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Defining pottery use and animal management at the Neolithic site of Bylany (Czech Republic)

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Abstract
Archaeological potsherds have become a valuable source of information about diet and the wider economies of ancient communities, especially through the analysis of lipids preserved in the microporous matrix of the ceramic vessels. This study investigated >160 potsherds recovered from settlement phase 19 dated to 5160-5100 cal. BC from the Neolithic site of Bylany, one of the largest Linearbandkeramik (LBK) settlement in Central Europe. The aim was to investigate vessel use and animal management at the site and explore variations in organic residue composition and thus human activity at the household level. Pottery technology was also studied revealing a predominance of micro- and mesopores, indicating an advanced level of pottery production technology. More than 70% of the analysed potsherds yielded appreciable amounts of lipids dominated by C_{16:0} and C_{18:0} fatty acids, with compound-specific
carbon isotope compositions indicating origins predominantly from ruminant and non-ruminant
animal fats. Detection of very long fatty acids, fatty alcohols and traces of terpene compounds
originating from plants suggested a combination of meat- and plant-based diet components and
specialised use of some vessels. However, evidence of the use of vessels for milk collection or
processing was not detectable at Bylany, at least during the settlement phase investigated
herein.

Highlights

• Lipids were extracted from late LBK sherds from Bylany (Czech Republic).
• Findings were interpreted in relation to pottery typology and households.
• No difference in food processing practices between house types could be identified.
• The processing of ruminant and non-ruminant carcass products was confirmed.
• The lack of dairy fats pointed at the absence of milk exploitation.

Key words: LBK pottery, organic residue analysis, gas chromatography, fatty acids, stable
carbon isotope analyses, vessel use, porosity.
1. Introduction

The Neolithic period saw major changes in the way food and natural resources were used. It is well-known that the early farmers cultivated crops and bred livestock, although many of the details of plant agriculture and animal management are yet to be elucidated (Pavlu and Zapotocka 2007). Neolithic settlements of the central European Linear Pottery culture (*Linearbandkeramik*, LBK) consist of small, middle or long houses with thatched roofs, supported by rows of poles (Coudart, 1998). It was thought that the size of the houses corresponded to the status of their inhabitants (e.g. Modderman, 1986; van de Velde, 1990), although recent research proposed that the three basic types of houses correspond to different household activities and roles within the settlement (Hachem, 2000; Gomart et al., 2015). The different house sizes may reflect the size of animal herds, the proportion of hunted animal species and/or the type and volume of cultivated or gathered crops. Notwithstanding, variable local environmental conditions which not have been particularly suitable for stable subsistence strategies (Pavlu, 2014b), some large LBK settlements persisted more than 400 years. Social groups with different economies would have coexisted responding to the fluctuations and pressures associated with the beginnings of Neolithic agriculture (Pavlu, 1987, 2014b).

The well-described site of Bylany (Kutna Hora, Czech Republic; see Fig. 1) is one of the largest central European Neolithic settlements of the LBK and following STK (*Stichbandkeramik*) cultures, comprising more than 100 house-plans. The settlement area was discovered in 1950s and over 7 ha of settlement remains were uncovered during excavations. The LBK period alone included 25 settlement phases (resp. ceramic phases), chronologically classified between 5350 and 4900 cal. BC (Podborsky, 1997; Pavlu and Zapotocka, 2007). Phase 19 (examined here) is dated to 5160-5100 cal. BC and falls within the 5th interval of the LBK settlement (late LBK, phases 18-20). Phase 19 of the settlement exhibited a complicated house development...
consisting of small \( (n = 3) \), middle \( (n = 4) \) and long \( (n = 3) \) houses, with many associated clay pits (i.e. large pits used as a source of clay) and grain pits, covering areas A and B of the site (Fig. 2). A pit containing ceramic artefacts was found alongside each house. The pottery assemblage of Bylany is very large, comprising >76,000 classified fragments of vessels (Kvetina and Koncelova, 2012), allowing functional classification of the vessels based on ethnoarchaeological markers (Varien and Mills, 1997), primarily the shape and rim diameter of the vessels (Fig. 5; Rice, 2006). The archaeozoological assemblage recovered at the site is particularly scarce, with only 1.6 kg of poorly preserved animal remains having been discovered during the 40-year long excavations (Pavlu, 2014a). Archaeobotanical remains at Bylany are lacking for environmental and historical reasons. Furthermore, no evidence of burial sites have been detected. The type and position of the houses, pits and trenches, macrolithic tools and pottery are thus the only source of information that have been examined so far regarding household economies and other human activities at the Neolithic site of Bylany.

The increasing range of biomolecular methods used in archaeology are proving particularly effective for investigating the diet and subsistence economies of Neolithic communities (Evershed et al., 1992). In particular, organic residue analysis of pottery vessels (e.g. Evershed, 2008b) has been successfully applied widely, allowing various levels of information to be revealed, ranging from vessel use and technological innovation (Roffet-Salque et al., 2013) to specialised animal management strategies (Copley et al., 2003; Evershed et al., 2008) and the exploitation of wild resources (Cramp et al., 2014a, b; Craig et al., 2015; Roffet-Salque et al., 2016). Organic residues accumulated during vessel use, mainly of lipophilic origin persist for millennia absorbed into the ceramic fabric of ancient pottery vessels (e.g. Evershed et al., 2002; Regert et al., 2003). The presence of characteristic lipidic biomarkers, including saturated fatty acids, triacylglycerols and a range of fatty acyl derivatives, waxes, long-chain ketones and
triterpenoid components, allow the type and origin of the residue to be assessed (for reviews see Evershed, 1993, 2008b; Regert et al., 2003; Mukherjee et al., 2005). Traces of animal fats, plant oils, beeswax, resins, tars, pitches, etc. have been identified in archaeological pottery vessels. A combination of chromatographic techniques (GC/FID) and mass spectrometric techniques (GC/MS) is used to separate and identify the compounds. Animal fat residues occur widely, however, the molecular composition of degraded animal fats alone does not allow fat type to be identified and thus compound–specific stable carbon isotopic analyses with GC-C-IRMS (gas chromatography-combustion-isotope ratio mass spectrometry) are carried out to enable ruminant adipose, ruminant dairy or non-ruminant adipose fats to be distinguished (e. g. Dudd and Evershed, 1998; Dudd et al., 1999; Copley et al., 2003). The possibility also exists of identifying milk residues in pottery vessels, which has opened up new avenues of investigation on the beginnings of dairying across Europe and the Near East (e.g. Evershed et al., 2008). Evidence for dairying has been revealed dating as early as the 7th millennium BC in the Near East and lipid residue analyses of potsherds from the 6th LBK have shown that some Central European LBK communities were processing milk into cheese using cheese-strainers (Salque et al., 2013).

Notwithstanding the latter findings, extensive work is required to identify the temporal and spatial patterning of milk use in Europe order to understand the lactase persistence allele amongst the first farmers of Central Europe (Itan et al., 2009). As a contribution to this endeavour, herein, we focus on the organic residue analysis of pottery vessels from the LBK site of Bylany (phase 19) in order to assess: (i) pottery vessel use, and (ii) animal management. The investigation also aims to explore variations in pottery vessel use at household and site levels. Further, given the differences observed in lipid preservation, porosimetry was used in an attempt to explore the mechanisms of preservation of lipids. The focus of this study was
phase 19 from the Bylany excavation, chosen as sherds of all functional categories (Pavlu, 2000) were recovered and, overall, the sherds were less-fragmented than in other phases, suggesting a simpler taphonomic history for this assemblage, which legitimises the comparisons presented (Pavlu, 2010).

2. Material and Methods

2.1. Selection of pottery sherds

A total of 1,842 rim potsherds were excavated from phase 19, from which 1,539 sherds were classified into 14 categories according to their presumed function (Fig. 5; Pavlu, 2010). Only 842 potsherds (46%) could be simultaneously categorized using one of 14 classes and associated to a house type. From this set, a subset of 163 upper rim sherds (20%) were sampled and submitted to organic residue analysis. The potsherds originated from presumed water storage/processing vessels (n = 60; categories F6, F9 - F11, F13), from food processing and serving vessels (n = 88; categories F1-F5, F7, F8, F12) and from vessels for storage of dry commodities (n = 15, category F14). The potsherds were sampled from pits alongside 9 different households, with 74 potsherds originating from long houses (houses 96, 162, 1246), 49 from middle houses (houses 361, 619, 702) and 40 from small houses (houses 959, 1161, 1240; see Table I).

Porosimetry studies were carried out on 7 sherds from Bylany phase 19, of which 3 (categories F9, F10, F13) were presumed to be water storage/processing vessels and 4 (categories F4, F7, F12) were presumed to be food processing and serving vessels. A portion (0.1-0.2 g) of each potsherd was sampled and subjected to mercury porosimetry using an AutoPore IV 9500 V1.06 instrument. Each sherd was placed in the porosimeter, evacuated, and porosity determined using
pressure ranges 0.0003-0.01 MPa for macropores, 0.13-200 MPa for mesopores. The pressure was gradually increased simultaneously while the volume of mercury entering the pore of the sherd was recorded.

2.2. Lipid extraction of potsherds

All solvents used for lipid analyses were HPLC grade and all the glassware was furnaced at 450 °C for a minimum of 4 h. The surface of a sub-sample of the archaeological potsherd was cleaned with a manual modelling drill to remove exogenous lipids (from the soil and post-exavation handling). The portion of 2-3 g of potsherd was then crushed and ground in a glass mortar using a pestle to obtain a fine powder, which was accurately weighed and 20 µg of internal standard (n-tetraatriacontane, Supelco Analytical, Bellefonte, USA) added. Lipids were extracted via the direct methanolysis method described in Correa-Ascencio and Evershed (2014). The method combines hydrolysis and transesterification reactions to obtain fatty acid methyl esters (FAMEs) from triacylglycerols and their derivatives simultaneously during the extraction of potsherds. Aliquots of total lipid extracts (TLEs) were taken and free hydroxyl groups trimethylsilylated by treatment with N, O-bis(trimethylsilyl)trifluoracetamide (BSTFA, 20 µL, 70 °C, 1 h) to obtain trimethylsilylated (TMS) derivatives prior to GC analyses. The excess BSTFA was evaporated under a gentle stream of nitrogen and methylated/trimethylsilylated extracts dissolved in hexane for analyses by GC/FID, GC/MS and GC-C-IRMS.

2.3. GC analyses

GC/FID analyses were performed on an Agilent Technologies 6890N gas chromatograph equipped with a (5%-phenyl)methylpolysiloxane coated fused silica capillary column (Agilent 19091S-433 HP-5MS; 30 m x 0.32 mm i.d., 0.25 µm film thickness). One microlitre of
methylated/trimethylsilylated extract dissolved in hexane was introduced using a split/splitless injector at 220 °C. The temperature of GC oven was programmed from 120 °C for 5 min, to 175 °C at 5 °C min⁻¹, followed by an isothermal hold for 25 min, then to 300 °C at 7 °C min⁻¹, followed by a third isothermal hold for 25 min. Helium was used as carrier gas with a constant flow of 1 mL min⁻¹. The GC/MS analyses were performed with the same temperature program on a GC system Agilent Technologies 7890A with a 5975C VL MSD detector. The GC/MS system was equipped with the same column as the GC-FID system.

Compound-specific stable carbon isotope analyses were performed using an Agilent Industries 7890A gas chromatograph coupled to an IsoPrime 100 isotope ratio mass spectrometer. One microlitre of methylated/trimethylsilylated portions of extract dissolved in hexane were introduced via a split/splitless injector operated in the splitless mode onto a 50 m x 0.32 i.d. fused silica capillary column coated with a 100% dimethylpolysiloxane stationary phase (Agilent HP 1; 0.17 μm film thickness). The GC oven temperature programme was held at 40 °C for 2 min, followed by a gradient increase to 300 °C at 10 °C min⁻¹, after which the oven was held isothermally for 10 min. Helium was used as carrier gas at a constant flow of 2 mL min⁻¹. The combustion reactor consisted of a quartz tube filled with copper oxide pellets maintained at a temperature of 850 °C. Data processing was carried out using the Ion Vantage software (version 1.5.6.0, Isoprime).

3. Results

3.1. Lipid recovery

More than 70% of potsherds from the 163 analysed yielded >5 μg g⁻¹ of (μg of lipid per gram of potsherd) TLE, while 18% yielded >100 μg g⁻¹. This high recovery rate is comparable to that observed at the LBK site of Kopydłowo (Poland; Roffet-Salque and Evershed, 2015).
3.2. Lipid compositions

Most of the TLEs were dominated by palmitic (C\textsubscript{16:0}) and stearic (C\textsubscript{18:0}) acids. Odd-numbered and branched-chain fatty acids (C\textsubscript{17:0} and C\textsubscript{17:0br}), biomarkers of bacterial population from the rumen and characteristic of ruminant fats (Keeney et al., 1962), were detected in 23% of the extracts. The relatively high abundance of the C\textsubscript{18:0} fatty acid compared to the C\textsubscript{16:0} fatty acid suggests that these lipids derive from animal fats (Copley et al., 2001). Low concentrations of oleic acid (C\textsubscript{18:1}) and its degradation products (9,10-dihydroxyoctadecanoic acid and azelaic acid) were detected in most of extracts. The presence of unsaturated fatty acids at high concentration is often considered as arising from modern contamination due to the lability of the double bond in oxidative conditions. However, considering that oleic acid can be found in animal fat triacylglycerols at high concentration (in the case of modern reference porcine or ruminant fats it ranges from 31 to 44%; Gunstone, 2007; Velisek, 2013), its occurrence at low concentration in well-preserved archaeological pottery is thus possible. The presence of its degradation products (Table 2) also points towards altered (archaeological) animal fats.

Myristic (C\textsubscript{14:0}) and arachidic (C\textsubscript{20:0}) acids were also detected. Longer branched fatty acids (C\textsubscript{15} to C\textsubscript{18}) detected in 23% of the sherds could originate from microbial flora of the rumen and originate from domestic ruminant adipose or venison fats (e.g. Duncan and Garton, 1978; Velisek, 2013). The presence of mid-chain ketones (C\textsubscript{31} and C\textsubscript{35}) in a single sherd from a pot of type F13, indicated that the pot was heated at high temperatures, leading to the pyrolysis of acyl lipids and their ketonic decarboxylation (Evershed et al., 1995; Raven et al., 1997).

Nearly 23% of the samples with the appreciable amount of lipids had significant concentrations of long-chain fatty acids and fatty alcohols, such as behenic (C\textsubscript{22:0}), lignoceric (C\textsubscript{24:0}) or cerotic
fatty acids (Fig. 3) and hexa- and octacosanol. These compounds derived mainly from
plant tissues and plant waxes and suggest a combination of meat- and plant-based foodstuffs in
some of the vessels (20 of 88 samples). Plant lipid residues were present in every type of vessels,
in bowls, dishes and jars, and could have been used as flavouring (Filipović and Tasić, 2012)
or waterproofing agents (Heron et al., 1994; Roffet-Salque et al., 2016). In 13 extracts n-alkanes
(C_{16} to C_{29}), resinous compounds and dicarboxylic acids were also detected (see Fig. 4b).
Shorter n-alkanes (C_{16}-C_{19}) might have arisen in the potsherds through pyrolysis (Eckmeier and
Wiesenberg, 2009; Schellekens et al., 2013), longer n-alkanes (C_{28}, C_{29}) could originate from
waxes of higher plants (Gunstone, 2007). Resinous diterpenic (abietic acid derivatives) and
triterpenic (betulin and friedelin) compounds were detected in small jars (type F13) from the
long house 162 and small house 959 (Fig. 4b) providing evidence for the presence of tar
adhesives possibly originating from a birch bark tar in case of betulin (e.g. Urem-Kotsou et al.,
2002; Grünberg, 2002; Regert et al., 2003) or from beach and oak barks in case of friedelin
(Chandler and Hooper, 1979; Urem-Kotsou et al., 2002; Prost et al., 2011) or from altered pine
resin in case of abietic acid derivatives (Regert, 2004).

3.3. Stable carbon isotope compositions of fatty acids
A total of 38 total lipid extracts identified as pure animal fats and with an appreciable
concentration of lipids (>10 µg g^{-1}) were analysed to determine the carbon isotopic composition
of the C_{16:0} and C_{18:0} fatty acids and identify the source of the animal fats. The $\delta^{13}C_{16:0}$ values
of archaeological animal fats ranged between -27.9 and -23.8‰, while $\delta^{13}C_{18:0}$ values range
between -30.6 and -22.9‰ (Fig. 8a). These $\delta^{13}C$ values are in agreement with pure fats and
mixtures of carcass fats from non-ruminant and ruminant animals raised on C_{3} diets (Copley et
al., 2003). The $\Delta^{13}C (= \delta^{13}C_{18:0} - \delta^{13}C_{16:0})$ proxy was used in order to identify the fat types by
emphasising the influence of animal metabolism (Evershed et al., 1999; Copley et al., 2003).
The archaeological animal fats extracted from the pots from Bylany exhibit $\Delta^{13}C$ values ranging between -3.1 and 1.4‰ (Fig. 8b), consistent with pure non-ruminant adipose fats ($n = 14$) or mixtures of ruminant adipose (carcass) fats and non-ruminant adipose fats ($n = 24$; Table 3). No dairy residues were detected in the extracts.

3.4. Porosity

The mercury porosimetry analyses revealed the presence of mostly mesopores ($10^{-7} \text{m} > \text{diameter} > 2 \cdot 10^{-9} \text{m}$) and micropores ($\text{diameter} < 2 \cdot 10^{-9} \text{m}$). The total pore surface of potsherds ranged between 4 and 11 m$^2$ g$^{-1}$, the average radius of pores ranged between 0.02 and 0.06 µm and the mean porosity was 23%.

4. Discussion

4.1. Analysis of pottery and lipid preservation

The presence of mesopores ($10^{-7} \text{m} > \text{diameter} > 2 \cdot 10^{-9} \text{m}$) and micropores ($\text{diameter} < 2 \cdot 10^{-9} \text{m}$) in pots from the site of Bylany (phase 19) detected by porosimetry analyses agrees with the hypothesis that pots were fired in open kilns with firing temperatures ranging between 700-800 °C (Pavlu and Zapotocka, 2007). Indeed, these temperatures are sufficient for creating hard microporous fabric and vessels with ‘suitable’ porosity. The well-developed technology of pottery manufacturing at Bylany would have had an influence on the everyday activities at the settlement, e.g. by decreasing the amount of fuel needed for heating cooking vessels. High porosity allows liquids to permeate easily through the vessel walls, extending the time for liquid contents to boil by cooling the outer surface of the vessel wall. On the contrary, low vessel wall porosity and reduction of wall thickness (mean thickness value of Bylany potsherds without counting of storage vessels of type F14 was 0.8 cm) increases thermal
shock resistance during repeated heating (Gosselain, 1992; Tite et al., 2001; Nelson, 2010) and heat conduction (Braun, 1983) while it decreases heat loss (Schiffer, 1990). Those properties had to be controlled also by a type of tempers and clays (Tite et al., 2001). Postfiring treatments can be applied to decrease permeability (Rice, 2006) and repetitive cooking of plant and animal tissues has been shown to seal vessel walls, improving the heat transfer during cooking (Charters and Evershed, 1997; Evershed, 2008b).

The basic assumption is that lipophilic compounds are capable of binding into submicron pores of ceramic fabric due, the hydrophobicity, hence, insoluble properties of lipids, the presence of carboxylic and hydroxy moieties enhancing their propensity to bind to the polar ceramic fabric. However, the question of enhanced physico-chemisorption of lipids was recognised nearly twenty years ago, with the use of a caustic methanol extractant follow CHCl$_3$/MeOH extraction was effective in revealing highly functionalised lipids produced via oxidation of unsaturated fatty acids (Regert et al., 1998). Building on this approach the new extraction method recently proposed by Correa-Ascencio and Evershed (2014) uses an acidified solution of methanol to extract chemisorbed compounds, which could not be extracted using the commonly used organic solvents (chloroform, dichloromethane and methanol). As with the caustic methanol extraction method, the new protocol results in higher extraction yields than a solvent extraction with a mixture of chloroform/methanol (Evershed et al., 1990), suggesting that some lipids are strongly bound into ceramic pores or on surfaces, e.g. to metal ions such as Ca$^{2+}$, Fe$^{3+}$, Al$^{3+}$ (as salts) or to SiOH (via hydrogen bonding), which create an inner ceramic lattice. In the sherds from Bylany, it appears that well-shaped micro- or mesopores protect adsorbed lipids from microbial utilization, as microbial flora cannot utilize unreachable substrates (mean size of bacteria $>10^{-6}$ m). Degradation of lipids in the clay walls of potsherds is thus only driven by
outer environmental conditions (humidity, air access, temperature, redox condition etc.; Evershed, 2008b).

Some of the sherds from Bylany contained >1.5 mg of lipids per gram. While, such concentrations of lipid are not uncommon, the highest lipid concentrations are observed in potsherds excavated from arid (Dunne et al., 2012) or acidic (Smyth and Evershed, 2015) burial environments. Within a site higher concentration of lipids in some vessels could reflect a frequency of use of certain vessels (Smyth and Evershed, 2015). The burial conditions at Bylany are neutral or slightly acidic, and the loess soil is considered reasonable water-permeable (Pye, 1995), but clearly these conditions lead to favourable preservation of lipids in potsherds. Not surprisingly, however, these same conditions cause extensive decalcification of bones at Bylany, dissolving the vast majority archaeozoological and human skeletal remains.

4.2. Concentrations of lipid residues in different vessel types

The function of the pottery vessels comparing the Bylany assemblage has been assessed in detail using typological analysis, correlating the shape of vessels to their potential use, with reference to ethnoarchaeological studies (Varien and Mills, 1997). Three basic shapes have been identified in the ceramic assemblage, namely: bowls, dishes and jars, and their volumes reconstructed based on orifice diameters and rim angles (Pavlu, 2000). This ethnoarchaeological approach has allowed the vessels to be classified into several categories of presumed use, e.g. cooking vessels, storage vessels or vessels for storing water, and a range of respective subcategories (Pavlu, 2000; Fig. 5). All the functional categories exhibited high recovery rate of lipids (above 60%), except sherds from the type F2 (31%, 4 residues extracted from 13 potsherds). The highest recoveries rates of lipids are observed for small dishes of types F1 and F3 (90% and 88%, respectively) but the median concentration of total lipid extract was <50 µg g⁻¹.
The typological set 1 (F6, F9, F10, F11 and F13) was interpreted as having been used for water storage and handling. Lipids were recovered from >75% of the sherds from this vessel category (45 residues extracted of 60 potsherds, one-sample $\chi^2$ test, $p < 0.01$), which is the highest recovery rate of lipids detected in functional sets from Bylany. Lipids detected in those sherds were identified as being animal fats ($n = 38$; 23% of examined potsherds), with traces of plant waxes ($n = 25$; 15%; Fig. 8-9). Some of the vessel could have been used for water storage, with the animal fats present resulting from post-firing waterproofing (e.g. Evershed et al., 1997; Skibo, 2013). However, more than 11% of sherds contained >500 µg of lipids per gram, suggesting that animal products were processed in these vessels. The presence of mid-chain ketones in jar F13 (Fig. 4a), provides compelling evidence for the heating of animal fats at high temperatures (Evershed et al., 1995; Raven et al., 1997) that could have occurred when animal fats were spread on the inner surface of the pots for waterproofing just after the firing or when animal products were processed in those large pots.

The typological vessel set 5 (F14) are large vessels proposed to be storage pots, as their substantial size would have prevented them being easily manoeuvred. Moreover, substantial thickness of their vessel wall (mean 1.6 cm) and toughness of the fired clay would have been important properties of storage vessels (Tite et al., 2001). Although lipids were recovered from 15 sherds of this category (73%; one-sample $\chi^2$ test, $p < 0.01$), the concentrations were very low (average 11 µg g$^{-1}$), which is entirely consistent with the hypothesis that the F14 pots were used for storage of dry goods or water.

Based on typological assessments liquid and solid food would have been served in pots from sets 3 and 4, respectively. However, cold or hot contacts of foodstuffs lead in both cases to lipid
adsorption, although concentrations may differ. Odd-carbon number mid-chain ketones, usually  
interpreted as demonstrating that pots were heated at high temperature (Raven et al., 1997) were  
not detected in these potsherds. Although it is not possible to determine whether the foodstuffs  
contained in these pots were hot or not, the hypothesis remains that such vessels were used as  
tableware suitable for serving (e.g. Urem-Kotsou and Kotsakis, 2007). Significantly, the  
potsherds from set 3 exhibited relatively high concentration of lipids (average 135 µg g\(^{-1}\)),  
which were skewed by high lipid concentrations in the potsherds from vessel types F3, F5 and  
F7 (Fig. 6a). This contrasted with the lower mean lipid concentrations in potsherds of set 4  
(average TLE concentration: 39 µg g\(^{-1}\)) implying these pots were used either less frequently or  
for processing different foodstuffs.  

Finally, the vessels from the set 2 (F4 and F12) were hypothesised to be the most commonly  
used ware for cooking, food processing and serving. Repetitive use of pots for cooking  
foodstuffs leads to the accumulation of lipids in the clay walls (Evershed, 2008a). Lipids were  
recovered from 71% of potsherds from this set (17 residues were extracted from 24 potsherds,  
one-sample \(\chi^2\) test, \(p < 0.01\)). Moreover, the mean lipid concentrations determined for the  
scherds from pots F4 and F12 were 121 and 152 µg g\(^{-1}\), respectively, which are relatively high  
compared to sherds from other sets except those from sets 1 or 2 (Fig. 6b). Significantly, the  
lipids detected in 8 potsherds from this set were identified as being animal fats (Table II)  
indicating that the original pots were used for food processing, likely cooking.  

No evidence was obtained from the analyses the specialisation in the use of pottery for  
processing specific types of foodstuff (Fig. 8), except for small bowls (\(n = 4\), analysed  
categories F7, F9 and F11) where only pure non-ruminant fats were detected. In contrast to the  
inferences based on typological assessments, the lipid concentrations (Fig. 6) and compositions
suggests no detectable hierarchy existed in vessel use at Bylany (Pavlu, 2014a; Fig. 5). The inference is that either: (i) lipid analyses lack the resolution to reveal specialisation, or (ii) that vessels were highly utilitarian and used for a wide range of purposes. The high concentrations of lipids in some vessels possibly reflect the repetitive use of vessels for cooking, as well as the use of vessels for longer time periods. However, in any discussion of concentrations of lipid observed we must be mindful of the taphonomic history of the sherds. Notwithstanding the latter, both repeated use and extended use-life will result in lipids being accumulated in appreciable concentrations in vessel walls. In contrast, vessels with lower recovery rates and low concentrations of lipids were either: (i) not used for cooking or processing of fat-rich foodstuffs, or (ii) had shortened use-lives due to early breakage of the vessels.

Consideration of the lipid recovery rates and concentrations in different vessel types in the context of households (Fig. 7, Tab. 1), shows highest lipid concentrations were exhibited by the vessels from middle house 702 and small house 959 (recovery rates 67% and 100%, respectively). Relatively constant recovery rates were observed for the different house types, with rates being 70%, 76% and 73% for small, middle and long houses, respectively (one-sample $\chi^2$ test, $p < 0.04$; Table 1). Sherds from long houses thus present slightly lower recovery rates than sherds from middle and small houses. However, this observation is biased as large and small bowls, which are presumed to be cooking pots, represented just over 24% (18/74 sherds) of the potsherds sampled from long houses.

4.3. Stable carbon isotope analysis of lipid residues and animal management

The faunal assemblage at Bylany is relatively scarce, with only 1.6 kg of poorly preserved bone and fragments recovered during the entire excavation. Archaeozoological remains of cattle (*Bos taurus*), aurochs (*Bos primigenius*), pigs (*Sus domesticus*), goats (*Capra aegargus*), sheep (*Ovis*...
orientalis), wild boar (Sus scrofa), wild horses (Equus ferus) and roe deer (Capreolus capreolus) were identified (Pavlu, 2014a). The remains were irregularly spread over the settlement mainly concentrated in pits situated alongside and between houses. Statistical correspondence analysis of the bone fragments found at the whole site of Bylany and at specific households showed that cattle and pigs were mainly associated with long and middle houses, while goats and sheep were more common in small houses (Pavlu, 2014a).

All potsherds examined herein were excavated from pits alongside long, middle or small houses or from the immediate surroundings of houses, and not from the inner space of houses (Soudsky, 1966; Pavlu, 2010). Animal fats were detected in sherds from across all types of houses (Fig. 8). Animal fats extracted from sherds from long, middle and short houses exhibited $\Delta^{13}C$ values ranging between -3.1 and 1.1‰ ($n=13$), 1.1 and 2.3 ‰ ($n=16$) and 1.4 and 2.8‰ ($n=9$), respectively. The $\Delta^{13}C$ values of animal fats extracted from sherds from long and middle houses are similar to those from short houses. The median of $\Delta^{13}C$ values for small houses (-0.6‰) and middle and long houses (-0.9‰) were statistically comparable (Mann-Whitney U test, $U=115, P<0.05$). Animal fats detected in sherds from long and middle houses exhibited $\delta^{13}C$ and $\Delta^{13}C$ values consistent with pure non-ruminant carcass ($n=10; 34\%$) fats and mixtures of non-ruminant and ruminant carcass fats ($n=18; 44\%$). However, non-ruminant carcass fats and mixtures of ruminant and non-ruminant carcass fats were also detected in sherds from pits alongside small houses ($n=9$), providing evidence that both non-ruminant and ruminant products were processed in the small houses. Products from ruminant (cattle/sheep/goats) and non-ruminants (pigs) could have thus been processed at the small houses. Mixtures of ruminant and non-ruminant products occur across all types of houses without any preference, although the exploitation of pigs seems to have been restricted to long and middle houses (Pavlu, 2014a). The inhabitants likely share their economies to support also
their neighbours (probably birth related), e.g. at the level of two or three houses, to maintain effective subsistence. For instance, if a cow, a pig or a large wild animal was slaughtered before winter or during some ceremonial rites, meat could have been divided between a bigger groups of people and processed at the level of each household, independently of house size, as evidenced in other Central European LBK settlements (Halstead, 2011; Marciniak 2011, 2008b).

Interestingly, no evidence for dairy fat residues was detected in potsherds from long, middle and small houses at the later settlement phase of Bylany (phase 19). The absence of dairy fats in sherds from Bylany can relate to: (i) the absence of milk use and processing at the site, (ii) the mixing of dairy and non-ruminant carcass products in pots, masking the milk signal, or (iii) the use of dairy products in perishable containers, which did not survive, e.g. in wooden vessels (Maigrot, 2003) or in leather containers (Morris, 2013). It should be also considered, dairy fat triacylglycerols with lower carbon number are more susceptible to degradation, especially when present in fresh milk and not concentrated e.g. in butter or cheese (see Dudd and Evershed 1998; Copley et al., 2005). However, per compound-specific stable carbon isotope analysis results, the high number of animal fats detected in the pots (38 potsherds of 94 with concentration of lipids > 10 µg g⁻¹) provide a relatively secure evidence for the absence of dairy fat residues in pots from phase 19 at Bylany. Unfortunately, the absence of sufficient archaeological remains prevents herd structures to be reconstructed and herding management to be assessed (Vigne and Helmer, 2007). Thus, milk exploitation at the site seems of rather low intensity or even non-existent. This agrees with lipid residue analysis studies carried out at other central European LBK sites (Salque et al., 2012; Roffet-Salque and Evershed, 2015) and with aDNA analyses performed on human skeletal remains from LBK sites in Germany, Hungary or Poland (Burger et al., 2007; Oelze et al., 2011).
Fresh milk drinking by early farming economies has been suggested to have offered an evolutionary advantage to Neolithic societies with a long tradition of cattle herding (Gerbault et al., 2007; Itan et al., 2009). Although Bylany inhabitants clearly exploited cattle and other ruminants, thus, raw milk would have been available to them. However, based upon lipid residues they appeared not to be processing dairy products in pottery. Explanations for this include absence of the genetic disposition to digest milk and/or the lack of knowledge of how to process it into a digestible form (Spangenberg et al., 2006; Evershed et al., 2008; Salque et al., 2013; Budja et al., 2013).

**Conclusions**

In order to extend our knowledge about diet and household economies at the later LBK phases of the Neolithic site of Bylany (phase 19) >160 potsherds were submitted to lipid residue analyses. The sherds studied originated from bowls, dishes and jars excavated from long, middle and small houses. More than 70% of potsherds exhibited detectable lipids, confirming that many of the vessels were used for cooking or serving of food, or the processing/storage of animal products.

The favourable preservation of lipids is enhanced by porous nature of the pottery microstructure and chemistry (Heron et al., 1991) as evidenced further by the porosimetry analyses reported herein. Mean porosity of the studied potsherds was 23% and they contained a predominance of micro- and mesopores, which would aid the protection of adsorbed lipids during burial. The porosity measurements also indicated that pottery production technology at Bylany was well-developed, which would have influenced the ways vessels were used and the extent to which
they survived in the archaeological record (Tite et al., 2001). The slightly acid pH burial conditions at the site appear favourable for lipid preservation (e.g. Smyth and Evershed, 2015).

Comparing lipid residue compositions to the pot shapes, indicate some differences in the foodstuffs processed in different types of pots, although some hypotheses regarding vessel specialisation appear not to hold.

Stable carbon isotopic analyses of the animal fats detected in potsherds from Bylany demonstrated that carcass products were obtained from both ruminant and non-ruminant sources. Mixtures of carcass fats from both ruminant and non-ruminant animals were detected across all types of vessels and houses without any significant context specificity. It appears that the inhabitants of Bylany shared their economies between each other, independent of the size of the houses, herds or fields they managed, thus, suggesting maintenance of extensive cultural relationships needed to maintain essential sustainable community-level subsistence (Richards, 2002; Halstead, 1999). Notwithstanding this, individual households may still have played a specific roles in the overall settlement economy.

Evidence for dairy fats was not detected in any of the sherds analysed in this study neither by lipid composition nor by compound-specific stable carbon isotope analysis, suggesting that cattle or other ruminants were likely not milked at Bylany, at least during the later LBK phase 19. The importance of dairying to the economy at Bylany, thus, remains an open question. Further work in progress will shed light on the exploitation of animal resources at earlier phases of the site.
Acknowledgements

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References


Fig. 1. Map showing the location of Bylany within the Early Neolithic (LBK) settlement area in Bohemia, Czech Republic (after Kvetina, Koncelova, 2012).
Fig. 2. Map of households from which potsherds were selected for analysis from the settlement of Bylany (Area A and B - settlement phases 9-25; area F - settlement phases 1-8).
Fig. 3. Partial gas chromatogram of total lipid extracts from sherds from Bylany phase 19 typical of animal fat. Peak identities: FAME = fatty acid methyl esters, br-branched, C16-MAG - monopalmitoylglycerol, C18-MAG-monostearoylglycerol, IS-internal standard (n-tetratriacontane).
Fig. 4. Partial gas chromatograms of (a) animal fats with mid-chain ketone and (b) traces of fatty acids and resinous components (magnified) Peak identities: FAME = fatty acid methyl esters, TMS-trimethylsilylated, br-branched, C16-MAG - monopalmitoylglycerol, C18-MAG- monostearoylglycerol, 9 DCA – azealic acid, 9,10- C18 FAOH – 9,10-dihydroxystearic acid, 31(35)-K – mid-chain ketones with 31 and 35 carbons, IS-internal standard (n-tetracontane), PL – plasticizer (contamination).
Fig. 5 Functional classification of archaeological pottery from Bylany according to their typologies (after Pavlu, 2000).
Fig. 6. Box plot of total lipid concentrations [µg g⁻¹] in different categories of vessels from Bylany (A) and functional sets (B); ○ remote values; * extremes. Set 1 - Water processing (cat. F6, F9, F10, F11, F13), Set 2 - Serving and food processing (cat. F4, F5), Set 3 - Serving liquid food (cat. F3, F5, F7, F8), Set 4 - Serving solid food (cat. F1, F2), Set 5 - Storage (cat. F14).
**Fig. 7.** Box plot of total lipid concentrations [µg g⁻¹] in pottery recovered from specific houses examined in this study. Recovery rates of lipids in brackets; ○ remote values; * extremes.
Fig. 8. (A) $\delta^{13}C$ values for the C\textsubscript{16:0} and C\textsubscript{18:0} fatty acids from the TLEs extracted from potsherds from Bylany phase 19 according to the type of houses (long △, middle ■ and small ○). The three fields correspond to the P = 0.684 confidence ellipses for animals raised on a strict C\textsubscript{3} diet in Britain (Copley et al., 2003). (B) Difference in the $\delta^{13}C$ values of the C\textsubscript{18:0} and C\textsubscript{16:0} fatty acids ($\Delta^{13}C = \delta^{13}C_{18:0} - \delta^{13}C_{16:0}$) for the same archaeological fats. The ranges represent the mean ± s.d. for a global database comprising modern animal fats from across the globe (Copley et al., 2003; Outram et al., 2009; Spangenberg et al., 2006; Gregg et al., 2009; Dunne et al., 2012). Each data point represents an individual potsherd. Analytical precision ± 0.3
Fig. 9. Scatter plots of stable carbon isotope compositions of animal fat residues extracted from the pottery of Bylany phase 19 in a context of presumed functional sets (A) where ● represent water processing vessels, ■ processing and food serving vessels and ▲ represent storage vessels, and vessel shapes (B) where ▲ represent big jar, ■ big dish, □ small dish, ● big bowl and ○ small bowl.
Table 1 Summary of the results of the lipid residue analyses of potsherds from Bylany (phase 19).

<table>
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</tr>
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<td>61</td>
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</tr>
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<td>72</td>
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Table 2 Summary of extracted lipids in the context of houses and vessel types

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<td>Big bowl</td>
<td>FA(m,l,vl,br), MAG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jar</td>
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</tr>
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<td>1161</td>
<td>Small bowl</td>
<td>FA(l,br,vl), MAG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>361</td>
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</tr>
<tr>
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<td></td>
<td>Big dish</td>
<td>FA(l,br,vl), MAG, OH(tr)</td>
</tr>
<tr>
<td></td>
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<td>Small bowl</td>
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</tr>
<tr>
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<td>FA(m,l,br), MAG, DCA, OH</td>
</tr>
<tr>
<td></td>
<td>619</td>
<td>Jar</td>
<td>FA(l,br), MAG</td>
</tr>
<tr>
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<td></td>
<td>Small dish</td>
<td>FA(l,br), MAG, OH(tr)</td>
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<td>FA(l,br), MAG</td>
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<td></td>
<td></td>
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</tr>
<tr>
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<td>702</td>
<td>Big dish</td>
<td>FA(l,br), MAG</td>
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<td></td>
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<td>Small dish</td>
<td>FA(m,l,br,vl), MAG, FAOH, DCA</td>
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<sup>a</sup>FA, n-alkanoic fatty acids (m-middle, l-long, br-branched, vl-very long); MAG, monoacylglycerols; OH, n-alcohols; DCA, dicarboxylic acids; ALK, n-alkanes; K, mid-chain ketones; FAOH, hydroxy fatty acids; TOH, triterpene alcohols; tr, traces.
Table 3: Details of potsherds selected for GC-C-IRMS, results and interpretation of the isotopic analyses.

<table>
<thead>
<tr>
<th>i</th>
<th>Lab number</th>
<th>House number</th>
<th>Category</th>
<th>Rim diameter [cm]</th>
<th>TLE [µg g⁻¹]</th>
<th>δ¹³C₁₆₀ [%]</th>
<th>δ¹³C₁₈₀ [%]</th>
<th>∆¹³C [%]</th>
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² Mixture N/R - mixture of non-ruminant adipose and ruminant adipose fats