29.48	-1.71	tmtd, phy	35.8		-	x	SFA($C_{14:0\text{-}18:0}$), br		
HR-15	Potsherd	Internal	77	1.78	-32.61	-32.49	0.12	APAA($C_{18\text{-}20}$), tmtd, pri, phy	86.8		x	-	SFA(C14:0-24:0), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br, chol	0.61	0.53
HR-16	Potsherd	Internal	414	0.71	-30.59	-32.83	-2.24	APAA($C_{18\text{-}20}$), tmtd, phy	n/a		x	-	SFA($C_{11:0\text{-}23:0}$), DC($C_{9:0}$), br, chol	0.62	0.51
HR-17	Potsherd	Internal	42	0.91	-29.32	-30.24	-0.92	APAA($C_{16\text{-}18}$), tmtd, phy	49.3		-	x	SFA($C_{14:0\text{-}24:0}$), UFA($C_{18:1}$), br		
HR-18	Potsherd	Internal	28	1	-29.43	-30.34	-0.92	APAA($C_{18\text{-}20}$), tmtd, phy	69.8		x	-	SFA($C_{14:0\text{-}20:0}$), UFA($C_{18:1}$), DC($C_{9:0}$)	0.54	0.53
HR-19	Potsherd	Internal	39	1.51	-27.32	-28.62	-1.3	APAA($C_{18\text{-}20}$), tmtd, phy	76.4		x	-	SFA($C_{13:0\text{-}19:0}$), UFA($C_{18:1,22:1}$), br	0.47	0.49
HR-20	Potsherd	Internal	87	1.58	-26.33	-29.6	-3.27	APAA($C_{16\text{-}18}$), tmtd, phy	72		-	x	SFA($C_{12:0\text{-}18:0}$), UFA($C_{18:1}$), DC($C_{9:0}$), br		
HR-21	Potsherd	Internal	25	1.14	-28.4	-29.63	-1.23	APAA(C_{18}), tmtd, phy	45.2		-	x	SFA($C_{14:0\text{-}20:0}$)		
HR-22	Potsherd	Internal	42	1.68	-31.39	-30.95	0.44	APAA($C_{16\text{-}20}$), tmtd, phy	93.4	0.2	x	-	SFA($C_{12:0\text{-}24:0}$), UFA($C_{18:1}$), br	0.6	0.53
HR-23	Potsherd	Internal	131	2.63	-30.22	-30.35	-0.12	APAA($C_{16\text{-}22}$), tmtd, pri, phy	60.1		x	-	SFA($C_{11:0\text{-}19:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br	0.67	0.61
HR-25	Potsherd	Internal	236	2.35	-29.91	-29.4	0.52	APAA($C_{16\text{-}20}$), tmtd, phy	83.6		x	-	SFA($C_{11:0\text{-}19:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br, chol	0.65	0.57
HR-26	Potsherd	Internal	163	1.32	-31.95	-31.63	0.32	APAA($C_{16\text{-}22}$), tmtd, pri, phy	78.9		x	-	SFA($C_{13:0\text{-}22:0}$), UFA($C_{16:1,18:1,20:1}$), DC($C_{9:0}$), br	0.66	0.57
HR-27	Potsherd	Internal	153	2.71	-32.52	-31.14	1.38	APAA(C_{18}), tmtd, phy	84		-	x	SFA($C_{12:0\text{-}22:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br, chol		
BR-01	Potsherd	Internal	1.343	1.21	-30.39	-29.8	0.59	APAA($C_{16\text{-}22}$), pri, phy	90	0.46	x	-	SFA($C_{10:0\text{-}22:0}$), UFA($C_{18:1,22:1}$), DC($C_{9:0}$), br	0.74	0.65
BR-03	Potsherd	Internal	249	2.91	-34.32	-32.62	1.7	APAA($C_{16\text{-}22}$), tmtd, phy	59.4		x	-	SFA($C_{10:0\text{-}18:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br, chol	0.68	0.62
BR-06	Potsherd	Internal	910	1.06	-26.2	-26.02	0.17	APAA($C_{16\text{-}22}$), tmtd, pri	n/a	0.71	x	-	SFA($C_{10:0\text{-}22:0}$), UFA($C_{18:1,\ 20:1,22:1}$), DC($C_{9:0}$), br	0.7	0.39
BR-08	Potsherd	Internal	406	1.04	-31.47	-36.38	-4.9	APAA($C_{16\text{-}20}$), tmtd, pri, phy	65.3		x	-	SFA($C_{11:0\text{-}28:0}$), DC($C_{9:0}$), br	0.56	0.59
BR-10	Potsherd	Internal	847	1.26	-31.6	-30.31	1.29	APAA($C_{16\text{-}20}$), tmtd, phy	93.6		x	-	SFA($C_{11:0\text{-}24:0}$), UFA($C_{20:1,22:1,24:1}$), DC($C_{9:0}$), br	0.82	0.66
BR-12	Potsherd	Internal	146	1.59	-31.32	-29.78	1.54	APAA($C_{18\text{-}20}$), tmtd, phy	88.6	0.24	x	-	SFA($C_{12:0\text{-}28:0}$), UFA($C_{18:1}$), DC($C_{9:0}$), br	0.64	0.62
BR-14	Potsherd	Internal	156	2.13	-31.83	-30.81	1.02	APAA($C_{16\text{-}20}$), tmtd, phy	92.7	0.16	x	-	SFA($C_{12:0\text{-}24:0}$), UFA($C_{16:1,18:1}$), DC($C_{9:0}$), br, chol	0.69	0.52
BR-16	Potsherd	Internal	118	2.63	-31.71	-30.83	0.89	APAA($C_{16\text{-}20}$), tmtd, phy	52.9	0.25	x	-	SFA($C_{11:0\text{-}24:0}$), UFA($C_{16:1,\ 18:1}$), DC($C_{9:0}$), br, chol	0.64	0.65
BR-18	Potsherd	Internal	204	2.14	-32.53	-32.35	0.18	APAA($C_{16\text{-}22}$), tmtd, phy	69.1	0.43	x	-	SFA($C_{12:0\text{-}24:0}$), UFA($C_{16:1,\ 18:1}$), DC($C_{9:0}$), br, chol	0.64	0.63
BR-20	Potsherd	Internal	130	1.9	-24.77	-25.9	-1.13	APPA($C_{16\text{-}20}$), tmtd, pri, phy	69.4		x	-	SFA($C_{14:0\text{-}24:0}$), UFA($C_{16:1,18:1,22:1}$), DC($C_{9:0}$), br, chol	0.49	0.22
BR-22	Potsherd	Internal	160	1.83	-33	-33.03	-0.03	APAA($C_{16\text{-}20}$), tmtd, phy	53.5		x	-	SFA($C_{12:0\text{-}24:0}$), UFA($C_{18:1}$), DC($C_{9:0}$), br, chol	0.54	0.4
BR-24	Potsherd	Internal	617	0.83	-30.93	-29.35	1.58	APAA($C_{16\text{-}20}$), tmtd, phy	97	0.18	x	-	SFA($C_{11:0\text{-}22:0}$), UFA($C_{18:1,26:1}$), DC($C_{9:0}$), br	0.65	0.58
BR-26	Potsherd	Internal	397	1.36	-30.95	-30.16	0.79	APAA($C_{16\text{-}22}$), tmtd, pri, phy	91.2	0.29	x	-	SFA($C_{11:0\text{-}24:0}$), UFA($C_{18:1}$), DC($C_{9:0,\ 10:0}$), br, chol	0.73	0.53
BR-28	Potsherd	Internal	114	1.65	-26.49	-26.54	-0.05	APAA($C_{16\text{-}18}$), tmtd, phy	61.8		-	x	SFA($C_{13:0\text{-}18:0}$), DC($C_{9:0}$), br, chol		

Supplementary Dataset -1: Results of organic residue analysis (continues)

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	APAA C_{20}/C_{18} ratio	Fully aquatic	Partially aquatic	Other identified lipid markers	C15iso (%)	C17iso (%)
HD-01	Potsherd	Internal	90	1.3	-26.49	-27.52	-1.03	APAA($C_{16\text{-}18}$), tmtd, phy	32.8		-	x	SFA($C_{14:0\text{-}28:0}$), UFA($C_{16:1,\ 17:1,\ 26:1}$), br, chol		
HD-03	Potsherd	Internal	36	1.54	-27.33	-27.88	-0.55	APAA($C_{16\text{-}18}$), tmtd, phy	n/a		-	x	SFA($C_{14:0\text{-}26:0}$), UFA($C_{15:1,17:1}$), br		
HD-05	Potsherd	Internal	92	1.37	-31.36	-30.92	0.44	APAA($C_{16\text{-}20}$), tmtd, phy	51.5		x	-	SFA($C_{13:0\text{-}30:0}$), DC($C_{9:0}$), br, chol, tr	0.57	0.64
HD-07	Potsherd	Internal	104	1.38	-27.63	-26.78	0.85	APAA(C_{18}), tmtd, phy	35.4		-	x	SFA($C_{14:0\text{-}24:0}$), chol		
HD-09	Potsherd	Internal	245	1.84	-32.42	-32.7	-0.28	APAA($C_{16\text{-}22}$), tmtd, phy	79.9	0.33	x	-	SFA($C_{13:0\text{-}28:0}$), UFA($C_{18:1,20:1,21:1}$), DC($C_{9:0}$), br	0.63	0.63
HD-11	Potsherd	Internal	22	0.95	-26.02	-26.23	-0.21	APAA($C_{16\text{-}20}$), tmtd, phy	41.3		x	-	SFA($C_{14:0\text{-}26:0}$), br	0.39	0.35
HD-13	Potsherd	Internal	43	1.22	-28.23	-27.63	0.61	APAA(C_{18}), tmtd, phy	28.4		-	x	SFA($C_{14:0\text{-}24:0}$), br		
HD-15	Potsherd	Internal	17	1.58	n/a	n/a	n/a	APAA($C_{16\text{-}18}$), phy	30.4		-	x	SFA($C_{14:0\text{-}24:0}$)		
HD-17	Potsherd	Internal	567	1.21	-30.13	-30.15	-0.01	APAA($C_{16\text{-}22}$), tmtd, pri, phy	92.7	0.68	x	-	SFA($C_{12:0\text{-}22:0}$), UFA($C_{20:1}$), DC($C_{9:0}$), br	0.55	0.65

(Cn:x) - carboxilic acids with carbon length n and number of unsaturations x, SFA – saturated fatty acid, UFA – unsaturated fatty acids, DC - α,ω-dicarboxylic acids, APAA - ω-(o-alkylphenyl) alkanoic acids, br -branched chain acids, tmtd - 4,8,12-trimethyltridecanoic acid, pri – pristanic acid, phy – phytanic acid with the percentage contribution of SRR diastereomer in total phytanic acid, chol - cholesterol or derivatives.

**All the sampled vessel fragments in this study represent individual vessels However, they do not represent all the individual vessels identified at each site.

Supplementary Dataset -2: Faunal data – Mammals, Birds, and Fish

			Polderweg 0	Polderweg 1	Polderweg 1/2	Polderweg 2	De Bruin 1	De Bruin 2	De Bruin 3	Brandwijk L30	Brandwijk L50	Brandwijk L60	Hazendonk 1 & 2
			>5500 cal BC	5500-5300 cal BC	5150-5050 cal BC	5050-4950 cal BC	5500-5100 cal BC	5100-4800 cal BC	4700-4450 cal BC	4610-4550 cal BC	4220-3940 cal BC	3940-3820 cal BC	4020-3960 cal BC
Mammals	**Class/order/family**	**Species**											
Beaver	Castoridae	Castor fiber	15	1174	144	194	107	808	294		8	15	60
Otter	Mustelidae	Lutra lutra	18	1159	121	26	44	451	118	1	16	22	51
Common seal	Phocidae	Phoca vitulina		1			1	6					
Gray seal	Phocidae	Halichoerus grypus		3			2	7	1				
Elk (without antler)	Cervidae	Alces alces					1	12	3		1		
Red deer (without antler)	Cervidae	Cervus elaphus	3	183	9	2	12	65	18				?
Roe deer (without antler)	Cervidae	Capreolus capreolus		14	1		1	17	4				
Deer (with antler)	Cervidae	-					8	71	19				2
Aurochs	Bovidae	Bos primigenius		9	1		1	8	2				
Cattle / Aurochs	Bovidae	Bos taurus / Bos primigenius						2	7				
Cattle	Bovidae	Bos taurus							15		6	3	25
Wild boar	Suidae	Sus scrofa	5	977	63	10	101	65	5				
Pig / Wild boar	Suidae	Sus domesticus / Sus scrofa					23	136	53	1	22	22	17
Pig	Suidae	Sus domesticus						1	3				
Sheep/goat	Bovidae	Ovis aries / Capra hircus						2	11		2	10	1
Dog	Canidae	Canis familiaris	1	312	23		15	26	28		3		
Other			3	60	4	1	23	51	10	1	8	20	2
Mammals (unidentified)													
Small mammal			38	6663	775	157	291	3605	2017				
Medium-sized mammal			3	778	78	5	170	551	210				
Medium to large mammal													
Large mammal			5	241	17	8	56	289	63				
Mammal, indet.			330	38555	3422	351	1187	6325	2363	24	218	136	176

In Brandwijk: just 'indet' (not clear if only mammal)

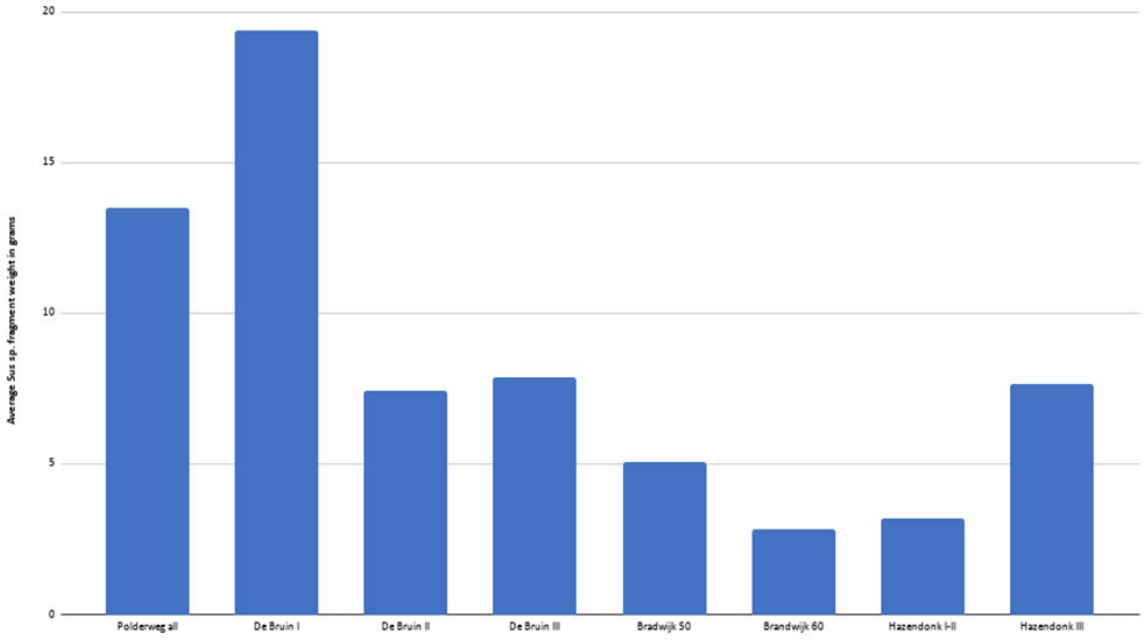
			Polderweg 0	Polderweg 1	Polderweg 1/2	Polderweg 2	De Bruin 1	De Bruin 2	De Bruin 3	Brandwijk L30	Brandwijk L50	Brandwijk L60	Hazendonk 1 & 2
			>5500 cal BC	5500-5300 cal BC	5150-5050 cal BC	5050-4950 cal BC	5500-5100 cal BC	5100-4800 cal BC	4700-4450 cal BC	4610-4550 cal BC	4220-3940 cal BC	3940-3820 cal BC	4020-3960 cal BC
Birds (identified)	**Class/order/family**	**Species**											
Mute swan	Anatidae	Cygnus olor		10	1	2	3	29	1				
Bewick's swan	Anatidae	Cygnus bewickii		2									
Whooper swan	Anatidae	Cygnus cygnus		2				2					
Mute swan/Whooper swan	Anatidae	Cygnus olor / Cygnus cygnus											
Swans	Anatidae	Cygnus sp.	1	27	1	1	7	30	1		3		
cf Swans	Anatidae	cf Cygnus sp.											
Bean goose	Anatidae	Anser fabalis		4				2					
Greylag goose	Anatidae	Anser anser		6	2	1	2	8					
Grey geese	Anatidae	Anser sp.	2	34	5	2	5	25	3				
Grey geese / Black geese	Anatidae	Anser sp. / Branta sp.											
Shelduck	Anatidae	Tadorna tadorna									1		
Mallard	Anatidae	Anas platyrhynchos	1	165	21	12	4	120	39		2		3
Northern shoveler	Anatidae	Anas clypeata											
Widgeon	Anatidae	Anas penelope		2	2	2	2	7	4				
Common teal	Anatidae	Anas crecca		4	3			1	1		1		
Common teal / Garganey	Anatidae	Anas crecca / Anas querquedula		5				1	1				
Pochard	Anatidae	Aythya ferina						1					
Tufted duck	Anatidae	Aythya fuligula					1						
Diving ducks	Anatidae	Aythya sp.	1	41	3		1	27	10				
Goosander	Anatidae	Mergus merganser		25		3		2	1				
Long-tailed duck	Anatidae	Clangula hyemalis								1			
Common goldeneye	Anatidae	Bucephula clangula		3	1			2					
Ducks	Anatidae	Anas sp. / Aythya sp. / Mergus sp. / Bucephala sp.		54	21	1	1	61	36				
Ducks	Anatidae	-		36	7	9	2	23	23				6
Coot	Rallidae	Fulica atra		9	1		1						
Common moorhern	Rallidae	Gallinula chloropus		7				3	1				
Little crake	Rallidae	Porzana parva						2					
Water rail	Rallidae	Rallus aquaticus		1				5					
Rails	Rallidae	-		2				4					
Common crane	Gruidae	Grus grus		1									
Little grebe	Podicipedidae	Tachybaptus ruficollis		5									
Great bittern	Ardeidae	Botaurus stellaris		7				1					
Grey heron	Ardeidae	Ardea cinerea		8				6					
Purple heron	Ardeidae	Ardea purpurea				1		1	1				
Herons	Ardeidae	Ardea sp.		1		1		5					
Red-throated diver	Gaviidae	Gavia stellata		9		1	1	1					
Cormorant	Phalacrocoracidae	Phalacrocorax carbo	1	10				7					
Plovers	Charadriidae	Charadrius sp.		1									
Eurasian woodcock	Scolopacidae	Scolopax rusticola		1									
Great spotted woodpecker	Picidae	Dendrocopos major		3									
Thrushes	Turdidae	Turdus sp.							1				
Common reed bunting	Emberizidae	Emberiza schoeniclus		2									
Small songbird	Passeriformes	-											
Eurasian eagle-owl	Strigidae	Bubo bubo		1				5	3				
Northern goshawk	Accipitridae	Accipiter gentilis						1					
Eurasian sparrowhawk	Accipitridae	Accipiter nisus		3									
White-tailed eagle	Accipitridae	Haliaeetus albicilla	1	30	1	1		9	2				
Common buzzard	Accipitridae	Buteo buteo		3									
Accipitrids	Accipitridae	-		2								1	
Birds (unidentified)													
Indet.			5	598	139	21	17	187	191		3	1	3

			Polderweg 0	Polderweg 1	Polderweg 1/2	Polderweg 2	De Bruin 1	De Bruin 2	De Bruin 3	Brandwijk L30	Brandwijk L50	Brandwiijk L60	Hazendonk 1 & 2
			>5500 cal BC	5500-5300 cal BC	5150-5050 cal BC	5050-4950 cal BC	5500-5100 cal BC	5100-4800 cal BC	4700-4450 cal BC	4610-4550 cal BC	4220-3940 cal BC	3940-3820 cal BC	4020-3960 cal BC
Fish (identified)	**Class/order/family**	**Species**											
			Scales indicated; totals are without scales				Including scales, but amount not in text/table						
Freshwater species													
Bream	Cyprinidae	Abramis brama	235	5878	18	4	287	349	193			2	
Silver bream	Cyprinidae	Abramis bjoerkna		28									
Chub	Cyprinidae	Squalius cephalus	3	8				2					
Ide	Cyprinidae	Leuciscus idus	1	36									
Roach	Cyprinidae	Rutilus rutilus	34	483			7	12	63				
Rudd	Cyprinidae	Rutilus erythrophthalmus	1	23									
Tench	Cyprinidae	Tinca tinca		22				1					
Chub / Rudd	Cyprinidae	Squalius cephalus / Rutilus erythrophthalmus	1	20									
Cyprinids (including squama)	Cyprinidae	-	148	3087	20	9	288	581	159				
Cyprinids (without squama)	Cyprinidae	-	148	3086	20	9							
Pike	Esocidae	Esox lucius	200	8930	106	81	539	1928	1031	2	2	7	
Perch (including squama)	Percidae	Perca fluviatilis	45	835	4	9	210	648	148				
Perch (without squama)	Percidae	Perca fluviatilis	41	828	4	9							
Eel	Anguillidae	Anguilla anguilla		15	1			4	1				
Catfish	Siluridae	Siluris glanis		44	2		13	38	10				
Migratory species													
European sturgeon	Acipenseridae	Acipenser sturio		17	1	1	32	118	16		1		
Houting	Salmonidae	Coregonus oxyrinchus	76	153									
Whitefish (fresh and migra	Salmonidae	Coregones sp.					1	4	1				
Salmon	Salmonidae	Salmo salar		1			4	2					
Salmon / Sea trout	Salmonidae	Salmo salar / Salmo trutta	8	5			1	29					
Salmonids	Salmonidae	-					4	9	6				
Allis shad	Clupeidae	Alosa alosa					69	49	1				
Twaite shad	Clupeidae	Alosa fallax		1									
Marine species													
Mullets	Mugilidae	-							1				
Fish (unidentified)													
Indet. (including squama)			630	36343	171	148	1897	3094	2402				
Indet. (without squama)			629	36288	171	148							

For fish remains for Hazendonk; Only multiple phase totals known (in Brinkhuizen 1979)

References used to gather data: Zeiler 1997, Table 2, Table 3; Raemaekers 1999, Table 3.27, 3.49; Oversteegen, J.F. et al. 2001, Table 8.7; Van Wijngaarden-Bakker et al. 2001, Table 8.9; Beerenhout 2001a, Table 9.3; Beerenhout 2001b, Table 9.11; Amkreutz 2013, Fig.7.4, Fig.7.4b; Çakırlar et al. 2019, SM Table 3; Çakırlar et al. 2020, Table 13.3

-All counts in NF (Dutch way of counting all fragments). Not to be confused by NISP
-Changes in Brandwijk data : this study and Çakırlar et al. 2020



Supplementary Dataset -2: Table 1: Site distribution of average Sus sp. fragment weight (in grams)

Supplementary Material Dataset-3

Common name	Taxa	Sample type	Period	Provenience	C15iso (%)	C17iso (%)
Beaver	Castor fiber	tissue	Modern	Estonia	0.19	0.31
Beaver	Castor fiber	tissue	Modern	Estonia	0.22	0.36
Beaver	Castor fiber	tissue	Modern	Estonia	0.23	0.34
Beaver	Castor fiber	tissue	Modern	Estonia	0.22	0.32
Beaver	Castor fiber	tissue	Modern	Estonia	0.18	0.38
Beaver	Castor fiber	tissue	Modern	Estonia	0.18	0.27
Beaver	Castor fiber	tissue	Modern	Estonia	0.22	0.32
Beaver	Castor fiber	tissue	Modern	Russia - Middle Don	0.18	0.38
castor	Castor fiber	tissue	Modern	Russia - Upper Volga	0.22	0.66
Beaver	Castor canadensis	Soft tissue	Modern	Canada	0.09	0.19

CHAPTER 5

Lipid residue analysis of ceramics from Hüde I (Lower Saxony, Germany): New Data to understand the transition to farming

Özge Demirci, Alexandre Lucquin, Florian Klimscha, Oliver E. Craig, Daan C.M. Raemaekers

Accepted for publication (February 25, 2021) in:

Florian Klimscha, Marion Heumüller, Daan Raemaekers, Hans Peters & Thomas Terberger (eds.), *Stone Age Borderland Experience. Mesolithic and Neolithic Parallel Societies in the North European Plain* (forthcoming).

Lipid residue analysis of ceramics from Hüde I (Lower Saxony, Germany): New Data to understand the transition to farming

Özge Demirci[1,2], Alexandre Lucquin[2], Florian Klimscha[3], Oliver E. Craig[2], Daan C.M. Raemaekers[1]

[1]Groningen Institute of Archaeology, Poststraat 6, 9712 ER, Groningen, the Netherlands
[2]BioArch, Department of Archaeology, University of York, York, YO10 5YW, UK
[3]Lower Saxony State Museum, Willy-Brandt-Allee 5, 30169, Hannover, Germany

Abstract

This project is a pilot study aiming to question the use and function of the pots from Hüde I (4,700-3,500 calBC), distr. Diepholz in Lower Saxony, Germany, through lipid residue analysis on its pottery. The results from this project not only demonstrated that lipids can be extracted from Hüde I vessels, but also indicated that the vessels were directly associated with food preparation and/or cooking. The results also indicated a functional variation in the pottery use, including processing aquatic (freshwater) resources, terrestrial animals (both ruminant and non-ruminant) and dairy products as well as possibly food plants.

Zusammenfassung

Der Beitrag stellt Ergebnisse einer Pilotstudie zum Gebrauch und zur Funktion der Gefäße der Fundstelle Hüde I, Lkr. Diepholz in Niedersachsen, durch Lipidanalysen von Krustenresten an Keramik vor. Die Ergebenisse zeigen nicht nur, dass Lipide aus den Gefäßen von Hüde I extrahiert werden können, sondern belegen ihre Verwendung mit der Nahrungszubereitung und / oder dem Kochen. Die Ergebnisse belegen eine funktionale Variabilität im Gefäßgebrauch. Dazu gehören die Verarbeitung von Süßwasser-Ressourcen, Wildtieren, Milchprodukte und vielleicht auch pflanzliche Nahrung.

Keywords: Lipid residue analysis, early pottery use, Mesolithic-Neolithic transition, northern central Europe, Hüde I

Introduction

The site of Hüde I, distr. Diepholz, Lower Saxony plays a key role in the discussion about the Neolithisation of Europe. It is particularly important in reference to the transition from the Ertebølle Culture to the Funnel Beaker Culture in southern Scandinavia and northern Germany, but also in reference to the Swifterbant culture chronology that spans the Mesolithic-Neolithic transition. It maintains this crucial position thanks to its long occupational span – on the basis of the discovered ceramic finds, dated 4,700-3,500 calBC[1], the preservation of bone material and its location - in between the hunter-gatherer and farming communities.

More recently, researchers have stressed the need to consider the transition at a regional or sub-regional scale moving away from the grand narratives regarding the degree of migration versus autochthonous change that have polarised the debate, particularly during the latter half of the twentieth century. In northern Germany, during the majority of the 5th millennium calBC, there was a boundary between hunter-gatherer societies of the Ertebølle Culture to the north in southern Scandinavia, and the Swifterbant Culture to the west in today's Dutch wetlands, and early farming groups such as *Linearbandkeramik* (LBK), established to the south and east of the river Elbe[2] (Fig. 1A-1C). The contacts between these hunter-gatherer groups and early farming groups are evident by the presence of shared material culture through exchange, especially of perforated adzes (*durchlochte Schuhleistenkeile)* and perforated wedges (*Breitkeile*).[3]

While the earliest Swifterbant pottery appears at c. 5,000 calBC[4] and was used in a purely hunter-gatherer context, domesticated animals and cereal cultivation were introduced at around 4400-4300 cal BC[5], probably as a result of interaction with the adjacent farming groups. In southern Scandinavia, the earliest Ertebølle pottery appears at around 4,800-4,600 calBC.[6] However, the arrival of the Funnel Beaker Culture (TRB) at around 3,950 calBC[7] marks the introduction of domesticated animals and cereals into the region as new elements in the subsistence economy.

The evidence for and the knowledge of the transition from hunter-gatherer to farming communities in large parts of northern Germany and the Netherlands is scarce as the sandy soils of this area do not

[1] Raemaekers 1999: 87.
[2] Terberger et al. 2009; Sørensen/Karg 2014.
[3] Fischer 1982; Czekaj-Zastawny et al. 2011; Raemaekers 2011; Raemaekers et al. 2011; Verhart 2012; Povlsen 2014.
[4] Raemaekers 2011.
[5] Out 2008, 2009; Çakırlar et al. 2020.
[6] Andersen 2010.
[7] Fischer 2002; Hartz/Lübke 2006.

allow a good preservation or detection of sites.[8] This sandy zone (part of the North European Plain) is located between the Dutch wetlands and Baltic coastal zone on the one hand, and the central European loess zone on the other hand. To understand the transition to farming and the role of the central European communities therein, we are dependent on well-preserved sites from the sandy zone. Even some 50 years after excavation, Hüde I at lake Dümmer, distr. Diepholz, remains an exceptional 'steppingstone' in understanding the expansion of the Neolithic to the Dutch wetlands, northern Germany and southern Scandinavia.

In this paper, we study the role of Hüde I as a crossroad between hunter-gatherers and early farming communities by means of functional analysis of ceramics through a pilot study of lipid residue analysis and aim to address three main questions: (1) Is the methodology of lipid residue analysis applicable to the ceramics from Hüde I? (2) If so, what was the role and function of ceramic vessels in Hüde I? and (3) Where do these ceramic vessels fit within the discussion of functional variation of pottery through the transition from hunter-gatherers to early farming communities in Europe? In order to answer these questions, we follow analytical procedures combining analysis of lipid biomarkers[9] and compound-specific isotopic analyses of the fatty acids, palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids.[10]

Hüde I (c. 4,700-3,500 calBC)

Hüde I is located on the southern edge of Lake Dümmer, in Lower Saxony, Germany. It was discovered when the area around Lake Dümmer was drained in 1953. After a test excavation in 1956, large-scale excavations were carried out by J. Deichmüller from 1961 to 1967, resulting in almost the total site surface, a total 1100 m^2 area, being excavated.[11] Hüde I was located on a patchy dry terrain in the middle of freshwater marshes separated by small creeks. The site was at a low peat elevation, not much higher than the surrounding environment and was connected to the lake through a creek on the north-western edge of this elevation. During the occupation of the site, this creek was filled with a sequence of gyttja, alluvium and brushwood peats as well as archaeological material, resulting in the formation of layers of natural and archaeological deposition.

The potential of the site to study the development of the Neolithic is restricted due to the lack of a clear stratigraphy. This not only holds true for the central part of the site[12], but also for the neighbouring creek. Younger and older material are found together throughout the creek fill as much as on the site

[8] Nösler et al. 2011.
[9] Hansel et al. 2004; Craig et al. 2007; Regert 2011; Cramp and Evershed 2014; Lucquin et al. 2016, 2018.
[10] Evershed et al. 1997, 2002a, 2002b, 2008a, 2008b; Copley et al. 2005; Craig et al. 2005, 2007, 2012; Colonese et al. 2017; Pääkkönen et al. 2020.
[11] Deichmüller 1964, 1965a, 1965b, 1968, 1969; Kampffmeyer 1991: 35-40; Stapel 1991: 3.
[12] cf. Stapel 1991: 10.

proper.[13] As a result, the pottery assemblage can be considered a catalogue of pots of which some can be attributed to pottery styles defined elsewhere. The majority of the assemblage lacks specific characteristics and is therefore difficult to assign to a cultural group based on technological, morphological or decorative criteria. This problem is illustrated by comparing pots from Hüde I to similar pots found in a wider region and in different cultural settings (see Fig. 1D). We conclude that caution is needed when assigning cultural labels to Hüde I pots without further research focusing on the technology and direct ^{14}C dates of food crusts, organic temper and/or organic residues.[14]

Available archaeozoological data from Hüde I indicates the exploitation of both wild and domesticated animals. About 90% of the mammal bone remains are coming from wild species, dominated by wild boar (*Sus scrofa*), aurochs (*Bos primigenius*), deer (Cervidae), beaver (*Castor fiber*) and otter (*Lutra lutra*).[15] The contribution of domesticates to the overall faunal spectrum at the site is small and consisted of pig (*Sus domesticus*), cattle (*Bos taurus*) and sheep/goat (*Ovis aries/Capra hircus*).[16] Birds and fish were also present at Hüde I. White-tailed eagle (*Haliaeetus albicilla*) and mallard (*Anas Platyrhynchos*) were the main bird species found at the site.[17] Hüde I also yielded remains from six fish species. Five of these are freshwater fish species which are pike (*Esox lucius*), perch (*Perca fluviatilis*), bream (*Abramis brama*), tench (*Tinca tinca),* and pope (*Acerina cernua).* The remaining sixth is eel (*Anguilla anguilla*), a catadromous fish species.[18] It is important to note here that the archaeozoological data cannot be associated with any of the "phases" defined by the pottery subjected to this study.

Regarding the archaeobotanical data from Hüde I, the only evidence for the presence of cereals, naked barley (*Hordeum vulgare var. nudum*) and einkorn wheat (*Triticum monococcom*), came from the impressions of cereals in three sherds, supplemented by an archaeobotanical study on charred material.[19] These sherds could not be assigned to any specific occupation phase.[20] The carbonised remains of gathered plants included the shell of hazelnuts (*Corylus avellana*) as one of the most common fruits, while the fruits and seeds of black alder (*Alnus glutinosa*) and willow (*Salix spp.*) trees, raspberry (*Rubus idaeus*), nettle (*Urtica dioica*), wild buckwheat (*Fallopia convolvulus)* and some other herbs were also present at the site.[21]

[13] Stapel 1991, compare various maps on pages 210-285; Raemaekers 1999: 74-89.
[14] Casanova et al. 2020.
[15] Hübner et al. 1988.
[16] Hübner et al. 1988 : Tables 30 and 44.
[17] Boessneck 1978 cited in Raemaekers 1999: 91.
[18] Hüster 1983: Table 24.
[19] Hopf 1981.
[20] Kampffmeyer 1991: 312.
[21] Kampffmeyer 1991: 313-6.

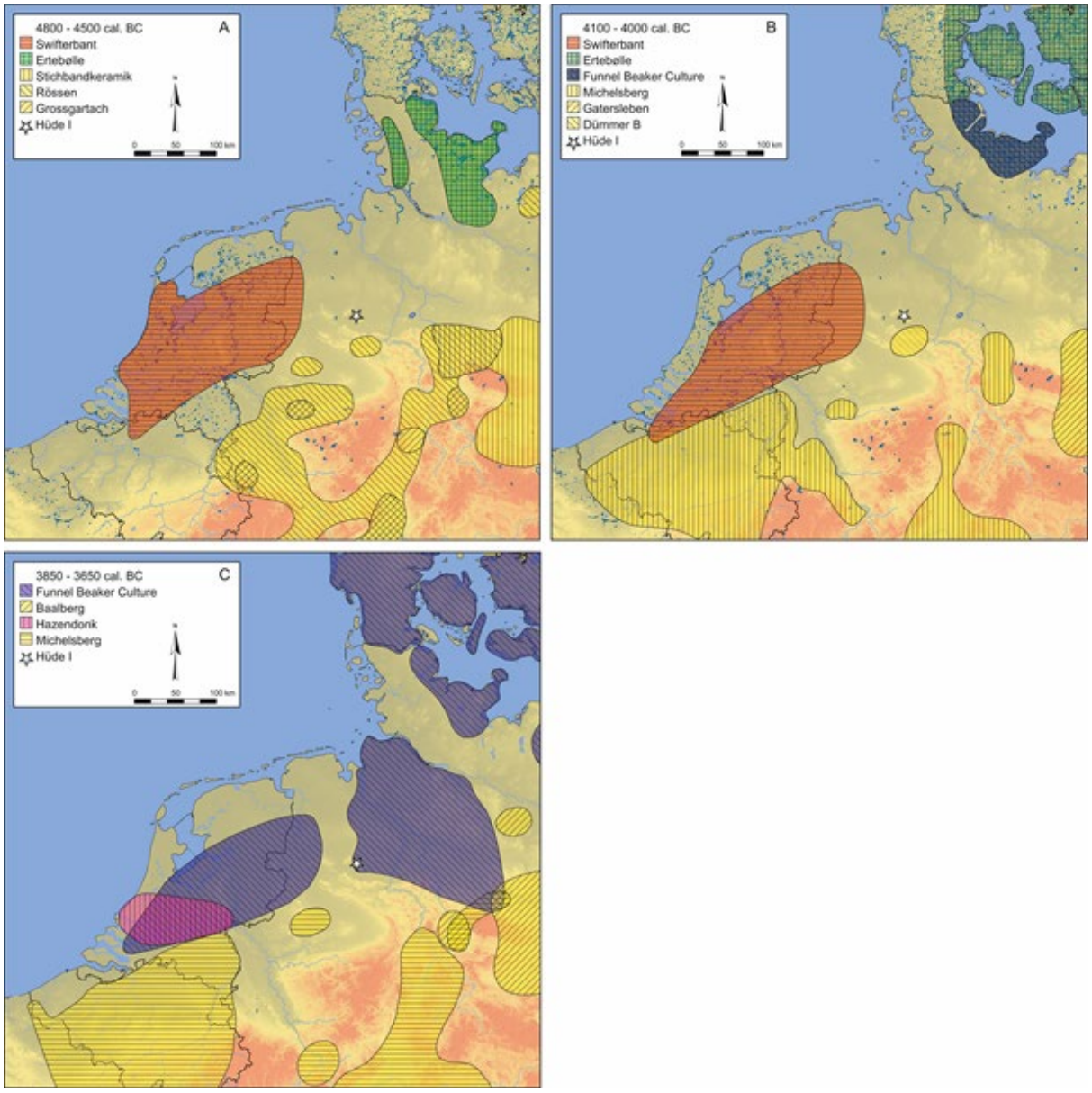


Fig. 1 (A) Hüde I is located between central Europe, southern Scandinavia and the Low Countries. (A) Cultural groups identified for 4,800-4,500 calBC; (B) 4,100-4,000 calBC; (C) 3,850-3,650 calBC respectively (based on Müller 2009). Map: S.Tiebackx.

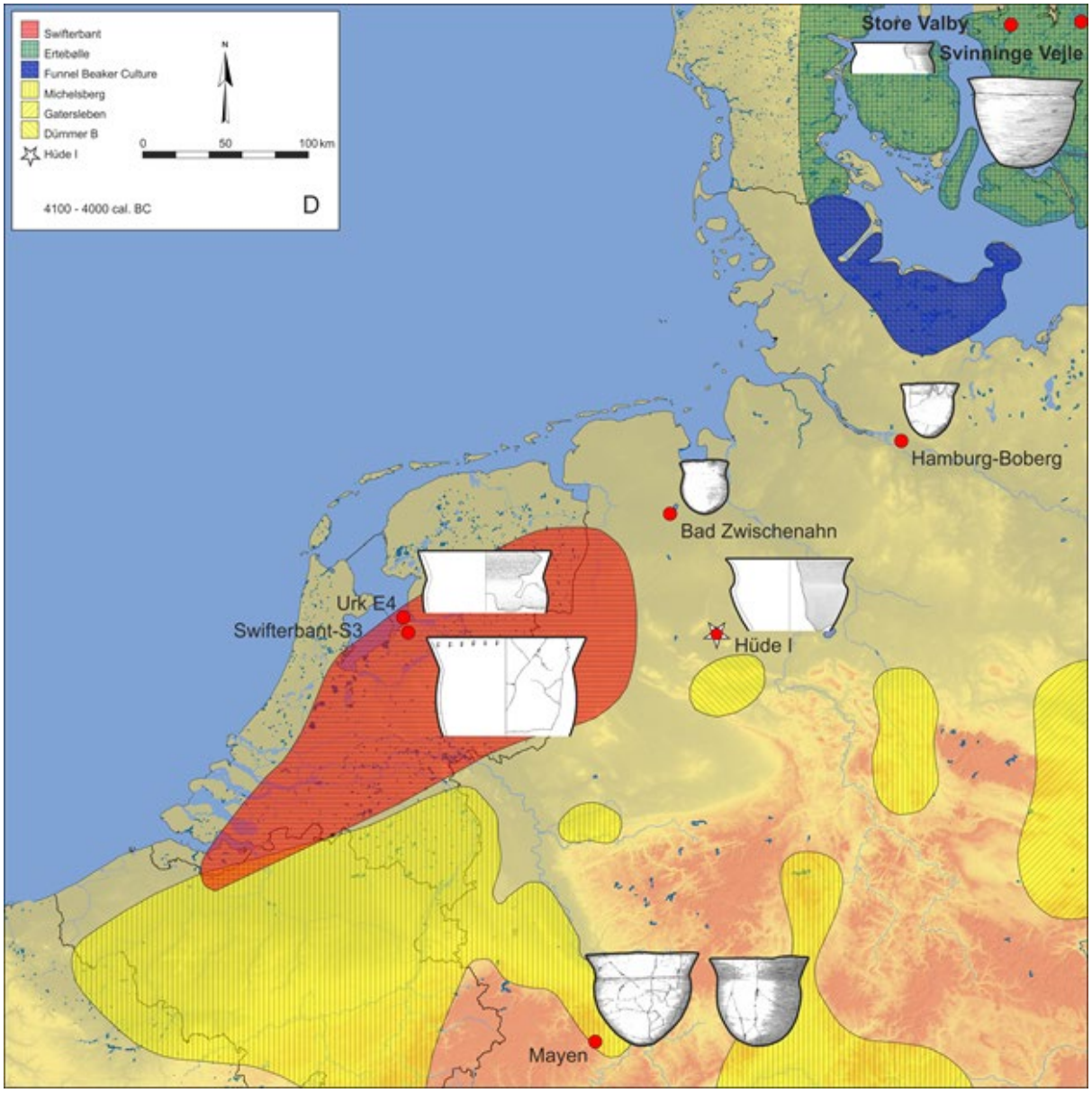


Fig. 2 Short-necked beakers found across this same area (based on Schwabedissen 1967: fig. 10 (Store Valby, Svinninge Vejle), fig. 24 (Bad Zwischenahn, Hamburg-Boberg, Mayen), De Roever 2004: fig. 11a (Swifterbant-S3) and Raemaekers 2005: fig. 6 (Urk-E4)). Map: S. Tiebackx.

Material and Methods

Sampling strategy and material

A total of 37 samples were subjected to lipid residue analysis, representing 35 individual vessels. Of all samples, 21 sherds had carbonised surface remains (foodcrusts), on interior and/or exterior, indicating that they had been used for cooking. This study was designed as an exploratory research to test the applicability of the lipid residue analysis on its ceramic material. The sampling strategy was aimed at

comparing the use of pottery by morphological and decorative attributes that were available.[22] The samples were selected from collections of the Landesmuseum in Hanover, Germany. Prior to actual sampling, the form, size, decoration, rim diameter, wall thickness, and temper of each pottery fragment was studied (Supplementary Dataset-1).

The selected sherds present two main vessel forms: S-shaped/carinated vessels and deep bowls. S-shaped/carinated vessel fragments (n = 34) consist of seventeen rim, six base and eleven body pieces. While the base fragments vary between slightly pointed, rounded and flat bases, two body fragments had shallow vertical handles and another three had unperforated knobs. These vessels are a combination of small, medium and large size pots often with everted rims, but straight ones are also present. Six of the S-shaped/carinated vessels are of small-size (rim diameter <20 cm), six are of mid-size (rim diameter between 20 and 25 cm) and five are larger sized vessels (rim diameter between 26 and 30 cm; see Supplementary Dataset-1). The majority of the sampled S-shaped/carinated vessel fragments were undecorated (22 out of 37). Within the ones with decoration, spatula impressions on the top of the rim is the most common decoration. Two rim fragments show decorations with hollow circular impressions and/or thumb impressions, right below the rim on the exterior. There are only three fragments that yield body decoration covering the lower neck and belly sections of the vessels. These decorations consist of double incisions, forming triangles. The wall thickness of these vessel fragments varies from 5 to 11 mm with the average of 8 mm and do not indicate any correlation with the size of the vessel or the decoration.

In general, it is not possible to assign the selected vessels to specific cultural groups, except for two Rössen pots that exhibited clear morphological and decorative characteristics (samples HU26 and HU30; see Fig. 3-7). These pots are small-sized S-shaped and carinated vessels with the diameters of 17.5 and 10 cm[23], respectively. They both have burnished exteriors and double incision decorations covering their lower neck and upper belly parts, indicating distinctive characteristics for the Rössen pottery culture.[24]

There are three bowls in the selected assemblage, all with slightly rounded bases. All three bowls have a diameter of 23-24 cm with the wall thickness of 7-9 mm. One of the three bowls is decorated with the spatula impressions on the top of the rim, while the remaining two have no decoration.

There is no significant difference between the fabric of the S-shaped/carinated vessels and the deep bowls. The most common inclusion for all the selected assemblage is grit although there is also a rare

[22] Drews 1977; Kampffmeyer 1991.
[23] Based on the complete drawing of the pot in Kampffmeyer 1991: Table 5 (554).
[24] Bogucki/Grygiel 1993.

appearance of sand, flint and grog. While the S-shaped/carinated vessels present examples of both extremely coarse pottery with no surface treatment and relatively finer pottery with smoothed, polished or burnished surface, all three bowls indicate fine pottery with polished or burnished surface treatment.

Lipid extraction

Lipids were extracted by using the established acidified methanol protocol.[25] Briefly, an internal standard (alkane C_{34}, 10 μL) and 4 mL methanol was added to 1 gr of pottery powder. The suspended solution was sonicated for 15 min, then acidified with concentrated sulphuric acid (H2SO4, 800 μL) and heated for 4 hours at 70 °C. Lipids were sequentially extracted with n-hexane (2 mL × 3). The extracts were combined into vials and copper sheets were added in order to remove cyclic octaatomic sulphur that was present in all some of the samples. All the samples were dried under nitrogen at 35 °C. Finally, an additional internal standard (n-hexatriacontane $C_{36:0,}$ 10 μL) was added to all samples prior to their analysis by gas chromatography-mass spectrometry (GC-MS) and gas chromatography-combustion isotope ratio mass spectrometry (GC-C-IRMS). 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 undertaken using an Agilent 7890A series Gas Chromatograph coupled to an Agilent 5975C inert XL mass-selective detector equipped with a quadrupole mass analyser (Agilent technologies, Cheadle, Cheshire, UK). A split/splitless injector (used in splitless mode) was 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 2 mL/min. The ionisation energy was 70 eV, and spectra were obtained by scanning between *m/z* 50 and 800. Samples (n = 37) were analysed by using an Agilent DB-5ms (5%phenyl) methylpolysiloxane column (PN 122-5532; 30 m x 250 μm x 0.25 μm; J&W Scientific technologies, Folsom, CA, USA). The temperature started at 50ºC (for 2 min), increasing by 10ºC min^{-1} up to 325ºC. The final temperature was maintained for 15 min. Compounds were identified by comparing them with the library of mass spectral data and published data.

[25] Craig et al. 2013; Papakosta et al. 2015.

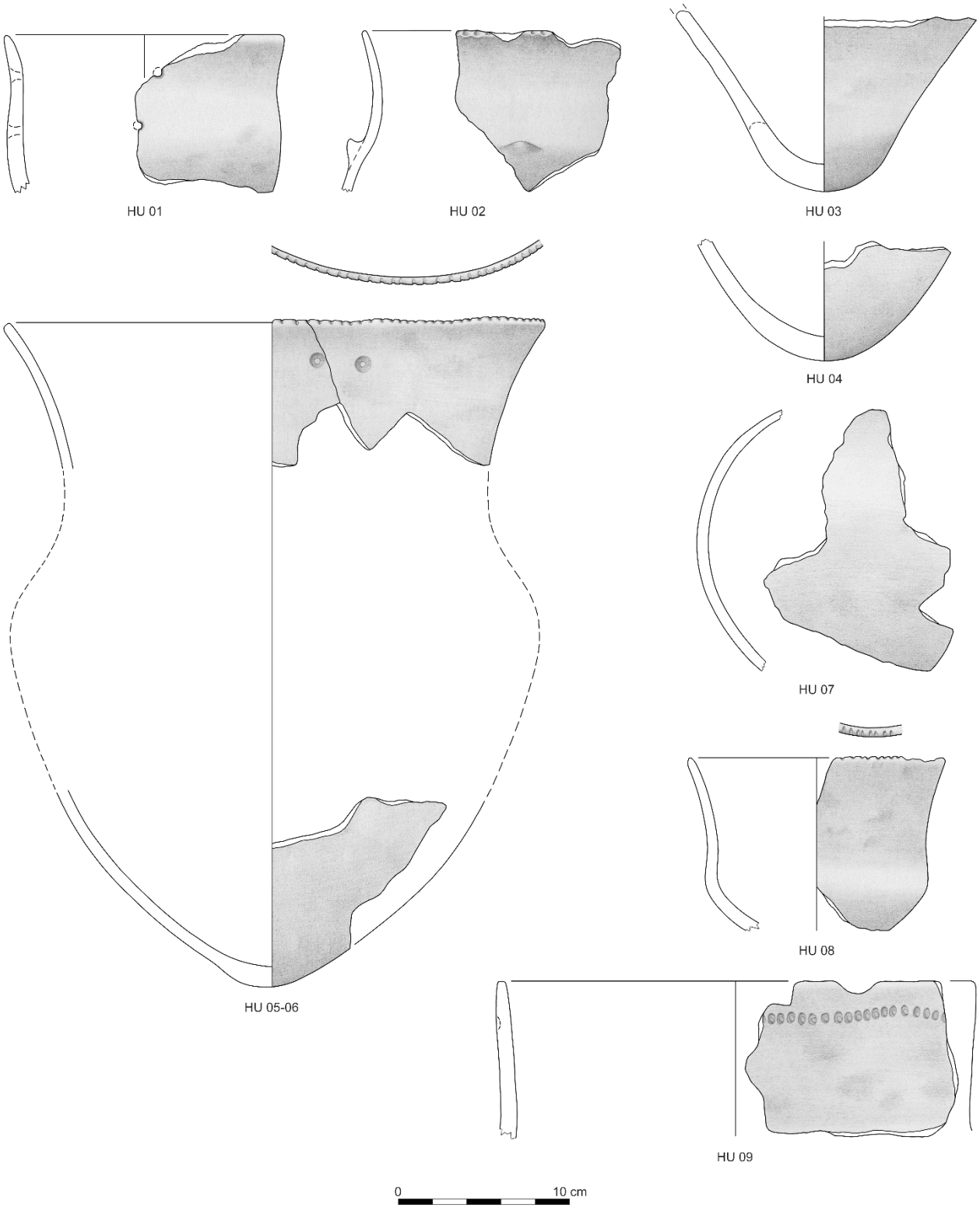


Fig. 3 Drawings of all the analysed pottery fragments from Hüde I. Scale 1:3. Drawings: M.A. Los-Weijns.

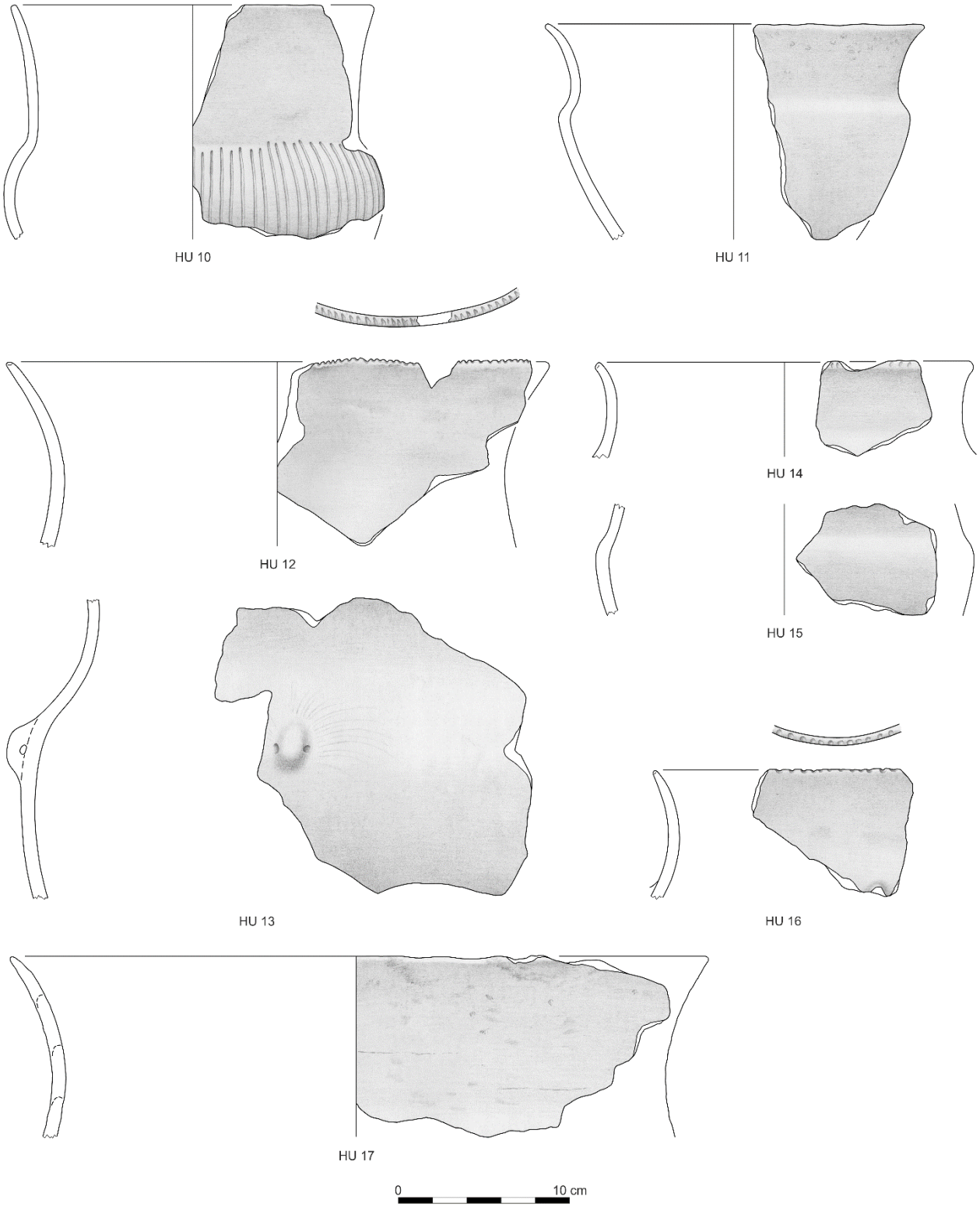


Fig. 4 Drawings of all the analysed pottery fragments from Hüde I. Scale 1:3. Drawings: M.A. Los-Weijns.

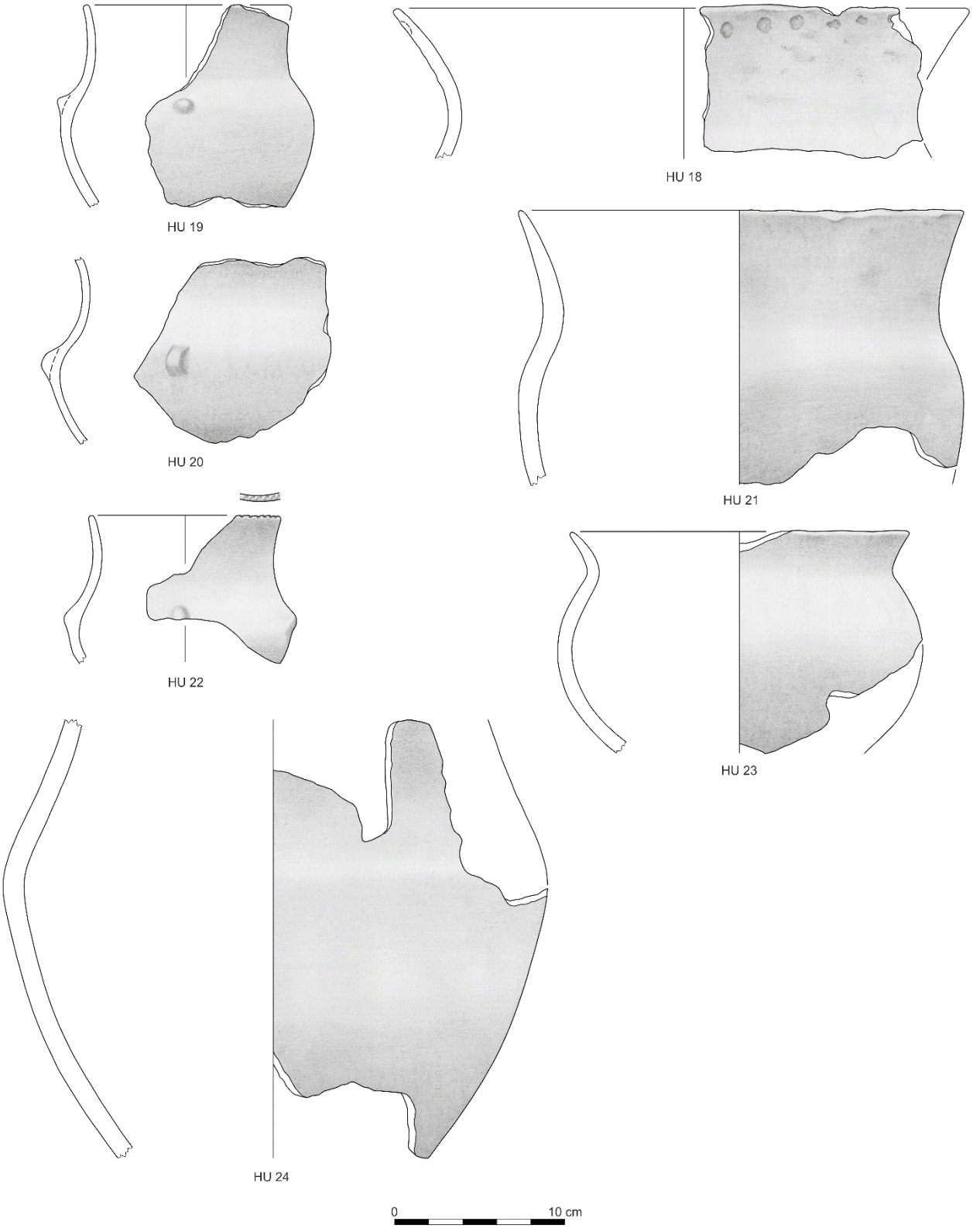


Fig. 5 Drawings of all the analysed pottery fragments from Hüde I. Scale 1:3. Drawings: M.A. Los-Weijns.

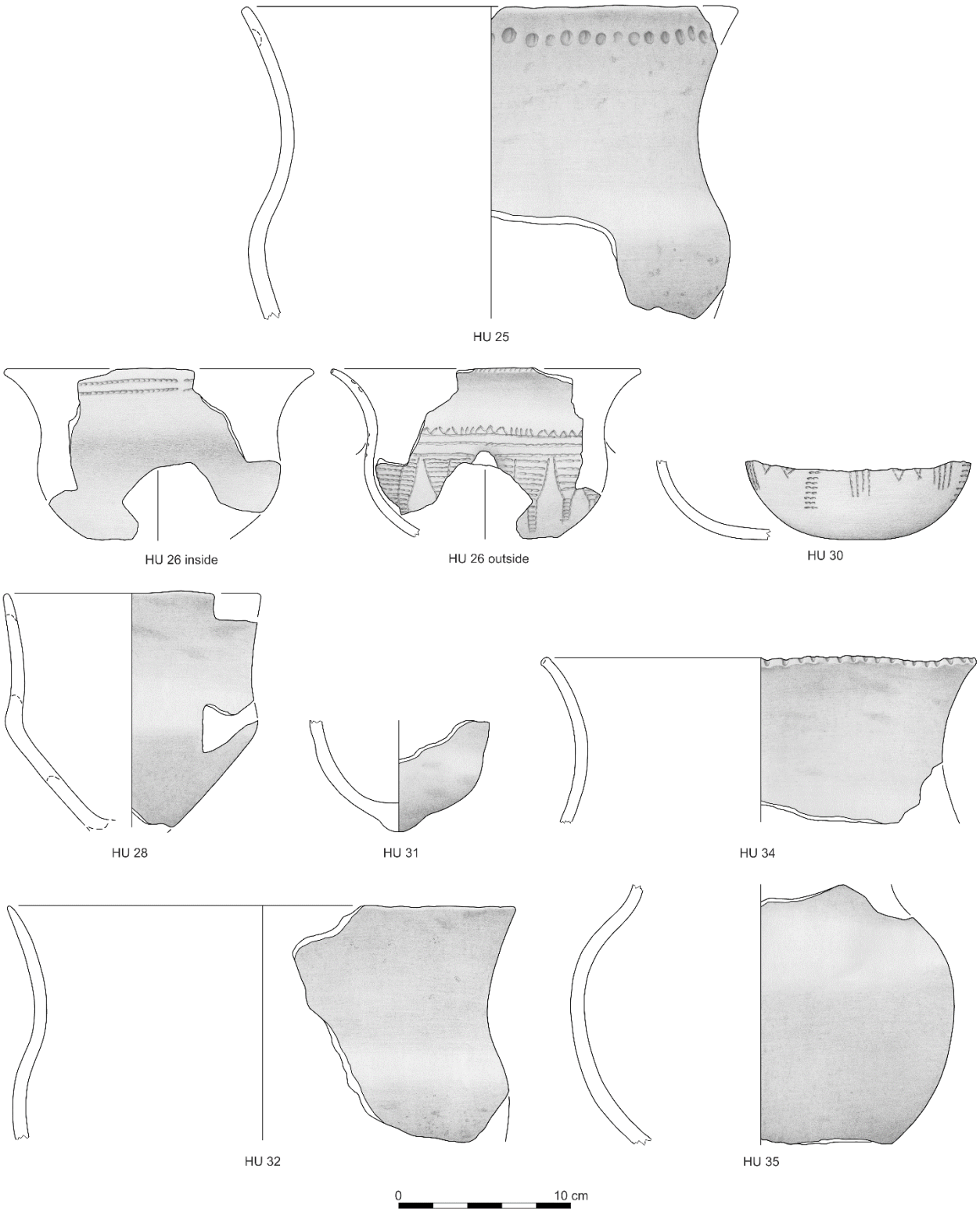


Fig. 6 Drawings of all the analysed pottery fragments from Hüde I. Scale 1:3. Drawings: M.A. Los-Weijns.

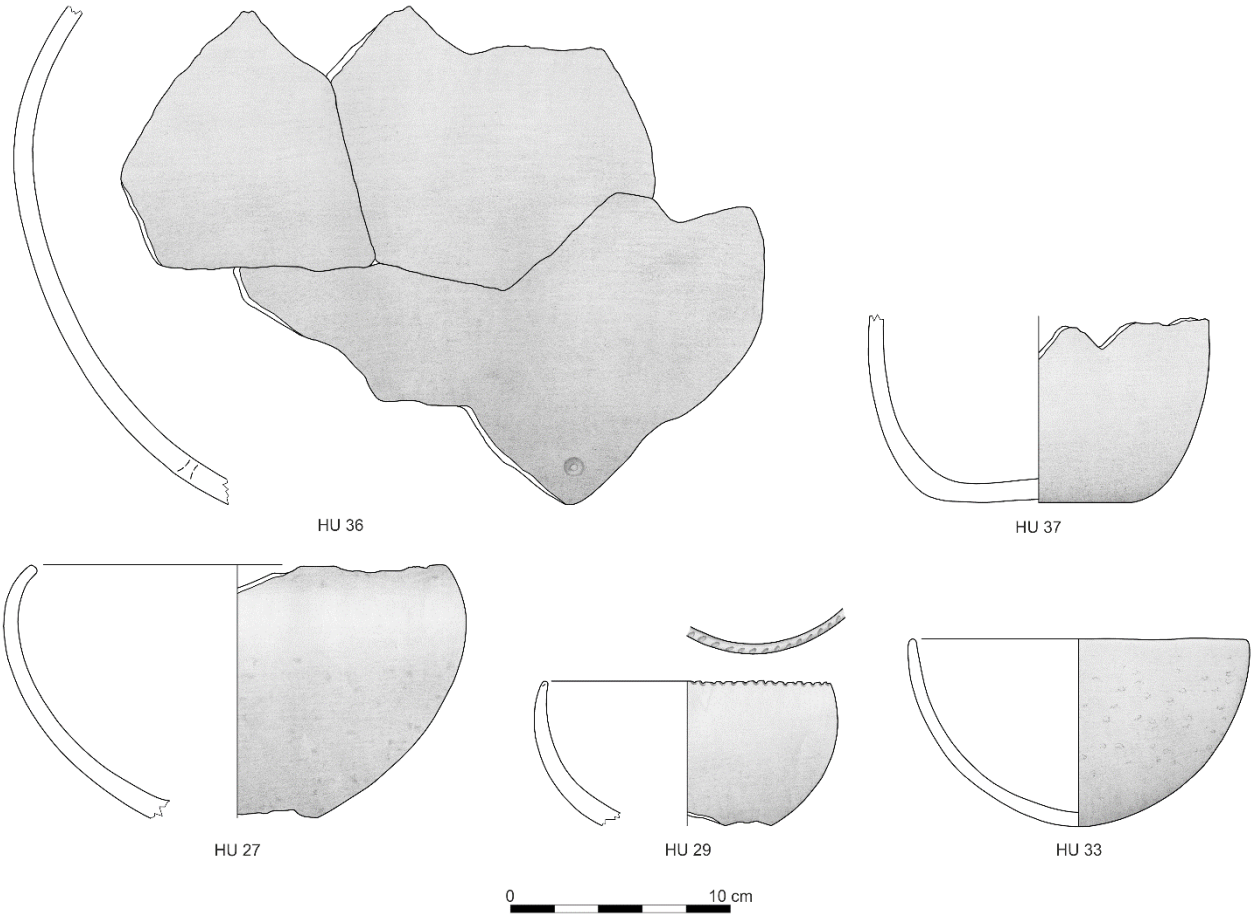


Fig. 7 Drawings of all the analysed pottery fragments from Hüde I. Scale 1:3. Drawings: M.A. Los-Weijns.

In order to identify ω-(o-alkylphenyl) alkanoic acids and isoprenoid fatty acids and to calculate the ratio of phytanic acid diastereomers, all samples (n = 37) were also analysed by using a DB23ms (50%-Cyanopropyl)-methylpolysiloxane column (60 m × 0.250 mm × 0.25 µm; J&W Scientific technologies, Folsom, CA, USA). Briefly, samples were re-dissolved in hexane and 1 µL was injected with a splitless injector at 300 °C. 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. The SIM (Selective Ion Monitoring) mode was used in order to target the specific markers - trimethyltridecanoic acid (TMTD), m/z 74, 88, 101, 312 for pristanic acid, m/z 74, 101, 171, 326 for phytanic acid and m/z 74, 105, 262, 290, 318, 346 for the detection of ω-(o-alkylphenyl)alkanoic acids of carbon lengths C 16 to C 22 (APAA 16-22). In addition, separation of the two phytanic acid diastereomers (3S,7R,11R,15-phytanic acid or SRR and 3R,7R,11R,15-phytanic acid or RRR) was obtained which enabled the calculation of the percentage of SRR in total phytanic acid (SRR%) by integrating the m/z 101 ion [48]. The carrier gas used was helium with a flow rate of 1.5 mL/min. 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)

All samples (n = 37) were analysed by GC-C-IRMS in duplicates based on the existing protocol[26], 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 ultra-inert-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 and raised by 25 °C/minute to 175 °C, then raised by 8 °C/minute to 325 °C. The temperature was then held at 325 °C for 20 min. Ultra-high-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 13C/12C ratio of each peak in the extracts.[27] 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 per mil (‰) 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 ± SD values of n-alkanoic acid esters were −31.65 ± 0.27‰ for the methyl ester of $C_{16:0}$ and −26.01 ± 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.

Elemental Analysis Isotope Ratio Mass Spectrometry (EA- IRMS)

A total of 21 carbonised surface deposit (foodcrust) samples, all coming from individual vessels, were collected and analysed. The samples were collected by scraping the food crust from the surface of the sherd with a sterilized scalpel at a sterile lab environment and were grounded to a homogeneous powder

[26] Craig et al. 2012.
[27] Heron et al. 2015.

level weighted out in duplicates into tin capsules (ca. 1mg). After the preparation, they were analysed by elemental analysis isotope ratio mass spectrometry. The values of bulk stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotopes were measured based on the methods described by Craig et al.[28] Precision of the instrument on repeated measurement was ±0.2‰ (standard error of the mean), $\delta^{13}C$, $\delta^{15}N = [(R_{sample}/ R_{standard} - 1)] \times 1000$, where $R = {}^{13}C/ {}^{12}C$ and ${}^{15}N/ {}^{14}N$. Accuracy was determined by measurements of international standard reference materials within each analytical run. These were IAEA 600 $\delta^{13}C_{raw} = -27.69 \pm 0.02$, $\delta^{13}C_{true} = -27.77 \pm 0.04$, $\delta^{15}N_{raw} = 1.49 \pm 0.38$, $\delta^{15}N_{true} = 1.0 \pm 0.2$; IAEA N2 $\delta^{15}N_{ra} = 20.9 \pm 0.33$, $\delta^{15}N_{true} = 20.3 \pm 0.2$; IA Cane, $\delta^{13}C_{raw} = -11.76 \pm 0.10$, $\delta^{13}C_{true} = -11.64 \pm 0.03$. Data were normalized to these international standards.

Results and Discussion

Lipid residue analysis

All samples (n = 37) yielded sufficient lipids required for interpretation (>5 μg g^{-1}) with a mean value of 374 μg g^{-1} (ranging from 74 μg g^{-1} to 956 μg g^{-1}) (Supplementary Dataset-1). In general, the lipid profiles obtained from each sample contained saturated fatty acids, ranging from $C_{10:0}$ to $C_{30:0}$. The main saturated fatty acids are the lauric ($C_{12:0}$), myristic ($C_{14:0}$), pentadecanoic ($C_{15:0}$), palmitic ($C_{16:0}$), margaric ($C_{17:0}$) and stearic ($C_{18:0}$) acids, maximizing at $C_{16:0}$ and $C_{18:0}$, respectively. The $C_{16:0}$ and $C_{18:0}$ ratios (P/S ratios) of all the samples are listed in the Supplementary Dataset-1. Thirty-three of all the samples yielded unsaturated fatty acids from $C_{11:1}$ to $C_{26:1}$, dominated by oleic ($C_{18:1}$) and palmitoleic ($C_{16:1}$) acid, respectively. Branched fatty acids (C_{11} - C_{29}) were also identified in all of the samples. Dicarboxylic acids are present in 32 samples, ranging from C_9 (azelaic acid) to C_{12}. A total of 32 samples yielded cholesterol and its derivatives, indicating the presence of animal fats. In all samples, traces of plasticizers were found, most likely deriving from packing materials. The levels of these were low and did not interfere with the analysis.

Evidence of aquatic biomarkers

Overall, many of the samples had biomarkers for aquatic products. Of 37 samples analysed, 20 yielded *ω*-(*o*-alkylphenyl) alkanoic acids (APAAs), with carbon atoms ranging from 18 to 22, and isoprenoid fatty acids which are TMTD (4,8,12-trimethyltridecanoic acid), pristanic acid (2,6,10,14-tetramethylpentadecanoic acid), and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid) (Supplementary Dataset-1). The co-occurrence of *ω*-(*o*-alkylphenyl) alkanoic acids (APAAs ranging from 18 to 22) and isoprenoid acids are an established criterion for identifying aquatic lipids in ancient

[28] Craig et al. 2007.

pottery[29]. Since APAAs are formed by heating (>270°, >17 h) of mono and polyunsaturated fatty acids, their presence confirms that they are derived from the use of the vessels.[30] A further six samples yielded partial aquatic biomarkers, containing C_{18} APAA and TMTD (Supplementary Dataset-1). This is also an indication of possible process of aquatic resources in these vessels[31], although not definitive. All these results confirm that aquatic products were regularly processed in the majority of Hüde I vessels.

Among the isoprenoid fatty acids, which are degradation products of phytol originating from phytoplankton, TMTD is considered more of a characteristic of aquatic oils[32], whereas pristanic and phytanic acids are present in both aquatic and ruminant resources.[33] We calculate the ratio of the two diastereomers of phytanic acid (3S,7R,11R,15-phytanic acid (SRR) and 3R,7R,11R,15-phytanic acid (RRR)) in order to understand the origin of the phytanic acid found in the samples. The SRR isomer tends to predominate in aquatic oils (>75.5% relative abundance) compared to ruminant fats.[34] Only 4 of our samples meet this criterion. Twenty samples have the SRR/RRR ratio below 75.5 % (ranging between 24.9% and 72.2%) falling within both the aquatic and ruminant range while the remaining 13 samples have no available SRR/RRR ratio.

To further investigate the sources of the lipids, the carbon stable isotope values of their palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids were examined for each sample (n = 37). Palmitic ($C_{16:0}$) and stearic($C_{18:0}$) fatty acids were used to distinguish lipids derived from ruminant meat and milk fats, following the approach of Evershed et al.[35] Dietary sources of these lipids are distinguished by characteristic $\delta^{13}C$ value ranges defined by $\delta^{13}C_{18:0}$ versus $\delta^{13}C_{16:0}$ values, as well as the isotopic difference between the two, $\Delta^{13}C_{18:0-16:0}$. The data from the samples (see in Supplementary Database-1) are plotted in Fig. 8 against the reference ranges which were adapted from authentic modern animal fats collected from Western Baltic. Overall, the $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids coming from the samples indicate a mixture of a wide range of foodstuffs including porcine, ruminant and dairy (Fig. 8A). Of all 37 samples, only three of the samples plot in the freshwater range. Considering that the majority of the samples have fully aquatic biomarkers, this may indicate a mixture of aquatic and ruminant animal fats in the Hüde I vessels.

The inland location of the site on the border of a freshwater lake supports the argument of these pots being used for exploitation and processing of freshwater resources. Fish account for ~6% of the total identified bones l at the site (n = 11,299).[36] While the freshwater fish species, pike, perch, bream, tench,

[29] Evershed et al. 2008a; Hansel et al. 2004; Craig et al. 2007; Cramp/Evershed 2014; Heron et al. 2015.
[30] Hansel et al. 2004; Craig et al. 2007
[31] Evershed et al. 2008a; Heron/Craig 2015.
[32] Ackman/Hooper 1968.
[33] Ackman/Hooper 1968; Heron/Craig 2015.
[34] Lucquin et al. 2016.
[35] Evershed et al. 2002a, 2002b, 2008b.
[36] Hüster 1983.

and pope, account for 74%, 18%, 5%, 1% and 0.09% of total fish remains, respectively (n = 1075)[37], eel, the only catadromous fish species found at the site, accounts for only 1%.[38] Catadromous fish species are migratory species which move down freshwater rivers to the sea only for spawning. If they are caught at the river mouths before entering the freshwater river systems, they would be expected to have marine carbon isotope signatures.[39] However, the eel bone remains coming from inland sites, caught in freshwater river systems proved to indicate carbon isotope values more consistent with freshwater residency or in between freshwater and marine carbon ranges.[40] Therefore, processing eel in these pots is also possible.

Evidence of ruminant adipose and ruminant dairy fats

Based on the molecular analysis, the presence and the results of the diastereomeric ratio (SRR/RRR ratio) of phytanic acid and the presence of branched chain C_{15} and C_{17} fatty acids found in some of the sherds are indicative of ruminant products (Supplementary Dataset-1).[41] In addition, fifteen samples have $\Delta^{13}C$ values lower than −1‰ (Fig. 8B), values typical for ruminant adipose fats.[42]

Zooarchaeological records from Hüde I present *Bos* sp. as the most dominant species at the site. It accounts for a total of 31% of identified mammal bones, n = 10,600).[43] This is followed by the presence of red deer, elk and roe deer (4.8%, 4.6% and 3.8% of identified mammal bones respectively, n = 10,600, excluding antler; respectively). Additionally, the high amount of waste material coming from antler tool production[44] indicates that deer was important to the economy at Hüde I and was used both as a meat and as a raw material for the manufacture of artefacts. Moreover, sheep/goats were also present at the site. Sheep and goat were not domesticated locally, as they are not native to the area.[45] Therefore, it is certain that these animals must have been introduced to the site from regions to the south, where animal husbandry and agriculture were already established.[46] While sheep/goat remains cover a relatively small percentage (0.6%, n = 10,600) of identified mammal bone material at the site, the few mandible fragments allows us to identify the presence of at least five individual specimens.[47]

[37] Hüster 1983.
[38] Hüster 1983.
[39] Robson et al. 2012, 2016.
[40] Robson et al. 2012.
[41] Regert 2011; Lucquin et al. 2016.
[42] Dudd et al. 1998; Evershed et al. 2002b; Copley et al. 2003; Craig et al. 2012.
[43] Hübner et al. 1988.
[44] Deichmuller 1965a.
[45] Luikart et al. 2001.
[46] Müller 1964; Piening 1998.
[47] Hübner et al. 1988.

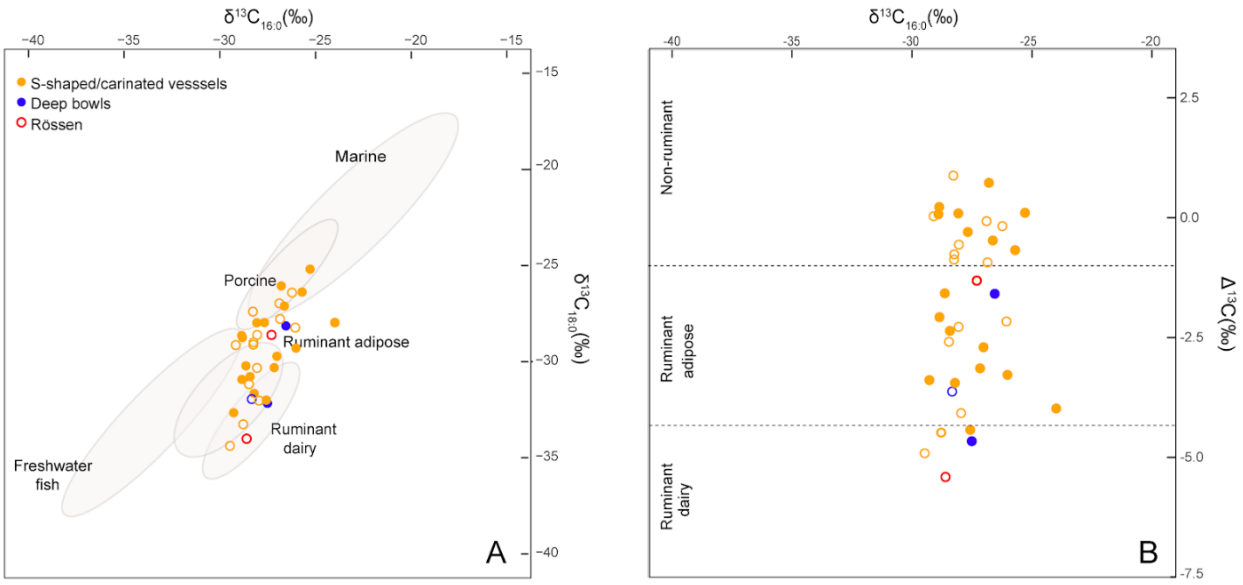


Fig. 8 (A) GC-C-IRMS results showing isotopic values of $C_{16:0}$ and $C_{18:0}$ fatty acids of Hüde I samples. S-shaped/carinated vessels (n = 34) are marked in yellow, deep bowls (n = 3) are in blue, and Rössen samples (n = 2) are in red. 95% confidence ellipses indicate areas of authentic reference values for each group of origins from Western Baltic, (B) Plot of $\Delta^{13}C$ ($\delta^{13}C_{18:0} - \delta^{13}C_{16:0}$ values) against $\delta^{13}C_{16:0}$ values of Hüde I pottery - collected from only ceramic matrices. Dotted lines indicate areas of authentic reference values for each group of origins from Western Baltic. Samples with the full set of aquatic biomarkers are shown by filled circles in both plots.

The lipid residue analysis helps us to understand the role that ruminant animals play in the subsistence strategy and the diet at Hüde I. Ruminant meat may have been processed and/or cooked in several different ways including roasting or grilling meat on open fire. However, based on our results of molecular and isotope analyses, we are able to confirm that ceramic vessels were one of the common ways of processing and/or cooking ruminant animal products at the site.

In addition, five of 37 samples have $\Delta^{13}C$ values below −4.3‰, the limit for wild ruminant carcass fats[48], meeting the widely accepted criteria for prehistoric dairy fats.[49] Reconciling the presence of dairy in the pots with the zooarchaeological assemblage is currently problematic due to the issues that come with the high fragmentation of the remains and the lack of up to date zooarchaeological analyses on the bone assemblage. Our current knowledge on the presence of domesticated cattle and sheep/goat at Hüde I comes from a relatively detailed but technologically limited osteological analysis.[50] Hübner[51] attests the presence of domesticated cattle solely based on the smaller size of few bone remains. However

[48] Craig et al. 2012.
[49] Copley et al. 2003; Evershed et al. 2008a; Debono Spiteri et al. 2016.
[50] Hübner et al. 1988.
[51] Hübner et al. 1988.

similar interpretations done at contemporaneous sites in northern Europe have been disputed.[52] The best-known example to this is the mtDNA analysis on a small number of presumed domesticated cattle remains from Rosenhof LA 58, reidentifying them as small individuals of aurochs that were present in the Late Mesolithic, in northern Germany.[53] Regarding the presence of sheep/goat, our current knowledge also does not go beyond the presence of few lower jaw fragments identified at the site. As a result, it is not possible to determine the presence of cattle at the site and whether these animals were kept for their meat or were also exploited for dairy products. Further analysis of the zooarchaeological remains with AMS ^{14}C dating, stable isotope, and palaeogenomic analyses is needed to address this issue.

Interestingly, ten out of the seventeen samples that plotted in the ruminant adipose range have fully aquatic biomarkers. In addition, two out of five samples in the dairy range also have fully aquatic biomarkers. This may indicate mixing of aquatic resources (freshwater fish) and ruminant carcass fats as well as dairy fats in these vessels. These results are consistent with the molecular and single compound isotope results.

Evidence of non-ruminant animal fats

The isotope data presented in Fig. 8B suggests that 16 of 37 samples yielded $\delta^{13}C$ values that match with non-ruminant terrestrial animals (i.e. wild boar /domesticated pig). Based on the faunal remains from Hüde I, *Sus* sp. is among the most abundant terrestrial animal species, covering 17.9% of the identified mammal remains at the site (n = 10,600).[54] Hübner[55] argues that domesticated pigs were present and have been subjected to fully developed pig farming and breeding activities carried out at the site. We are less certain because the identification of domesticated pig, similar to domesticated cattle, was solely based on the measurements of the few bone remains available.

Similar to the samples with ruminant adipose and ruminant dairy fats, samples with heavy porcine fats indicate a possible mixing with aquatic, mainly freshwater fish, resources as seven of them have fully aquatic biomarkers (Fig. 8B; Supplementary Dataset-1).

Evidence of food plant residues

[52] Kabaciński et al. 2009; Sørensen and Karg 2014;Schmölcke/ Nikulina 2015.
[53] Scheu et al. 2008.
[54] Hübner et al. 1988.
[55] Hübner et al. 1988.

Our analysis based on acid extraction does not indicate a clear evidence of processing food plants in any of the Hüde I vessels. As we have not undertaken further solvent extraction to identify cereal derived lipids in any of our samples from Hüde I, it is difficult to know whether any of the vessels analysed here were used for processing cereals at the site. However, as the recent studies done on plant lipids showed that plants contain substantially lower lipid concentrations than animal products, therefore animal fats may dominate the lipid extracts where vessels have been used to process both plant and animal products.[56] This makes it very difficult to detect them through lipid residue analysis. Therefore, we cannot exclude a possible food plant processing in any of our samples. Although, identifying plant lipids is not straightforward, 36 of the 37 samples yielded plant derived lipids such as campesterol (ergost-5-en-3b-ol) of which four of them also had traces of stigmasterol (stigmasta-5,22-dien-3b-ol) (Supplementary Dataset-1) indicating a possible contributions from food plants. Campesterol and stigmasterol are the most common steroids (phytosterols) in vascular plants[57] which is consistent with the vegetation at and around the site (see section 2).

Our knowledge on the cereals present at the site is primarily based on the three sherds with carbonised remains of cereals (i.e. naked barley and einkorn wheat); however these sherds were not accessible at the time of the research and therefore morphological and functional analyses on them were not possible. In addition, to our knowledge, no archaeobotanical analysis of the carbonised remains has been carried out. The pollen analysis[58] does not report any human impact on the vegetation or evidence for agricultural activities and provides scarce identification of cereal-type pollen at the site. Even if local cultivation was carried out, this comes as no surprise. In northern Germany, agriculture has been assumed to have started around 4,100 calBC with the arrival of Funnel Beaker culture to the region, but archaeobotanical evidence is reported to be scarce for the first 500 years of the Neolithic and the pollen grains of cereal-type and further evidence for human impact on the environment are only visible after 3,700 calBC.[59] Further residue analysis on the pottery, in conjunction with Scanning Electron Microscopy (SEM) analysis of carbonised surface deposits, is required to contribute to this topic.

Results of bulk stable isotope analysis by (EA- IRMS)

Twenty-one carbonised surface deposits (foodcrusts), found only on the S-shaped/carinated vessels, were analysed in order to measure the bulk carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope values with the aim of broadening our understanding of Hüde I pottery. Bulk stable isotope measurements obtained

[56] Colonese et al. 2017; Hammann/Cramp 2018.
[57] Baker 1982; Bianchi 1995.
[58] Schütrumpf 1988.
[59] Kirleis et al. 2012.

from carbonised surface deposits from our samples (n = 21) are plotted in Fig. 9 (also see Supplementary Dataset-1).

The bulk $\delta^{13}C$ isotope values of the Hüde I samples range from −22.0‰ to −27.3‰ (mean = −24.6‰) which is considered to represent C_3 plants and/or animals consuming C_3 plants, relatively depleted in ^{13}C. However, it is argued that these values are affected and can be altered by loss of proteinaceous material in the post-depositional environment in various degrees and therefore are difficult to interpret.[60] Nitrogen stable isotope ($\delta^{15}N$) values of protein that is available in the foodcrusts provides the information on the trophic level of different organisms processed in the pottery. $\delta^{15}N$ values that are above ca. +7.0/+9.0‰ are usually indicative of aquatic resources[61], whereas lower ones are more consistent with terrestrial organisms.[62] The $\delta^{15}N$ isotope values of the samples discussed in this study range from +5.4‰ to +8.7‰ (mean = 7.2‰), which are consistent with proteins from terrestrial herbivores, although the presence of fish, specifically anadromous species based on the low $\delta^{15}N$ isotope values, cannot be ruled out. The results of this analysis are consistent with molecular and single compound isotope analyses.

The C/N ratios may indicate the contribution of proteins versus lipids and/or other non-nitrogenous compounds such as carbohydrates. The low C/N ratios of the Hüde I samples, varying between 5.4 and 11.3, suggest that these foodcrusts were formed from the mixture of low lipid content and protein rich animal (both aquatic and terrestrial) tissues. This is again consistent with the results of our molecular and isotope analyses.

In addition, the offsets between averaged fatty acid $\delta^{13}C$ values ($\delta^{13}C_{16:0-18:0}$) and the corresponding bulk $\delta^{13}C$ values in foodcrusts from the same sherds ($\Delta^{13}C_{16:0-18:0}$−bulk $\delta^{13}C$) can be used as a tool to understand the composition of the foodcrusts. Small offsets and high C/N ratios generally indicate that the foodcrusts are mainly formed from fatty adipose tissues or aquatic oils, as both analytic techniques are measuring the $\delta^{13}C$ value of the lipid component. In contrast, foodcrusts derived from a higher proportion of protein-rich tissues, such as muscle tissues, would be expected to have a higher $\Delta^{13}C_{16:0-18:0}$−bulk offset as a result of mixing carbon from protein and fat which have the different isotope values.

All 21 of our foodcrust samples yielded a high offset varying between 0.13 and +7.28, C/N ratios between 5.4 and 11.3, and $\delta^{15}N$ values between +5.4 and +8.7 (Supplemental Dataset-1). These values may indicate that the foodcrusts consist of both aquatic oils and protein-rich tissues of animal products

[60] Craig et al. 2007, 2011, 2013; Heron et al. 2015; Heron/Craig 2015.
[61] Craig et al. 2013.
[62] Craig et al. 2007, 2011.

and/or plants. Although all these samples contained plant biomarkers (Supplemental Dataset-1), the C/N ratios are too low and the $\delta^{15}N$ values are too high to have a notable plant contribution.[63] Therefore, we suggest that our foodcrust data is indicative of mixing aquatic oil (from freshwater fish) and protein-rich tissues of animal products. This eliminates the oil production as a possible use of these vessels and demonstrates that they were used for food preparation/cooking activities.

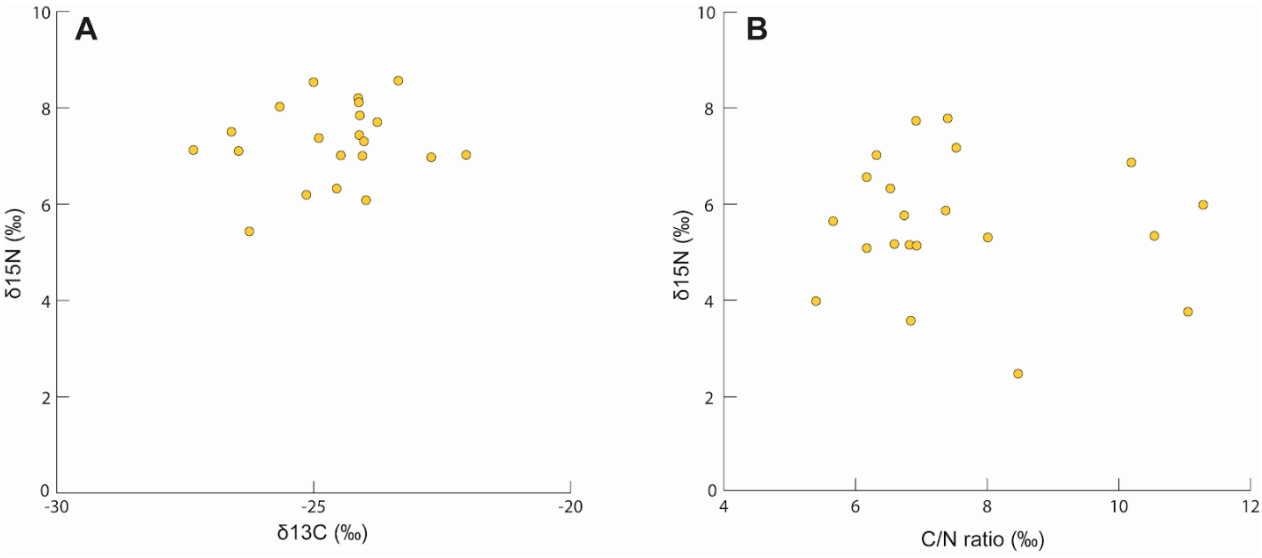


Fig. 9 (A) Bulk $\delta^{13}C$ and $\delta^{15}N$ data and (B) $\delta^{15}N$ and C/N ratio data of surface residues obtained from carbonised surface residues- collected from only S-shaped/carinated vessels of Hüde I.

Conclusion

Our results from lipid residue analysis of Hüde I vessels has shown that lipid residues are preserved in large quantities in the fabric of the vessel fragments studied, and that the origin of these lipids can be identified through the application of our chosen methodology. The results of the lipid residue analysis clearly show that Hüde I vessels were indeed directly associated with preparation, storing and/or cooking of foodstuffs included aquatic (freshwater) resources, terrestrial animals (both ruminant and non-ruminant) and dairy products as well as possibly food plants, although the latter requires further analysis. This is in agreement with the extensively analysed osteological assemblage from Hüde I which shows the presence of both aquatic and terrestrial animal resources at the site.

The results furthermore indicate that there is no clear functional differentiation in the sample of Hüde I vessels presented here. On the contrary, our study shows that both S-shaped/carinated vessels and deep bowls have been used for processing freshwater and terrestrial products regardless of vessel form, size,

[63] Bondetti et al. 2019.

or decoration. Traces of dairy products also appear in both vessel types. It is important to note here that the small number of deep bowls sampled in this study may not be representative of the whole assemblage and therefore should be addressed in a future analytical work on the pottery from Hüde I. It is difficult to correlate the use of Hüde I pottery to the occupation history of the site due to its problematic stratigraphy. However, the consistency of the results of lipid residue analysis lends weight to the fact that vessels had a similar function throughout its occupation span.

Regarding the two Rössen pots, our results indicate that while one of these vessels (HU30) was used processing ruminant meat, the other one (HU26) was heavily used for processing dairy products (Fig. 3A and 3B). This is consistent with the mixed agricultural practices of Rössen culture in which domesticated animals were part of the main economy and were probably kept both for their meat and milk.[64] Whether this also holds true for Hüde I is uncertain, due to the limited zooarchaeological analysis.

A recent study done by Cubas et al.[65] indicated that there is a very clear difference in pottery use between the last hunter-gatherers and the first agrarian communities in western Europe but there is clear continuity across the transition in parts of northern Europe.[66] However, the early farming pottery from southern and southwestern Europe demonstrates a major focus on processing terrestrial animal and dairy products with a total lack of aquatic resources.[67] Interestingly, our results contradict with this. Two of five dairy samples indicate a mixture of dairy and freshwater fish signal. Hence, even though we do not know the phasing of these vessels, we can eliminate the possibility that fishing was totally replaced with pastoralism as in southern and southwestern Europe.

For further clarification concerning the problem of correlating the pottery use to the occupation history of Hüde I, further methodological work focusing on the combination of different analyses such as scanning electron microscope (SEM) analysis, petrographic analysis and accelerator mass spectrometry (AMS) ^{14}C dating is required. SEM analysis on the carbonised surface deposits is a highly valued methodology to examine the charred plant and cereal residues possibly preserved in the crusts through the cooking process.[68] As detecting plant biomarkers through lipid residue analysis is challenging due to their low lipid content, SEM analysis is needed to further advance our understanding of whether food plants had a role in the use of pottery and if they did what kind of plants were processed in the Hüde I vessels. Furthermore, the Hüde I vessels need to be examined through petrographic analysis in order to

[64] Lüning 2000.
[65] Cubas et al. 2020.
[66] Craig et al. 2007.
[67] Cubas et al. 2020.
[68] e.g. Raemaekers et al. 2013.

determine the origin of these vessels. Although Drews[69] applied this method to a selection of sherds collected from Hüde I and its surroundings, the information provided is very limited, and the material requires a more detailed analysis. Understanding the origin of these vessels would allow us to possibly identify the different cultural groups present at Hüde I as well as to question the human mobility and/or interaction between different groups in the region. Finally, as there is a clear chronological association between the occupation of the site and the pottery, direct ^{14}C dates of food crusts and/or organic temper (e.g. moss[70]) of the pottery would allow us to correlate the pottery to specific occupational phases of Hüde I. Direct dating of food crusts should be targeted on samples without aquatic biomarkers in order to avoid freshwater reservoir effect on the pottery.[71]

Acknowledgement

This project is part of a Marie Sklodowska-Curie European Joint Doctoral Training Program, funded by the European Union's EU Framework program for Research and Innovation Horizon 2020 under the Grant Agreement No 676154 (ArchSci2020 program). Special thanks to Landesmuseum Hannover staff for their collaboration and help during the sample selection stage. We would like to thank Sander Tiebackx (Groningen Institute of Archaeology) who produced the map for Fig.1-2 and Miriam A. Los-Weijns (Groningen Institute of Archaeology) for the pottery illustrations in Fig. 3-7. We thank Helen Talbot and Matthew Von Tersch for their assistance with aspects of laboratory work. Finally, we also thank the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (The Innovation, Dispersal and Use of Ceramics in NE Europe, grant agreement no 695539).

[69] Drews 1977.
[70] see Teetaert et al. 2020.
[71] Fischer/Heinemeier 2003; Philippsen 2013.

References

Ackman / Hooper 1968:

R. G. Ackman / N. S. Hooper, Examination of isoprenoid fatty acids as distinguishing characteristics of specific marine oils with particular reference to whale oils. *Comp Biochem Physiol, 24,* 1968, 549-565.

Andersen 2010:

S. H. Andersen, The first pottery in South Scandinavia. In: B. Vanmontfort / L. Louwe Kooijmans, / L. Amkreutz / L. Verhart, (eds.), *Pots, Farmers and Foragers: How Pottery Traditions Shed a Light on Social Interaction in the Earliest Neolithic of the Lower Rhine Area,* (Leiden 2010) 167-176.

Baker 1982:

E. A. Baker, Chemistry and morphology of plant epicuticular waxes. In: D. F. Cutler / K. L. Alvin / C.E. Price (eds), *The Plant Cuticle. Linn. Soc. Symp. Ser. 10*, (London 1982) 139-165.

Bianchi 1995:

G. Bianchi, Plant waxes. In: R.J. Hamilton (ed.), *Waxes: Chemistry, Molecular Biology and Functions.* (Dundee 1995) 175-222.

Boessneck 1978:

J. Boessneck, Die Vogelknochen aus der neolithischen Moor-siedlung Hüde I am Dümmer, Kreis Grafschaft Diepholz, *Neue Ausgrabungen und Forschungen in Niedersachsen, 12*, 1978, 155-169

Bogucki / Grygiel 1993:

P. Bogucki / R. Grygiel, The First Farmers of Central Europe: A Survey Article. *Journal of Field Archaeology*, *20*(4), 399-426.

Bondetti et al. 2019:

M. Bondetti / S. Scott / A. Lucquin / J. Meadows / O. Lozovskaya / E. Dolbunova / P. Jordan / O. E. Craig, Fruits, fish and the introduction of pottery in the Eastern European plain: Lipid residue analysis of ceramic vessels from Zamostje 2. *Quaternary International: The Journal of the International Union for Quaternary Research*.
https://doi.org/10.1016/j.quaint.2019.05.008.

Casanova et al. 2020:

E. Casanova / R.-M. Arbogast / A. Denaire / C. Jeunesse /P. Lefranc / R. P. Evershed, Spatial and temporal disparities in human subsistence in the Neolithic Rhineland gateway. *Journal of Archaeological Science*, *122*, 2020, 105215.

Colonese et al. 2017:

A. C. Colonese / A. Lucquin / E. P. Guedes / R. Thomas/J. Best / B. T. Fothergill / N. Sykes / A. Foster / H. Miller / K. Poole / M. Maltby / M. Von Tersch / O. E. Craig, The identification of poultry processing in archaeological ceramic vessels using in-situ isotope references for organic residue analysis. *Journal of Archaeological Science, 78*, 2017, 179-192.

Copley et al. 2003:

M. S. Copley / R. Berstan / S. N. Dudd / G. Docherty / A. J. Mukherjee / V. Straker / S. Payne/ R. P. Evershed, Direct chemical evidence for widespread dairying in prehistoric Britain. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(4), 1524–1529.

Copley et al. 2005:

M. S. Copley / R. Berstan, / A. J. Mukherjee / S. N. Dudd / V. Straker / S. Payne / R. P. Evershed, Dairying in antiquity. III. Evidence from absorbed lipid residues dating to the British Neolithic. *Journal of Archaeological Science*, *32*(4), 2005, 523-546.

Craig et al. 2005:

O. E. Craig / G. Taylor / J. Mulville / M. J. Collins / M. Parker Pearson, The identification of prehistoric dairying activities in the Western Isles of Scotland: an integrated biomolecular approach. *Journal of Archaeological Science*, *32*(1), 2005, 91-103.

Craig et al. 2007:

O. E. Craig / M. Forster / S. H. Andersen/ E. Koch / P. Crombé / N. J. Milner / B. Stern / G. N. Bailey / C. P. Heron, Molecular and Isotopic Demonstration of the Processing of Aquatic Products in Northern European Prehistoric Pottery. *Archaeometry, 49*(1), 2007, 135-152.

Craig et al. 2012:

O. E. Craig / R. B. Allen / A. Thompson / R. E. Stevens / V. J. Steele / C. Heron, Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. *RapidCommunications in Mass Spectrometry: RCM, 26*(19), 2012, 2359-2364.

Craig et al. 2013:

O. E. Craig / H. Saul / A. Lucquin / Y. Nishida / K. Taché / L. Clarke / A. Thompson / D. T. Altoft / J. Uchiyama / M. Ajimoto / K. Gibbs / S. Isaksson / C. P. Heron / P. Jordan, Earliest evidence for the use of pottery. *Nature, 496*(7445), 2013, 351-354.

Cramp / Evershed 2014:

L. J. E. Cramp / R. P. Evershed, Reconstructing Aquatic Resource Exploitation in Human Prehistory Using Lipid Biomarkers and Stable Isotopes. In: H. D. Holland / K. K. Turekian (eds.), *Treatise on Geochemistry (second edition)*, (Oxford 2014) 319-339.

Cubas et al. 2020:

M. Cubas / A. Lucquin / H. K. Robson / A. C. Colonese / P. Arias / B. Aubry / C. Billard / D. Jan / M. Diniz / R. Fernandes / R. Fábregas Valcarce / C. Germain-Vallée / L. Juhel / A. de Lombera-Hermida / C. Marcigny / S. Mazet / G. Marchand / C. Neves / R. Ontañón-Peredo / X. P. Rodriguez Alvarez / T. Simoes / J. Zilhao / O. E. Craig, Latitudinal gradient in dairy production with the introduction of farming in Atlantic Europe. *Nature Communications, 11*(1), 2020, 2036.

Czekaj-Zastawny et al. 2013:

A. Czekaj-Zastawny / J. Kabaciński / T. Terberger / J. Ilkiewicz, Relations of Mesolithic hunter-gatherers of Pomerania (Poland) with Neolithic cultures of central Europe. *Journal of Field Archaeology, 38*(3), 2013, 195-209.

Çakırlar et al. 2020:

C. Çakırlar / R. Breider / F. Koolstra / K. M. Cohen / D.C.M. Raemaekers, Dealing with domestic animals in the 5th millennium cal BC Dutch wetlands: new insights from old Swifterbant assemblages. In: K. J. Gron / L. Sørensen / P. Rowley-Conwy (eds). *Farmers at the Frontier: A Pan-European Perspective on Neolithisation,* (Oxford 2020) 263-287.

Debono Spiteri. et al. 2016:

C. Debono Spiteri / R. E. Gillis / M. Roffet-Salque / L. C. Navarro / J. Guilaine / C. Manen / I. M. Muntoni / M. S. Segui / D. Urem-Kotsou / H. L. Whelton /O. E. Craig / J.D. Vigne / R. P. Evershed, Regional asynchronicity in dairy production and processing in early farming communities of the northern Mediterranean. *Proceedings of the National Academy of Sciences, 113*(48), 2016, 13594-13599.

Deichmüller 1964:

J. Deichmüller, Dümmer-Grabung 1963, *Nachrichten aus Niedersachsens Urgeschichte, 33*, 1964, 69-73.

Deichmüller 1965a:

J. Deichmüller, Die neolithsiche Moorsiedlung Hüde I am Dümmer. Kreis Grafschaft Diepholz Vorläufiger Bericht über die Grabungen 1962-1964, *Neue Ausgrabungen und Forschungen in Niedersachsen, 2*, 1865, 1-18.

Deichmüller 1965b:

J. Deichmüller, Eine Rössener stilvariant am Dümmer, *Ger- mania, 43*, 1965, 334-343

Deichmüller 1968:

J. Deichmüller, Die neolithische Moorsiedlung Hüde I. Abschlußbericht, *Nachrichten aus Niedersachsens Urgeschichte, 37*, 1965, 106-110.

Deichmüller 1969:

J. Deichmüller, Die neolithische Moorsiedlung Hüde I am Dümmer. Vorläufiger Abschlußbericht, *Neue Ausgrabungen und Forschungen in Niedersachsen, 4*, 1969, 28-36.

De Roever 2004:

J. P. de Roever, *Swifterbant-aardewerk. Een analyse van de neolithische nederzettingen bij Swifterbant, 5e millennium voor Chr.* Dissertation Groningen University (Groningen 2004).

Drew 1977:

G. Drews, Geochemische Klassifizierung und Lokalisierung keramischer Bodenfunde, *Jahrbuch Römisch Germanisch Zentral-museum zu Mainz, 23/24*, 1977, 229-249.

Dudd et al. 1998:

S. N. Dudd / M. Regert / R. P. Evershed, Assessing microbial lipid contributions during laboratory degradations of fats and oils and pure triacylglycerols absorbed in ceramic potsherds. *Org. Geochem., 29*(5-7), 1998, 1345-1354.

Evershed et al. 1997:

R. P. Evershed / H. R. Mottram / S. N. Dudd / S. Charters / A. W. Stott / G. J. Lawrence / A. M. Gibson / A. Conner / P. W. Blinkhorn / V. Reeves, New Criteria for the Identification of

Animal Fats Preserved in Archaeological Pottery. *Die Naturwissenschaften, 84*(9), 1997, 402-406.

Evershed et al. 2002a:

R. P. Evershed / S. N. Dudd / M. S. Copley / R. Berstan / A. W. Stott / H. Mottram / S. A. Buckley / Z. Crossman, Chemistry of archaeological animal fats. *Accounts of Chemical Research, 35*(8), 2002, 660-668.

Evershed et al. 2002b:

R. P. Evershed / S. N. Dudd / M. S. Copley / A. J. Mukherjee, Identification of animal fats via compound specific δ13C values of individual fatty acids: assessments of results for reference fats and lipid extracts of archaeological pottery vessels. *Documenta Praehistorica, 21*, 2002, 73-96.

Evershed et al. 2008a:

R. P. Evershed / M. S. Copley / L. Dickson / F. A. Hansel, Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. *Archaeometry, 50* (1), 2008, 101-113.

Evershed et al. 2008b:

R. P. Evershed / S.Payne / A. G. Sherratt / M. S. Copley / J. Coolidge / D. Urem-Kotsu / K. Kotsakis / M. Özdoğan / A. E. Özdoğan / O. Nieuwenhuyse / P. M. M. G. Akkermans / D. Bailey / R. R.Andeescu /S. Campbell / S. Farid / I. Hodder / N. Yalman / M. Özbaşaran / E. Bıçakçı / Y. Garfinkel / T. Levy / M. M. Burton, Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding. *Nature, 455*(7212), 2008, 528-531.

Fischer 1982:

A. Fischer, Trade in Danubian Shaft-Hole Axes and the Introduction of Neolithic Economy in Denmark. *Journal of Danish Archaeology*, *1*(1), 7–12.

Fischer 2002:

A. Fischer, Food for Feasting? An evaluation of explanations of the neolithisation of Denmark and southern Sweden. In: A. Fischer / K. Kristiansen (eds.), *The Neolithisation of Denmark: 150 Years of Debate,* (Sheffield 2002) 343-393.

Fischer / Heinemeier 2003:

A. Fischer / J. Heinemeier, Freshwater reservoir effect in 14C dates of food residue on pottery. *Radiocarbon, 45*, 2003, 449-466.

Hanmann / Cramp 2018:

S. Hammann / L. J. E. Cramp, Towards the detection of dietary cereal processing through absorbed lipid biomarkers in archaeological pottery. *Journal of Archaeological Science, 93*, 2018, 74-81

Hansel et al. 2004:

F. A. Hansel / M. S. Copley / L. A. S. Madureira / R. P. Evershed, Thermally produced ω-(o-alkylphenyl) alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. *Tetrahedron Letters, 14*(45), 2004, 2999-3002.

Hartz / Lübke 2006:

S. Hartz / H. Lübke, New Evidence for a Chronostratigraphic Division of the Ertebølle Culture and the Earliest Funnel Beaker Culture on the Southern Mecklenburg Bay. In: C. J. Kind (ed.), *After the ice age. Settlement, subsistence and social development in the Mesolithic of Central Europe,* (Stuttgart 2006) 59-74.

Heron / Craig 2015:

C. Heron / O. E. Craig, Aquatic Resources in Foodcrusts: Identification and Implication. *Radiocarbon, 57*(4), 2015, 707-719.

Heron et al. 2015:

C. Heron / O. E. Craig / A. Luquin / V. J. Steele / A. Thompson / G. Piličiauskas, Cooking fish and drinking milk? Patterns in pottery use in the southeastern Baltic, 3300-2400 cal BC. *Journal of Archaeological Science, 63*, 2015, 33-43.

Hopf 1981:

M. Hopf, Die Planzenreste aus Schernau, Ldkr. Kitzingen, In: J. Lüning (ed.), *Eine Siedlung der Mittelneolitischen Gruppe Bischheim in Schernau,* Ldkr. Kitzingen, Kallmünz (Materialhefte zur Bayerischen Vorgeschichte. Reihe A, Fundinventare und Ausgrabungsbefunde 44), (1981) 152-160.

Hübner et al. 1988

K. O. Hübner / R. Saur / H. Reichstein, Die Säugetierknoche der neolithischen Seeufersiedlung Hüde I am Dümmer, LKr. Diepholz, Niedersachsen. In: G. Jacob-Friesen (ed.), *Palynologische und säugetierkundliche Untersuchungen zum Siedlungsplatz Hüde I am Dümmer*, LKr. Diepholz (= Göttinger Schriften zur Vor- und Frühgeschichte 23), (1988) 35-133.

Hüster 1983:

H. Hüster, *Die Fischknochen der neolithischen Moorsiedlung Hüde I am Dümmer*, Kreis Grafschaft Diepholz, Neue Ausgrabungen und Forschungen in Niedersachsen. Neue Ausgrabungen und Forschungen in Niedersachsen 16, (1983) 401-480.

Kabaciński / Heinrich / Terberger 2009:

J. Kabaciński / D. Heinrich / T. Terberger, Dąbki revisited. New evidence on the question of earliest cattle use in Pomerania. In: McCartan S, Schulting R, Warren G, Woodman P. (eds.). *Mesolithic Horizons,* (Oxford 2009) 548-555.

Kampffmeyer 1991:

U. Kampffmeyer, *Die Keramik der Siedlung Hüde I am Dümmer. Untersuchungen zur Neolithisierung der nordwestdeutschen Flachlands*.Dissertation, Göttingen University (Göttingen 1991).

Kirleis et al. 2012:

W. Kirleis / S. Klooß / H. Kroll / J. Müller, Crop growing and gathering in the northern German Neolithic: a review supplemented by new results. *Vegetation History and Archaeobotany*, *21*(3), 221–242.

Lucquin et al. 2016:

A. Lucquin / A. C. Colonese / T. F. G. Farrell / O. E. Craig, Utilising phytanic acid diastereomers for the characterisation of archaeological lipid residues in pottery samples. *Tetrahedron Letters, 57*(6), 2016, 703-707.

Lucquin et al. 2018:

A. Lucquin / H. K. Robson / Y. Eley / S. Shoda / D. Veltcheva / K. Gibbs / C. P. Heron / S. Isaksson / Y. Nishida / Y. Taniguchi / S. Nakajima / K. Kobayashi / P. Jordan / S. Kaner / O. E. Craig, The impact of environmental change on the use of early pottery by East Asian

hunter-gatherers. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(31), 7931–7936.

Luikart et al. 2001:

G. Luikart / L. Gielly / L. Excoffier / J. D. Vigne / J. Bouvet / P. Taberlet, Multiple maternal origins and weak phylogeographic structure in domestic goats. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(10), 5927-5932.

Lüning 2000:

J. Lüning, *Steinzeitliche Bauern in Deutschland - die Landwirtschaft im Neolithikum.* Universitätsforschungen zur prähistorischen Archäologie 58 (Bonn 2000).

Müller 2008:

J. Müller, Early pottery in the North - a southern perspective. *Bericht Der RomischGermanischen Kommission, 89*, 2008, 287-299.

Nösler et al. 2011:

D. Nösler / A. Kramer / H. Jöns / K. Gerken / F. Bittmann, Aktuelle Forschungen zur Besiedlung und Landnutzung zur Zeit der Trichterbecher- und Einzelgrabkultur in Nordwestdeutschland –ein Vorbericht zum DFG-SPP "Monumentalität". *Nachr Nieders Urgesch, 80*, 2011, 23-45.

Out 2008:

W. A. Out, Growing habits? Delayed introduction of crop cultivation at marginal Neolithic wetland sites. *Vegetation History and Archaeobotany, 17*(1), 2008, 131-138.

Out 2009:

W. A. Out, *Sowing the Seed: Human impact and plant subsistence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC).* Dissertation, Leiden University (Leiden 2009).

Pääkkönen et al. 2020:

M. Pääkkönen / R. P. Evershed / H. Asplund, Compound-specific stable carbon isotope values of fatty acids in modern aquatic and terrestrial animals from the Baltic Sea and Finland as an aid to interpretations of the origins of organic residues preserved in archaeological pottery. *Journal of Nordic Archaeological Science 19*, 2020.

Papakosta et al. 2015:

V. Papakosta / R. H. Smittenberg / K. Gibbs / P. Jordan / S. Isaksson, Extraction and derivatization of absorbed lipid residues from very small and very old samples of ceramic potsherds for molecular analysis by gas chromatography--mass spectrometry (GC--MS) and single compound stable carbon isotope analysis by gas chromatography--combustion--isotope ratio mass spectrometry (GC--C--IRMS). *Microchemical Journal, Devoted to the Application of Microtechniques in All Branches of Science, 123*, 2015, 196-200.

Philippsen 2013:

B. Philippsen, The freshwater reservoir effect in radiocarbon dating. *Heritage Science, 1*, 2013, 24. https://doi.org/10.1186/2050-7445-1-24.

Piening 1998:

U. Piening, Die Pflanzenreste aus Gruben der Linearbandkeramik und der Rössener Kultur von Ditzingen, Kr. Ludwigsburg. *Fundberichte Aus Baden-Württemberg, 22*(1), 1998, 125-160.

Povlsen 2014:

K. Povlsen, The introduction of ceramics in the Ertebølle Culture. *Danish Journal of Archaeology, 2*(2), 2014, 146-163.

Raemaekers 1999:

D. C. M. Raemaekers, *The articulation of a "New Neolithic".* Dissertation, Leiden University (Leiden 1999).

Raemaekers 2005:

D. C. M. Raemaekers, An outline of Late Swifterbant pottery in the Noordoostpolder (province of Flevoland, the Netherlands) and the chronological development of the pottery of the Swifterbant culture, *Palaeohistoria*, *45/46*, 2005, 11-36.

Raemaekers 2011:

D. C. M. Raemaekers, Early Swifterbant pottery (5000-4600 BC): research history, age, characteristics and the introduction of pottery. *Berichte Römisch-Germanische Kommission, 89*, 2011, 485-500.

Raemaekers et al. 2011:

D. C. M. Raemaekers /J. Geuverink / M. Schepers / B. P. Tuin / E. de Van Lagemaat / M. der Van Wal, *A biography in stone: Typology, age, function and meaning of Early Neolithic perforated wedges in the Netherlands (14 ed.),* (Groningen 2011).

Raemaekers et al. 2013:

D. C. M. Raemaekers / L. Kubiak-Martens / T. F. M. Oudemans, New food in old pots - charred organic residues in Early Neolithic ceramic vessels from Swifterbant, the Netherlands (4300-4000 cal BC). *Archäologisches Korrespondenzblatt, 43*(3), 2013, 315-334.

Regert 2011:

M. Regert, Analytical strategies for discriminating archeological fatty substances from animal origin. *Mass Spectrom. Rev., 30,* 2011, 177-220.

Robson et al. 2012:

H. K. Robson / S. H. Andersen / O. E. Craig / A. Fischer / A. Glykou / S. Hartz / H. Lübke / U. Schmölcke / C. Heron, Carbon and nitrogen isotope signals in eel bone collagen from Mesolithic and Neolithic sites in northern Europe. *Journal of Archaeological Science, 39*(7), 2012, 2003-2011.

Robson et al. 2016:

H. K. Robson / S. H. Andersen / L. Clarke / O. E. Craig / K. J. Gron / A. K. G. Jones / P. Karsten / N. Milner / T. D. Price / K. Ritchie / M. Zabilska-Kunek / C. Heron, Carbon and nitrogen stable isotope values in freshwater, brackish and marine fish bone collagen from Mesolithic and Neolithic sites in central and northern Europe. *Environmental Archaeology, 21*(2), 2016, 105-118.

Scheu et al.2008:

A. Scheu / S. Hartz / U. Schmölcke / A. Tresset / J. Burger / R. Bollongino, Ancient DNA provides no evidence for independent domestication of cattle in Mesolithic Rosenhof, Northern Germany. *Journal of Archaeological Science, 35*(5), 2008, 1257-1264.

Schmölcke / Nikulina 2015:

U. Schmölcke / E. A. Nikulina, Mesolithic beaver hunting station or base camp of supra-regional Stone Age fur trade? New archaeozoological and archaeogenetic results from Dąbki 9 (Pomerania, Poland). In: J. Kabaciński / S. Hartz / D. C. M. Raemaekers / T. Terberger

(eds.). *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000–3000 calBC), (*Rahden/Westf. 2015) 65-86.

Schütrumpf 1988:

R. Schütrumpf, Moorgeologisch-pollenanalytische Untersuchungen zu der neolithischen Moorsiedlung Hüde I, Landkreis Diepholz/Niedersachsen, *Göttinger Schriften zur Vor- und Frühgeschichte der Georg-August-Universität, 23*, 1988, 9-33.

Schwabedissen 1967:

H. Schwabedissen, Ein horizontierter "Breitkeil" aus Satrup und die mannigfachen Kulturverbindungen des beginnenden Neolithikums im Norden und Nordwesten. *Palaeohistoria, 12*, 1991, 409-468.

Stapel 1991:

B. Stapel, *Die geschlagene Steingeräte der Siedlung Hüde I am Dümmer* (= Veröffentlichen der Urgeschichtlichen Sammlungen des Landesmuseum zu Hannover 38) (Honnover 1991).

Sørensen / Karg 2014:

L. Sørensen / S. Karg, The expansion of agrarian societies towards the north – new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. *Journal of Archaeological Science, 51*, 2014, 98-114.

Teetaert et al. 2020:

D. Teetaert / M. Boudin / E. Goemaere / P. Crombé, Reliability of AMS 14C dates of moss temper preserved in Neolithic pottery from the Scheldt River Valley (Belgium). *Radiocarbon*, 2020, 1-12.

Terberger et al. 2009:

T. Terberger / S. Hartz / J. Kabaciński, Late hunter-gatherer and early farmer contacts in the southern Baltic - a discussion. In: H. Glørstad / C. Prescott (eds.). *Neolithisation as if history mattered: process of neolithisation in North-Western Europe*, (Uddevalla 2009) 257-298.

Verhart 2012:

L.B.M. Verhart, Contact in stone: adzes, Keile and Spitzhauen in the Lower Rhine Basin: Neolithic stone tools and the transition from Mesolithic to Neolithic in Belgium and the Netherlands, 5300-4000 cal BC, *Journal of Archaeology in the Low Countries, 4*, 2012, 5-35.

Authors' contributions (%)

Özge Demirci:

Conceptualization	98%
Formal analysis (lab work)	100%
Investigation (data analysis)	95%
Visualization of data	100% (also see Acknowledgements)
Writing - original draft	100%
Writing - review & editing	90%

Alexandre Lucquin:

Investigation (data analysis)	5%

Florian Klimscha:

Resources (material access)	50%
Writing - review & editing	1%

Oliver E. Craig:

Methodology	100%
Resources (lab access)	50%
Validation	50%
Supervision	40%
Project administration	50%
Funding acquisition	50%
Writing - review & editing	5%

Daan C. M. Raemaekers:

Conceptualization	2%
Validation	50%
Supervision	60%
Project administration	50%
Funding acquisition	50%
Writing - review & editing	4%

All authors gave their final approval for publication.

SUPPLEMENTARY MATERIAL

(DATASET-1)

for

Lipid residue analysis of ceramics from Hüde I (Lower Saxony, Germany) stresses the research potential to understand the transition to farming

Özge Demirci, Alexandre Lucquin, Florian Klimscha, Oliver E. Craig, Daan C.M. Raemaekers

Supplementary Dataset -1: Sampled pottery information

**The sample selection was based on the morphological and decorative variability of the pottery fragments available to us at the time of the research, therefore it is not representative for the whole Hüde I pottery assemblage.
*Based on the complete drawing of the pot in Kampffmeyer 1991: Table 5 (554).

sample ID	Find number	Pre-treatment	Site	Region	Location	Site type	Vessel type	Vessel form	Vessel part	Decoration	other features	Rim diameter (cm)	Weight (mm)	Wall thickness (mm)	Main temper material
HU-01	31206	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		20	123.7	10	grit-sand
HU-02	31840 (3A)	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no	knob	15	87.7	9	sand??
HU-03	30655	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	base	no			200.9	8	fine sand / grit
HU-04	31233	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	base	no			172.2	9	grit-sand //quartz
HU-05	31145a	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		26	104.5	6	grit (granite)
HU-06	31145b	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	base	no			101.6	6	grit (granite)
HU-07	30984	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			96.6	7	grit-sand?
HU-08	31176	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		17.5	107.9	8	grit-sand
HU-09	31224/ 13224	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		28	122.4	11	grit-sand
HU-10	31029/31426	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		15	194.8	8	grit
HU-11	30996	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		>20/25	166.4	9	flint
HU-12	30974	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes			141.2	8	grit? quartz
HU-13	31359	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no	handle		45.7	8	grit-sand
HU-14	30979c	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes			30.1	8	grit-sand
HU-15	30979a	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			52.3	7	grit-sand
HU-16	30985	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		19	56.8	7	flint // granite?
HU-17	30972	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		26	274.1	8	grit-sand (granite)
HU-18	30997	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes	handle	31/32	175.7	9	grit-sand
HU-19	31157	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no	knob		127.7	6	sand?
HU-20	31273	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no	handle		99.5	5	grit-sand?
HU-21	30959 a+b	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		27	78.6	9	grit (granite)
HU-22	9125A	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	yes	knob		19.7	7	grit-sand?
HU-23	9258	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		~20	179	9	grit-sand
HU-24	9452	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			89.5	11	grit (granite)
HU-25	4532	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			161.3	10	flint // grit - quartz?
HU-26	3002+30352	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim/body	yes		17.5	19	6	grog??
HU-27	29191	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	Deep bowl	rim	yes		23	131.9	8	grog // grit-sand?
HU-28	22900	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	no		14-15	61.9	8	grit
HU-29	30669	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	Deep bowl	rim	yes		11	90.6	9	sand?
HU-30	30732	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body/base	yes		10*	130.1	6	grit-sand
HU-31	30727	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	base	no			84.2	7	sand
HU-32	29928	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		29/30	198	8	flint // quartz?
HU-33	28742	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	Deep bowl	rim	no		>20	225	7	grit? quartz
HU-34	22522/22552/25649	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	rim	yes		25	139.9	6	grit
HU-35	30644	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			89.7	8	grit
HU-36	29937	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	body	no			186.2	8	grit-sand
HU-37	30733	AE	Hüde I	Lower Saxony	Inland	Waterlogged settlement site	Cooking pot	S-shaped/carinated vessel	base (flat)	no			135	7	flint? grit?

Supplementary Dataset -1: Results of organic residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Partially aquatic	Other identified lipid markers
HU-01	Pot sherd	Internal	803	1.08	-26.63	-27.11	-0.48	APAA(C16-22), tmtd, phy	88.2	x	-	SFA(C10:0-30:0), UFA(C15:1,16:1,18:1,26:1), br, chol, campesterol
HU-02	Pot sherd	Internal	597	1.46	-25.7	-26.38	-0.68	APAA(C16-20), tmtd, phy	55.7	x	-	SFA(C11:0-28:0), UFA(C18:1,22:1,26:1), br, chol, campesterol
HU-03	Pot sherd	Internal	76	1.54	-26.85	-27.78	-0.93	APAA(C18), tmtd(tr), phy	69.3	-	x	SFA(C12:0-24:0), br, chol, campesterol
HU-04	Pot sherd	Internal	168	1.33	-28.05	-28.61	-0.56	APAA(C18), tmtd, phy	76.2	-	x	SFA(C12:0-30:0), br, chol, campesterol
HU-05	Pot sherd	Internal	366	1.19	-28.21	-31.65	-3.45	APAA(C16-20), tmtd(tr), phy	51	x	-	SFA(C11:0-30:0), br, chol, campesterol
HU-06	Pot sherd	Internal	83	1.06	-28.24	-29	-0.76	tmtd(tr), phy	n/a	-	-	SFA(C12:0-24:0), DA(C9:0), br, chol, campesterol
HU-07	Pot sherd	Internal	738	1.56	-26.23	-26.41	-0.18	n/a	n/a	-	-	SFA(C10:0-26:0), UFA(C16:1,18:1), DA(C9:0), br, chol, campesterol
HU-08	Pot sherd	Internal	706	0.69	-28.64	-30.22	-1.58	APAA(C16-20), tmtd, pri(tr), phy	70.9	x	-	SFA(C10:0-20:0), UFA(C16:1,18:1), DA(C9:0), br, chol, campesterol
HU-09	Pot sherd	Internal	436	1.92	-27.67	-27.97	-0.3	APAA(C16-22), tmtd, pri(tr), phy	72.2	x	-	SFA(C10:0-23:0), UFA(C11:1,16:1), DA(C9:0), br, chol, campesterol
HU-10	Pot sherd	Internal	724	1.34	-28.82	-28.75	0.07	APAA(C16-20), tmtd, pri(tr), phy	81.1	x	-	SFA(C10:0-25:0), UFA(C16:1,18:1,19:1,26:1), DA(C9:0,10:0), br, chol, campesterol
HU-11	Pot sherd	Internal	879	0.88	-28.78	-33.26	-4.48	phy	59.2	-	-	SFA(C10:0-28:0), UFA(C18:1), DA(C9:0,11:0), br
HU-12	Pot sherd	Internal	124	1.13	-28.85	-30.93	-2.08	APAA(C16-20), tmtd, pri(tr), phy	59.8	x	-	SFA(C12:0-19:0), UFA(C16:1,18:1), DA(C9:0,11:0,12:0), br, chol(tr), campesterol
HU-13	Pot sherd	Internal	498	1.12	-28.06	-30.33	-2.28	APAA(C16-18(tr)), phy	29.2	-	-	SFA(C12:0-30:0), UFA(C16:1,18:1), DA(C9:0,11:0), br, chol, campsterol
HU-14	Pot sherd	Internal	531	1.48	-26.89	-26.97	-0.07	APAA(C18(tr)), tmtd, phy	n/a	-	-	SFA(C10:0-21:0), UFA(C16:1,18:1,21:1), DA(C9:0,11:0), br, chol, campesterol
HU-15	Pot sherd	Internal	246	1.82	-28.86	-28.64	0.22	APAA(C16-20), tmtd, phy	n/a	x	-	SFA(C12:0-24:0), UFA(C16:1,17:1,18;1), DA(C9:0), br, chol(tr), campesterol
HU-16	Pot sherd	Internal	956	1.49	-26.79	-26.06	0.73	APAA(C16-22), tmtd, pri(tr), phy	41.1	x	-	SFA(C10:0-23:0), UFA(C16:1,18:1),DA(C9:0), br, chol, campesterol
HU-17	Pot sherd	Internal	130	0.7	-28.42	-30.78	-2.36	APAA(C16-22(tr)), tmtd(tr), phy	57.3	x	-	SFA(C10:0-23:0), UFA(C16:1,18:1),DA(C9:0), br, chol(tr), campesterol(tr)
HU-18	Pot sherd	Internal	125	0.79	-29.17	-29.14	0.03	phy	n/a	-	-	SFA(C12:0-24:0), UFA(C18:1), DA(C9:0), br, chol, campesterol
HU-19	Pot sherd	Internal	108	0.8	-29.47	-34.38	-4.91	APAA(C18), tmtd(tr), phy	49.1	-	x	SFA(C12:0-30:0), UFA(C18:1), DA(C9:0), br, campesterol
HU-20	Pot sherd	Internal	121	1.75	-25.29	-25.19	0.1	APAA(C18-20), tmtd(tr), phy	67.4	x	-	SFA(C10:0-23:0), UFA(C16:1,18:1), DA(C9:0,11:0), br, campesterol
HU-21	Pot sherd	Internal	74	0.66	-27.95	-32.03	-4.08	tmtd(tr), pri(tr), phy	55.4	-	-	SFA(C11:0-24:0), UFA(C16:1,18:1), DA(C9:0,11:0), br, chol(tr), campesterol
HU-22	Pot sherd	Internal	595	0.96	-27.57	-32	-4.43	APAA(C16-22(tr)), tmtd, phy	33.5	x	-	SFA(C10:0-26:0), UFA(C16:1,18:1), DA(C9:0,11:0), br, chol, campesterol, stigmasterol(tr)
HU-23	Pot sherd	Internal	641	0.91	-27.02	-29.72	-2.7	APAA(C16-22(tr)), tmtd, pri(tr), phy	68.2	x	-	SFA(C11:0-26:0), UFA(C18:1), DA(C9:0,10:0,11:0), br, chol(tr), campesterol
HU-24	Pot sherd	Internal	489	1.15	-28.07	-27.98	0.09	APAA(C16-22), tmtd, pri(tr), phy	79.3	x	-	SFA(C11:0-24:0), UFA(C16:1,18:1), DA(C9:0,10:0,11:0), br, chol, campesterol
HU-25	Pot sherd	Internal	635	0.81	-27.16	-30.31	-3.15	APAA(C16-22), tmtd, phy	n/a	x	-	SFA(C12:0-26:0), UFA(C16:1,18:1), DA(C9:0), br, chol, campesterol
HU-26	Pot sherd	Internal	488	1.06	-27.3	-28.61	-1.31	tmtd(tr), pri(tr), phy	n/a	-	-	SFA(C12:0-27:0), UFA(16:1,18:1) , DA(C9:0,10:0), br, chol, campesterol
HU-27	Pot sherd	Internal	442	1.02	-28.33	-31.95	-3.63	APAA(C16-20(tr)), tmtd, pri, phy	61.6	-	x	SFA(C12:0-28:0), UFA(16:1,18:1), DA(C9:0), br, chol, campestenol
HU-28	Pot sherd	Internal	130	0.69	-28.48	-31.18	-2.7	tmtd(tr), phy	n/a	-	-	SFA(C11:0-26:0), UFA(C16:1,18:1), DA(C9:0), br, chol(tr), campesterol, stismasterol(tr)
HU-29	Pot sherd	Internal	386	1.9	-26.55	-28.14	-1.59	APAA(C16-22(tr)), tmtd, pri, phy	24.9	x	-	SFA(C10:0-24:0), UFA(C16:1,18:1), DA(C9:0,10:0,11:0,12:0), br, chol, campesterol
HU-30	Pot sherd	Internal	119	0.66	-28.6	-34.01	-5.41	APAA(C16-18), tmtd	n/a	-	x	SFA(C10:0-27:0), UFA(C16:1,18:1), DA(9:0,10:0,11:0,12:0), br, campesterol, stigmasterol(tr)
HU-31	Pot sherd	Internal	112	1.68	-28.25	-29.12	-0.87	APAA(C16-18(tr)), tmtd, pri, phy	25.9	-	-	SFA(C12:0-26:0), UFA(C16:1,18:1), DA(C9:0,10:0,11:0), br, chol, campesterol
HU-32	Pot sherd	Internal	104	0.89	-29.28	-32.66	-3.39	APAA(C16-22), tmtd, pri(tr), phy	65.6	x	-	SFA(C12:0-26:0), UFA(C18:1), DA(C9:0,10:0,11:0,12:0), br, chol, campesterol
HU-33	Pot sherd	Internal	110	1.03	-27.51	-32.17	-4.66	APAA(C16-22(tr)), tmtd, phy	66.9	x	-	SFA(C10:0-24:0), UFA(C16:1,18:1), DA(C9:0,11:0,12:0), br, chol(tr), campesterol, stigmasterol(tr)
HU-34	Pot sherd	Internal	164	1.01	-23.99	-27.97	-3.98	APAA(C16-22), tmtd, phy	61.7	x	-	SFA(C10:0-26:0), UFA(C16:1,18:1), DA(9:0,11:0,12:0), br, campesterol
HU-35	Pot sherd	Internal	495	1.11	-26.02	-29.3	-3.28	APAA(C16-20), tmtd, phy	59.1	x	-	SFA(C10:0-26:0), UFA(C16:1,18:1), DA(C9:0,10:0,11:0,12:0), br, chol(tr), campesterol
HU-36	Pot sherd	Internal	221	2.02	-28.27	-27.4	0.88	APAA(C16-18), tmtd, pri, phy	n/a	-	x	SFA(C12:0-24:0), UFA(C16:1,18:1), DA(C11:0), br, chol, campesterol
HU-37	Pot sherd	Internal	216	1.27	-26.06	-28.23	-2.17	phy	n/a	-	-	SFA(C11:0-21:0), UFA(C16:1,18:1), DA(C9:0,11:0), br, chol(tr), campesterol

(Cn:x) - carboxilic acids with carbon length n and number of unsaturations x, SFA – saturated fatty acid, UFA – unsaturated fatty acids, DC - α,ω-dicarboxylic acids, APAA - ω-(o-alkylphenyl) alkanoic acids, br -branched chain acids, tmtd - 4,8,12-trimethyltridecanoic acid, pri – pristanic acid, phy – phytanic acid with the percentage contribution of SRR diastereomer in total phytanic acid, chol - cholesterol or derivatives.

Supplementary Dataset -1: Results of bulk stable isotope analysis on foodcrust

sample ID	EA-IRMS	Sampling location	%C	δ13C	sd	%N	δ15N	sd	C/N ratio	d13C offset
HU-01	x	interior	50.58	-25	0.8	8.53	8.11	0.15	6.92	1.87
HU-02	x	interior	52.91	-24.13	0.1	8.2	7.99	0.03	7.53	1.91
HU-03	-									
HU-04	x	interior	33.83	-24.1	0.24	6.39	7.84	0.04	6.17	4.23
HU-05	x	interior	50.41	-26.6	0.75	5.22	7.5	0	11.28	3.33
HU-06	x	interior	24.56	-26.46	0.23	3.58	7.1	0	8.01	2.16
HU-07	x	interior	26.73	-22.03	11.28	5.18	7.02	2.82	6.59	4.29
HU-08	x	interior	53.11	-27.34	0.12	5.89	7.12	0.28	10.54	2.09
HU-09	-									
HU-10	x	interior	40.56	-24.9	0.13	7.03	7.37	0.15	6.74	3.89
HU-11	-									
HU-12	x	interior	32.22	-24.55	0.34	6.96	6.32	0.01	5.4	5.34
HU-13	x	interior	43.85	-23.98	0.13	7.48	6.08	0.03	6.84	5.22
HU-14	x	exterior	42	-25.66	0.62	4.81	8.02	0.08	10.19	1.27
HU-15	x	interior	45.86	-24.12	0.46	8.46	8.11	0.08	6.32	4.63
HU-16	x	interior	43.62	-23.76	0.55	7.79	7.7	0.1	6.53	2.67
HU-17	x	interior	38.49	-25.14	0.56	4.06	6.19	0.06	11.05	4.46
HU-18	-									
HU-19	-									
HU-20	x	interior	48.82	-23.35	0.33	7.7	8.56	0.09	7.4	1.89
HU-21	x	interior	47.6	-22.71	0.05	9	6.97	0.03	6.17	7.28
HU-22	x	interior	42.65	-26.25	0.34	5.87	5.43	0.03	8.47	3.54
HU-23	-									
HU-24	x	interior	49.2	-24.47	0.47	8.42	7.01	0.07	6.82	3.56
HU-25	-									
HU-26	-									
HU-27	-									
HU-28	-									
HU-29	-									
HU-30	-									
HU-31	-									
HU-32	-									
HU-33	-									
HU-34	x	interior	45.27	-24.11	0.03	7.17	7.43	0.01	7.37	1.87
HU-35	x	interior	36.11	-24.05	0.16	6.08	7	0.03	6.93	3.61
HU-36	x	interior	30.35	-24.02	0.77	6.26	7.3	0.16	5.66	3.82
HU-37	-									

CHAPTER 6

Fusion cuisine: the impact of farming on hunter-gatherer culinary traditions in Northern Europe

Özge Demirci, Harry K. Robson, Alexandre Lucquin, Søren H. Andersen, Daan C.M. Raemaekers & Oliver E. Craig

Fusion cuisine: the impact of farming on hunter-gatherer culinary traditions in Northern Europe

Özge Demirci[1,2*], Harry K. Robson[2], Alexandre Lucquin[2], Søren H. Andersen[3], Daan C.M. Raemaekers[1] & Oliver E. Craig[2]

[1]Groningen Institute of Archaeology, Poststraat 6, 9712 ER, Groningen, the Netherlands
[2]BioArch, Department of Archaeology, University of York, York, YO10 5YW, UK
[3]Moesgård Museum, Moesgård Allé 20, DK-8270 Højbjerg, Denmark

Keywords

Early pottery use; hunter-gatherers; early farmers; Mesolithic-Neolithic transition; Northern Europe; Swifterbant; Ertebølle, Funnel Beaker

Introduction

How farming came to be established in regions once occupied by hunter-gatherers is one of the key debates in European prehistory. Economic arguments have been made for the benefits of farming (Richards et al. 2003; Fischer et al. 2007), social arguments invoking power and agency (Fischer 2002) and more recently demographic explanations have resurfaced (Bramanti et al. 2009; Malmström et al. 2015; Hofmanová et al. 2016), largely thanks to the analysis of ancient genomes from human skeletal remains. In many of these models, hunter-gatherers are viewed as passive agents during the transitional process. In Northern Europe, it has been long argued that this assumption is less appropriate. Here, groups of hunter-gatherer-fishers, such as the Ertebølle of Southern Scandinavia (c. 5000-4000 cal BC) or the Swifterbant (c. 5400-4000/3400 cal BC) of the Northwest European Lowlands, settled along resource-rich coastlines, lakeshores, wetlands and river banks, and thrived during the Late Mesolithic period. In Southern Scandinavia, communities of hunter-gatherers created and stored surpluses and became increasingly sedentary from the start of the Holocene (Jordan & Zvelebil 2009; Boethius et al. 2020). Indeed, both the Swifterbant and Ertebølle populations had access to mass harvesting technologies, such as fish traps (Brinkhuizen 1983; Enghoff 1994; Out 2008a), and made pottery; attributes often associated with delayed return economies and early farming societies.

Nevertheless, evidence of farming eventually appears in the archaeological sequences of both regions, through contact with adjacent farming groups who were already established to the south (Fischer 2002; Terberger et al. 2009; Sørensen 2014). Domesticated animal bones are recorded on Swifterbant sites from c. 4500 cal BC and the earliest finds of cereals date to c. 4300-4000 cal BC (Cappers & Raemaekers 2008; Out 2008b; Çakırlar et al. 2020). Whereas both cereals and domesticated animals appear in territories once occupied by Ertebølle groups from c. 4000 cal BC (Fischer 2002) and, in contrast to the Swifterbant, are associated with a change in pottery styles marking the transition to the Early Neolithic Funnel Beaker culture (hereafter TRB). Considering the Southern Scandinavian record, Gron and Sørensen have recently argued that hunter-gatherer societies must have played an active role in the transition to agriculture, and that the Neolithic was negotiated for at least several centuries (Gron & Sørensen 2018). It is also clear that in these regions the shift from foraging to food production was far from complete, at least, at the start of the Neolithic period (Milner et al. 2004; Craig et al. 2011).

If we accept then that indigenous Mesolithic foragers did have a role in the adoption of agriculture and pastoralism in Northern Europe, then it becomes extremely pertinent to better understand both the nature of these final Mesolithic societies immediately prior to the first arrival of domesticates and how they responded to the introduction. Often these groups are viewed economically and socially as a monolithic entity, in the paleogenetic literature they are lumped into the category of “western hunter-gatherers” again without distinction (Lazaridis et al. 2014; Mittnik et al. 2018). The prevailing view

from cultural archaeologists over the last 40 years is that the Swifterbant culture represents a 'western variant' of the Ertebølle culture, largely based on comparisons of the shape and technological characteristics of their pottery (Van Der Waals 1972; Louwe Kooijmans 1974, 2010; de Roever 1979, 2004; Stapel 1991; Raemaekers 1997; Andersen 2010; Rowley-Conwy 2013). Whilst the cultures share some similarities, for instance the presence of pointed-based vessels, there are differences in pottery characteristics as well as other material culture (e.g. flint technology) and subsistence practices, which are generally overlooked (Deckers 1982; Raemaekers 1998; Stilborg 1999; Andersen 2010; Ten Anscher 2012; Ballin 2014). Ultimately, site visibility makes direct comparisons of subsistence practices difficult; the Ertebølle is generally associated with a maritime economy due to the immense number of coastal sites that have been identified (Andersen 1995) whereas the Swifterbant sites are restricted to inland locations due to erosion of the coastal zone.

Here we aim to complete a diachronic comparison of pottery use across inland sites in the Dutch wetlands and Southern Scandinavia that encompasses the transition to farming (Fig. 1). Pottery is the key indicator of cultural change in these regions but it is not clear whether the apparent continuity in styles and manufacturing techniques in the Swifterbant represents a different response to the introduction of farming compared to Southern Scandinavia where there is a sharp change from Ertebølle to TRB pottery. Lipid residue analysis offers a direct approach to test these hypotheses. At numerous coastal sites in Southern Scandinavia, extensive residue analysis has shown that there is some continuity in pottery use across the transition reflecting the persistence of a maritime economy (Craig et al. 2011; Cubas et al. 2020) but continuity or change at inland sites, comparable with Swifterbant site locations, has not been addressed to the same degree (though see Robson et al. 2021). More broadly throughout the Baltic it has been suggested that hunter-gatherer pottery use at a sub-regional scale is strongly influenced by the surrounding foodscape and pre-existing culinary practices and that these may strongly influence the adoption of farming (Courel et al. 2020). If so then are different Mesolithic subsistence strategies reflected in pottery use and do these explain regional differences in agricultural adoption.

Ceramic traditions across the introduction of farming

Swifterbant

In the Dutch wetlands, the earliest ceramics (c. 5000 cal BC; Raemaekers 2001a, 2001b) are associated with the Swifterbant culture (c. 5000-4000/3400 cal BC). They are characterised as S-shaped vessels with commonly open forms and slightly pointed or rounded bases (Fig. 2). They were constructed using the coiling technique (U-technique as the most common). While the Swifterbant culture has a ceramic tradition with continuous morphological and technological aspects throughout the 5th millennium BC, its decoration exhibits temporal variation between earlier and later pottery assemblages. In the first half

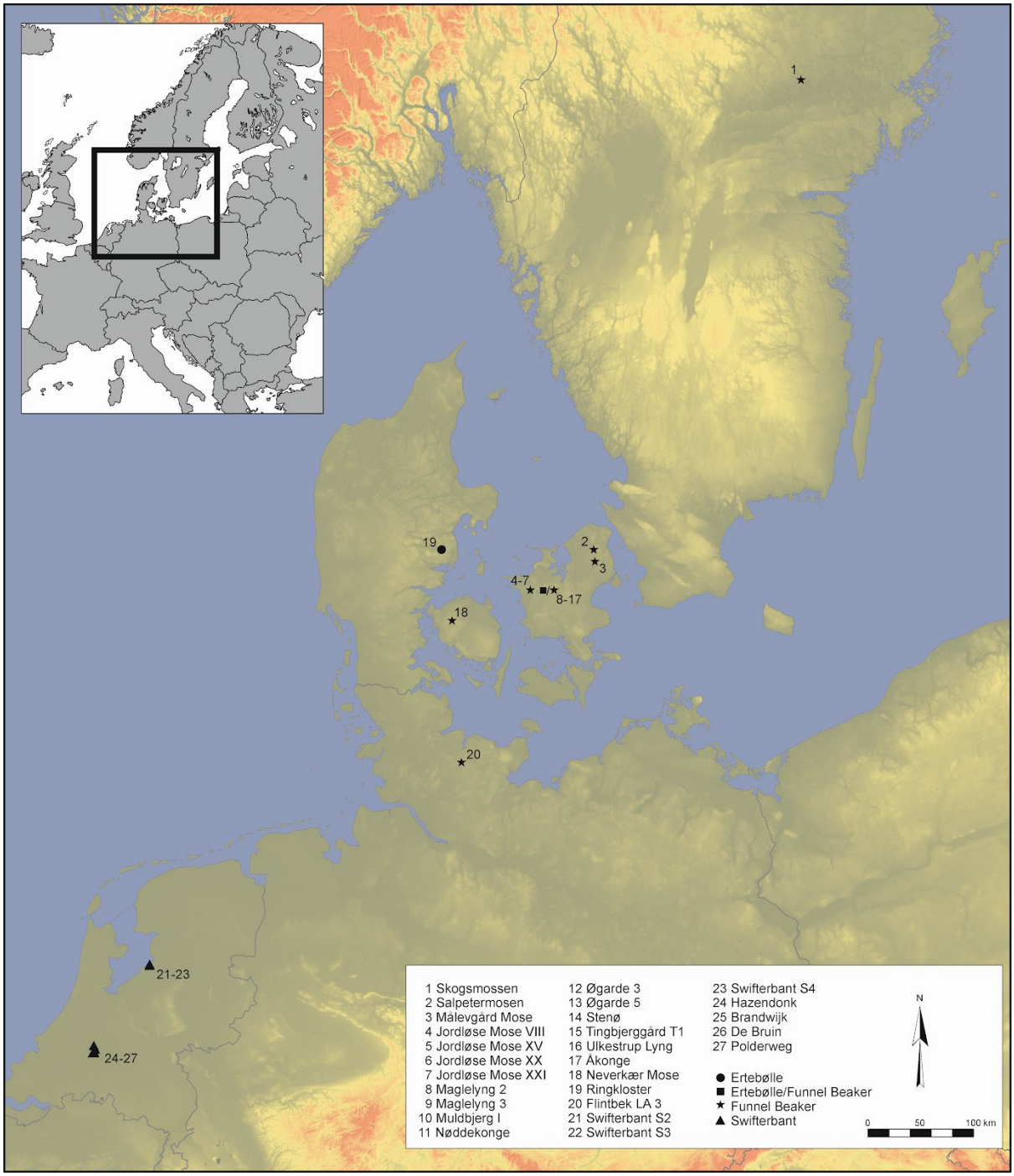


Fig. 1. Location map of the sites mentioned in the text. Insert indicates the geographical location of the focused area in relation to Northern Europe.

of the 5th millennium BC, decoration of the Swifterbant ceramics is confined to the occasional appearance of a series of spatula impressions on the top of the rim. In the second half of the 5th millennium BC, Swifterbant pottery assemblages demonstrate a higher proportion of wall decorations which mostly consists of fingertip and/or finger nail impressions (Raemaekers 1999; de Roever 2004; Louwe Kooijmans 2010). The two main fabric inclusion materials of Swifterbant ceramics are plant

material and/or grit with the rare addition of grog (only in the earlier assemblages) and sand (Raemaekers & de Roever 2010). Interestingly, the appearance of the thin-walled, well-fired, grit tempered ceramics at the end of the 5th millennium BC, especially in one of the type Swifterbant sites, Swifterbant S3, is argued as a technological shift towards Funnel Beakers, as a response to the introduction of a novel food resource (i.e. cereals) into the culture (Raemaekers 2015). This so-called pre-Drouwen TRB was also found at Schokland-P14 (ten Anscher 2012, 2015). At P14 it also includes clays discs and collared flasks, dating to the first half of the 4th millennium BC. The pre-Drouwen TRB developed into the Drouwen TRB c. 3400 cal BC. At this stage a wide spectrum of pottery forms occurred, often with complex decorative patterns (Brindley 1986).

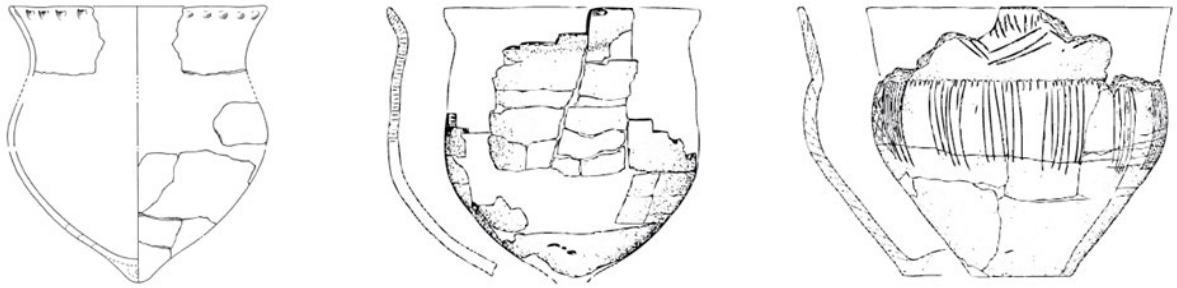


Fig. 2 Typical vessel forms of the Swifterbant (left), Ertebølle (middle) and Funnel Beaker (right) cultures (after de Roever 2004, Craig *et al*. 2011).

Ertebølle to Funnel Beaker

In Southern Scandinavia, a different development can be seen. The earliest ceramics associated with the Ertebølle culture appear at c. 4800-4600 cal BC (Andersen 2010). They are characterised by two main vessel forms, pointed-based vessels and oval bowls (Prangsgaard 1992; Heron et al. 2013). However, within the scope of this study, we will only focus on the ceramic technology of the pointed-based vessels, because of the specialised function of the oval bowls (Heron et al. 2013) and their absence in the Swifterbant culture. Pointed-based vessels are generally characterised by conical shaped open forms with pointed bases (Fig. 2). They were constructed using the coiling technique (H-technique being the most common; Andersen 2010). Although there are a few examples with small spatula impressions on the top of the rim and geometric patterns or incised fishnet motifs covering the upper part of the body, decoration on the Ertebølle vessels appears to be an uncommon feature. At c. 4000 cal BC, with the first appearance of domesticated animals in the region (Fischer 2002; Hartz & Lubke 2006; Andersen 2010), there is a distinct change in ceramic technology in Southern Scandinavia. Around this time, Ertebølle vessels were completely replaced by thin walled and flat or rounded based TRB ceramics which are characterised by their higher quality compared to both the pottery of the Swifterbant and Ertebølle cultures (Fig. 2). Early TRB ceramics (c. 4000-3800 cal BC) are characterised by having a

simple decoration just below or on the top of the rim (Koch 1998); rather similar to the pre-Drouwen TRB in North-western Europe.

Pottery use across the transition to farming

Lipid residue analyses of a total of 208 samples, collected from ceramic potsherds (n = 193) as well as interior charred surface deposits (n = 15), largely corresponding to individual vessels were integrated in this study (Supplementary Dataset-1) to compare the use of pottery across inland sites in the Dutch wetlands and Southern Scandinavia at the transition to farming. We include published data from seven Swifterbant sites (Polderweg, De Bruin, Brandwijk, Hazendonk, S2, S3, S4) (n = 95) and three inland Ertebølle sites (Ringkloster, Stenø, Åkonge) (n = 26) (Fig. 1). We also include unpublished data from one inland TRB site (Flintbek LA 3) (n = 10) as well as published data from a further 16 inland TRB find spots (Jordløse Mose VIII, Jordløse Mose XV, Jordløse Mose XX, Jordløse Mose XXI, Maglelyng 2, Maglelyng 3, Målevgård Mose, Neverkær Mose, Tingbjerggård T1, Salpetermosen, Ulkestrup Lyng, Øgårde 3 (kar S), Øgårde 5 (kar A) - grouped under 'bog pots' in Fig. 3d and Fig. 4d) and sites (Skogsmossen, Stenø, and Åkonge) (n = 77) (Fig. 1).

The overall results show that these vessels were used to process freshwater fats (i.e. fish, molluscs, birds and mammals) and/or terrestrial animal fats (i.e. ruminants, including red deer (Cervus elaphus), roe deer (Capreolus capreolus), elk (Alces alces), aurochs (Bos primigenius) etc.) rather than marine fats ($\delta^{13}C$ values < −25‰; Supplementary Document-1). Despite this, there are also important differences between all three datasets (Fig. 3 and Fig. 4).

Swifterbant

The lipid residue analyses of the earliest Swifterbant pottery from Polderweg (Phase 2, c. 5000-4950 cal BC) shows that these vessels were mainly used for processing aquatic oils, primarily from freshwater organisms (Fig. 3a) (Demirci et al. 2021). Although further analyses indicate a similar pattern for the younger Swifterbant culture vessels in the Lower Rhine-Meuse area, some of these vessels had also been used to process terrestrial animal fats, the only evidence for a change in the use of ceramics from the early to the late 5th millennium BC in this area. In addition to the continued processing of freshwater fats, ruminant animal fats (either domestic and/or wild resources) were identified in pottery from c. 4500 cal BC, at De Bruin (Phase 2 and 3, Fig. 4b). At c. 4300 cal BC, the evidence for the processing of ruminant animal fats disappeared and was replaced by the processing of porcine fats (i.e. wild boar/domestic pig), as clearly demonstrated in the Brandwijk and Hazendonk vessels (Fig. 3b). Around this time, we also witnessed the first direct evidence for the presence of dairy fats (i.e. milk, cheese, butter) in Swifterbant pottery (Demirci et al. 2021). The Swifterbant type sites S2, S3, and S4 (c. 4300-4000 cal BC), contemporaneous to Brandwijk and Hazendonk, had clear evidence for the processing of

aquatic oils, probably freshwater fish (Fig. 3b). Interestingly, the absence of ruminant and dairy fats in these vessels suggests a specialised pottery use in these three sites (Demirci et al. 2020). Unfortunately, there is as yet no comparable data for the use of Swifterbant vessels dating post 4000 cal BC.

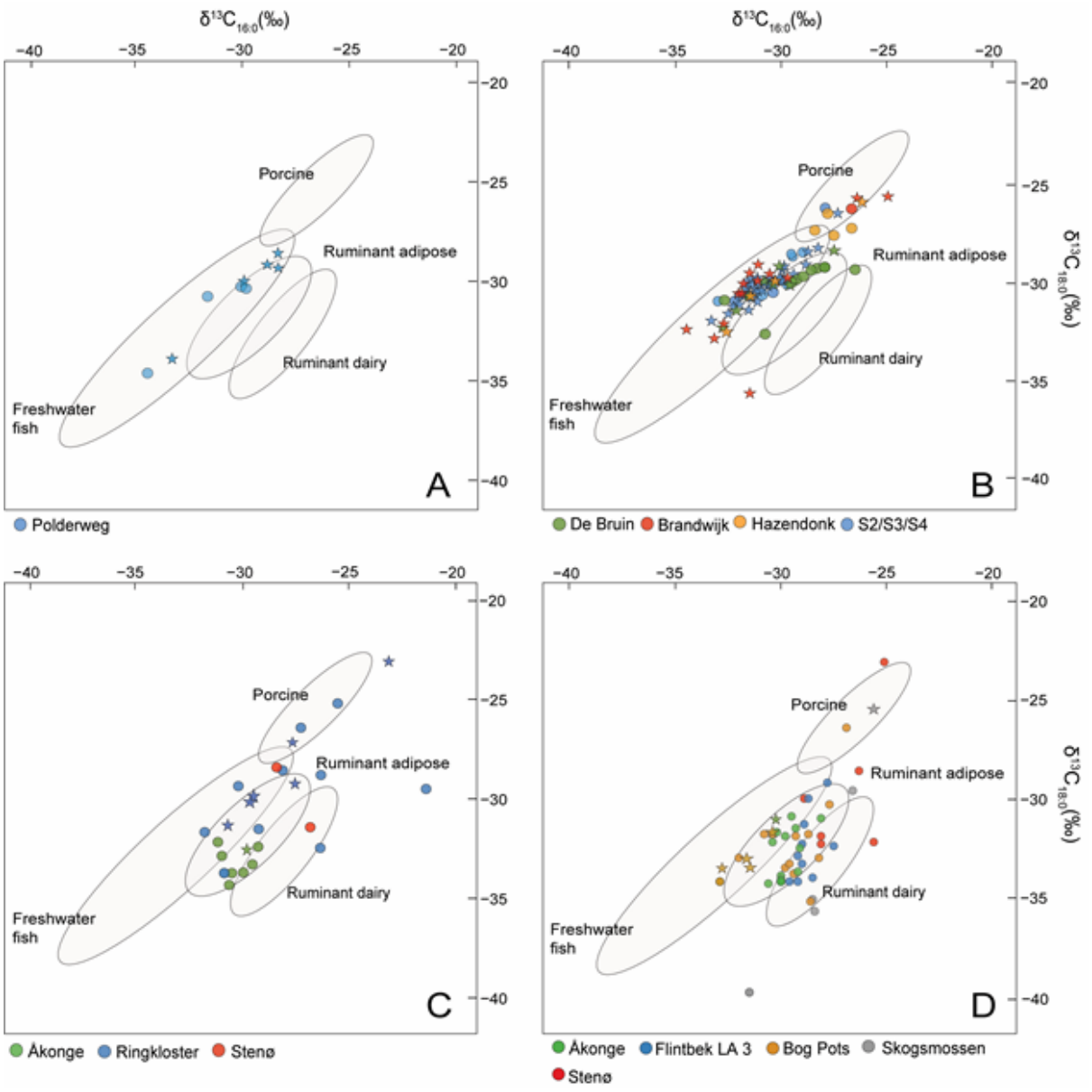


Fig. 3 Results of the analyses by GC-C-IRMS showing the isotopic values of the $C_{16:0}$ and $C_{18:0}$ mid-chain length fatty acids from Swifterbant pottery in (a) Polderweg and in (b) De Bruin, Brandwijk, Hazendonk, S2, S3, and S4; (c) Ertebølle pottery and (d) TRB pottery. Datapoints shown as stars indicate samples with fully aquatic biomarkers (Supplementary Dataset-1). 95% confidence ellipses indicate areas of authentic reference values for each group of origins from the Western Baltic.

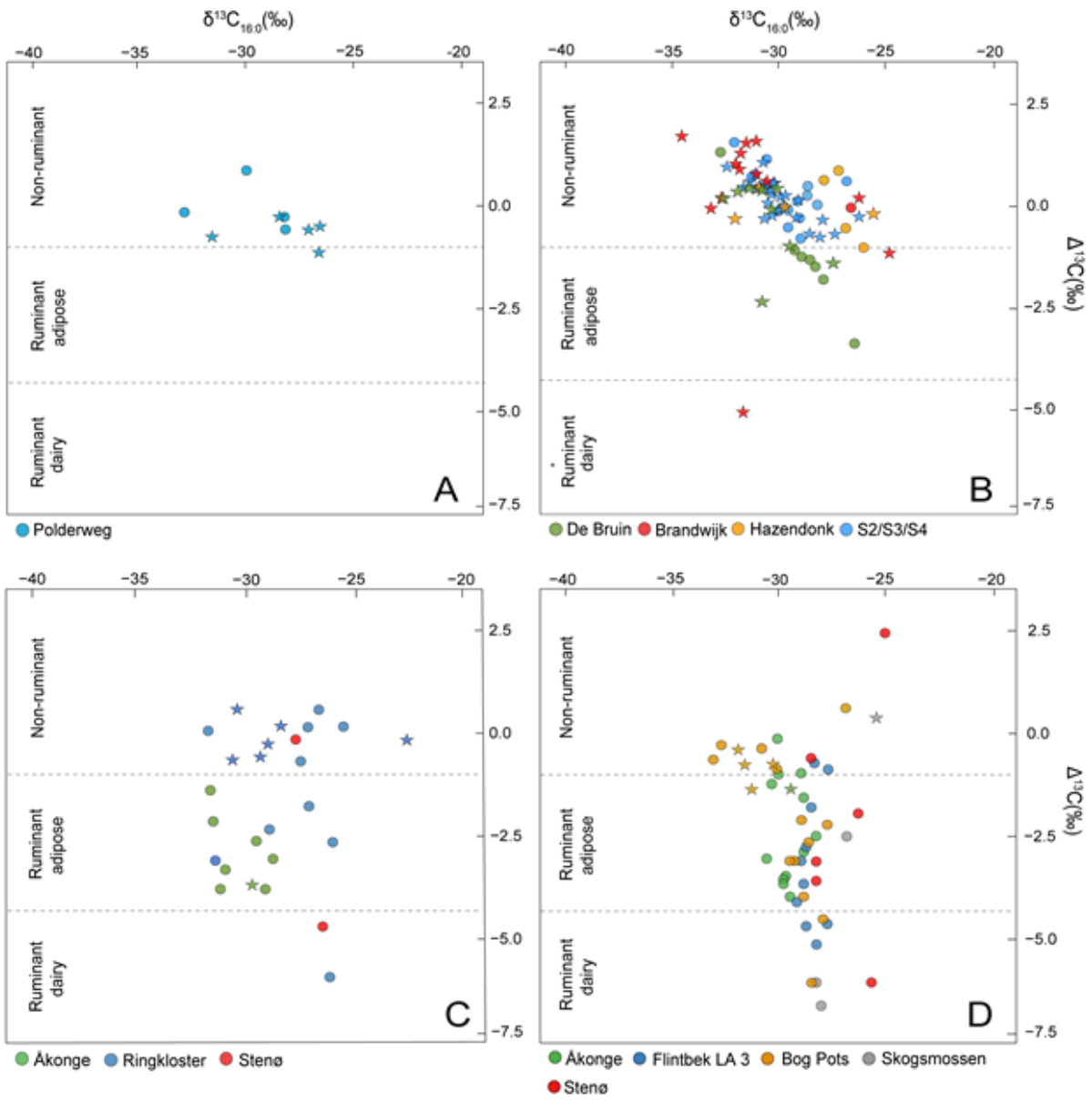


Fig. 4 $\Delta^{13}C$ ($\delta^{13}C_{18:0}$ - $\delta^{13}C_{16:0}$ values) against the mid chain-length $\delta^{13}C_{16:0}$ values of Swifterbant pottery in (a) Polderweg and in (b) De Bruin, Brandwijk, Hazendonk, S2, S3, and S4; (c) Ertebølle pottery and (d) TRB pottery. Datapoints shown as stars indicate samples with fully aquatic biomarkers (Supplementary Dataset-1). Dotted lines indicate designated areas of authentic modern reference values for each group of origins from Western Baltic.

Ertebølle to Funnel Beaker

The lipid residue analyses of the vessels from three major inland Ertebølle sites, Ringkloster, Stenø and Åkonge, covering the time span from c. 4600-4000 cal BC, provides clear evidence for the processing of a wide range of foodstuffs including freshwater, ruminant and dairy fats and their products (Fig. 3c and Fig 4c) (Craig et al. 2011; Robson 2015; Courel et al. 2020). In terms of the processing of aquatic

resources, the isotopic analysis demonstrates that they too were derived from a freshwater rather than a marine environment (Supplementary Document-1), consistent with their inland locations (Fig. 1). While the processing of ruminant fats in the vessels, especially from Åkonge, is extremely prominent, we can clearly see the varied use of pottery through the isotopic variation in the data of the vessels from Ringkloster and also Stenø (Fig. 3c). By c. 4000 cal BC, with the introduction of the TRB, we do not see a sharp change in pottery use. The isotopic data shows that the vessels from the inland TRB contexts, traditionally associated with early farming groups, present a clear continuation in the use of pottery for the processing of a wide range of food resources along with the increasing frequency of dairy and possibly meat from domesticated animals (Fig. 4d) (Craig et al. 2007; Isaksson & Hallgren 2012; Cubas et al. 2020; Robson et al. 2021). In addition, some of these vessels had been used to process aquatic resources (from both marine and freshwater environments) mixed with terrestrial food products (Fig. 4d, Supplementary Dataset-1), a clear demonstration for the continued use of pottery and the processing of aquatic resources beyond the arrival of domesticated plants and animals into the region.

Changes in animal bone assemblages across the transition to farming

Swifterbant

In contrast to the relatively narrow range of foodstuffs found in pottery, faunal remains from all the Swifterbant sites show highly diversified subsistence strategies, which include large and small game animals, terrestrial and aquatic food resources. In the older Swifterbant assemblages, Polderweg and De Bruin, Sus sp., deer (Cervidae), beaver (*Castor fiber*) and otter (*Lutra lutra*) are the most abundantly identified mammalian remains (Fig. 5, Supplementary Dataset-2) (Oversteegen et al. 2001; Van Wijngaarden-Bakker et al. 2001). Significantly high numbers of beaver and otter remains in these assemblages indicate that they were hunted in large numbers, presumably for their meat as well as their fur. Domesticated animals are completely absent in the Polderweg assemblages. We see the first appearance of *Bos* sp. in the younger phases of De Bruin (Phase 2) in small numbers (Çakırlar et al. 2020). *Bos* sp. becomes more visible in the zooarchaeological records by the mid-5th millennium BC,

as it is present in the assemblages of De Bruin (Phase 3), Brandwijk and Hazendonk (Fig. 5, Supplementary Dataset-2). The size and age-at-death variation represented by *Bos* sp. from these three sites may suggest the possible presence of domesticated cattle herds in this period, although this is still the subject of debate (Çakırlar et al. 2020).

In the second half of the 5th millennium BC, we witness smaller numbers of sheep/goat (*Ovis aries/Capra hircus*) remains in the zooarchaeological assemblages of De Bruin (Phase 3) and Brandwijk (Çakırlar et al. 2020). The earliest ^{14}C date obtained from a sheep/goat remain from De Bruin is 4520-4356 cal BC (Çakırlar et al. 2020). The zooarchaeological records from the Swifterbant type sites S2, S3, and S4 (c. 4300-4000 cal BC) indicates the exploitation of *Bos* sp., *Sus* sp., and sheep/goat as well

as game animals such as beaver and otter (Fig. 4, Supplementary Dataset-2) (Zeiler 1997; Raemaekers 2003; Kranenburg & Prummel 2020). The continuous exploitation of *Sus* sp. throughout the 5th millennium BC loses its importance and is replaced by the raising of domesticated cattle only after c. 4000 cal BC (e.g. Schipluiden in the Lower Rhine-Meuse area; Zeiler 2006; Kamjan et al. 2020).

All the Swifterbant sites yielded numerous fish remains, predominated by freshwater fish species. While freshwater species predominate, such as northern pike (*Esox lucius*), European perch (*Perca fluviatilis*), Wels catfish (*Silurus glanis*) and species of the Cyprinidae family (i.e. carps and minnows), anadromous species, including sturgeon (*Acipenser sturio*), European eel (*Anguilla anguilla*), species of the Salmonidae family (salmonids), and allis shad (*Alosa alosa*) are also represented. There is also the occasional appearance of marine dwelling species, such as the mullet family (Mugilidae) (Supplementary Dataset-2) (Clason 1978; Brinkhuizen 1979; Zeiler 1997; Beerenhout 2001a; 2001b).

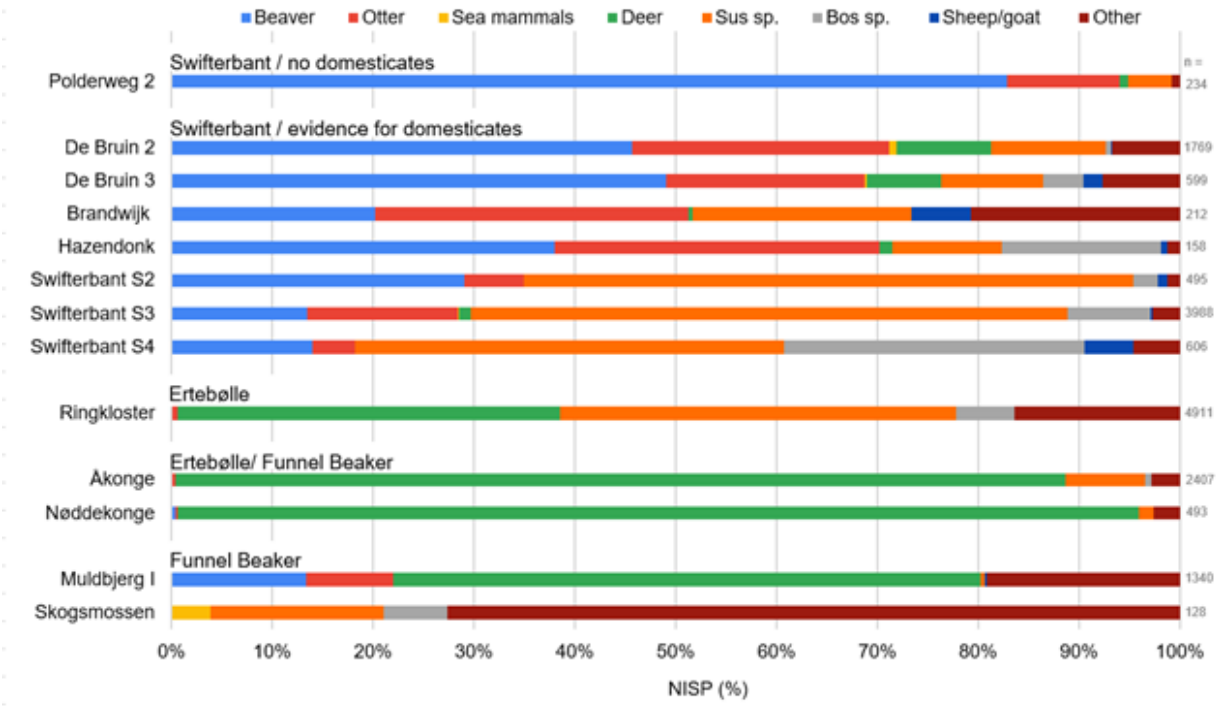


Fig. 5 Distribution of identified mammal bone remains (Number of Identified Specimens = NISP). Table omits birds and fish. Due to tentative or mixed identifications of wild and domesticated suids and bovids, they are grouped under '*Sus* sp.' and '*Bos* sp.'. Based on the references listed in Supplementary Dataset-2.

Ertebølle to Funnel Beaker

In the zooarchaeological assemblages from inland Ertebølle sites, there is great variation in the exploited taxa, including species from terrestrial and aquatic environments. The site of Ringkloster is a prime example. The assemblage is heavily dominated by terrestrial game animals, such as deer, Sus sp. and

Bos sp. (Fig. 5) (Rowley-Conwy 2013). In terms of the fish remains, freshwater species (i.e. Cyprinids, northern pike and European perch) predominate, in accordance with the location of the site on the shore of a prehistoric branch of the lake (Enghoff 1994, 1995). Freshwater species are followed by marine and migratory species, albeit in smaller numbers (Supplementary Dataset-2). The identified marine species consists of Atlantic cod (Gadus morhua), pollock/saithe (Pollachius sp.) and species of the Pleuronectidae family (righteye flounders). Added to this are the remains of bottle-nosed dolphin (Tursiops truncatus) and European oyster shells (Ostrea edulis) (Enghoff 1995) indicating contact between the inland settlement and the marine environment.

The Ertebølle and TRB faunal remains from Åkonge could not be disaggregated to culture, therefore they are discussed as one, covering a time span of c. 4600-3500 cal. BC. The mixed bone assemblage recovered from Åkonge indicates a great abundance of deer and Sus sp. along with few remains of Bos sp. (wild and/or domesticated) (Fig. 5; Gotfredsen 1998). The high abundance of fish remains, predominated by freshwater fish, indicates the continued exploitation of aquatic resources across the 5^{th}-4^{th} millennium BC (Enghoff 1994). Starting from c. 4000 cal BC onwards, in Southern Scandinavia, the addition of domesticated animals into forager environments becomes visible in the faunal assemblages, especially inland sites, albeit in small numbers (Sørensen & Karg 2014). The earliest date for the arrival of domesticated animals into the region is c. 4000-3810, which derives from a directly dated domesticated cattle bone found on the site of Åkonge (Noe-Nygaard et al. 2005). While the dependency on hunting game animals, especially deer, at Muldbjerg I in Zealand indicates a continuity in the subsistence strategies of forager lifeways (Fig.5), the small bone assemblage from Skogsmossen in Sweden (c. 3900-3500 cal BC) includes the remains of both wild resources (e.g. Sus sp., seal and fish) and domestic animals (e.g. sheep/goat) (Fig. 5; Hallgren 2008), and is clear evidence for the coexistence of both forager and farming subsistence strategies across the transition.

Stable isotope data from human bone collagen

Swifterbant

In the first half of the 5^{th} millennium BC, carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotopic data obtained from human remains from both Polderweg and De Bruin demonstrate the consumption of freshwater derived protein, presumably fish (Supplementary Dataset-4; Smits et al. 2010). In the second half of the 5^{th} millennium BC, the $\delta^{13}C$ and $\delta^{15}N$ stable isotopic data obtained from the human remains from the two Swifterbant type sites, S2 and S3, also indicates the consumption of freshwater derived protein but with a small contribution of terrestrial derived protein (Supplementary Dataset-3; Smits & van der Plicht 2009). Whether this is a reflection of a change in diet, defined by the introduction of domestic plants and animals at this time, remains a subject of debate, with the sample size currently not large enough to make valid comparisons.

Ertebølle to Funnel Beaker

The $\delta^{13}C$ and $\delta^{15}N$ stable isotope analyses of human remains from both coastal and inland Ertebølle settlements indicates the consumption of marine derived protein during the late 5th millennium BC (Supplementary Dataset-3; Tauber 1981; Richards et al. 2003; Fischer et al. 2007; Robson 2015). The presence of marine foodstuffs at inland sites is further evidence for contact between the coast and interior and offers a valuable contribution to understanding the degree of human mobility in this period. At c. 4000 cal BC, in this region, we witness a significant shift in dietary practices, from one reliant on the consumption of marine derived protein to one reliant on terrestrial derived protein. A very distinct decline in $\delta^{13}C$ and $\delta^{15}N$ values (Supplementary Dataset-3), consistent with the consumption of terrestrial-derived protein and possibly some low trophic level freshwater food, can be observed from both coastal and inland TRB sites (Fischer et al. 2007).

Discussion

Did Late Mesolithic foragers of Southern Scandinavia and the Dutch wetlands have similar uses of pottery?

Based on the different datasets discussed above, we conclude that the Ertebølle and Swifterbant pottery reflects two distinct approaches towards the hunter-gatherer-fisher pottery and its use in Northern Europe. It is clear that they did not share similar drivers for pottery adoption, and that ceramics had divergent techno-functions. Swifterbant ceramics were probably introduced through contacts with Central-European farmers (Louwe Kooijmans 2010; ten Anscher 2012, 2015), an interpretation not only based on similarities in pottery morphology, coiling technique, but also on the presence of stone and flint artefacts from these same farming communities on Swifterbant sites. From the start, Swifterbant ceramics served a specialised use in direct correlation with the exploitation of freshwater resources (Supplementary Dataset-2). Whilst, this also corresponds with an aquatic-oriented diet (Smits & van der Plicht 2009; Smits et al. 2010) throughout the 5th millennium BC, it contrasts with the highly diverse faunal assemblage as noted above.

In contrast to the Swifterbant, Ertebølle ceramics from inland settlements were not primarily used to process a specific food resource but were used for processing a much wider range of terrestrial and aquatic foodstuffs. The use of pots to process ruminant animal fats in the Ertebølle ceramics is also evident (Fig. 4c) and correlates well with the faunal data where we see a dominance of ruminant animals (i.e. deer) in some inland assemblages (Fig. 5). In addition, ruminant animal fats were also frequently observed in pots from coastal Ertebølle sites (Papakosta et al. 2019; Courel et al. 2020), indicating a general pattern in the use of Ertebølle vessels.

Overall, despites similarities in their subsistence economies, hunter-gatherer-fisher groups of the Swifterbant and Ertebølle cultures had different notions regarding how pots should be used. This observation supports the idea that use of hunter-gatherer pottery was under strong sub-regional cultural control (Courel et al. 2020). As pottery production spread, its use was adapted by the local groups of hunter-gatherers perhaps replacing other pre-existing culinary techniques involving perishable artefacts. In other words, there is no underlying economic driver for the adoption of pottery by these groups.

How did Late Mesolithic foragers respond to the arrival of farming?

The datasets discussed above also indicate that there are regional differences on how the two hunter-gatherer-fisher cultures of Northern Europe responded to the arrival of farming. The transition to farming in the Swifterbant culture can be argued as a gradual event starting with the arrival of domesticated animals at c. 4500 cal BC and cereal cultivation at c. 4300 cal BC (Cappers & Raemaekers 2008; Çakırlar et al. 2020) which were incorporated into the already existing hunter-gatherer-fisher subsistence strategies in the region. Although the remains of *Sus* sp. and *Bos* sp. are problematic in terms of separating wild from domestic forms, and currently the subject of on-going research, the arrival of domesticates into the Swifterbant culture is clearly demonstrated by the presence of sheep/goat bones in the faunal assemblages of all the Swifterbant sites in the Dutch Wetlands dating after c. 4500 cal BC (Supplementary Dataset-2; Çakırlar et al. 2020). The clear continuation of hunter-gatherer-fisher subsistence strategies, including the exploitation of terrestrial game animals and aquatic resources, as well as an aquatic-oriented diet, however, suggests that the domesticated animals played a lesser role in the Swifterbant culture and presumably only increase in importance after 4000 cal BC (see Kamjan et al. 2020). Interestingly, the only visible response to the arrival of farming in the Swifterbant culture, in terms of material culture, comes from the ceramic traditions which possibly indicates a technological shift towards TRB ceramics at c. 4300 cal BC - about 200 years after the arrival of domesticated animals into the culture. Even then, we do not see any fundamental change in pottery use. Quite the contrary, the use of Swifterbant pottery specifically for the processing of aquatic -freshwater- resources appears to be continuous, and the primary function throughout the 5th millennium BC.

In contrast, the transition from the Ertebølle to TRB in Southern Scandinavia seems to be a very rapid event, in terms of material culture, with very clear changes in ceramic technology and morphology. Changes in pottery use and subsistence strategies, however, were more gradual. During the Late Mesolithic In Southern Scandinavia, we see a somewhat continuous pattern in subsistence and material culture, as well as human diet, all reflecting a hunter-gatherer-fisher lifeway. Faunal data from inland Ertebølle settlements does not present any change in hunter-gatherer-fisher subsistence strategies with no evidence of domesticated animals as well as plants throughout the 5th millennium BC. It is only at

the beginning of the 4th millennium BC, along with the arrival of early farming communities into Southern Scandinavia, when we first witness domesticated animals as well as plants. Interestingly, it seems that the newly introduced agrarian way of life was practised on inland sites contemporaneously with hunting and fishing activities (Fig, 5; Supplementary Dataset-2). In addition, despite the clear change in ceramic traditions and the increase in the processing of dairy fats in pots after c. 4000 cal BC, we also see a continuation in the processing of ruminant animal fats as well as aquatic oils in the early TRB pottery, although latter is on a reduced scale.

Dairying in the Late Mesolithic?

One striking point that needs to be addressed here is the evidence for the presence of dairy fats in both Swifterbant and Ertebølle ceramics. Whilst, the results of lipid residue analyses on Swifterbant pottery indicate evidence for the presence of dairy fats (i.e. milk, cheese, butter) in one vessel from Brandwijk, in the Lower Rhine-Meuse area (Fig. 4b) (Demirci et al. 2021), similar results were obtained in two Ertebølle vessels, one from Ringkloster and another one from Stenø (Fig. 4c) (Robson 2015).

For Swifterbant, the 'dairy pot' can be explained by the presence of domesticates as the faunal assemblage includes the presence of sheep/goat and Bos sp. (domestic and/or wild) at the site (Fig. 5; Supplementary Dataset-2). Whether this 'dairy pot' is an indication of small scale animal husbandry and perhaps an underrepresentation of a wider use of dairy products in the Swifterbant culture, especially for the sites in the Lower Rhine-Meuse area, or if it is the result of interactions with neighbouring farmer communities remains the subject of debate. Interestingly, in the Swifterbant sites S2, S3 and S4, where sheep and goats were the major domestic animals as well as *Bos* sp.(domestic and/or wild) (Fig.5; Supplementary Dataset-2), dairy fats are absent in ceramic vessels (Demirci et al. 2020). This may indicate possible regional differences in the culinary practices and value of food as well as human-animal relations within the Swifterbant culture which requires further research.

In contrast to Swifterbant, the two possible 'dairy pots' from inland Ertebølle sites cannot be explained by the presence of domesticates as the faunal data shows their absence at both sites (Supplementary Dataset-2). Therefore, we suggest that the dairy fats present in the Ertebølle vessels seem to be more about the consumption rather than possible local production. Interestingly, dairy fats have previously been encountered in Ertebølle vessels from Rosenhof and Neustadt in Northern Germany (Courel et al. 2020). These were interpreted as representing the exchange of goods between the foragers of the Ertebølle culture and early farming communities located in the adjacent areas to the south. Based on the different dataset presented above, this explanation could also be put-forward for Ringkloster and Stenø and would imply direct contact between farming communities and Danish Ertebølle groups, involving the exchange of dairy products and perhaps other perishable commodities.

We see that dairy is among the first domesticated products associated with the transition to agriculture especially in Southern Scandinavia. It predates the bone evidence for domesticates in the Ertebølle culture and appears as a novel food resource not as part of the main subsistence economy but highly likely a controlled - possibly due to the issues of lactose intolerance in the late 5th to early 4th millennium cal BC in Northern Europe (Burger et al. 2007; Malmström et al. 2010) - non-local addition into the local culinary practices. If we consider the abundant presence of terrestrial game animals including ruminants (e.g. deer) in the subsistence strategies of hunter-gatherer-fisher communities such as Ertebølle, the drive for the arrival of domestication may not have been solely related to meat production as it was already available. Therefore, we argue that dairy may have been one of the main drives for the arrival of domestication into these cultures - whether it has been an "exotic" and new food resource or nutritious food or even prestige product.

Conclusion

The transition from the Mesolithic to the Neolithic is traditionally defined by a sudden change in subsistence strategies. Hunter-gatherer-fisher communities change their way of life and transform into or were replaced by early farming communities. New ideas were adapted as animal husbandry and cereal cultivation spread throughout Europe. Our datasets from the Swifterbant and Ertebølle cultures, however, somewhat contradict these viewpoints. We conclude that the Swifterbant and Ertebølle cultures of Northern Europe exhibit two separate traditions in the way pots were used which continues through well into the Neolithic. Through the transition to farming in the Swifterbant culture of the Dutch Wetlands, it is evident that the material culture as well as the culinary practices remained essentially unchanged and continued to reflect a hunter-gatherer-fisher economy. Whilst the Ertebølle - TRB transition for the inland settlements of Southern Scandinavia resulted in a change in the material culture, the culinary practices of hunter-gatherer lifeways continued well into the Neolithic period, reflecting a gradual change.

Acknowledgement

We are thankful to Sander Tiebackx (Groningen Institute of Archaeology) who produced the map for Fig.1. We thank Helen Talbot (University of York) and Matthew Von Tersch (University of York) for their assistance with aspects of laboratory work as well as Anders Fischer, Fredrik Hallgren and Peter Rowley-Conwy for answering questions concerning relevant background information.

Funding statement

This project is part of a Marie Sklodowska-Curie European Joint Doctoral Training Program, funded by the European Union's EU Framework program for Research and Innovation Horizon 2020 under the Grant Agreement No 676154 (ArchSci2020 program).

References

Andersen, S. H. (1995). Coastal adaption and marine exploitation in Late Mesolithic Denmark—with special emphasis on the Limfjord region. In: Fischer, A (ed). *Man, and Sea in the Mesolithic. Coastal settlement above and below present sea level*. Oxbow Monograph 53, Oxford, pp. 41–66.

Andersen, S. H. (2010). The first pottery in South Scandinavia. In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.). *Pots, Farmers and Foragers: How Pottery Traditions Shed a Light on Social Interaction in the Earliest Neolithic of the Lower Rhine Area*. Leiden: Leiden University Press, pp. 167–176.

Ballin, T. B. (2014). The Culture Concept and the Ertebølle-Swifterbant Dispute. A spin-off from the debate between Raemaekers and Stilborg (or: the basic elements of prehistoric territorial studies).[online]Available at https://www.academia.edu.

Beerenhout, B. (2001a). Vissen. In: Louwe Kooijmans, L. P. (ed.), *Hardinxveld-Giessendam Polderweg. Een mesolithisch jachtkamp in het rivierengebiet (5500-5000 v. Chr.)*. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek, pp. 243–276.

Beerenhout, B. (2001b). Vissen. In: Louwe Kooijmans, L. P. (ed.), *Hardinxveld-Giessendam De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.).* Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek., pp. 243–276.

Boethius, A., Bergsvik, K. A., & Nilsson, B. (2020). Knowledge from the ancient sea – a long-term perspective of human impact on aquatic life in Mesolithic Scandinavia. *Holocene*, *30*(5), 632–645.

Bramanti, B., Thomas, M. G., Haak, W., Unterlaender, M., Jores, P., Tambets, K., Antanaitis-Jacobs, I., Haidle, M. N., Jankauskas, R., Kind, C.-J., Lueth, F., Terberger, T., Hiller, J., Matsumura, S., Forster, P., & Burger, J. (2009). Genetic Discontinuity Between Local Hunter-Gatherers and Central Europe's First Farmers. *Science*, *326*(5949), 137–140.

Brindley, A. L. (1986). The typochronology of TRB West Group Pottery. *Palaeohistoria*, 28, 93–132.

Brinkhuizen, D. C. (1979). Preliminary notes on fish remains from archaeological sites in the Netherlands. *Palaeohistoria*, 21(0), 83–90.

Brinkhuizen, D. C. (1983). Some Notes on Recent and Pre- and Protohistoric Fishing Gear from Northwestern Europe. *Palaeohistoria*, *25*, 7–53.

Burger, J., Kirchner, M., Bramanti, B., Haak, W. & Thomas, M. G. (2007). Absence of the lactase-persistence-associated allele in early Neolithic Europeans. *Proceedings of the National Academy of Sciences of the United States of America* 104, 3736–41.

Cappers, R. T. J., & Raemaekers, D. C. M. (2008). Cereal cultivation at Swifterbant? Neolithic wetland farming on the north European plain. *Current Anthropology* 49(3), 385-402.

Clason, A. T. (1978). Worked bone, antler and teeth. A preliminary report (Swifterbant Contribution 9). *Helinium*, 18, 83–86.

Courel, B., Robson, H. K., Lucquin, A., Dolbunova1, E., Oras, E., Adamczak, K., Andersen, S. H., Astrup, P. M., Charniauski, M., Czekaj-Zastawny, A., Ezepenko, I., Hartz, S., Kabaciński, J., Kotula, A., Kukawka, S., Loze, I., Mazurkevich, A., Piezonka, H., Piličiauskas, Sørensen, A. S., Talbot, H. M., Tkachou, A., Tkachova, M., Wawrusiewicz, A., Meadows, J., Heron, C. P., and Craig, O . E. (2020). Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter-gatherers. *Royal Society Open Science*, 7. https://doi.org/10.1098/rsos.192016.

Craig, O. E., Steele, V. J., Fischer, A., Hartz, S., Andersen, S. H., Donohoe, P., Glykou, A., Saul, H., Jones, D. M., Koch, E., & Heron, C. P. (2011). Ancient lipids reveal continuity in culinary practices across the transition to agriculture in Northern Europe. *Proceedings of the National Academy of Sciences of the United States of America*, 108(44), 17910–17915.

Cubas, M., Lucquin, A., Robson, H. K., Colonese, A. C., Arias, P., Aubry, B., Billard, C., Jan, D., Diniz, M., Fernandes, R., Fábregas Valcarce, R., Germain-Vallée, C., Juhel, L., de Lombera-Hermida, A., Marcigny, C., Mazet, S., Marchand, G., Neves, C., Ontañón-Peredo, R., Rodriguez Alvarez X. P., Simoes, T., Zilhao, J., and Craig, O. E. (2020). Latitudinal gradient in dairy production with the introduction of farming in Atlantic Europe. *Nature Communications*, 11(1), 2036.

Çakırlar, C., Breider, R., Koolstra, F., Cohen, K. M. and Raemaekers, D.C.M. (2020). Dealing with domestic animals in the fifth millennium cal BC Dutch wetlands: new insights from old Swifterbant assemblages. In: Gron, K. J., Sørensen, L., Rowley-Conwy, P. (eds.), *Farmers at the Frontier: A Pan-European Perspective on Neolithisation.* Oxbow Books, pp. 263-287.

Deckers, P. H. (1982). Preliminary notes on the neolithic flint material from Swifterbant (Swifterbant contribution 13). *Helinium* 22, 33–39.

Demirci, Ö., Lucquin, A., Craig, O. E., & Raemaekers, D. C. M. (2020). First lipid residue analysis of Early Neolithic pottery from Swifterbant (the Netherlands, ca. 4300–4000 BC). *Archaeological and Anthropological Sciences*, *12*(5), 105.

Demirci, Ö., Lucquin, A., Çakırlar, C., Craig, O. E., & Raemaekers, D. C. M. (2021). Lipid residue analysis on Swifterbant pottery (c. 5000-3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process. *Journal of Archaeological Science: Reports,* 36(3), 102812.

Enghoff, I. B. D. (1994). Fishing in Denmark During the Erteballe Period. *International Journal of Osteoarcbaeology*, 4, 65–96.

Enghoff, I. B. D. (1995). Freshwater fishing at Ringkloster, with a supplement of marine fishes. *Journal of Danish Archaeology*, 12(1), 99–106.

Fischer, A. (2002). Food for Feasting? An evaluation of explanations of the neolithisation of Denmark and southern Sweden. In: Fischer, A. and Kristiansen, K. (eds.), *The Neolithisation of Denmark: 150 Years of Debate*. J. R. Collis Publications, pp. 343–393.

Fischer, A., Olsen, J., Richards, M., Heinemeier, J., Sveinbjörnsdóttir, Á. E., & Bennike, P. (2007). Coast–inland mobility and diet in the Danish Mesolithic and Neolithic: evidence from stable isotope values of humans and dogs. *Journal of Archaeological Science*, 34(12), 2125–2150.

Gotfredsen, A. B. (1998). En rekonstruktion af palæomiljøet omkring tre senmesolitiske bopladser i Store Åmose, Vestsjælland – baseret på pattedyr- og fugleknogler. *Geologisk Tidsskrift*, *2*, 92–103.

Gron, K. J. and Sørensen, L. (2018). Cultural and economic negotiation: a new perspective on the Neolithic Transition of Southern Scandinavia. *Antiquity*, 92(364), pp. 958–974.

Hallgren, F. (2008). Identitet i praktik. In: *Lokala, regionala och överregionala sociala sammanhang inom nordlig trattbägarkultur.* Coast to Coast-books, vol. 17. Uppsala University, Uppsala.

Hartz, S. and Lübke, H. (2006). New Evidence for a Chronostratigraphic Division of the Ertebølle Culture and the Earliest Funnel Beaker Culture on the Southern Mecklenburg Bay. In: Kind, C. J. (ed.), *After the ice age. Settlement, subsistence and social development in the Mesolithic of Central Europe.* Konrad Theiss Verlag, pp. 59-74.

Heron, C., Andersen, S., Fischer, A., Glykou, A., Hartz, S., Saul, H., Steele, V., & Craig, O. (2013). Illuminating the Late Mesolithic: residue analysis of "blubber" lamps from Northern Europe. *Antiquity*, 178–188.

Hofmanová, Z. et al. (2016). Early farmers from across Europe directly descended from Neolithic Aegeans. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(25), 6886–6891.

Huisman, D. J., & Raemaekers, D. C. M. (2014). Systematic cultivation of the Swifterbant wetlands (The Netherlands). Evidence from Neolithic tillage marks (c. 4300–4000 cal. BC). *Journal of Archaeological Science*, *49*, 572–584.

Huisman, D. J., Jongmans, A. G., & Raemaekers, D. C. M. (2009). Investigating Neolithic land use in Swifterbant (NL) using micromorphological techniques. *Catena*, *78*(3), 185–197.

Isaksson, S., & Hallgren, F. (2012). Lipid residue analyses of Early Neolithic funnel-beaker pottery from Skogsmossen, eastern Central Sweden, and the earliest evidence of dairying in Sweden. *Journal of Archaeological Science*, *39*(12), 3600–3609.

Jordan, P. D., & Zvelebil, M. (2009). *Ceramics Before Farming: The Dispersal of Pottery Among Prehistoric Eurasian Hunter-Gatherers*. Left Coast Press.

Kamjan, S., Gillis, R. E., Çakırlar, C., & Raemaekers, D. C. M. (2020). Specialized cattle farming in the Neolithic Rhine-Meuse Delta: Results from zooarchaeological and stable isotope (δ18O, δ13C, δ15N) analyses. *PloS One*, *15*(10), e0240464.

Koch, E. (1998). *Neolithic Bog Pots: From Zealand, Møn, Lolland and Falster*. Copenhagen: Det Kongelige Nordiske Oldskriftselskab.

Kranenburg, H. & Prummel. W. (2020). The use of domestic and wild animals. In: Raeamaekers, D. C. M. & de Roever, J. P. (eds.), *Swifterbant S4 (the Netherlands): Occupation and exploitation of a Neolithic levee site (c. 4300-4000 cal. BC)*. Barkuis (Groningen Archaeological Studies 36), pp. 36–76.

Lazaridis, I., Patterson, N., Mittnik, A., Renaud, G., Mallick, S., Kirsanow, K., Sudmant, P. H., Schraiber, J. G., Castellano, S., Lipson, M., Berger, B., Economou, C., Bollongino, R., Fu, Q., Bos, K. I., Nordenfelt, S., Li, H., de Filippo, C., Prüfer, K., … Krause, J. (2014). Ancient human genomes suggest three ancestral populations for present-day Europeans. *Nature*, *513*(7518), 409–413.

Louwe Kooijmans, L. P. (2010). The ceramisation of the Low Countries, seen as the result of gender-specific processes of communication. In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.), *Pots, Farmers and Foragers: Pottery Traditions and Social Interaction in the Earliest Neolithic of the Lower Rhine Area.* Amsterdam University Press, pp. 27–40.

Malmström, H., Linderholm, A., Lidèn, K., Srora, J., Molnar, P., Hlomund, G., Jakobsson, M. and Götherström, A. (2010). High frequency of lactose intolerance in a prehistoric hunter-gatherer population in northern Europe. *BMC Evolutionary Biology* 10, 89–95.

Malmström, H., Linderholm, A., Skoglund, P., Storå, J., Sjödin, P., Gilbert, M. T. P., Holmlund, G., Willerslev, E., Jakobsson, M., Lidén, K., & Götherström, A. (2015). Ancient mitochondrial DNA from the northern fringe of the Neolithic farming expansion in Europe sheds light on the dispersion process. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *370*(1660), 20130373.

Milner, N., Craig, O. E., Bailey, G. N., Pedersen, K., & Andersen., S. H. (2004). Something fishy in the Neolithic? A re-evaluation of stable isotope analysis of Mesolithic and Neolithic coastal populations. *Antiquity*, *78*(299), 9–22.

Mittnik, A., Wang, C.-C., Pfrengle, S., Daubaras, M., Zariņa, G., Hallgren, F., Allmäe, R., Khartanovich, V., Moiseyev, V., Tõrv, M., Furtwängler, A., Andrades Valtueña, A., Feldman, M., Economou, C., Oinonen, M., Vasks, A., Balanovska, E., Reich, D., Jankauskas, R., Haak, W., Schiffels, S., Krause, J. (2018). The genetic prehistory of the Baltic Sea region. *Nature Communications*, *9*(1), 442.

Noe-Nygaard, N., Price, T. D., & Hede, S. U. (2005). Diet of aurochs and early cattle in southern Scandinavia: evidence from 15N and 13C stable isotopes. *Journal of Archaeological Science*, *32*(6), 855–871.

Out, W. A. (2008a). Selective use of Cornus sanguinea L. (red dogwood) for Neolithic fish traps in the Netherlands. *Environmental Archaeology*, *13*(1), 1–10.

Out, W. A. (2008b). Neolithisation at the site Brandwijk-Kerkhof, the Netherlands. *Vegetation History and Archaeobotany* 17: 25–39.

Out, W. A. (2009). *Sowing the Seed: Human impact and plant subsistence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC).* Dissertation Leiden University.

Oversteegen, J. F. et al. (2001). Zoogdieren, vogels, reptielen. In: Louwe-Kooijmans, L. P. (ed.), *Hardinxveld-Giessendam De Bruin: Een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.).* Amersfoort, pp. 209–298.

Papakosta, V., Oras, E., & Isaksson, S. (2019). Early pottery use across the Baltic – A comparative lipid residue study on Ertebølle and Narva ceramics from coastal hunter-gatherer sites in southern Scandinavia, northern Germany and Estonia. *Journal of Archaeological Science: Reports*, *24*, 142–151.

Prangsgaard, K. (1992). Introduktion af Keramik i den yngre Ertebolle-Kultur i Sydskandinavien, *LAG* 3, 29-52.

Raemaekers, D. C. M. (1997). The History of the Ertebølle Parallel in Dutch Neolithic Studies and the Spell of the Point-Based Pottery1. *Archaeological Dialogues*, *4*(2), 220–234.

Raemaekers, D. C. M. (1998). Ertebølle and Swifterbant: a comparison of attitudes. Anthropologie et Préhistoire 109:155–161.

Raemaekers, D. C. M. (1999). *The articulation of a "New neolithic".* Dissertation University of Leiden.

Raemaekers, D.C. M. (2001a). Aardewerk en verbrande klei. In: Louwe Kooijmans, L.P. (ed.), *Hardinxveld-Giessendam Polderweg. Een mesolithisch jachtkamp in het rivierengebied (5500-5000 v. Chr.)*, Amersfoort (Rapportage Archeologische Monumentenzorg 83), 105-118.

Raemaekers, D. C. M. (2001b). Aardewerk en verbrande klei. In: Louwe Kooijmans, L.P.(ed.), *Hardinxveld-Giessendam De Bruin. Een kampplaats uit het laatmesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.)*, Amersfoort (Rapportage Archeologische Monumentenzorg 88), 117-152.

Raemaekers, D. C. M. (2003). Cutting a long story short? The process of neolithization in the Dutch delta re-examined. *Antiquity 77*, 780-789.

Raemaekers, D. C. M. (2015). Rethinking Swifterbant S3 ceramic variability. Searching for the transition to TRB before 4000 cal BC. In: Kabacinski, J., Hartz, S., Raemaekers, D. C. M., Terberger, T. (eds), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000–3000 calBC).* Verlag Marie Leidorf GmbH (Archäologie und Geschichte im Ostseeraum), pp. 321–334.

Raemaekers, D. C. M. and de Roever, J. P. (2010). The Swifterbant pottery tradition (5000-3400 BC). In: Vanmontfort, B., Louwe Kooijmans, L., Amkreutz, L., Verhart, L. (eds.) *Pots, Farmers and*

Foragers. Pottery traditions and social interaction in the earliest Neolithic of the Lower Rhine Area. Leiden University Press, pp. 135-149.

Raemaekers, D. C. M., & de Roever, J. P. (2020). *Swifterbant S4 (the Netherlands): Occupation and exploitations of a Neolithic levee site (c. 4300-4000 cal. BC)*. Barkhuis Publishing, Groningen.

Richards, M., Price, T. D. and Koch, E. (2003). Mesolithic and Neolithic Subsistence in Denmark: New Stable Isotope Data. *Current anthropology*, 44(2), pp. 288–295.

Robson, H. (2015). *Evaluating the change of consumption and culinary practices at the transition to agriculture: a multi-disciplinary approach from a Danish kitchen midden*. Unpublished Dissertation University of York.

Robson, H. K., Saul, H., Steele, V. J., Meadows, J., Nielsen, P. O., Fischer, A., Heron, C. P., & Craig, O. E. (2021). Organic residue analysis of Early Neolithic "bog pots" from Denmark demonstrates the processing of wild and domestic foodstuffs. *Journal of Archaeological Science: Reports*, *36*, 102829.

de Roever, J. P. (1979). The Pottery from Swifterbant- Dutch Ertebølle? (Swifterbant Contribution 9). *Helinium*, *19*, 13–39.

de Roever, J. P. (2004). *Swifterbant aardewerk : Een analyse van de neolithische nederzettingen bij Swifterbant 5e millennium voor Christus* (Louwe Kooijmans, L.& Reinders, H. R. (eds.)) Dissertation University of Groningen. https://doi.org/10.1163/1877-5888_rpp_sim_09064

Rowley-Conwy, P. (2013). North of the frontier: Early domestic animals in Northern Europe. In: Colladge, S., Conolly, J., Dobney, K., Manning, K., Shennan, S. (eds.), *The Origins and spread of domestic animals in southwest Asia and Europe*. Left Cost Press, pp. 283–311.

Schepers, M. & Bottema-Mac Gillavry, N. (2020). The vegetation and exploitation of plant resources. In: Raemaekers, D.C.M., de Roever, J.P. (eds.), *Swifterbant S4 (the Netherlands) Occupation and exploitation of a neolithic levee seite (c. 4300-4000 cal. BC)*. Barkhuis Publishing, pp. 51–75.

Stapel, B. (1991). *Die geschlagenen Steingerdte der Siedlung Htide I am Diimmer, Hannover* (Veroffentlichungen der urgeschichtlichen Sammlungen des Landesmuseum zu Hannover 38).

Stilborg, O. (1999) Dutch Swifterbant and Swedish Ertebølle: a debate on regionality and ceramic analysis. *Archaeological Dialogues* 6(1): 47–54.

Sørensen, L. & Karg, S. (2014). The expansion of agrarian societies towards the north – new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. *Journal of archaeological science*, 51, 98–114.

van Der Waals, J. D. (1972). Die durchlochten rössener Keile und das frühe Neolithikum in Belgien und in den Niederlanden. *Fundamenta A*3: 154-184.

Van Wijngaarden-Bakker, L. H., Cavallo, C., van Kolfschoten, T., Maliepaard, C. H., Oversteegen, J. F. S. (2001). Zoogdieren, vogels, reptielen. In: Louwe-Kooijmans, L. P. (ed.), *Hardinxveld-Giessendam Polderweg: Een mesolithisch jachtkamp in het rivierengebied (5500-5000 v. Chr.).* Amersfoort, pp. 181–242.

Tauber, H. (1981). Analysis of stable isotopes in prehistoric populations. In: Bernd, H. (ed.), *Innovative Trends in der pra¨historischen Anthropologie*. Mitteilungen der Berliner Gesellschaft für Anthropologie, Ethnologie und Urgeschichte, pp. 731-738.

ten Anscher, T. J. (2012). *Leven met de Vecht: Schokland-P14 en de Noordoostpolder in het neolithicum en de bronstijd*. Dissertation University of Amsterdam.

ten Anscher, T. J. (2015). Under the radar: Swifterbant and the origins of the Funnel Beaker culture. In: Kabaciński, J., Hartz, S., Raemaekers, D. C. M., Terberger, T. (ed.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000–3000 calBC)*, Verlag Marie Leidorf GmbH. Rahden/Westf., pp. 335–358.

Terberger, T., Hartz, S., Kabaciński, J. (2009). Late hunter-gatherer and early farmer contacts in the southern Baltic – a discussion. In: Glørstad, H., Prescott, C. (eds). *Neolithisation as if history mattered: process of neolithisation in North-Western Europe*, Uddevalla, Sweden: Bricoleur Press, pp. 257–298.

Zeiler, J. T. (1997). *Hunting, fowling and stock-breeding at Neolithic sites in the western and central Netherlands*. Dissertation Groningen University.

Zeiler, J. T. (2006). Mammals. In: Louwe Kooijmans, L. P., Jongste, P. F. B (eds), *Schipluiden, a Neolithic Settlement on the Dutch North Sea Coast c. 3500 cal BC*). Leiden: Leiden University (Analecta Praehistorica Leidensia 37/38), pp. 375–420.

Authors' contributions (%)

Özge Demirci:

Conceptualization	80%
Formal analysis (lab work)	60%
Investigation (data analysis)	60%
Visualization of data	95% (also see Acknowledgements)
Writing - original draft	92%
Writing - review & editing	85%

Harry K. Robson:

Conceptualization	10%
Formal analysis (lab work)	40%
Investigation (data analysis)	30%
Visualization of data	5% (also see Acknowledgements)
Writing - review & editing	5%

Alexandre Lucquin:

Investigation (data analysis)	5%

Søren H. Andersen:

Investigation (data analysis)	5%

Daan C. M. Raemaekers:

Conceptualization	5%
Validation	50%
Supervision	40%
Project administration	50%
Funding acquisition	50%
Writing - original draft	3%
Writing - review & editing	5%

Oliver E. Craig:

Conceptualization	5%
Validation	50%
Supervision	60%

Project administration	50%
Funding acquisition	50%
Writing - original draft	5%
Writing - review & editing	5%

SUPPLEMENTARY MATERIAL

(SUPPLEMENTARY DATASET-1, 2, 3)

for

Fusion cuisine: the impact of farming on hunter-gatherer culinary traditions in Northern Europe

Özge Demirci, Harry K. Robson, Alexandre Lucquin, Søren H. Andersen, Daan C.M. Raemaekers & Oliver E. Craig

Supplementary Material Dataset-1: Ertebølle samples: general information

sample ID	sample name	Pre-treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel typology	Vessel part
B001	KML 50.0/75.5:8i	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Interior rim
B002	KML 49.5/77.0:113i	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Body
B003	KML 49.5/77.0:113f	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B004	KML 49.5/78.0:49i	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Body
B005	KML 49.5/78.0:49f1+2	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B006	KML 50.0/75.5:84i	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Body
B007	KML 50.0/75.5:84f	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B008	KML 50.0/77.0:155i	SE	Åkonge	Late Mesolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B010	1592_ARSBW	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B011	1592_ACETIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B012	1592_CJBIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B013	1592_VGIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B014	1592_EAJJIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B015	1592_ACFEIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B016	1592_ACCSIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B017	1592_ADSYIM	SE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B151	1592_AAALA	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B163	1592_AACAV	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B169	1592_AADNV	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B170	1592_AADRY	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B171	1592_AADSY	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B172	1592_AADYS	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B173	1592_AAEEV	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B174	1592_AAOYQ	AE	Ringkloster	Late Mesolithic	Skanderborg Lake	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	
B055	ST_X087_007i	SE	Stenø	Late Mesolithic	North Zealand	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Body
B056	ST_X095_039i	SE	Stenø	Late Mesolithic	North Zealand	Denmark	Inland	Waterlogged settlement	Ertebølle	4600-4000	Cooking pot	Pointed based vessel	Neck

Supplementary Material Dataset-1: Funnel Beaker samples: general information

sample ID	sample name	Pre-treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel typology	Vessel part
KLM01	KML Peter's Poti	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-0	Whole vessel
KLM02	KML 49.5/77.0:18i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-0	
KLM03	KML 49.5/74.0:127i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Rim
KLM04	KML 49.5/76.5:9i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Fragment
KLM05	KML 49.5/77.0:26i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Rim
KLM06	KML 49.5/77.5:80i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Body
KLM07	KML 50.0/74.0:12i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Rim
KLM08	KML 50.0/74.0:9i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Interior body
KLM09	KML 50.0/76.0:8i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Interior rim
KLM10	KML 50.0/76.0:98i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	
KLM11	KML 50.0/77.5:10i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Interior body
KLM12	KML 50.0/78.5:11i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Body
KLM13	KML 50.0/77.0:155i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Body
KLM14	KML 49.5/7.70:18i	SE	Åkonge	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Rim
FL01	FL_2i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL02	FL_5i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL03	FL_6i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL04	FL_7i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL05	FL_9i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL06	FL_10i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL07	FL_11i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL08	FL_12i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL09	FL_13i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
FL10	FL_14i	AE	Flintbek LA 3	Early Neolithic	Schleswig-Holstein	Germany	Inland	Tumulus	Funnel Beaker	3629-3379	Cooking pot	Cooking pot	
NM01	NM I A 40764fa	SE	Jordløse Mose VIII	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; MN A V	
NM02	NM I A 40871fa (food crust - M 39114)	SE	Jordløse Mose XV	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-III	
NM03	NM I A 40884f	SE	Jordløse Mose XX	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-III	
NM04	NM I A 40882i	SE	Jordløse Mose XX	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
NM05	NM I A 40883f	SE	Jordløse Mose XX	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-III	

Supplementary Material Dataset-1 (continues): Funnel Beaker samples: general information

sample ID	sample name	Pre-treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel typology	Vessel part
NM06	NM I A 40883i	SE	Jordløse Mose XX	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-III	
NM07	NM I A 40220i	SE	Jordløse Mose XXI	Early Neolithic	Lille Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Flat open bowl	
NM08	NM I A 49819i	SE	Maglelyng 2	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Lugged flask	
NM09	NM I A 49818i	SE	Maglelyng 2	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
NM10	NM I A 49818i	SE	Maglelyng 2	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
NM11	NM I A 44340da (food crust - M 39111)	SE	Maglelyng 3	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-IV	
NM12	NM I A 40211f	SE	Målevgård Mose	Early Neolithic	Københavns Amt	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-I	
NM13	NM I A 40211i	SE	Målevgård Mose	Early Neolithic	Københavns Amt	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-I	
NM14	Neverkæra+b	AE	Neverkær Mose	Early Neolithic	Fyn	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker, Type III	Body
NM15	NM I A 51879fa (at NM VIII the vessel is called vessel S)	SE	Øgårde 3 (kar S)	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
NM16	NM I A 51872fa (at NM VIII the vessel is called vessel A); M54867a	SE	Øgårde 5 (kar A)	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
NM17	NM I A 53073fa+b	SE	Salpetermosen	Early Neolithic	Frederiksborg Amt	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-VI	
NM18	NM I A 54875a (Vessel A at NM VIII)	SE	Tingbjerggård T1	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type VIII	
NM19	NM I A 43323fa (food crust - M 39113)	SE	Ulkestrup Lyng	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged find spot	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker; Type-II	
SK01	1		Skogsmossen	Early Neolithic	Mälaren	Sweden	Inland	Waterlogged offering fen	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker	
SK02	4		Skogsmossen	Early Neolithic	Mälaren	Sweden	Inland	Waterlogged offering fen	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker	
SK03	5		Skogsmossen	Early Neolithic	Mälaren	Sweden	Inland	Waterlogged offering fen	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker	
SK04	7		Skogsmossen	Early Neolithic	Mälaren	Sweden	Inland	Waterlogged offering fen	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker	
SK05	8		Skogsmossen	Early Neolithic	Mälaren	Sweden	Inland	Waterlogged offering fen	Funnel Beaker	3900-3500	Cooking pot	Funnel Beaker	
ST01	ST_X036_096i	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	Body sherd
ST02	ST_X082_015i	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Bowl	Body sherd
ST03	ST_X082_015e	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Bowl	Body sherd
ST04	ST_X122_105i	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	
ST05	ST_X177_091i	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	
ST06	ST_X177_092i	SE	Stenø	Early Neolithic	Store Åmose	Denmark	Inland	Waterlogged settlement	Funnel Beaker	3900-3500	Cooking pot	Funnel beaker	

Supplementary Material Dataset-1: Swifterbant samples: general information

sample ID	Pre treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel part	Decoration
HR-01	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	rim	yes
HR-02	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	base	no
HR-03	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	body	no
HR-04	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	rim	yes
HR-05	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	body	no
HR-06	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	rim	no
HR-07	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	rim	no
HR-08	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	body	no
HR-09	AE	Polderweg	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5050-4950	Cooking pot	body	no
HR-10	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	body	no
HR-11	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	body	no
HR-12	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	body	no
HR-13	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	no
HR-14	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	yes
HR-15	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	body	no
HR-16	AE	De Bruin	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5100-4800	Cooking pot	rim	yes
HR-17	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	no
HR-18	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	yes
HR-19	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	yes
HR-20	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	yes
HR-21	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	no
HR-22	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	no
HR-23	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	base	no
HR-25	AE	De Bruin	Phase 2	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	5100-4800	Cooking pot	base	no
HR-26	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	base	no
HR-27	AE	De Bruin	Phase 3	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4700-4450	Cooking pot	rim	yes
HD-01	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	rim	yes
HD-03	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	body	yes
HD-05	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	body	no
HD-07	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	body	yes
HD-09	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	rim	yes
HD-11	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	body	no
HD-13	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	rim	no
HD-15	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	rim	yes
HD-17	AE	Hazendonk	1	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4020-3960	Cooking pot	rim	no

Supplementary Material Dataset-1 (continues): Swifterbant samples: general information

sample ID	Pre treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel part	Decoration
BR-01	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-03	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-06	AE	Brandwijk	L60	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	3940-3820	Cooking pot	rim	no
BR-08	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-10	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-12	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	no
BR-14	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	body	yes
BR-16	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	body	yes
BR-18	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	base	no
BR-20	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	body	yes
BR-22	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-24	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-26	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	rim	yes
BR-28	AE	Brandwijk	L50	Lower Rhine-Meuse area	Netherlands	Inland	Waterlogged settlement	Swifterbant	4220-3940	Cooking pot	body	yes
S2-01	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-03	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-06	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-08	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-10	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S2-15	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-17	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	

Supplementary Material Dataset-1: Swifterbant samples: general information (continues)

sample ID	Pre treatment	Site	Phase/period	Region	Country	Location	Site type	Cultural group	Date (cal BC)	Vessel type	Vessel part	Decoration
S2-17	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S2-19	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S2-20	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S2-21	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S2-22	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S2-23	AE	Swifterbant S2		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S3-03	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S3-05	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S3-12	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S3-14	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S3-16	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S3-28	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S3-30	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S3-34	AE	Swifterbant S3		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-01	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-02	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S4-03	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-06	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-07	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-08	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	base	
S4-09	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-11	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-12	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-13	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-14	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-15	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-16	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-17	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-18	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-19	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-20	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-21	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-23	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-24	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	
S4-25	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	rim	
S4-26	AE	Swifterbant S4		Swifterbant	Netherlands	Inland	Waterlogged settlement	Swifterbant	4300-4000	Cooking pot	body	

Supplementary Material Dataset-1: Ertebølle samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	Sample type	%C	δ13C	sd	%N	δ15N	sd	C/N ratio	d13C offset	Reference
B001	Potsherd	Interior	>5	-30.4	-33.7	-3.3		n/a	-		-										Craig et al. 2011
B002	Potsherd	Interior	>5	-29.8	-32.5	-2.7		n/a	-		-										Craig et al. 2011
B003	Charred deposit	Interior	>100	-31	-32.3	-1.3		n/a	-		x	foodcrust	31.3	-29.6	0.4	4.4	7.3	0.2	8.3	2.1	Robson 2015
B004	Potsherd	Interior	>5	-29.5	-33.3	-3.8	APAA (C16-22), tmtd, Pri, Phy	n/a	x		-										Craig et al. 2011
B005	Charred deposit	Interior	>100	-29.3	-32.4	-3.1		n/a	-		x	foodcrust	17.5	-28.1	0	2.5	7.3	0.3	8.3	2.7	Robson 2015
B006	Potsherd	Interior	>5	-30.9	-33	-2.1	Phy	n/a	-		-										Craig et al. 2011
B007	Charred deposit	Interior	>100	-30.5	-34.3	-3.8		n/a	-		x	foodcrust	27.2	-27.5	0.1	4.6	7.7	0.2	6.9	4.9	Robson 2015
B008	Potsherd	Interior	>5	-29.9	-33.6	-3.7		n/a	-		-										Robson 2015
B010	Potsherd	Interior	>5	-27.1	-26.4	0.8		n/a	-		-										Robson 2015
B011	Potsherd	Interior	>5	-31.7	-31.7	0		n/a	-		-										Robson 2015
B012	Potsherd	Interior	>5	-29.5	-30.1	-0.6		n/a	-		-										Robson 2015
B013	Potsherd	Interior	>5	-27.4	-29.2	-1.8		n/a	-		-										Robson 2015
B014	Potsherd	Interior	>5	-26.4	-32.6	-6.2		n/a	-		-										Robson 2015
B015	Potsherd	Interior	>5	-26.1	-28.8	-2.7		n/a	-		-										Robson 2015
B016	Potsherd	Interior	>5	-25.5	-25.3	0.2		n/a	-		-										Robson 2015
B017	Potsherd	Interior	>5	-21.4	-29.5	-8.1		n/a	-		-										Robson 2015
B151	Potsherd	Interior	4.7	-29.2	-31.5	-2.3	TMTD, Pri, Phy	51.7	-		-										Courel et al. 2020
B163	Potsherd	Interior	15.4	-29.4	-29.7	-0.3	APAA (C16-22), tmtd, Pri, Phy	47.8	x		-										Courel et al. 2020
B169	Potsherd	Interior	14.1	-30.1	-29.3	0.8	APAA (C18-20), tmtd, Pri, Phy	42.9	x		-										Courel et al. 2020
B170	Potsherd	Interior	1.6	-27.5	-27.2	0.3	APAA (C18-20), tmtd, Pri, Phy	57.2	x		-										Courel et al. 2020
B171	Potsherd	Interior	60.6	-28	-28.6	-0.7	APAA (C16-20), tmtd, Pri, Phy	46.7	x		-										Courel et al. 2020
B172	Potsherd	Interior	5.5	-22.9	-23.2	-0.2	APAA (C16-22), tmtd, Pri, Phy	43.3	x		-										Courel et al. 2020
B173	Potsherd	Interior	9.7	-30.7	-33.7	-3	APAA (C18), tmtd, Pri, Phy	39.8	-		-										Courel et al. 2020
B174	Potsherd	Interior	6.9	-30.6	-31.3	-0.7	APAA (C16-20), tmtd, Pri, Phy	45.9	x		-										Courel et al. 2020
B055	Potsherd	Interior	>5	-28.3	-28.5	-0.2		n/a	-		-										Robson 2015
B056	Potsherd	Interior	>5	-26.6	-31.3	-4.7		n/a	-		-										Robson 2015

Supplementary Material Dataset-1 (continues): Funnel Beaker samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	Sample type	%C	δ13C	%N	δ15N	C/N ratio	d13C offset	Reference
KLM01	Potsherd	Interior	>5	-30.5	-33.8	-3.3		n/a	-		-								Craig et al. 2011
KLM02	Potsherd	Interior	>5	-29.9	-33.7	-3.8		n/a	-		-								Craig et al. 2011
KLM03	Potsherd	Interior	>5	-29	-32	-3		n/a	-		-								Craig et al. 2011; Saul 2011
KLM04	Potsherd	Interior	>5	-30.2	-30.6	-0.4		n/a	-		-								Craig et al. 2011; Saul 2011
KLM05	Potsherd	Interior	>5	-30.3	-31.7	-1.4		n/a	-		-								Craig et al. 2011
KLM06	Potsherd	Interior	>5	-29.2	-31	-1.8		n/a	-		-								Craig et al. 2011; Saul 2011
KLM07	Potsherd	Interior	>5	-29.7	-31.4	-1.7	APAA (C16-22(tr)), tmtd, Phy	n/a	x		-								Craig et al. 2011; Saul 2011
KLM08	Potsherd	Interior	>5	-30.1	-31.2	-1.1		n/a	-		-								Craig et al. 2011; Saul 2011
KLM09	Potsherd	Interior	>5	-29.9	-33.4	-3.5		n/a	-		-								Craig et al. 2011; Saul 2011
KLM10	Potsherd	Interior	>5	-28	-30.5	-2.5		n/a	-		-								Craig et al. 2011; Saul 2011
KLM11	Potsherd	Interior	>5	-29.4	-30.4	-1		n/a	-		-								Craig et al. 2011; Saul 2011
KLM12	Potsherd	Interior	>5	-29.1	-33.2	-4.1		n/a	-		-								Craig et al. 2011; Saul 2011
KLM13	Potsherd	Interior	>5	-29.9	-33.6	-3.7		n/a	-		-								Robson 2015
KLM14	Potsherd	Interior	>5	-29.9	-33.7	-3.8		n/a	-	FAs (C9:0-C34:0), UFA, DA, Phy, Chol, Kets (C33, C35)	-								Cubas et al. 2020
FL01	Potsherd	Interior	1633.2	-29.1	-32.4	-3.3	APAA (C18), tmtd, pri, phy	56.4	-		-								Robson unpublished
FL02	Potsherd	Interior	164.6	-28.9	-32.8	-3.8	tmtd, pri, phy	57.4	-		-								Robson unpublished
FL03	Potsherd	Interior	98.7	-27.7	-28.7	-1	tmtd, pri, phy	49.4	-		-								Robson unpublished
FL04	Potsherd	Interior	1577	-29.5	-33.7	-4.2	APAA (C16-C18), tmtd, pri, phy	51.6	-		-								Robson unpublished
FL05	Potsherd	Interior	524.2	-29.1	-33.7	-4.7	tmtd, pri, phy	55.2	-		-								Robson unpublished
FL06	Potsherd	Interior	52.4	-28.6	-29.5	-0.9	tmtd, pri, phy	55.4	-		-								Robson unpublished
FL07	Potsherd	Interior	533.3	-28.8	-30.8	-2	tmtd, pri, phy	55.2	-		-								Robson unpublished
FL08	Potsherd	Interior	972.5	-27.4	-31.9	-4.6	APAA (C16-C18), tmtd, pri, phy	72.5	-		-								Robson unpublished
FL09	Potsherd	Interior	1325	-28.9	-31.8	-2.9	tmtd, phy	54.8	-		-								Robson unpublished
FL10	Potsherd	Interior	1185.5	-28.4	-33.5	-5.2	APAA (C18), tmtd, phy	61.5	-		-								Robson unpublished
NM01	Charred deposit	Interior	>100	-29.7	-33	-3.3		n/a	-		x	foodcrust	55.5	-27.1	8.1	9.1	8	4.3	Craig et al. 2007; Koch 1998
NM02	Charred deposit	Interior	>100	-28.1	-32.5	-4.4		n/a	-		x	foodcrust	47.5	-25.7	4.3	6.7	12.9	4.6	Craig et al. 2007; Koch 1998
NM03	Charred deposit	Interior	>100	-30.3	-31.3	-1	APAA (C18)	n/a	-	FAs (C6:0-C22:0), UFA, DA, glycerol, MAGs, Chol	x	foodcrust	29.3	-26.3	4.3	9.4	7.9	4.5	Cubas et al. 2020
NM04	Potsherd	Interior	>5	-32.6	-33.1	-0.5	APAA (C18-C22), tmtd, Phy	n/a	x	FAs (C6:0-C32:0), UFA, DA, HFAs, Chol, MAGs	-								Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
NM05	Charred deposit	Interior	>100	-30.3	-31.2	-0.9	APAA (C16-C22), tmtd, Phy	n/a	x	FAs (C6:0-C32:0), UFA, DA, Alk, MAGs, Alc, Ket (C31),	x	foodcrust	45.1	-27.4	4	6.1	13.2	3.4	Cubas et al. 2020; Fischer 2002; Koch 1998; Robson 2015;

Supplementary Material Dataset-1 (continues): Funnel Beaker samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	type	%C	δ13C	%N	δ15N	C/N ratio	d13C offset	Reference
NM06	Potsherd	Interior	>5	-31.3	-33	-1.7	APAA (C16-C22), tmtd, Phy	n/a	x	FAs (C6:0-C32:0), UFA, Alks, DA, HFAs, Alc, Chol, MAGs,	-								Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
										Ket (C31), Terp, Dehydroabietic acid,	-								Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
NM07	Potsherd	Interior	>5	-27.6	-29.8	-2.2	Phy	n/a	-	FAs (C6:0-C30:0), UFA, Alk, Alcs, MAGs, Terp,	-								Cubas et al. 2020
										Dehydroabietic acid	-								Koch 1998; Robson 2015; Robson et al. 2021
NM08	Potsherd	Interior	>5	-31.9	-32.5	-0.6	APAA (C18), tmtd, Phy	n/a	-	FAs (C6:0-C32:0), UFA, Alks, DA, HFAs, diHFAs, MAGs,	-								Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
										DAGs, Chol, Sit, Ket (C31-C33)	x	Exterior sooted crust	60.2	-28.8	9.5	9.5	7.4	4.5	Craig et al. 2007; Koch 1998
NM09	Potsherd	Interior	>5	-29.3	-33.3	-4		n/a	-										
NM10	Potsherd	Interior	>5	-31.5	-32.4	-0.9	APAA (C18-C22), tmtd, Phy	n/a	x	FAs (C6:0-C32:0), UFA, Alk, HFAs, Ket (C31- C 35), Chol	x	foodcrust	47.5	-28.1	5.3	6.5	10.5	1.9	Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
NM11	Charred deposit	Interior	>100	-32.8	-33.7	-0.9		n/a	-										
NM12	Charred deposit	Interior	>100	-28.6	-31.3	-2.7	APAA (C18), Phy	n/a	-	FAs (C7:0-C28:0), UFA, DA, Alks (23-25), HFAs, diHFAs,	-								Cubas et al. 2020; Koch 1998; Robson 2015; Robson et al. 2021
										MAGs, Chol, dehydroabietic acid, didehydroabietic acid									
NM13	Potsherd	Interior	>5	-29.2	-31.4	-2.2	APAA (C18), Phy	n/a	-	FAs (C6:0-C34:0), UFA, DA, Alk, HFAs, diHFAs, MAGs, DAGs, Terp, Dehydroabietic acid, Chol, Ket (C29-C35)	x	foodcrust	49.8	-27.3	7	6.6	8.3	3.7	Cubas et al. 2020
NM14	Charred deposit	Interior	436.1	-30.7	-31.3	-0.6	APAA (tr. C16, tr. C18), Phy	50	-	FAs (C14:0-C26:0), UFA	x	foodcrust	78.7	-27.5	9.9	6.4	9.3	3.7	Craig et al. 2007; Koch 1998
NM15	Charred deposit	Interior	>100	-29.5	-32.8	-3.3		n/a	-		x	foodcrust	49.3	-26.3	6	4.5	9.6	5.3	Craig et al. 2007; Koch 1998
NM16	Charred deposit	Interior	>100	-28.5	-34.7	-6.2		n/a	-		x	foodcrust	63.7	-27.3	0.8	1.1	92.9		Craig et al. 2011; Robson 2015; Robson et al. 2021
NM17	Charred deposit	Interior	>100	-26.8	-26	0.8		n/a	-		x	foodcrust	49.9	-25.9	20.2	1	2.9	4.7	Craig et al. 2007; Koch 1998; Robson et al. 2021
NM18	Charred deposit	Interior	>100	-30.6	30.6			n/a	-		x	foodcrust	40.7	-27.5	7.4	8	6.4	5.8	Craig et al. 2007; Koch 1998; Robson 2015; Robson et al. 2021
NM19	Charred deposit	Interior	>100	-32.8	-33.7	-0.9		n/a	-		-								Isaksson and Hallgren 2012
SK01	Potsherd	Interior	110	-26.5	-29.1	-2.6	tmtd tr.	n/a	-		-								Isaksson and Hallgren 2012
SK02	Potsherd	Interior	4220	-31.4	-39.3	-7.9		n/a	-		-								Isaksson and Hallgren 2012
SK03	Potsherd	Interior	350	-25.5	-25	0.5	APAA (C16-22), tmtd	n/a	x		-								Isaksson and Hallgren 2012
SK04	Potsherd	Interior	6430	-28.4	-34.6	-6.2	APAA (C18), tmtd	n/a	-		-								Isaksson and Hallgren 2012
SK05	Potsherd	Interior	620	-28.3	-35.2	-6.9	APAA (C18), tmtd	n/a	-		-								Cubas et al. 2020
ST01	Potsherd	Interior	>5	-25	-22.6	2.4		n/a	-		-								Cubas et al. 2020
ST02	Potsherd	Interior	>5	-28	-31.8	-3.8	APAA (C18), Phy	n/a	-	FAs (C10:0-C26:0), UFA, Alks, MAGs, DAGs, Kets (C31-C35), Chol	-								Cubas et al. 2020
ST03	Potsherd	Exterior	>5	-28	-31.4	-3.4	APAA (C16-C20), Phy	n/a	-	FAs (C12:0-C24:0), UFA, Alks, MAGs, DAGs, Alcs,	-								Cubas et al. 2020; Robson 2015; Saul 2011
										Alkes (16-24), Chol	-								Cubas et al. 2020; Robson 2015; Saul 2011
ST04	Potsherd	Interior	>5	-26.2	-28.1	-1.9	TMTD	n/a	-	FAs (C12:0-C24:0), UFA, Alks, Phytane	-								Cubas et al. 2020
ST05	Potsherd	Interior	>5	-28.8	-29.5	-0.7		n/a	-	FAs (C12:0-C18:0), UFA, Alks, Alkes, Chol, MAGs, Alcs									

Supplementary Material Dataset-1: Swifterbant samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	Sample type	%C	δ13C	%N	δ15N	C/N ratio	d13C offset	Reference
HR-01	Potsherd	Interior	203	1.4	-28.2	-28.7	-0.5	APAA (C16-22), tmtd, pri, phy	94.9	x	SFA(C13:0-22:0), UFA(C16:1,17:1,18:1), DC(C9:0), br	-								Demirci et al. 2021
HR-02	Potsherd	Interior	594	1	-33.2	-33.9	-0.7	APAA (C16-20), phy	68.6	x		-								Demirci et al. 2021
HR-03	Potsherd	Interior	58	1.1	-30	-30.3	-0.2	APAA (C16-20), tmtd, phy	93.6	x	SFA(C14:0-20:0), UFA(C18:1,22:1), br, chol	-								Demirci et al. 2021
HR-04	Potsherd	Interior	45	1	-29.8	-30.4	-0.6	APAA (C16-18), tmtd, phy	69.2	-	SFA(C14:0-20:0), UFA(C18:1), br	x	foodcrust	46.3	-26.5	4.5	9.8	12	3.6	Demirci et al. 2021
HR-05	Potsherd	Interior	791	1.7	-34.5	-34.6	-0.2	APAA (C16-18)	n/a	-	SFA(C11:0-24:0), UFA(C18:1), DC(C9:0,10:0), br	x	foodcrust	50.7	-28.8	8.4	11	7.1	5.8	Demirci et al. 2021
HR-06	Potsherd	Interior	117	1.2	-28.7	-29.3	-0.6	APAA (C16-22), tmtd, pri, phy	86.7	x	SFA(C12:0-22:0), UFA(C16:1,18:1,20:1,22:1), DC(C9:0), br	-								Demirci et al. 2021
HR-07	Potsherd	Interior	101	1.4	-28.2	-29.4	-1.2	APAA (C16-22), phy	n/a	x	SFA(C13:0-20:0), UFA(C16:1,18:1,22:1), DC(C9:0), br	-								Demirci et al. 2021
HR-08	Potsherd	Interior	14	1.3	-31.6	-30.8	0.8	phy	89.8	-		x	foodcrust	42.6	-28.3	6.9	9.1	7.2	2.9	Demirci et al. 2021
HR-09	Potsherd	Interior	13	1	-29.8	-30.1	-0.3	tmtd	n/a	-	SFA(C14:0-24:0), UFA(C16:1,18:1), br	-								Demirci et al. 2021
HR-10	Potsherd	Interior	186	1.3	-30.7	-30.2	0.4	APAA (C16-22), phy	72.4	x	SFA(C12:0-24:0), UFA(C16:1, 18:1), DC(C9:0), br	x	foodcrust	49.2	-27.4	6.6	9.4	8.7	3	Demirci et al. 2021
HR-11	Potsherd	Interior	8	0.8	-29.1	-30.1	-1	tmtd, phy	76.8	-	SFA(C14:0-20:0), br	x	foodcrust	57.8	-26.9	5.9	8.4	11.4	2.7	Demirci et al. 2021
HR-12	Potsherd	Interior	22	1.2	-28.1	-29.5	-1.4	tmtd, pri, phy	31.7	-	SFA(C14:0-20:0), br	-								Demirci et al. 2021
HR-13	Potsherd	Interior	26	1	-28.8	-29.9	-1.2	tmtd, phy	51.2	-	SFA(C14:0-24:0), br	-								Demirci et al. 2021
HR-14	Potsherd	Interior	15	1.3	-27.8	-29.5	-1.7	tmtd, phy	35.8	-	SFA(C14:0-18:0), br	-								Demirci et al. 2021
HR-15	Potsherd	Interior	77	1.8	-32.6	-32.5	0.1	APAA (C18-20), tmtd, pri, phy	86.8	x	SFA(C14:0-24:0), UFA(C16:1,18:1), DC(C9:0), br, chol	-								Demirci et al. 2021
HR-16	Potsherd	Interior	414	0.7	-30.6	-32.8	-2.2	APAA (C18-20), tmtd, phy	n/a	x	SFA(C11:0-23:0), DC(C9:0), br, chol	-								Demirci et al. 2021
HR-17	Potsherd	Interior	42	0.9	-29.3	-30.2	-0.9	APAA (C16-18), tmtd, phy	49.3	-	SFA(C14:0-24:0), UFA(C18:1), br	-								Demirci et al. 2021
HR-18	Potsherd	Interior	28	1	-29.4	-30.3	-0.9	APAA (C18-20), tmtd, phy	69.8	x	SFA(C14:0-20:0), UFA(C18:1), DC(C9:0)	-								Demirci et al. 2021
HR-19	Potsherd	Interior	39	1.5	-27.3	-28.6	-1.3	APAA (C18-20), tmtd, phy	76.4	x	SFA(C13:0-19:0), UFA(C18:1,22:1), br	-								Demirci et al. 2021
HR-20	Potsherd	Interior	87	1.6	-26.3	-29.6	-3.3	APAA (C16-18), tmtd, phy	72	-	SFA(C12:0-18:0), UFA(C18:1), DC(C9:0), br	-								Demirci et al. 2021
HR-21	Potsherd	Interior	25	1.1	-28.4	-29.6	-1.2	APAA (C18), tmtd, phy	45.2	-	SFA(C14:0-20:0)	-								Demirci et al. 2021
HR-22	Potsherd	Interior	42	1.7	-31.4	-31	0.4	APAA (C16-20), tmtd, phy	93.4	x	SFA(C12:0-24:0), UFA(C18:1), br	-								Demirci et al. 2021
HR-23	Potsherd	Interior	131	2.6	-30.2	-30.4	-0.1	APAA (C16-22), tmtd, pri, phy	60.1	x	SFA(C11:0-19:0), UFA(C16:1,18:1), DC(C9:0), br	-								Demirci et al. 2021
HR-25	Potsherd	Interior	236	2.4	-29.9	-29.4	0.5	APAA (C16-20), tmtd, phy	83.6	x	SFA(C11:0-19:0), UFA(C16:1,18:1), DC(C9:0), br, chol	-								Demirci et al. 2021
HR-26	Potsherd	Interior	163	1.3	-32	-31.6	0.3	APAA (C16-22), tmtd, pri, phy	78.9	x	SFA(C13:0-22:0), UFA(C16:1,18:1,20:1), DC(C9:0), br	-								Demirci et al. 2021
HR-27	Potsherd	Interior	153	2.7	-32.5	-31.1	1.4	APAA (C18), tmtd, phy	84	-	SFA(C12:0-22:0), UFA(C16:1,18:1), DC(C9:0), br, chol	x	foodcrust	37.8	-28.9	5.7	7.3	7.7	3	Demirci et al. 2021
HD-01	Potsherd	Interior	90	1.3	-26.5	-27.5	-1	APAA (C16-18), tmtd, phy	32.8	-	SFA(C14:0-28:0), UFA(C16:1, 17:1, 26:1), br, chol	-								Demirci et al. 2021
HD-03	Potsherd	Interior	36	1.5	-27.3	-27.9	-0.6	APAA (C16-18), tmtd, phy	n/a	-	SFA(C14:0-26:0), UFA(C15:1,17:1), br	-								Demirci et al. 2021
HD-05	Potsherd	Interior	92	1.4	-31.4	-30.9	0.4	APAA (C16-20), tmtd, phy	51.5	x	SFA(C13:0-30:0), DC(C9:0), br, chol, tr	-								Demirci et al. 2021
HD-07	Potsherd	Interior	104	1.4	-27.6	-26.8	0.8	APAA (C18), tmtd, phy	35.4	-	SFA(C14:0-24:0), chol	-								Demirci et al. 2021
HD-09	Potsherd	Interior	245	1.8	-32.4	-32.7	-0.3	APAA (C16-22), tmtd, phy	79.9	x	SFA(C13:0-28:0), UFA(C18:1,20:1,21:1), DC(C9:0), br	-								Demirci et al. 2021
HD-11	Potsherd	Interior	22	1	-26	-26.2	-0.2	APAA (C16-20), tmtd, phy	41.3	x	SFA(C14:0-26:0), br	-								Demirci et al. 2021
HD-13	Potsherd	Interior	43	1.2	-28.2	-27.6	0.6	APAA (C18), tmtd, phy	28.4	-	SFA(C14:0-24:0), br	-								Demirci et al. 2021
HD-15	Potsherd	Interior	17	1.6	n/a	n/a		APAA (C16-18), phy	30.4	-	SFA(C14:0-24:0)	-								Demirci et al. 2021
HD-17	Potsherd	Interior	567	1.2	-30.1	-30.2	0	APAA (C16-22), tmtd, pri, phy	92.7	x	SFA(C12:0-22:0), UFA(C20:1), DC(C9:0), br	-								Demirci et al. 2021

Supplementary Material Dataset-1 (continues): Swifterbant samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	Sample type	%C	δ13C	%N	δ15N	C/N ratio	d13C offset	Reference
BR-01	Potsherd	Interior	1.3	1.2	-30.4	-29.8	0.6	APAA (C16-22), pri, phy	90	x	SFA(C10:0-22:0), UFA(C18:1,22:1), DC(C9:0), br	x	foodcrust	49.6	-28.3	6.2	10.6	9.4	1.8	Demirci et al. 2021
BR-03	Potsherd	Interior	249	2.9	-34.3	-32.6	1.7	APAA (C16-22), tmtd, phy	59.4	x	SFA(C10:0-18:0), UFA(C16:1,18:1), DC(C9:0), br, chol	x	foodcrust	38.3	-29.2	6.4	9.1	7	4.3	Demirci et al. 2021
BR-06	Potsherd	Interior	910	1.1	-26.2	-26	0.2	APAA (C16-22), tmtd, pri	n/a	x	SFA(C10:0-22:0), UFA(C18:1, 20:1,22:1), DC(C9:0), br	x	foodcrust	51.6	-26.7	4.5	9	13.4	-0.6	Demirci et al. 2021
BR-08	Potsherd	Interior	406	1	-31.5	-36.4	-4.9	APAA (C16-20), tmtd, pri, phy	65.3	x	SFA(C11:0-28:0), DC(C9:0), br	-								Demirci et al. 2021
BR-10	Potsherd	Interior	847	1.3	-31.6	-30.3	1.3	APAA (C16-20), tmtd, phy	93.6	x	SFA(C11:0-24:0), UFA(C20:1,22:1,24:1), DC(C9:0), br	x	foodcrust	52	-27.2	5.1	11.7	11.9	3.7	Demirci et al. 2021
BR-12	Potsherd	Interior	146	1.6	-31.3	-29.8	1.5	APAA (C18-20), tmtd, phy	88.6	x	SFA(C12:0-28:0), UFA(C18:1), DC(C9:0), br	x	foodcrust	49.5	-28.3	6.9	9.9	8.4	2.3	Demirci et al. 2021
BR-14	Potsherd	Interior	156	2.1	-31.8	-30.8	1	APAA (C16-20), tmtd, phy	92.7	x	SFA(C12:0-24:0), UFA(C16:1,18:1), DC(C9:0), br, chol	x	foodcrust	47.9	-28	8.4	9.5	6.7	3.4	Demirci et al. 2021
BR-16	Potsherd	Interior	118	2.6	-31.7	-30.8	0.9	APAA (C16-20), tmtd, phy	52.9	x	SFA(C11:0-24:0), UFA(C16:1, 18:1), DC(C9:0), br, chol	x	foodcrust	45	-29.1	7.6	9.3	6.9	2.2	Demirci et al. 2021
BR-18	Potsherd	Interior	204	2.1	-32.5	-32.4	0.2	APAA (C16-22), tmtd, phy	69.1	x	SFA(C12:0-24:0), UFA(C16:1, 18:1), DC(C9:0), br, chol	-								Demirci et al. 2021
BR-20	Potsherd	Interior	130	1.9	-24.8	-25.9	-1.1	APPA (C16-20), tmtd, pri, phy	69.4	x	SFA(C14:0-24:0), UFA(C16:1,18:1,22:1), DC(C9:0), br, chol	-								Demirci et al. 2021
BR-22	Potsherd	Interior	160	1.8	-33	-33	0	APAA (C16-20), tmtd, phy	53.5	x	SFA(C12:0-24:0), UFA(C18:1), DC(C9:0), br, chol	x	foodcrust	38.7	-27.4	5.1	9.8	8.8	5.6	Demirci et al. 2021
BR-24	Potsherd	Interior	617	0.8	-30.9	-29.4	1.6	APAA (C16-20), tmtd, phy	97	x	SFA(C11:0-22:0), UFA(C18:1,26:1), DC(C9:0), br	x	foodcrust	36.6	-27.3	4.6	10.4	9.3	2.8	Demirci et al. 2021
BR-26	Potsherd	Interior	397	1.4	-31	-30.2	0.8	APAA (C16-22), tmtd, pri, phy	91.2	x	SFA(C11:0-24:0), UFA(C18:1), DC(C9:0, 10:0), br, chol	x	foodcrust	46.9	-28.4	6.1	9.7	9	2.1	Demirci et al. 2021
BR-28	Potsherd	Interior	114	1.7	-26.5	-26.5	-0.1	APAA (C16-18), tmtd, phy	61.8	-	SFA(C13:0-18:0), DC(C9:0), br, chol	-								Demirci et al. 2021
S2-01	Potsherd	Interior	105		-29.7	-29.6	0.1	APAA (C16-22), tmtd, phy	79.1	x	SFA(C13:0-22:0), UFA(C18:01), DC(C9:0), br									Demirci et al. 2020 Demirci et al. 2020
S2-03	Potsherd	Interior	343		-31	-30.6	0.4	APAA (C18-20), tmtd, phy	92.2	x	SFA(C11:0-19:0), UFA(C18:01), DC(C9:0), br									Demirci et al. 2020 Demirci et al. 2020
S2-06	Potsherd	Interior	295		-29.3	-29	0.3	APAA (C16), phy	65.1	-	SFA(C14:0-18:0)									Demirci et al. 2020
S2-08	Potsherd	Interior	33		-28.6	-28.9	-0.3	APAA (C18-20), tmtd, phy	86.2	x	SFA(C14:0-20:0), UFA(C17:01), br									Demirci et al. 2020
S2-10	Potsherd	Interior	36		-29.6	-30.4	-0.8	APAA (C18), tmtd, phy	84.1	-	SFA(C14:0-19:0), UFA(C18:01), br									Demirci et al. 2020
S2-15	Potsherd	Interior	31		-32.9	-31.3	1.6	APAA (C16-18)	n/a	-	SFA(C14:0-24:0), br		foodcrust	34.8	-26.8	5.9	8.8	6.8	5	Demirci et al. 2020
S2-17	Potsherd	Interior	88		-29.4	-28.9	0.5	APAA (C16-18)	n/a	-	SFA(C14:0-20:0), br									Demirci et al. 2020

Supplementary Material Dataset-1 (continues): Swifterbant samples: Results of lipid residue analysis

sample ID	Sample type	Sampling location	Lipid conc. (ug/g)	P/S ratios (C16/C18)	δ13C16:0	δ13C18:0	Δ13C	Aquatic biomarkers	SRR%	Fully aquatic	Other identified lipid markers	EA-IRMS	Sample type	%C	δ13C	%N	δ15N	C/N ratio	d13C offset	Reference
S2-17	Potsherd	Interior	88		-29.4	-28.9	0.5	APAA (C16-18)	n/a	-	SFA(C14:0-20:0), br									Demirci et al. 2020
S2-19	Potsherd	Interior	266		-32	-31.4	0.6	APAA (C16-22), tmtd, phy	91.6	x	SFA(C10:0-19:0), UFA(C16:1, 18:1), DC(C9:0)		foodcrust	45.7	-27	8.5	6.4	6.3	3.2	Demirci et al. 2020
S2-20	Potsherd	Interior	127		-28.8	-28.8	0	phy	67.7	-	SFA(C12:0-21:0), UFA(C18:01), br		foodcrust	27.7	-26.9	3.8	7.6	8.5	3.6	Demirci et al. 2020
S2-21	Potsherd	Interior	469		-31	-31.2	-0.2	APAA (C16-22)	n/a	-	SFA(C13:0-28:0), UFA(C18:1, 20:1), br									Demirci et al. 2020
S2-22	Potsherd	Interior	83		-30.4	-30.1	0.3	APAA (18-20), tmtd, phy	n/a	x	SFA(C14:0-20:0), UFA(C18:1), br									Demirci et al. 2020
S2-23	Potsherd	Interior	160		-30.8	-30.3	0.6	APAA (C18-20), tmtd	n/a	x	SFA(C12:0-18:0), UFA(C16:1, 18:1), br									Demirci et al. 2020
S3-03	Potsherd	Interior	194		-30.5	-30.3	0.2	APAA (C16-20), phy	81.4	x	SFA(C13:0-18:0), UFA(C16:1, 18:1), br, chol									Demirci et al. 2020 Demirci et al. 2020
S3-05	Potsherd	Interior	30		-27.4	-26.8	0.6	tmtd, pri	n/a	-	SFA(C14:0-26:0), br, chol		foodcrust	45	-26.2	8.5	9.6	6.1	2.1	Demirci et al. 2020
S3-12	Potsherd	Interior	75		-31.4	-30.3	1.1	APAA (C16-20), tmtd, pri, phy	n/a	x	SFA(C14:0-20:0), UFA(C18:01)									Demirci et al. 2020
S3-14	Potsherd	Interior	54		-31	-30.7	0.3	APAA (C16-20), tmtd, phy	53.8	x	SFA(C14:0-24:0)		foodcrust	45.9	-25.8	6.8	10.2	7.9	1.2	Demirci et al. 2020
S3-16	Potsherd	Interior	30		-32	-31.2	0.7	APAA (C16-18), tmtd, pri, phy	18.4	x	SFA(C14:0-18:0), UFA(C18:01)									Demirci et al. 2020
S3-28	Potsherd	Interior	33		-28	-28.7	-0.7	APAA (C18-20), pri, phy	49.8	x	SFA(C14:0-24:0), UFA(C18:01)									Demirci et al. 2020
S3-30	Potsherd	Interior	63		-30.9	-30.1	0.9	APAA (C16-20), tmtd, pri, phy	27.3	x	SFA(C13:0-26:0), UFA(C16:1,18:1)									Demirci et al. 2020
S3-34	Potsherd	Interior	483		-26.8	-27	-0.2	APAA (16-20), pri, phy	n/a	x	SFA(C12:0-24:0), UFA(C18:01)									Demirci et al. 2020
S4-01	Potsherd	Interior	524		-29.8	-30.1	-0.3	APAA (C16-22), phy	74.9	-	SFA(C12:0-24:0), UFA(C18:01), br, chol									Demirci et al. 2020
S4-02	Potsherd	Interior	31		-28.7	-29.4	-0.7	APAA (C16-20), tmtd	n/a	x	SFA(C14:0-20:0), UFA(C18:1,22:1), br									Demirci et al. 2020
S4-03	Potsherd	Interior	39		-31.5	-31	0.5	APAA (C16-20), tmtd, phy	n/a	x	SFA(C13:0-18:0), UFA(16:1, 18:1), br, chol									Demirci et al. 2020 Demirci et al. 2020
S4-06	Potsherd	Interior	148		-30.6	-30.7	-0.1	APAA (C16-20), tmtd, phy	n/a	x	SFA(C14:0-20:0), UFA(18:1), br									Demirci et al. 2020
S4-07	Potsherd	Interior	26		-29.8	-29.6	0.1	APAA (C18), tmtd	n/a	-	SFA(C14:0-18:0), UFA(18:1, 22:1), br									Demirci et al. 2020
S4-08	Potsherd	Interior	110		-29.2	-29.8	-0.7	APAA (C16-22), tmtd, pri, phy	49.2	x	SFA(C12:0-24:0), UFA(C18:01), br									Demirci et al. 2020
S4-09	Potsherd	Interior	16		-30.7	-30.8	-0.1	tmtd	n/a	-	SFA(C14:0-18:0), UFA(C22:01), br									Demirci et al. 2020
S4-11	Potsherd	Interior	68		-30.4	-30.4	0	APAA (C16), tmtd, phy	n/a	-	SFA(C12:0-18:0), UFA(C16:1,18:1), br									Demirci et al. 2020
S4-12	Potsherd	Interior	203		-30.8	-30.3	0.5	APAA (C16-22), tmtd, phy	90.4	x	SFA(C12:0-20:0), UFA(C18:1), br		foodcrust	47.8	-30.4	5.4	9.2	10.3	0.3	Demirci et al. 2020
S4-13	Potsherd	Interior	15		-31.2	-30.1	1.2	APAA (C16-18), tmtd phy	2.9	-	SFA(C14:0-24:0), UFA(C18:1), br									Demirci et al. 2020
S4-14	Potsherd	Interior	579		-31.3	-31.6	-0.3	APAA (C16-22), tmtd, phy	n/a	x	SFA(C14:0-28:0), UFA(C18:1,22:1), br		foodcrust	46	-27.1	2.5	8.8	21.9	4.3	Demirci et al. 2020
S4-15	Potsherd	Interior	96		-31.8	-31	0.8	APAA (C16-18), phy	83.6	-	SFA(C12:0-18:0), UFA(C16:1,18:1), DC(C9:0), chol		foodcrust	20	-27.8	3.8	9.5	6.2	2.1	Demirci et al. 2020 Demirci et al. 2020
S4-16	Potsherd	Interior	18		-29.7	-30	-0.3	tmtd, phy	15.2	-	SFA(C14:0-20:0), UFA(C18:01)		foodcrust	46.8	-28.1	4.4	8.7	12.4	4	Demirci et al. 2020
S4-17	Potsherd	Interior	193		-31.3	-30.9	0.4	tmtd	n/a	-	SFA(C12:0-18:0), UFA(C16:1,18:1)		foodcrust	22.6	-25.8	1.9	11.4	13.7	5.7	Demirci et al. 2020
S4-18	Potsherd	Interior	163		-32.3	-31.9	0.5	APAA (C16-20), tmtd, phy	91.4	x	SFA(C13:0-18:0), UFA(C16:1,18:1)									Demirci et al. 2020
S4-19	Potsherd	Interior	140		-31.7	-31.3	0.4	APAA (C16-22), tmtd, phy	91.7	x	SFA(C12:0-22:0), UFA(C16:1,18:1)		foodcrust	46	-26	7.2	8.6	7.4	5.1	Demirci et al. 2020
S4-20	Potsherd	Interior	93		-30.2	-30.7	-0.5	tmtd	n/a	-	SFA(C14:0-20:0), UFA(C18:01)									Demirci et al. 2020
S4-21	Potsherd	Interior	34		-31.4	-30.8	0.5	APAA (C18-20), phy	n/a	-	SFA(C13:0-22:0), UFA(C16:1, 18:1), DC(C9:0), br		foodcrust	38.4	-25.7	6.6	9.1	6.8	6.9	Demirci et al. 2020 Demirci et al. 2020
S4-23	Potsherd	Interior	17		-30.2	-30.3	-0.1	APAA (C16), tmtd, phy	19.8	-	SFA(C14:0-26:0), UFA(C18:01), br									Demirci et al. 2020
S4-24	Potsherd	Interior	590		-33.1	-32.2	1	APAA (C16-22), tmtd	n/a	x	SFA(C12:0-18:0), UFA(C18:1), br									Demirci et al. 2020
S4-25	Potsherd	Interior	164		-31.2	-31.1	0.1	APAA (C16-22), tmtd, phy	n/a	x	SFA(C14:0-24:0), UFA(C16:1,18:1), br									Demirci et al. 2020
S4-26	Potsherd	Interior	132		-30.9	-30.1	0.8	APAA (C16-20), tmtd, phy	90.4	x	SFA(C14:0-20:0), chol									Demirci et al. 2020

Supplementary Dataset-2: Swifterbant faunal data

Mammals (identified)	Class/order/family	Species	5050-4950 cal BC Polderweg 2	5100-4800 cal BC De Bruin 2	4700-4450 cal BC De Bruin 3	4610-3820 cal BC Brandwijk L50/L60	4020-3960 cal BC Hazendonk 1&2	4300-4000 cal BC Swifterbant S2	4300-4000 cal BC Swifterbant S3	4300-4000 cal BC Swifterbant S4
Beaver	Castoridae	*Castor fiber*	194	808	294	41	60	144	536	85
Otter	Mustelidae	*Lutra lutra*	26	451	118	63	51	29	598	25
Bottlenose dolphin	Genus	*Tursiops*							1	
Seal	Phocidae			13	1				1	
Deer (Elk, red deer, roe deer)	Cervidae		2	165	44	1	2	?	49	?
Wild boar	Suidae	*Sus scrofa*	10	65	5	44		103	47	41
Pig / Wild boar	Suidae	*Sus domesticus / Sus scrofa*		136	53		17	162	2214	92
Pig	Suidae	*Sus domesticus*		1	3			34	99	125
Aurochs	Bovidae	*Bos primigenius*		8	2				2	1
Cattle / Aurochs	Bovidae	*Bos taurus / Bos primigenius*		2	7				1	17
Cattle	Bovidae	*Bos taurus*			15	9	25	12	323	163
Sheep/goat	Bovidae	*Ovis aries/Capra hircus*		2	11	12	1	5	9	29
Other			2	118	46	42	2	6	108	28
total number of identified mammals			**234**	**1769**	**599**	**212**	**158**	**495**	**3988**	**606**
Birds (identified)			**37**	**391**	**128**	**8**	**9**	**8**	**644**	**26**
Fish (identified)										
Freshwater fish			103	3563	1605	13	?	141	3016	165
Migratory fish (salmon/trout, eel)			1	211	24	1			28	22
Marine fish (cod, saithe/pollock, gadids, pleuronectids)					1				21	1
total number of identified fish			**104**	**3774**	**1630**	**14**		**141**	**3065**	**188**

Supplementary Dataset-2 (continues): Ertebølle and Funnel Beaker faunal data

Mammals (identified)	Class/order/family	Species	4600-4000 cal BC Ringkloster	4600-3500 cal BC Åkonge	4600-3500 cal BC Stenø	3960-3660 cal BC Nøddekonge	3950-2900 cal BC Muldbjerg I	3900-3500 cal BC Skogsmossen
Beaver	Castoridae	*Castor fiber*	3			2	179	
Otter	Mustelidae	*Lutra lutra*	26	10		1	115	
Bottlenose dolphin	Genus	*Tursiops*	1					
Seal	Phocidae							5
Deer (Elk, red deer, roe deer)	Cervidae		1862	2125	P	470	781	
Wild boar	Suidae	*Sus scrofa*	1930	189				
Pig / Wild boar	Suidae	*Sus domesticus / Sus scrofa*				7	5	22
Pig	Suidae	*Sus domesticus*						
Aurochs	Bovidae	*Bos primigenius*	282					
Cattle / Aurochs	Bovidae	*Bos taurus / Bos primigenius*						
Cattle	Bovidae	*Bos taurus*		16				8
Sheep/goat	Bovidae	*Ovis aries/Capra hircus*					3	
Other			807	67		13	257	93
total number of identified mammals			**4911**	**2407**		**493**	**1340**	**128**
Birds (identified)			**10**	**132**	**P**	**132**	**321**	**1**
Fish (identified)								5
Freshwater fish			905	5392	P	P	1468	
Migratory fish (salmon/trout, eel)			10	12		P		
Marine fish (cod, saithe/pollock, gadids, pleuronectids)			26					
total number of identified fish			**941**	**5404**	**P**	**P**	**1468**	**5**

P = Present

EBK = Ertebølle; TRB = Funnel Beaker

References for faunal data	
Muldbjerg I (TRB)	Noe-Nygaard 1995 (in Enghoff 2011, Tables 52-54)
Nøddekonge (EBK-TRB)	Gotfredsen 1998, Noe-Nygaard 1995 (in Enghoff 2011, Tables 52-54)
Stenø (EBK-TRB)	Fischer personal communication
Åkonge (EBK-TRB)	Enghoff 1994 (fish); Gotfredsen 1998 (in Enghoff 2011, Tables 53 and 54; Rowley-Conwy 2013, Table 15.1) (mammals and birds)
Ringkloster (EBK)	Enghoff 1995 (fish); Møhl 1975; Rowley-Conwy 1998, 2013, Table 15.1 (mammals and birds)
Polderweg	Van Wijngaarden-Bakker et al. 2001, Table 8.9; Beerenhout 2001a, Table 9.3 (fish); Cakirlar et al. 2019, SM Table 3 (all)
De Bruin	Oversteegen et al. 2001, Table 8.7; Beerenhout 2001b, Table 9.11 (fish); Cakirlar et al. 2019, SM Table 3 (all); Cakirlar et al. 2020, Table 13.3
Brandwijk	Brinkhuizen 1979 (fish); Raemaekers 1999, Table 3.27 (fish and birds), Zeiler 1997, Table 2, Table 3; Çakırlar et al. 2019
Hazendonk	Brinkhuizen 1979 (fish); Zeiler 1997, Table 2, Table 3; Çakırlar et al. 2019 (all)
Swifterbant S2	Çakırlar et al. 2019, SM Table 3 (all)
Swifterbant S3	Zeiler 1997 (Archaeofauna), Brinkhuizen 1979 (fish); Çakırlar et al. 2019, SM Table 3 (all)
Swifterbant S4	Çakırlar et al. 2019, SM Table 3
Skogsmossen (TRB)	Hallgren 2008

Supplementary Dataset-3: Stable isotope data from human bone collagen for Swifterbant, Ertebølle and Funnel Beaker

site	sample reference no	Location	Region	Cultural epoch	Species	Skeletal element	δ13C VPDB (‰)	δ15N AIR (‰)	C:N atom	% C	%N	% collagen	Reference
Swifterbant S2	S2-38A-2543-X X XIX	Riverine	Swifterbant	Swifterbant	Human	thoot M3	-21.5	13.9	3.1			5.8	Smits et al. 2010
Swifterbant S2	S2-37A-X X X VII	Riverine	Swifterbant	Swifterbant	Human	thoot M3	-21.1	13.8	3			5.1	Smits et al. 2010
Swifterbant S2	S2-1952	Riverine	Swifterbant	Swifterbant	Human	thoot M3	-21.2	13.8	3.2			5.1	Smits et al. 2010
Swifterbant S2	S2-642-III P M2	Riverine	Swifterbant	Swifterbant	Human	P M2	-21.9	13.1	2.4			10.1	Smits et al. 2010
Swifterbant S2	S2 900016	Riverine	Swifterbant	Swifterbant	Human	M2	-21.8	10	2.5			8.1	Smits et al. 2010
Swifterbant S2	S2-1483	Riverine	Swifterbant	Swifterbant	Human	M1	-21.5	13.7	3			8.8	Smits et al. 2010
Swifterbant S3	S3-17576	Riverine	Swifterbant	Swifterbant	Human	m1	-21.6	16	3.2			4.4	Smits et al. 2010
Swifterbant S3	S3-G43-loose	Riverine	Swifterbant	Swifterbant	Human	P2	-21.5	12.7	2.5			14.4	Smits et al. 2010
Swifterbant S3	S3-643-(loose find)	Riverine	Swifterbant	Swifterbant	Human	P M2+ M2	-22.4	12.7	2.8			15.1	Smits et al. 2010
Swifterbant S3	S3-30648	Riverine	Swifterbant	Swifterbant	Human	M3 ?	-22.7	12.5	3.6			4.1	Smits et al. 2010
De Bruin	43658	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.6	15.8	2.9	42.4	14.5		Smits and van der Plicht 2009
De Bruin	42082	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-23	13.3	2.4	38.5	16.2		Smits and van der Plicht 2009
De Bruin	43659	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.5	15.7	3.6	40	11.2		Smits and van der Plicht 2009
De Bruin	22277	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.4	17.2	3.5	25.1	7.2		Smits and van der Plicht 2009
De Bruin	22278	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21	16.5	1.8	28.2	15.8		Smits and van der Plicht 2009
Polderweg	41945	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22	14.6	2.2	36.6	16.3		Smits and van der Plicht 2009
Polderweg	41939	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-20.8	15.3	2.5	36.3	14.6		Smits and van der Plicht 2009
Polderweg	41948	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-20.3	16.7	2.6	37.2	14.5		Smits and van der Plicht 2009
Polderweg	41943	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.4	14.8	2.5	35.2	14		Smits and van der Plicht 2009
Polderweg	41941	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.8	15	2.7	37.9	13.9		Smits and van der Plicht 2009
Polderweg	41944	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.9	14.7	2.4	35.4	14.7		Smits and van der Plicht 2009
Polderweg	41949	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.2	14.9	2.7	41.5	15.4		Smits and van der Plicht 2009
Polderweg	41946	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-20	9.9	2.8	39.9	14.1		Smits and van der Plicht 2009
Polderweg	41947	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.7	14	2.3	38.9	17.2		Smits and van der Plicht 2009
Polderweg	41937	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.3	14.6	2.1	31.3	14.8		Smits and van der Plicht 2009
Polderweg	41952	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.3	14	2.8	38.7	13.6		Smits and van der Plicht 2009
Polderweg	41942	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.1	15.4	2.4	34.8	14.5		Smits and van der Plicht 2009
Polderweg	41936	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-21.9	14.4	2.6	37.5	14.4		Smits and van der Plicht 2009
Polderweg	22019	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-24	16.5	2.8	45.2	15.8		Smits and van der Plicht 2009
Polderweg	43657	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.5	13.9	3	33.2	10.9		Smits and van der Plicht 2009
Polderweg	41951	Riverine	Lower Rhine-Meuse area	Swifterbant	Human		-22.8	13.3	2.4	35	14.4		Smits and van der Plicht 2009
Polderweg	GrA-11830	Riverine	Lower Rhine-Meuse area	Swifterbant	Human	Loose skull, level 2	-23.9	16.5					Mol and Louwe Kooijmans 2001; Smits and van der Plicht 2009
Polderweg	GrA-9804	Riverine	Lower Rhine-Meuse area	Swifterbant	Human	Grave G1	-22.4	13.9					Mol and Louwe Kooijmans 2001; Smits and van der Plicht 2009
Dragsholm		Coastal	Zealand	Ertebølle	Human F (18 years)	Bone	-11.7	14.5					Price et al. 2007
Dragsholm		Coastal	Zealand	Ertebølle	Human F (40-50 years)	Bone	-10.7	13	3.2	39.4	14.2		Price et al. 2007
Dragsholm		Coastal	Zealand	Ertebølle	Human	Calvarium, juvenile	-11.5	13.8	3.3	38.4	13.8		Price et al. 2007
Dyrholm		Coastal	Jutland	Ertebølle	Human	Tibia dxt., >25 y	-10.8	13.3	3.3	39.2	13.9	12.9	Fischer et al. 2007a
Ertebølle		Coastal	Jutland	Ertebølle	Human		-15.2	13.3	3.2	42.4	15.5	4.5	Fischer et al. 2007a
Fannerup F		Coastal	Jutland	Ertebølle	Human		-10.8	14.3	3.2			4.7	Maring and Riede 2018
Fannerup F		Coastal	Jutland	Ertebølle	Human		-10.8	12.9	3.2			3.2	Maring and Riede 2018

site	sample reference no	Location	Region	Cultural epoch	Species	Skeletal element	δ13C VPDB (‰)	δ15N AIR (‰)	C:N atom	% C	%N	% collagen	Reference
Henriksholm-Bøgebakken	HB: 1	Coastal	Zealand	Ertebølle	Human F	Femur (35-50)	-14.3	15.8	3.3			0.5	Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 2	Coastal	Zealand	Ertebølle	Human M	Ulna (20-30)	-14.1	15	3.3			3.2	Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 3	Coastal	Zealand	Ertebølle	Human M	femur (35-45)	-15.6	14.6	3.3			3.3	Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 4	Coastal	Zealand	Ertebølle	Human M	Second mandibular molar	-13.5	16.4	3.2			1.2	Brinch Petersen 2015
Henriksholm-Bøgebakken	VED 48	Coastal	Zealand	Ertebølle	Human M	Third mandibular molar	-14.4	16.4	3.4	37.7	12.8	0.6	Gunther et al. 2018
Henriksholm-Bøgebakken	VED 49	Coastal	Zealand	Ertebølle	Human M	Metatarsal (35-50)	-14.5	15.8	3.4	36.9	12.7	0.5	Gunther et al. 2018
Henriksholm-Bøgebakken	HB: 5	Coastal	Zealand	Ertebølle	Human F	Skull (18-20)	-14.5	16.2	3.9			4.2	Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 6	Coastal	Zealand	Ertebølle	Human F	Premolar	-14	15.3	3.3			1.1	Brinch Petersen 2015
Henriksholm-Bøgebakken	VED 24	Coastal	Zealand	Ertebølle	Human M	Long bone (40-60)	-13.9	15.6	3.3				Gunther et al. 2018
Henriksholm-Bøgebakken	HB: 8A	Coastal	Zealand	Ertebølle	Human M	Femur (30-50)	-14.8	15.6	3.3			1.2	Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 12	Coastal	Zealand	Ertebølle	Human M	Premolar	-13.6	16.5	3.3			1.3	Brinch Petersen 2015
Henriksholm-Bøgebakken	VED 52	Coastal	Zealand	Ertebølle	Human M	First mandibular molar	-15.5	11.9	3.1			5.6	Gunther et al. 2018
Henriksholm-Bøgebakken	VED 13	Coastal	Zealand	Ertebølle	Human F	Second mandibular molar	-17.4	16.5	3.1			1.1	Gunther et al. 2018
Henriksholm-Bøgebakken	VED 14	Coastal	Zealand	Ertebølle	Human F	Incisor	-15.3	15.5	3.5			1.4	Gunther et al. 2018
Henriksholm-Bøgebakken	VED 23	Coastal	Zealand	Ertebølle	Human F	Mandibula (25-35)	-14.6	14.1	3.3			0.9	Gunther et al. 2018
Henriksholm-Bøgebakken	HB: 14	Coastal	Zealand	Ertebølle	Human F	Third mandibular molar	-14.7	13.3				0.4	Brinch Petersen 2015
Henriksholm-Bøgebakken	VED 22	Coastal	Zealand	Ertebølle	Human infant	Second decidious molar (germ)	-14.4	13.8	3.2			1.9	Gunther et al. 2018
Henriksholm-Bøgebakken	VED 18	Coastal	Zealand	Ertebølle	Human infant	Cranium	-14.5	18.1	3.3			2.4	Gunther et al. 2018
Henriksholm-Bøgebakken	HB: 19A	Coastal	Zealand	Ertebølle	Human F	Femur (adult)	-14.4	16.9					Brinch Petersen 2015
Henriksholm-Bøgebakken	HB: 20	Coastal	Zealand	Ertebølle	Human		-15.7	15.5	3.6				Brinch Petersen 2015
Holmegård		Coastal	Jutland	Ertebølle	Human M	Tibia, adult	-10.7	16.1	3.2	39	14	3	Robson 2015
Holmegård		Coastal	Jutland	Ertebølle	Human	Ulna, adolescent/adult	-12.7	15.6	3.5	41.9	13.8	4.2	Robson 2015
Holmegård		Coastal	Jutland	Ertebølle	Human	Proximal hand phalanx, 2nd/3rd digit, adolescent/adult	-10.7	16.2	3.2	39.2	14.2	3.6	Robson 2015
Holmegård		Coastal	Jutland	Ertebølle	Human M	Os parietale sin., adult	-11.6	16.1	3.4	37.1	12.7	3.4	Robson 2015
Korsør Glasværk		Coastal	Zealand	Ertebølle	Human	Tibia sin., 30-50 y	-11.3	14.2	3.2	32	11.7		Fischer et al. 2007a
Korsør Nor, inhumation		Coastal	Zealand	Ertebølle	Human		-15.9	12.3	3.3	31.1	11.2	19.4	Fischer et al. 2007a
Melby		Coastal	Zealand	Ertebølle	Human		-10.7	13.3	3.2	43.5	15.6	5.6	Fischer et al. 2007a
Møllegabet		Coastal	Ærø	Ertebølle	Human		-12.6	15.7	3.4	40.8	14.1	11.3	Fischer et al. 2007a
Norsminde		Coastal	Jutland	Ertebølle	Human		-11.8	15.3	3.2	32.4	11.9	9.5	Fischer et al. 2007a
Tybrind Vig		Coastal	Fyn	Ertebølle	Human F		-17.6	8.5	3.7	27.7	8.8	1.7	Richards et al. 2003; Tauber 1983
Vængesø I		Coastal	Jutland	Ertebølle	Human	1850 (BMY)	-11.7	15.3	3.2	32.4	11.7	5.3	Fischer et al. 2007a
Vedbæk Bøgebakken		Coastal	Zealand	Ertebølle	Human M	Adult	-14.5	11.3	3	36.1	13.9	5.2	Fischer et al. 2007a; Richards et al. 2003; Tauber 1981
Vedbæk Bøgebakken		Coastal	Zealand	Ertebølle	Human M	Adult	-13.4	13.8	3.1	31.3	11.8	4.9	Richards et al. 2003
Vedbæk Bøgebakken		Coastal	Zealand	Ertebølle	Human F	Adult (ca. 20 y)	-15	11.9	3.2	32.9	12.2	6.5	Fischer et al. 2007a; Richards et al. 2003; Tauber 1981
Vedbæk Bøgebakken		Coastal	Zealand	Ertebølle	Human M	Adult	-14.4	10.6	3	35.2	13.4		Fischer et al. 2007a; Richards et al. 2003
Vedbæk Bøgebakken		Coastal	Zealand	Ertebølle	Human M	Radius (mature)	-13.6	13	3.1	34.6	13.1	2	Richards et al. 2003
Vedbæk boldbaner	VB: 1	Coastal	Zealand	Ertebølle	Human		-15.9	15.2	3.3			6.2	Brinch Petersen 2015
Bodal K		Inland	Zealand	Ertebølle	Human	Humerus sin., adult	-16.1	13.4	3.2	41.1-41.3	14.8-15.3	14.7-19.4	Fischer et al. 2007a
Vængesø II		Coastal	Jutland	Ertebølle/Funnel Beaker	Human F	Femur etc., adult	-12.7	15.7	3.3	39.8	13.9	8.5	Fischer et al. 2007a
Vængesø II		Coastal	Jutland	Ertebølle/Funnel Beaker	Human M	Costa, vertebra etc., 20-30 y	-12.6	16.1	3.3	42.6	14.9	14.3	Fischer et al. 2007a

site	sample reference no	Location	Region	Cultural epoch	Species	Skeletal element	δ13C VPDB (‰)	δ15N AIR (‰)	C:N atom	% C	%N	% collagen	Reference
Tingbjerggård Vest		Inland		Ertebølle/Funnel Beaker	Human F	Femur, adult	-21.9	12.2	3.2	40.9	15.2	20.6	Fischer et al. 2007a
Bjørnsholm		Coastal	Jutland	Funnel Beaker	Human F	Adult	-19.7	9.5	3.2	34.6	12.5	4	Fischer et al. 2007a
Bjørnsholm		Coastal	Jutland	Funnel Beaker	Human M	Adult	-19.8	10.2	3.3	35	12.5	7.3	Fischer et al. 2007a
Bjørnsholm		Coastal	Jutland	Funnel Beaker	Human	Juvenile	-20.9	7.4	3.2	37.2	13.7	9.7	Fischer et al. 2007a
Boelkilde		Coastal	Jutland	Funnel Beaker	Human M	Femur dxt., >30 y	-19.7	12	3.2	30.8	11.1	6.3	Fischer et al. 2007a
Dragsholm		Coastal	Zealand	Funnel Beaker	Human M	Bone	-19.6	10.4	3.3	39.2	14.1		Price et al. 2007
Kassemose		Coastal	Zealand	Funnel Beaker	Human M	Femur sin, adult	-20.5	8.9	3.2	40.2	14.8	19	Fischer et al. 2007a
Pandebjerg		Coastal	Nekselø	Funnel Beaker	Human	Mandibula	-18.8	11.4	3.3	44.6	15.9	13.7	Fischer et al. 2007a
Rødhals		Coastal	Sejerø	Funnel Beaker	Human M	Femur dxt., ~25 y	-11.7	12.7	3.2	42.2	15.3	10.7	Fischer et al. 2007a
Aldersro		Inland	Zealand	Funnel Beaker	Human F	Adult	-20.7	7.5	3.2	43.4	15.8	6.7	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human F	Adult	-19.5	8	3.2	43	15.6	6.9	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human M	Adult	-19.7	8	3.3	42	15.1	3.2	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human	Child (3-5)	-20	8.7	3.2	42.8	15.7	5.9	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human	Child (5-7)	-20.2	6.3	3.2	44.9	16.3	9.8	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human	Adult	-19.6	9.3	3.3	40.5	14.4	6.5	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human	Adult	-20	8.7	3.2	45.1	16.7	9.4	Richards and Koch 2001; Richards et al. 2003
Aldersro		Inland	Zealand	Funnel Beaker	Human	Adult	-19.2	9	3.2	45.1	16.4	5.2	Richards and Koch 2001; Richards et al. 2003
Aldersro X621		Inland	Zealand	Funnel Beaker	Human	Femur dxt., adult	-20.1	8.5	3.4	33.8	11.6	4.2	Fischer et al. 2007a
Aldersro X622		Inland	Zealand	Funnel Beaker	Human	Femur dxt., adult	-20.1	9.3	3.3	34.7	12.3	5.3	Fischer et al. 2007a
Bodal K		Inland	Zealand	Funnel Beaker	Human M	Tibia sin., adult	-21.5	9.7	3.4	40.5-42.2	13.2-14.9	2.2-6.1	Fischer et al. 2007a
Bodal Mose, Store Åmose		Inland	Zealand	Funnel Beaker	Human M	Adult	-20.8	8	3.2	43.1	15.6	6.7	Fischer et al. 2007a; Koch 1998; Richards and Koch 2001
Ferle Enge		Inland	Zealand	Funnel Beaker	Human F	Tibia sin., 25-35 y	-22.6	9.3	3.4	35.7	12.2	7.1	Fischer et al. 2007a
Føllenslev		Inland	Zealand	Funnel Beaker	Human M	Femur sin, adult	-20.7	9.4	3.3	40.2	14.2	9.2	Fischer et al. 2007a
Hallebygård		Inland	Zealand	Funnel Beaker	Human M	Femur dxt., adult	-21.1	9.9	3.3	41	14.4	9.9	Fischer et al. 2007a
Hesselbjerggårds Mose		Inland	Zealand	Funnel Beaker	Human	Os frontale, adult	-20.5	9.8	3.2	38.3-41.1	13.6-15.2	7.6	Fischer et al. 2007a
Hulbjerg		Inland	Langeland	Funnel Beaker	Human	Femur	-20.8	10.6	3.3	44.1	15.6	19	Fischer et al. 2007a
Jorløse Mose		Inland	Zealand	Funnel Beaker	Human M	Tibia sin., 30-40 y	-20.5	10.8	3.5	40.9	13.3	11.1	Fischer et al. 2007a
Klokkehøj		Inland	Fyn	Funnel Beaker	Human	Costae and os coxa, adult	-19.7	9.7	3.4	43.4	15	9.5	Fischer et al. 2007a
Klokkehøj		Inland	Fyn	Funnel Beaker	Human	Femur dxt., adult	-20.2	9.6	3.2	36.8	13.4		Fischer et al. 2007a
Klokkehøj		Inland	Fyn	Funnel Beaker	Human	Femur, adult	-20.1	9.2	3.4	41.8	14.2	6.3	Fischer et al. 2007a
Nissehøj		Inland	Zealand	Funnel Beaker	Human	Fibula dxt.	-20.3	8.4	3.2	37.2	14.2	15.1	Fischer et al. 2007a
Øgårde boat III		Inland	Zealand	Funnel Beaker	Human (M)	Adult	-20.1	9.2	3.2	43.6	15.8	15	Fischer et al. 2007a
Østrup homo II		Inland	Zealand	Funnel Beaker	Human	femur sin., 35-45 y	-19.4	10.5	3.3	44.3	15.9	22	Fischer et al. 2007a
Østrup Mose, Store Åmose		Inland	Zealand	Funnel Beaker	Human F	Adult	-19.6	9.9	3.2	43.5	16	6.8	Fischer et al. 2007a; Koch 1998; Richards and Koch 2001
Østrup Mose, Store Åmose		Inland	Zealand	Funnel Beaker	Human M	Adult	-20.4	10	3.3	46.5	16.2	12.5	Fischer et al. 2007a; Koch 1998; Richards and Koch 2001
Porsmose		Inland	Zealand	Funnel Beaker	Human M	Costae, 35-40 y	-20.4	8.6	3.1	39.8	15		Fischer et al. 2007a
Sigersdal A		Inland	Zealand	Funnel Beaker	Human F	Costae, 18-20 y	-20.4	10	3.3	35.9	12.9		Fischer et al. 2007a
Sigersdal B		Inland	Zealand	Funnel Beaker	Human F	Costae and pes, 16 y	-19.2	10.5	3.3	37.1	13.7		Fischer et al. 2007a
Tagmosegård		Inland	Zealand	Funnel Beaker	Human	Femur dxt., 7-8 y	-22.4	8.9	3.3	36.3	12.7	8.2	Fischer et al. 2007a
Trudstrupgård		Inland	Zealand	Funnel Beaker	Human M	Os coxa dxt., 40-50 y	-20.7	9.5	3.3	42.5-43.2	14.2-15.8	3.3-17.2	Fischer et al. 2007a
Trudstrupgård 2		Inland	Zealand	Funnel Beaker	Human M	Femur dxt., adult	-19.9	9.3	3.1	41.9	15.7	11	Fischer et al. 2007a
Ulkestrup Lyng U		Inland	Zealand	Funnel Beaker	Human	Cranium, juvenile/adult	-20.1	9.2	3.1	40.5-42.3	14.8-15.7	15.8	Fischer et al. 2007a
Undløse (Vængegård) Store Åmose		Inland	Zealand	Funnel Beaker	Human F	Adult	-20.3	8.2	3.3	44.3	15.8	15.1	Fischer et al. 2007a; Koch 1998; Richards and Koch 2001
Veksø Mose		Inland	Zealand	Funnel Beaker	Human F	Femur sin., 30-40 y	-20.5	9.6	3.3	41.5	14.9	20.9	Fischer et al. 2007a

Chapter 7

General conclusions

The primary aim of this study was to develop a better understanding on the adoption, function, and functional variation of pottery of Swifterbant Culture (c. 5000 – 4000/3400 cal. BC) in the Dutch Wetlands, Northern Europe, and to illustrate its relationship to the changing subsistence strategies through the Neolithisation process in the region. Despite the relationship between changing subsistence strategies and the function of the early pottery has been extensively studied in the other regions of Northern Europe, there has been a gap in terms of extensive and detailed research on pottery function of Swifterbant culture. This study aims o fill this gap in knowledge and provide first direct evidence on the function of Swifterbant pottery through lipid residue analysis.

This main research questions of this study were "What was the function of Swifterbant pottery?", "Why was the drive behind its adoption into Swifterbant culture?", and "Was there any functional variation between the use of Swifterbant pottery?". This study addressed these research questions by the first systematic application of lipid residue analysis to Swifterbant pottery coming from seven Swifterbant sites in the Netherlands: Polderweg, De Bruin, Brandwijk and Hazendonk in the Lower Rhine-Meuse area (c. 5000- 3800 cal BC) and Swifterbant type sites S2, S3, and S4 in Oostelijk, Flevoland (c. 4300-4000 cal BC) as well as one transitional site in the Lower Saxony, Germany which is in reference to the Swifterbant culture chronology: Hüde I (c. 4700-3500 cal BC). Having access to numerous assemblages, this study is also the first large-scale study of Swifterbant pottery.

The functional analysis of Swifterbant pottery and its relationship to -changing- subsistence strategies through the Neolithisation period in the region formed the basis of the first two case studies (Chapter 3 and 4) presented in this study. The first case study focused on the functional analysis of Swifterbant pottery from three Swifterbant type sites, S2, S3, and S4 dating between c.4300-4000 cal BC. The main discussion on the functional analysis of Swifterbant pottery was also supported with sub discussions on "Relationship between form of the Swifterbant pottery and its function", "Comparison between pottery use and the other evidence for subsistence strategies" and "Inter-site variation". In addition, a foundation was set up for a wider discussion on comparison of Swifterbant pottery and Ertebølle pottery that had been extensively addressed in Chapter 6.

In general, the results of the first analysis of lipids from these three Swifterbant type sites demonstrated that Swifterbant pottery was exclusively and heavily used for processing aquatic food resources, specifically freshwater fish. Even though a previous study that had been carried out on a different data set from S3 distinguished two functional groups within the Swifterbant pottery (see Raemaekers et al. 2013), the results of the lipid residue analysis contradicts with this previous study, indicating no variation in pottery function. Swifterbant pottery from these three type sites was used for processing freshwater fish regardless of vessel form, size, decoration, or temper. Based on the results of lipid residue analysis, same argument seems to be valid for "Comparison between the pottery use and other evidence for subsistence strategies" and "inter-site variation" sub discussions. The use of Swifterbant pottery in all three type sites did not indicate any change despite the presence of much varied subsistence economies or possible differences in site functions. This case study successfully present that this new material technology was incorporated into the daily life as a specialised tool which was only used for processing one specific food resource which is freshwater fish.

Interestingly, a somewhat similar pattern of pottery use seems to emerge in the second case study. This case study was focused on the functional analysis of pottery from the four Swifterbant sites, Polderweg, De Bruin, Brandwijk, and Hazendonk in the Lower Rhine-Meuse Area, dating between c. 5000-3800 cal BC. The overall results of the lipid residue analysis of the Swifterbant pottery from these four Lower Rhine-Meuse area sites indicate that Swifterbant pottery from this area was also heavily used for processing freshwater resources. The combined results coming from these two case studies show that processing aquatic resources, exclusively freshwater fish was the main use of Swifterbant pottery in the Dutch Wetlands. It appears as a consistent and deliberate choice which also continued during and after the introduction of animal husbandry and cereal cultivation into the region.

Surprisingly, along with a clear continuation on the processing of aquatic resources in the Swifterbant pottery, this study presents two other important outcomes on the use of Swifterbant pottery. These are temporal variation in the pottery use and the first evidence of dairy products in the Swifterbant pottery. A temporal change in the use of Swifterbant pottery starting from its first appearance at c. 5000 cal BC till the end of 5th millennium BC, was illustrated in the Lower Rhine-Meuse area sites. The results of the analysis illustrated that while the earliest Swifterbant pottery from Polderweg (beginning of the 5th century BC) was exclusively used for processing freshwater fish, there is a clear evidence for processing terrestrial animals in the pottery from De Bruin, Brandwijk and Hazendonk (mid and late 5th century BC). In addition to the continuous exploitation of freshwater resources, we see that processing ruminant foodstuff became an important part of pottery use in the mid-5th millennium BC in De Bruin. This was followed by the first

appearance of dairy in the Swifterbant pottery. By the late 5th millennium BC, there was another shift in the use of Swifterbant pottery as the ruminant animal fats completely disappeared from the pots and get replaced by porcine fats, specifically in Brandwijk and Hazendonk. Although, it requires further research, this kind of temporal shifts in the use of Swifterbant pottery may be explained as a reflection of changing human-animal relations in the region during the Neolithisation period as well as a direct indication for different sub-cultural responses to the food preparation and consumption in the Swifterbant Culture.

Finally, This study forms a significant contribution to the wider discussions on the adoption, function, and the functional variation of pottery in the hunter-gatherer-fisher societies in Northern Europe throughout the Mesolithic-Neolithic transition. It does not only represent the first direct evidence for the function of the Swifterbant pottery in the Dutch Wetlands but also build up a synthesis of pottery use by comparing the Swifterbant dataset created for this study with the late Ertebølle and early Funnel Beaker datasets to understand regional differences of pottery use and its relationship to the subsistence strategies during the Neolithisation period in Northern Europe (Chapter 6).

On the basis of both Swifterbant and Ertebølle datasets, this study concludes that hunter-gatherer groups of Swifterbant and Ertebølle cultures present a two very different approach towards the adaptation of pottery and its function in Northern Europe. It is evident that they did not share the same motivation to adopt this new material technology into their daily lives. While Swifterbant pottery was primarily and continuously associated with processing of freshwater fish throughout the 5th millennium BC, Ertebølle pottery was used to process a much wider range of food resources including terrestrial and aquatic foodstuffs. This clearly shows that the function of the early pottery in t Northern Europe was not necessarily shaped by the subsistence economies but reflected strong cultural preferences varied in different sub-regions (also see Courel et al. 2020).

Interestingly, being established as two different pottery cultures, Swifterbant pottery in the Dutch Wetlands and late Ertebølle pottery in Southern Scandinavia present similar trajectories towards the Neolithisation period and its relationship to the pottery use. While Swifterbant pottery presents a clear evidence for continuity in its culinary traditions after the introduction of domesticated animals and cereals into the region, pottery assemblages in Southern Scandinavia indicate a similar kind of continuation in the culinary practices during the Ertebølle- Funnel Beaker transition in the region. Despite the similarities, it is important to mention here that the Neolithisation process in both regions followed in their own separate timelines which were shaped by different cultural preferences and unique regional conditions.

Implications for further research on Swifterbant pottery: What else is needed to be done?

This study has made a significant contribution to our knowledge of the adoption, function, and functional variation of Swifterbant pottery in the Dutch Wetlands by presenting the first direct evidence of its function through the first systematic application of lipid residue analysis on Swifterbant pottery. The results presented in the core chapters of this study, Chapter 3, 4, 5, and 6, are significant not only locally but also in the light of wider discussions on hunter-gatherer-fisher pottery in Northern Europe. However, in the course of answering previously designated questions through the case studies, this study also generated a new set of questions and further research ideas that are presented below.

First of all, this study highlights the importance of application of lipid residue analysis on a much wider dataset, not only in terms increasing the sample numbers by site but also sampling from other key Swifterbant sites located both in the Dutch Wetlands and the surrounding areas. This is important in order to broaden our knowledge on the function of Swifterbant pottery and to illustrate possible sub-cultural and regional differences on pottery use that might emerge within the Swifterbant culture. In addition, as this study was the very first attempt to apply lipid residue analysis on Swifterbant pottery, the sampling strategies were somewhat dependent on having as clear information on the characteristics of pottery as possible in order to create a valid correlation between form and the function of the pottery. In this regard, although the consistency of the results provides the needed confidence on the reliability of the conclusions this study has driven, this study can still be considered as a pilot study which needs a wider dataset to expand its grounds.

Another very crucial area that need attention is detecting the presence of plant remains in the archaeological pottery. As it was explained in Chapter 2 and mentioned in all case studies, plants have low lipid content, and they might be easily overprinted by other animal fats in the sample. As a result of this, it may be very difficult to detect them through lipid residue analysis (Colonese et al. 2017, Hammann and Cramp 2018). Interestingly, the only indication of presence of plant processing in the Swifterbant pottery comes from an earlier study that applied Scanning Electron Microscope (SEM) on the carbonized surface deposits (foodcrust) collected from pottery of S3 (Raemaekers et al. 2013). SEM analysis on the carbonised surface deposits is a highly effective methodology to examine the charred plant and cereal residues possible preserved in the crusts through the cooking process. As, combining the applications of lipid residue analysis on pottery and SEM analysis on the carbonised surface deposit collected from the same pottery is proven to be an effective way for getting an insight on possible plant processing in the Swifterbant pottery, Dr. Lucy Kubiak of BIAX and I have started a pilot research project focusing on analysis of six pottery

fragments from S4 through the application of both lipid residue and SEM analyses in 2019 and currently working on the results.

As it was discussed in Chapter 4, the dairy residue found in the Swifterbant pottery is clearly associated with flask-like vessels which have small rim diameters and are decorated with bird bone impressions around the neck, rather than the typical S-Shaped cooking pots of the Swifterbant culture. This indicates that further lipid residue analysis on more flask-like vessels found in the Swifterbant contexts as well as petrographic analyses of these assemblages is needed in order to test the results of this study with a bigger dataset and also distinguish whether these "dairy pots" were produced on site or were vessels that were brought to the site, with their specific content.

Finally, the results on the functional analysis of Swifterbant pottery and its relationship to the subsistence strategies during the 5th millennium BC, through the Neolithisation period in the Dutch Wetlands create the need of expanding the dataset in time and conduct lipid residue analysis on the Swifterbant pottery that is coming from the sites which are dated to after c. 4000 cal BC such as Schipluiden (c.3630–3380 cal BC), the earliest known year-round settlement in the Lower Rhine Meuse area (Jongste and Kooijmans 2006, also see Kamjan et al. 2020) and Schokland-P14 (c. 3900–3400 cal BC) (ten Anscher 2015). This kind od a research would allow us to develop a better understanding of the function and the role of the pottery in the Swifterbant Culture during and after Neolithisation period in the region.

While there is still a lot to be done, this study has made a significant contribution to the knowledge of adoption, function, and functional variation of Swifterbant pottery in the Dutch Wetlands. It the overall results have demonstrated that Swifterbant pottery has been primarily and continuously used for processing aquatic resources, almost exclusively freshwater fish which continued after the introduction of domesticates into the Swifterbant culture. It also contributed to the wider discussion on adoption, function, and functional variation of early pottery in Northern Europe by presenting the regional differences in the use of early pottery which highlights the need of adopting a regional approach to assess pottery and culinary practices rather than considering Mesolithic pottery as on single entity.

References

Courel, B., Robson, H. K., Lucquin, A., Dolbunova1, E., Oras, E., Adamczak, K., Andersen, S. H., Astrup, P. M., Charniauski, M., Czekaj-Zastawny, A., Ezepenko, I., Hartz, S., Kabaciński, J., Kotula, A., Kukawka, S., Loze, I., Mazurkevich, A., Piezonka, H., Piličiauskas, Sørensen, A. S., Talbot, H. M., Tkachou, A., Tkachova, M., Wawrusiewicz, A., Meadows, J., Heron, C. P., and Craig, O . E. (2020). Organic residue analysis shows sub-regional patterns in the use of pottery by Northern European hunter-gatherers. *Royal Society Open Science*, 7. https://doi.org/10.1098/rsos.192016.

Jongste, P. F. B. and Kooijmans, L. P. L. (2006). *Schipluiden: a Neolithic settlement on the Dutch North Sea coast c. 3500 CAL BC.* Analecta Praehistorica Leidensia 37/38, Faculty of Archaeology, Leiden University.

Kamjan, S., Gillis, R. E., Çakırlar, C., & Raemaekers, D. C. M. (2020). Specialized cattle farming in the Neolithic Rhine-Meuse Delta: Results from zooarchaeological and stable isotope (δ18O, δ13C, δ15N) analyses. *PloS One*, *15*(10), e0240464.

Raemaekers, D., Kubiak-Martens, L., & Oudemans, T. F. M. (2013). New food in old pots - charred organic residues in Early Neolithic ceramic vessels from Swifterbant, the Netherlands (4300-4000 cal BC). *Archäologisches Korrespondenzblatt*, *43*(3), 315–334.

ten Anscher, T. J. (2015). Under the radar: Swifterbant and the origins of the Funnel Beaker culture. In: J. Kabaciński, S. Hartz, D. C. M. Raemaekers and T. Terberger (eds.), *The Dąbki Site in Pomerania and the Neolithisation of the North European Lowlands (c. 5000–3000 calBC)* Verlag Marie Leidorf GmbH. Rahden/Westf. pp. 335–358.