Matlova, V., Roffet-Salque, M., Pavlu, I., Kyselka, J., Sedlarova, I., Filip, V., & Evershed, R. (2017). Defining pottery use and animal management at the Neolithic site of Bylany (Czech Republic). *Journal of Archaeological Science: Reports*, *14*, 262-274. https://doi.org/10.1016/j.jasrep.2017.05.028

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 rooves, 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

104 triterpenoid components, allow the type and origin of the residue to be assessed (for reviews
105 see Evershed, 1993, 2008b; Regert et al., 2003; Mukherjee et al., 2005). Traces of animal fats,
106 plant oils, beeswax, resins, tars, pitches, etc. have been identified in archaeological pottery
107 vessels. A combination of chromatographic techniques (GC/FID) and mass spectrometric
108 techniques (GC/MS) is used to separate and identify the compounds. Animal fat residues occur
109 widely, however, the molecular composition of degraded animal fats alone does not allow fat
110 type to be identified and thus compound–specific stable carbon isotopic analyses with GC-C-
111 IRMS (gas chromatography-combustion-isotope ratio mass spectrometry) are carried out to
112 enable ruminant adipose, ruminant dairy or non-ruminant adipose fats to be distinguished (e. g.
113 Dudd and Evershed, 1998; Dudd et al., 1999; Copley et al., 2003). The possibility also exists
114 of identifying milk residues in pottery vessels, which has opened up new avenues of
115 investigation on the beginnings of dairying across Europe and the Near East (e.g. Evershed et
116 al., 2008). Evidence for dairying has been revealed dating as early as the 7th millennium BC in
117 the Near East and lipid residue analyses of potsherds from the 6th LBK have shown that some
118 Central European LBK communities were processing milk into cheese using cheese-strainers
119 (Salque et al., 2013).
120
121 Notwithstanding the latter findings, extensive work is required to identify the temporal and
122 spatial patterning of milk use in Europe order to understand the lactase persistence allele
123 amongst the first farmers of Central Europe (Itan et al., 2009). As a contribution to this
124 endeavour, herein, we focus on the organic residue analysis of pottery vessels from the LBK
125 site of Bylany (phase 19) in order to assess: (i) pottery vessel use, and (ii) animal management.
126 The investigation also aims to explore variations in pottery vessel use at household and site
127 levels. Further, given the differences observed in lipid preservation, porosimetry was used in
128 an attempt to explore the mechanisms of preservation of lipids. The focus of this study was

129 phase 19 from the Bylany excavation, chosen as sherds of all functional categories (Pavlu,
130 2000) were recovered and, overall, the sherds were less-fragmented than in other phases,
131 suggesting a simpler taphonomic history for this assemblage, which legitimises the
132 comparisons presented (Pavlu, 2010).

133

134 **2. Material and Methods**

135 *2.1. Selection of pottery sherds*

136 A total of 1,842 rim potsherds were excavated from phase 19, from which 1,539 sherds were
137 classified into 14 categories according to their presumed function (Fig. 5; Pavlu, 2010). Only
138 842 potsherds (46%) could be simultaneously categorized using one of 14 classes and
139 associated to a house type. From this set, a subset of 163 upper rim sherds (20%) were sampled
140 and submitted to organic residue analysis. The potsherds originated from presumed water
141 storage/processing vessels ($n = 60$; categories F6, F9 - F11, F13), from food processing and
142 serving vessels ($n = 88$; categories F1-F5, F7, F8, F12) and from vessels for storage of dry
143 commodities ($n = 15$, category F14). The potsherds were sampled from pits alongside 9
144 different households, with 74 potsherds originating from long houses (houses 96, 162, 1246),
145 49 from middle houses (houses 361, 619, 702) and 40 from small houses (houses 959, 1161,
146 1240; see Table I).

147

148 Porosimetry studies were carried out on 7 sherds from Bylany phase 19, of which 3 (categories
149 F9, F10, F13) were presumed to be water storage/processing vessels and 4 (categories F4, F7,
150 F12) were presumed to be food processing and serving vessels. A portion (0.1-0. 2 g) of each
151 potsherd was sampled and subjected to mercury porosimetry using an AutoPore IV 9500 V1.06
152 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-excavation 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*-tetratriacontane, 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

177 methylated/trimethylsilylated extract dissolved in hexane was introduced using a split/splitless
178 injector at 220 °C. The temperature of GC oven was programmed from 120 °C for 5 min, to
179 175 °C at 5 °C min^{-1}, followed by an isothermal hold for 25 min, then to 300 °C at 7 °C min^{-1},
180 followed by a third isothermal hold for 25 min. Helium was used as carrier gas with a constant
181 flow of 1 mL min^{-1}. The GC/MS analyses were performed with the same temperature program
182 on a GC system Agilent Technologies 7890A with a 5975C VL MSD detector. The GC/MS
183 system was equipped with the same column as the GC-FID system.
184
185 Compound-specific stable carbon isotope analyses were performed using an Agilent Industries
186 7890A gas chromatograph coupled to an IsoPrime 100 isotope ratio mass spectrometer. One
187 microlitre of methylated/trimethylsilylated portions of extract dissolved in hexane were
188 introduced via a split/splitless injector operated in the splitless mode onto a 50 m x 0.32 i.d.
189 fused silica capillary column coated with a 100% dimethylpolysiloxane stationary phase
190 (Agilent HP 1; 0.17 μm film thickness,). The GC oven temperature programme was held at 40
191 °C for 2 min, followed by a gradient increase to 300 °C at 10 °C min^{-1}, after which the oven
192 was held isothermally for 10 min. Helium was used as carrier gas at a constant flow of
193 2 mL min^{-1}. The combustion reactor consisted of a quartz tube filled with copper oxide pellets
194 maintained at a temperature of 850 °C. Data processing was carried out using the Ion Vantage
195 software (version 1.5.6.0, Isoprime).

196 **3. Results**

197 *3.1. Lipid recovery*

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

201

202 *3.2. Lipid compositions*

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

216

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

223

224 Nearly 23% of the samples with the appreciable amount of lipids had significant concentrations
225 of long-chain fatty acids and fatty alcohols, such as behenic ($C_{22:0}$), lignoceric ($C_{24:0}$) or cerotic

($C_{26:0}$) 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}m > diameter > $2{\cdot}10^{-9}$ m) and micropores (diameter < $2{\cdot}10^{-9}$ 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} m > diameter > $2{\cdot}10^{-9}$ m) and micropores (diameter < $2{\cdot}10^{-9}$ 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 hydoxy 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

299 outer environmental conditions (humidity, air access, temperature, redox condition etc.;
300 Evershed, 2008b).

301 Some of the sherds from Bylany contained >1.5 mg of lipids per gram. While, such
302 concentrations of lipid are not uncommon, the highest lipid concentrations are observed in
303 potsherds excavated from arid (Dunne et al., 2012) or acidic (Smyth and Evershed, 2015) burial
304 environments. Within a site higher concentration of lipids in some vessels could reflect a
305 frequency of use of certain vessels (Smyth and Evershed, 2015). The burial conditions at Bylany
306 are neutral or slightly acidic, and the loess soil is considered reasonable water-permeable (Pye,
307 1995), but clearly these conditions lead to favourable preservation of lipids in potsherds. Not
308 surprisingly, however, these same conditions cause extensive decalcification of bones at
309 Bylany, dissolving the vast majority archaeozoological and human skeletal remains.

310

311 *4.2. Concentrations of lipid residues in different vessel types*

312 The function of the pottery vessels comparing the Bylany assemblage has been assessed in
313 detail using typological analysis, correlating the shape of vessels to their potential use, with
314 reference to ethnoarchaeological studies (Varien and Mills, 1997). Three basic shapes have
315 been identified in the ceramic assemblage, namely: bowls, dishes and jars, and their volumes
316 reconstructed based on orifice diameters and rim angles (Pavlu, 2000). This
317 ethnoarchaeological approach has allowed the vessels to be classified into several categories of
318 presumed use, e.g. cooking vessels, storage vessels or vessels for storing water, and a range of
319 respective subcategories (Pavlu, 2000; Fig. 5). All the functional categories exhibited high
320 recovery rate of lipids (above 60%), except sherds from the type F2 (31%, 4 residues extracted
321 from 13 potsherds). The highest recoveries rates of lipids are observed for small dishes of types
322 F1 and F3 (90% and 88%, respectively) but the median concentration of total lipid extract was
323 <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 χ^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 χ^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

349 adsorption, although concentrations may differ. Odd-carbon number mid-chain ketones, usually
350 interpreted as demonstrating that pots were heated at high temperature (Raven et al., 1997) were
351 not detected in these potsherds. Although it is not possible to determine whether the foodstuffs
352 contained in these pots were hot or not, the hypothesis remains that such vessels were used as
353 tableware suitable for serving (e.g. Urem-Kotsou and Kotsakis, 2007). Significantly, the
354 potsherds from set 3 exhibited relatively high concentration of lipids (average 135 μg g^{-1}),
355 which were skewed by high lipid concentrations in the potsherds from vessel types F3, F5 and
356 F7 (Fig. 6a). This contrasted with the lower mean lipid concentrations in potsherds of set 4
357 (average TLE concentration: 39 μg g^{-1}) implying these pots were used either less frequently or
358 for processing different foodstuffs.
359
360 Finally, the vessels from the set 2 (F4 and F12) were hypothesised to be the most commonly
361 used ware for cooking, food processing and serving. Repetitive use of pots for cooking
362 foodstuffs leads to the accumulation of lipids in the clay walls (Evershed, 2008a). Lipids were
363 recovered from 71% of potsherds from this set (17 residues were extracted from 24 potsherds,
364 one-sample χ^2 test, $p < 0.01$). Moreover, the mean lipid concentrations determined for the
365 sherds from pots F4 and F12 were 121 and 152 μg g^{-1}, respectively, which are relatively high
366 compared to sherds from other sets except those from sets 1 or 2 (Fig. 6b). Significantly, the
367 lipids detected in 8 potsherds from this set were identified as being animal fats (Table II)
368 indicating that the original pots were used for food processing, likely cooking.
369
370 No evidence was obtained from the analyses the specialisation in the use of pottery for
371 processing specific types of foodstuff (Fig. 8), except for small bowls ($n = 4$, analysed
372 categories F7, F9 and F11) where only pure non-ruminant fats were detected. In contrast to the
373 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 χ^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*

399 *orientalis*), wild boar (*Sus scrofa*), wild horses (*Equus ferus*) and roe deer (*Capreolus*
400 *capreolus*) were identified (Pavlu, 2014a). The remains were irregularly spread over the
401 settlement mainly concentrated in pits situated alongside and between houses. Statistical
402 correspondence analysis of the bone fragments found at the whole site of Bylany and at specific
403 households showed that cattle and pigs were mainly associated with long and middle houses,
404 while goats and sheep were more common in small houses (Pavlu, 2014a).
405
406 All potsherds examined herein were excavated from pits alongside long, middle or small houses
407 or from the immediate surroundings of houses, and not from the inner space of houses
408 (Soudsky, 1966; Pavlu, 2010). Animal fats were detected in sherds from across all types of
409 houses (Fig. 8). Animal fats extracted from sherds from long, middle and short houses exhibited
410 $\Delta^{13}C$ values ranging between -3.1 and 1.1‰ (n = 13), 1.1 and 2.3 ‰ (n =16) and 1.4 and 2.8‰
411 (n = 9), respectively. The $\Delta^{13}C$ values of animal fats extracted from sherds from long and
412 middle houses are similar to those from short houses. The median of $\Delta^{13}C$ values for small
413 houses (-0.6‰) and middle and long houses (-0.9‰) were statistically comparable (Mann-
414 Whitney U test, U = 115, $P < 0.05$). Animal fats detected in sherds from long and middle houses
415 exhibited $\delta^{13}C$ and $\Delta^{13}C$ values consistent with pure non-ruminant carcass (n = 10; 34%) fats
416 and mixtures of non-ruminant and ruminant carcass fats (n = 18; 44%). However, non-ruminant
417 carcass fats and mixtures of ruminant and non-ruminant carcass fats were also detected in sherds
418 from pits alongside small houses (n = 9), providing evidence that both non-ruminant and
419 ruminant products were processed in the small houses. Products from ruminant
420 (cattle/sheep/goats) and non-ruminants (pigs) could have thus been processed at the small
421 houses. Mixtures of ruminant and non-ruminant products occur across all types of houses
422 without any preference, although the exploitation of pigs seems to have been restricted to long
423 and middle houses (Pavlu, 2014a). The inhabitants likely share their economies to support also

424 their neighbours (probably birth related), e.g. at the level of two or three houses, to maintain
425 effective subsistence. For instance, if a cow, a pig or a large wild animal was slaughtered before
426 winter or during some ceremonial rites, meat could have been divided between a bigger groups
427 of people and processed at the level of each household, independently of house size, as
428 evidenced in other Central European LBK settlements (Halstead, 2011; Marciniak 2011,
429 2008b).
430
431 Interestingly, no evidence for dairy fat residues was detected in potsherds from long, middle
432 and small houses at the later settlement phase of Bylany (phase 19). The absence of dairy fats
433 in sherds from Bylany can relate to: (i) the absence of milk use and processing at the site, (ii)
434 the mixing of dairy and non-ruminant carcass products in pots, masking the milk signal, or (iii)
435 the use of dairy products in perishable containers, which did not survive, e.g. in wooden vessels
436 (Maigrot, 2003) or in leather containers (Morris, 2013). It should be also considered, dairy fat
437 triacylglycerols with lower carbon number are more susceptible to degradation, especially when
438 present in fresh milk and not concentrated e.g. in butter or cheese (see Dudd and Evershed 1998;
439 Copley et al., 2005). However, per compound-specific stable carbon isotope analysis results,
440 the high number of animal fats detected in the pots (38 potsherds of 94 with concentration of
441 lipids > 10 μg g^{-1}) provide a relatively secure evidence for the absence of dairy fat residues in
442 pots from phase 19 at Bylany. Unfortunately, the absence of sufficient archaeological remains
443 prevents herd structures to be reconstructed and herding management to be assessed (Vigne and
444 Helmer, 2007). Thus, milk exploitation at the site seems of rather low intensity or even non-
445 existent. This agrees with lipid residue analysis studies carried out at other central European
446 LBK sites (Salque et al., 2012; Roffet-Salque and Evershed, 2015) and with aDNA analyses
447 performed on human skeletal remains from LBK sites in Germany, Hungary or Poland (Burger
448 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

473 they survived in the archaeological record (Tite et al., 2001). The slightly acid pH burial
474 conditions at the site appear favourable for lipid preservation (e.g. Smyth and Evershed, 2015).
475
476 Comparing lipid residue compositions to the pot shapes, indicate some differences in the
477 foodstuffs processed in different types of pots, although some hypotheses regarding vessel
478 specialisation appear not to hold.
479
480 Stable carbon isotopic analyses of the animal fats detected in potsherds from Bylany
481 demonstrated that carcass products were obtained from both ruminant and non-ruminant
482 sources. Mixtures of carcass fats from both ruminant and non-ruminant animals were detected
483 across all types of vessels and houses without any significant context specificity. It appears that
484 the inhabitants of Bylany shared their economies between each other, independent of the size
485 of the houses, herds or fields they managed , thus, suggesting maintenance of extensive cultural
486 relationships needed to maintain essential sustainable community-level subsistence (Richards,
487 2002; Halstead, 1999). Notwithstanding this, individual households may still have played a
488 specific roles in the overall settlement economy.
489
490 Evidence for dairy fats was not detected in any of the sherds analysed in this study neither by
491 lipid composition nor by compound-specific stable carbon isotope analysis, suggesting that
492 cattle or other ruminants were likely not milked at Bylany, at least during the later LBK phase
493 19. The importance of dairying to the economy at Bylany, thus, remains an open question.
494 Further work in progress will shed light on the exploitation of animal resources at earlier phases
495 of the site.

Acknowledgements

We would like to thank Institute of Archaeology in Kutna Hora for providing the potsherds from Bylany. We also wish to thank Doc. Ing. Jan Vidensky, CSc at the Department of Inorganic Technology of UCT Prague for the mercury porosimetry analyses. We thank the European Research Council (FP7-IDEAS-ERC/324202 attributed to R.P.E.) for funding and the Natural Environment Research Council (R8/H10/63) for partial funding of the mass spectrometry facility at Bristol.

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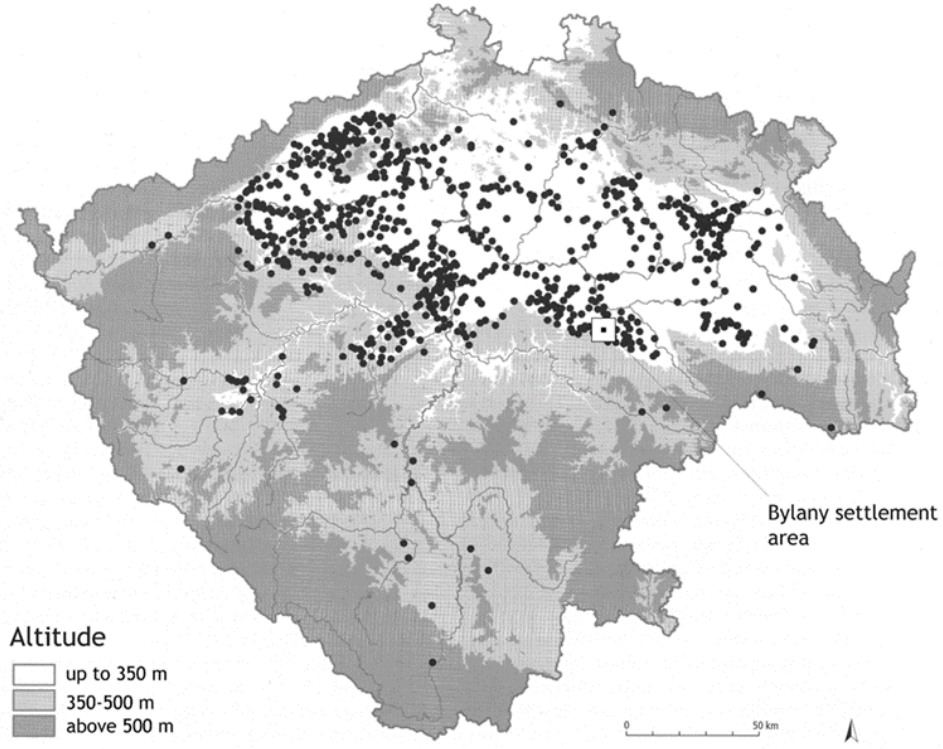


798 **Fig.1.** Map showing the location of Bylany within the Early Neolithic (LBK) settlement area
799 in Bohemia, Czech Republic (after Kvetina, Koncelova, 2012).

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).

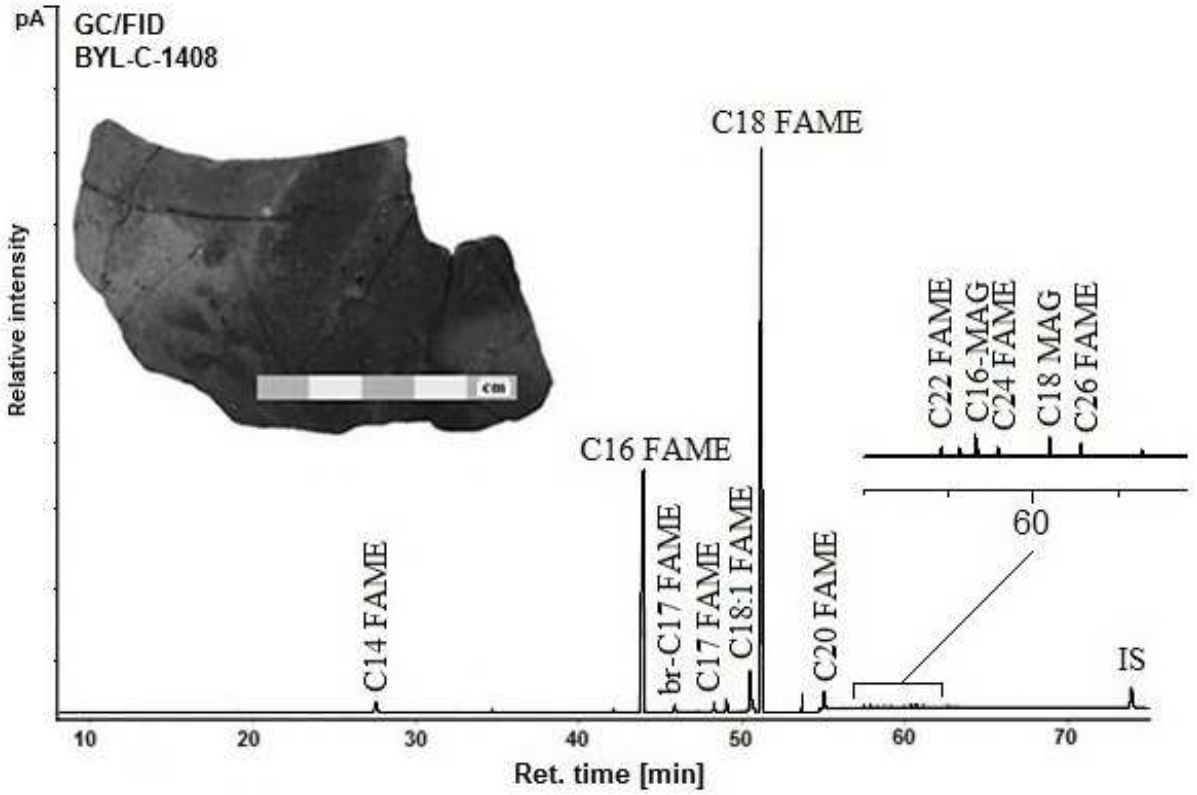


Fig. 3. Partial gas chromatogram of total lipid extracts from sherds from Bylany phase 19 typical of animal fat. Peak identities: FAME = fatty acid methyl esters, br-branched, C16-MAG - monopalmitoylglycerol, C18-MAG-monostearoylglycerol, IS-internal standard (*n*-tetratriacontane).

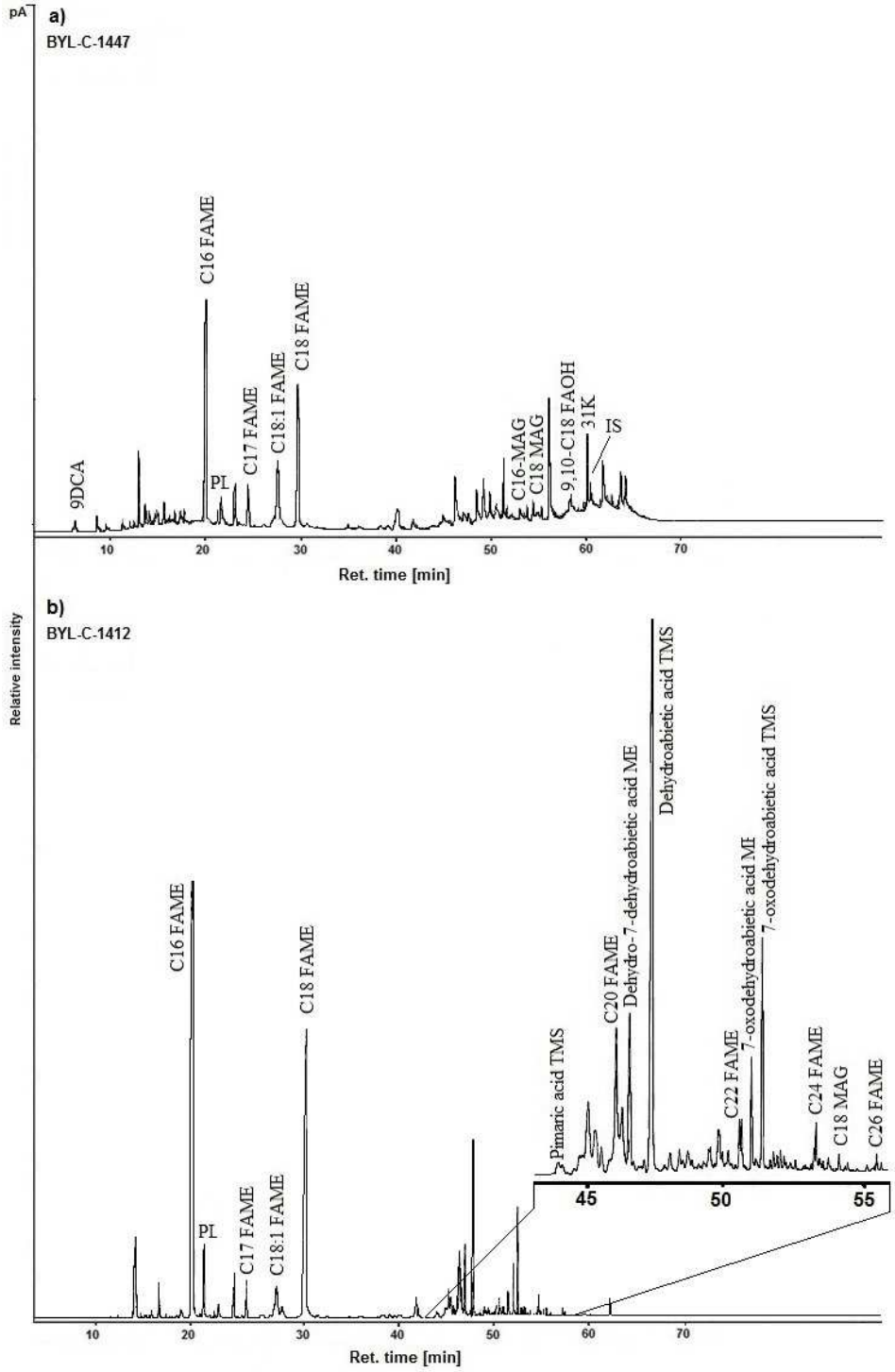


Fig. 4. Partial gas chromatograms of (**a**) animal fats with mid-chain ketone and (**b**) traces of fatty acids and resinous components (magnified). Peak identities: FAME = fatty acid methyl esters, TMS-trimethylsilylated, br-branched, C16-MAG - monopalmitoylglycerol, C18-MAG-monostearoylglycerol, 9 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*-tetratriacontane), PL – plasticizer (contamination).

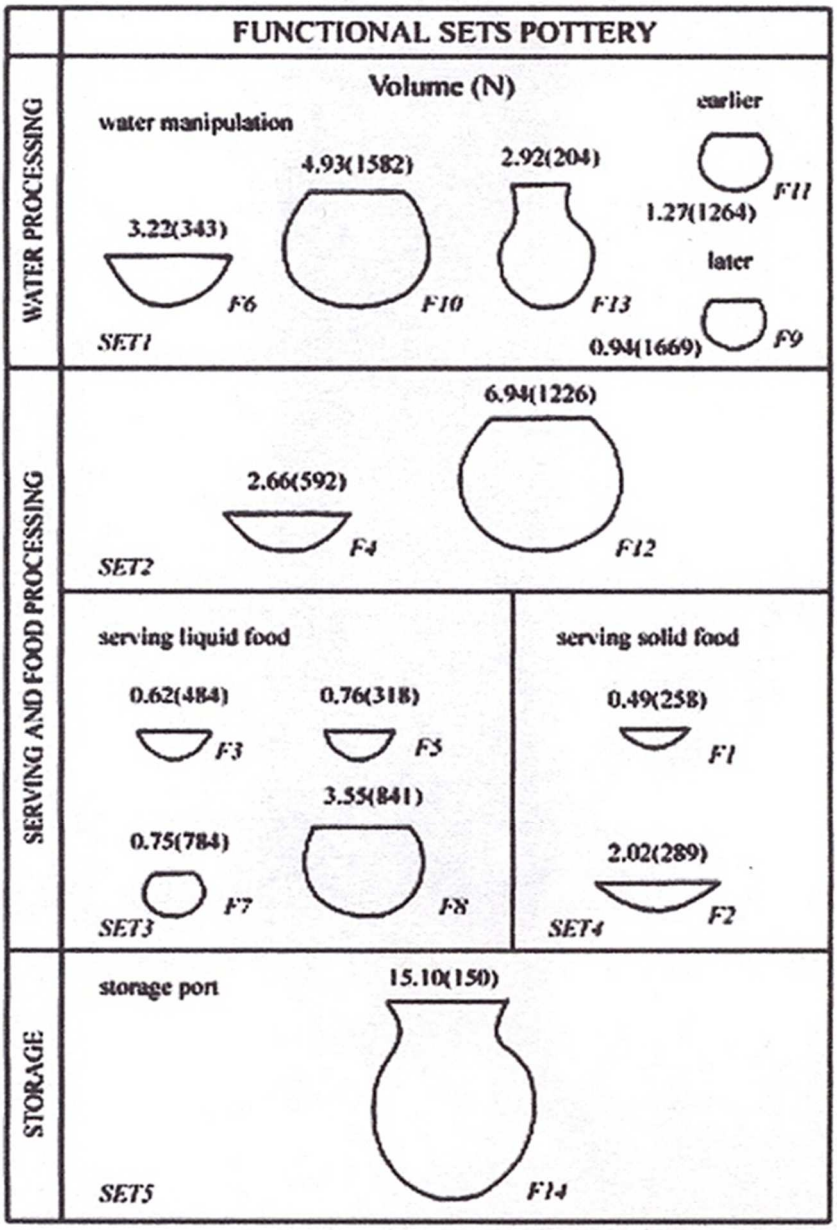


Fig. 5 Functional classification of archaeological pottery from Bylany according to their typologies (after Pavlu, 2000).

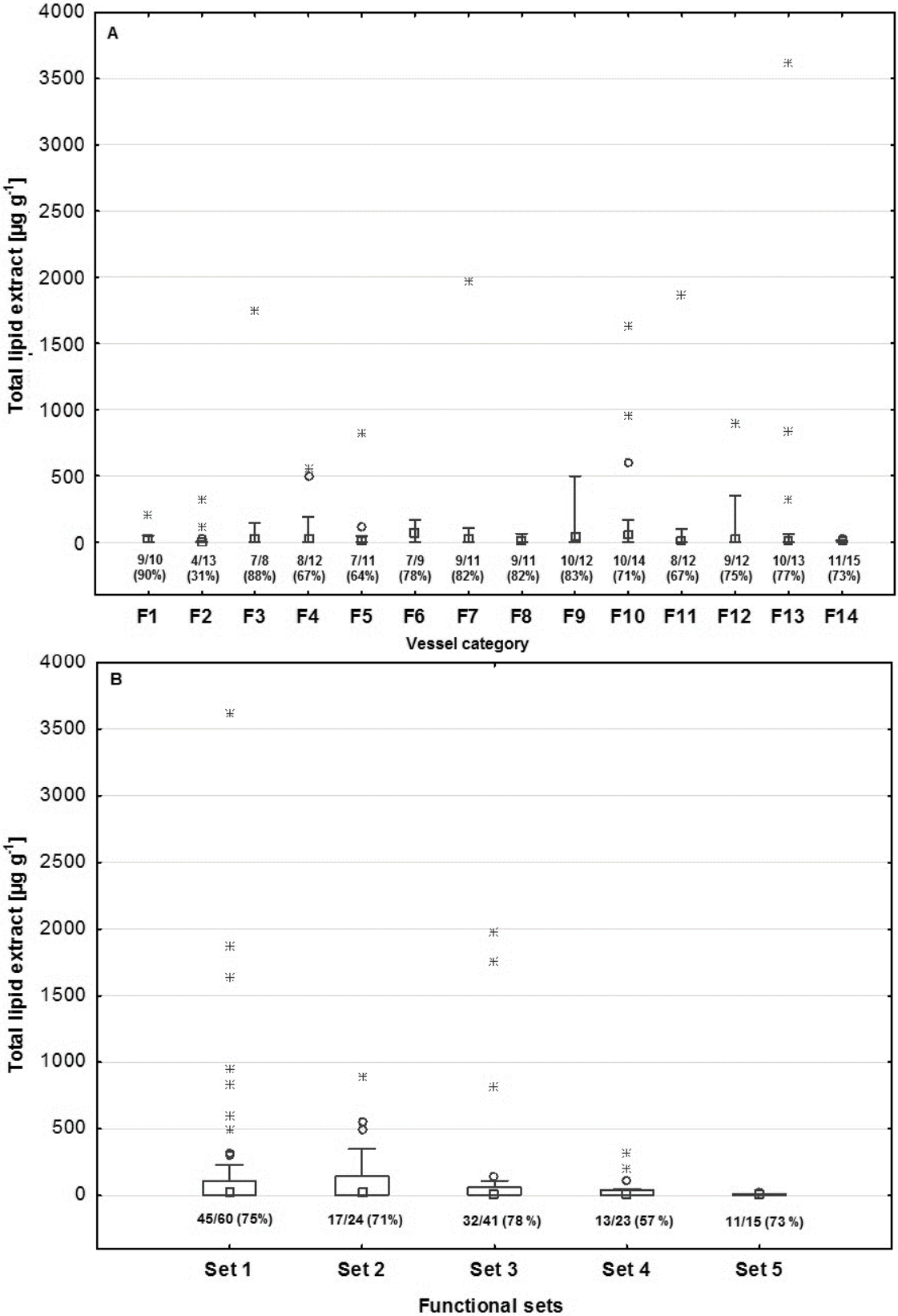
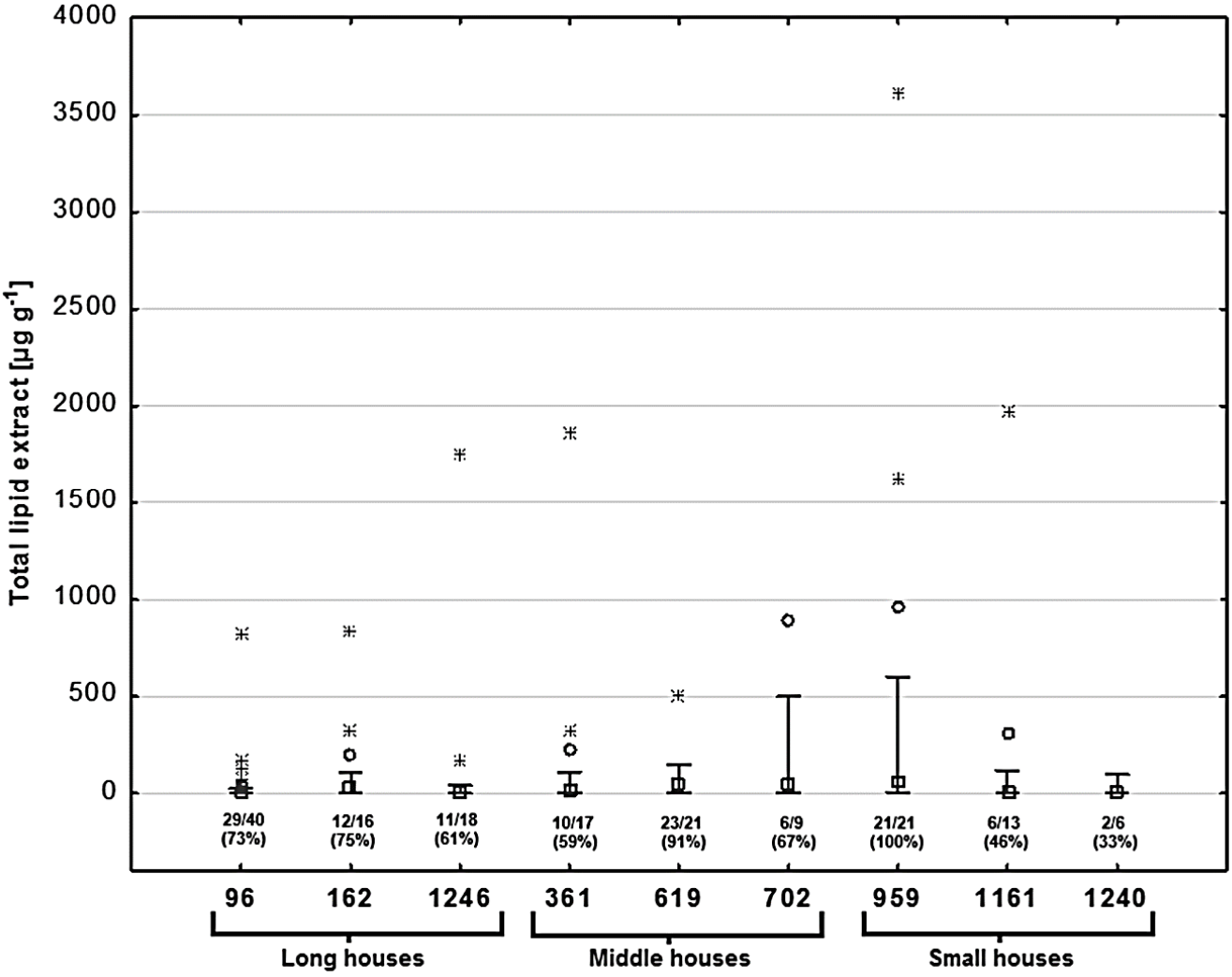


Fig. 6. Box plot of total lipid concentrations [µg g^{-1}] in different categories of vessels from Bylany (A**)** and functional sets (B); ○ remote values; ∗ extremes. Set 1 - Water processing (cat. F6, F9, F10, F11, F13), Set 2 - Serving and food processing (cat. F4, F5), Set 3 - Serving liquid food (cat. F3, F5, F7, F8), Set 4 - Serving solid food (cat. F1, F2), Set 5 - Storage (cat. F14).



823 **Fig. 7.** Box plot of total lipid concentrations [µg g^{-1}] in pottery recovered from specific houses
824 examined in this study. Recovery rates of lipids in brackets; ○ remote values; ∗ extremes.

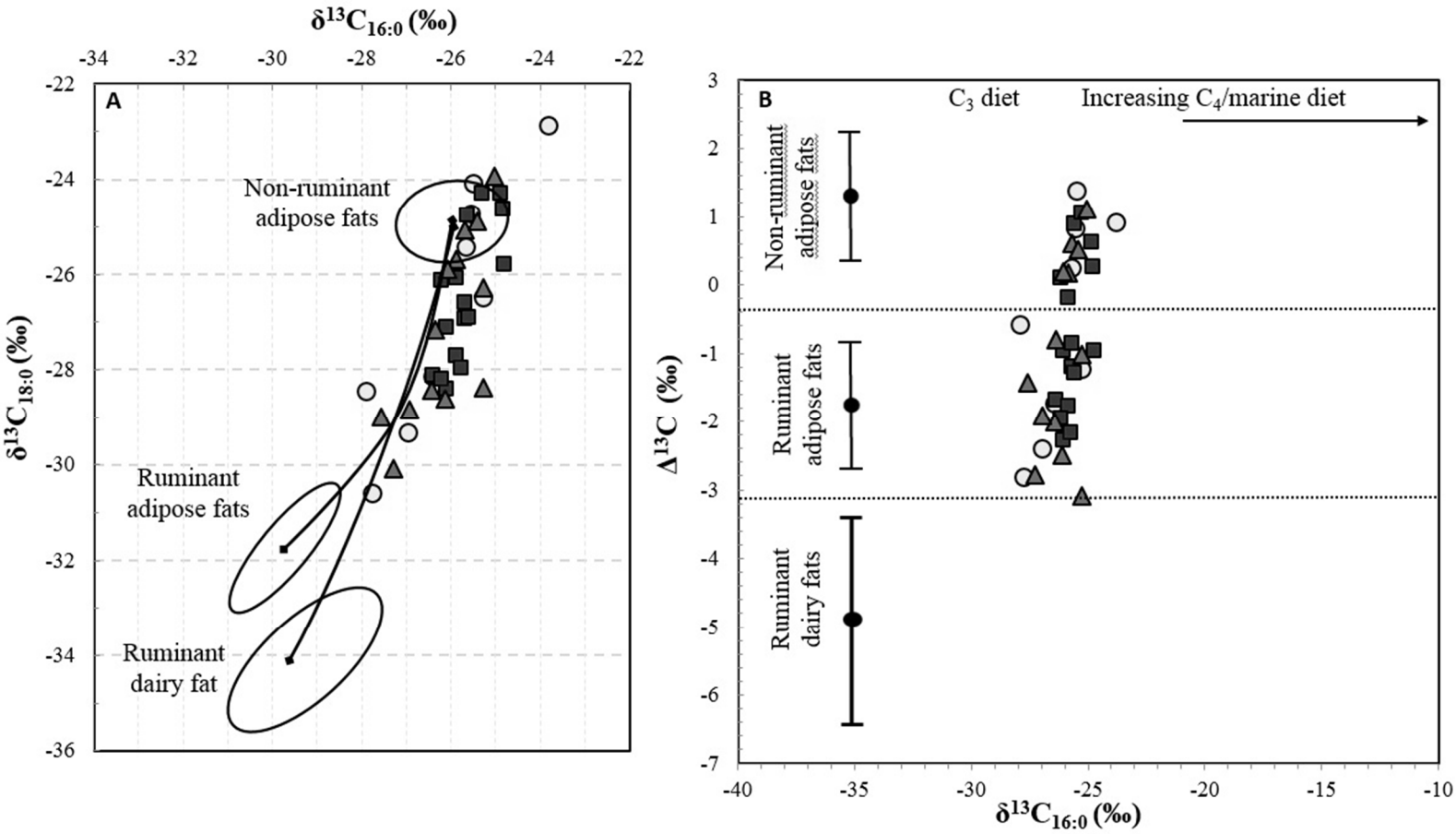


Fig. 8. (A) $\delta^{13}C$ values for the $C_{16:0}$ and $C_{18:0}$ fatty acids from the TLEs extracted from potsherds from Bylany phase 19 according to the type of houses (long ▲, middle ■ and small ○). The three fields correspond to the P = 0.684 confidence ellipses for animals raised on a strict C_3 diet in Britain (Copley et al., 2003). (B) Difference in the $\delta^{13}C$ values of the $C_{18:0}$ and $C_{16:0}$ 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

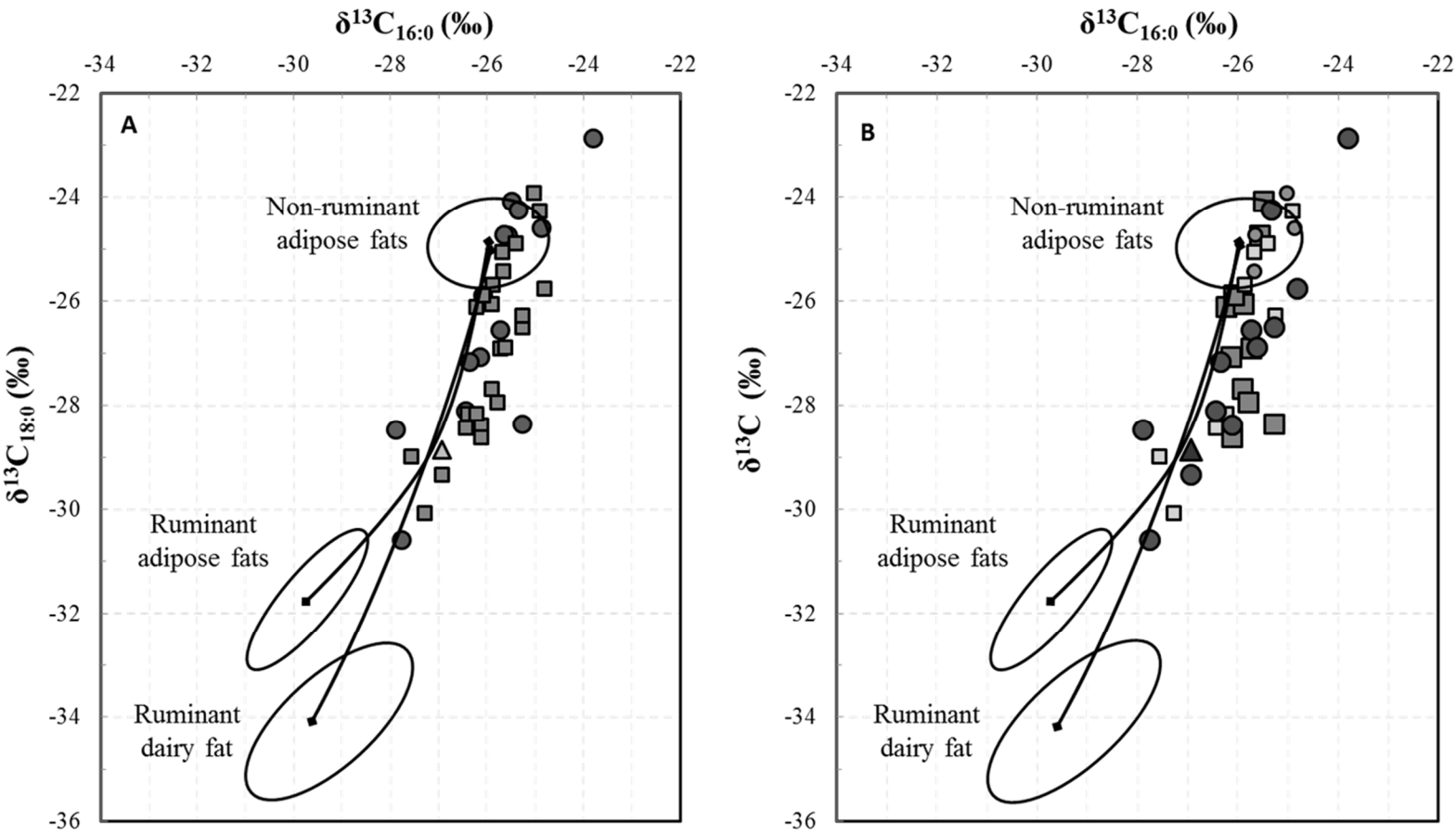


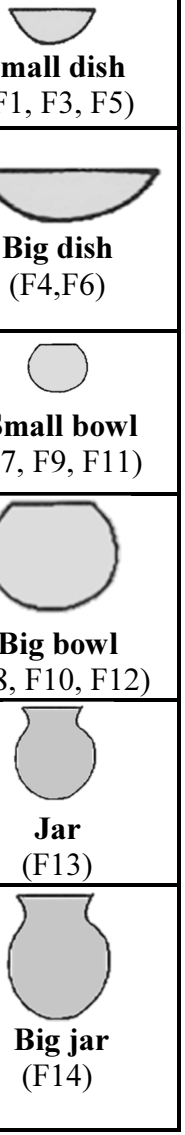
Fig. 9. Scatter plots of stable carbon isotope compositions of animal fat residues extracted from the potsherds of Bylany phase 19 in a context of presumed **functional sets** (**A**) where ● represent water processing vessels, ■ processing and food serving vessels and △ represent storage vessel, and **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).

			Potsherds analysed	**Residues detected**	**Recovery rate**
			n	*n*	[%]
Houses	**Size**				
96	Long		40	29	73
162	Long		16	12	75
1246	Long		18	11	61
361	Middle		17	10	59
619	Middle		23	21	91
702	Middle		9	6	67
959	Small		21	21	100
1161	Small		13	6	46
1240	Small		6	2	33
Total			163	118	72
Category	**Shape**	**Functional set**			
F1	Small dish	4	10	9	90
F2	Big dish		13	4	31
F3	Small dish	3	8	7	88
F4	Big dish	2	12	8	67
F5	Small dish	3	11	7	64
F6	Big dish	1	9	7	78
F7	Small bowl	3	11	9	82
F8	Big bowl		11	9	82
F9	Small bowl	1	12	10	83
F10	Big bowl		14	10	71
F11	Small bowl		12	8	67
F12	Big bowl	2	12	9	75
F13	Jar	1	13	10	77
F14	Big jar	5	15	11	73
Total			163	118	72

Table 2 Summary of extracted lipids in the context of houses and vessel types

House type	House number	Vessel type	Lipids detected[a,]
 **Small house**	**959**	Big dish	FA(l,vl,br), MAG
		Big bowl	FA(m,l,vl,br), MAG
		Jar	FA(m,l,vl,br), MAG, OH, TOH, ALK, DCA
	1161	Small bowl	FA(l,br,vl), MAG
 **Middle house**	**361**	Small dish	FA(l,br,vl), MAG, OH(tr)
		Big dish	FA(l,br,vl), MAG, OH(tr)
		Small bowl	FA(l,br,vl), MAG, DCA (tr), OH(tr)
		Big bowl	FA(m,l,br), MAG, DCA, OH
	619	Jar	FA(l,br), MAG
		Small dish	FA(l,br), MAG, OH(tr)
		Big dish	FA(l,br,vl), MAG
		Small bowl	FA(l,br), MAG
		Big bowl	FA(m,l,br), MAG
	702	Big dish	FA(l,br), MAG
 **Long house**	**96**	Small dish	FA(m,l,br,vl), MAG, FAOH, DCA
		Big dish	FA(m,l,br,vl), MAG, DCA
		Small bowl	FA(tr)
		Big bowl	FA(tr), MAG(tr)
		Big jar	FA(tr)
	162	Small dish	FA(l,br,vl), MAG, DCA
		Jar	FA(m,l,br,vl), MAG, DCA, ALK, K, FAOH, TOH
	1246	Small dish	FA(l,br,vl), MAG
		Big bowl	FA(l,br,vl), MAG



[a]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.

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Table 3 Details of potsherds selected for GC-C-IRMS, results and interpretation of the isotopic analyses.

i	Lab number	House number	Category	Rim diameter [cm]	TLE [µg g^{-1}]	$\delta^{13}C_{16:0}$ [‰]	$\delta^{13}C_{18:0}$ [‰]	$\Delta^{13}C$ [‰]	Classification by $\Delta^{13}C$ values
1	BYL-C-1321	702	F4	unknown	193	-25.9	-27.7	-1.8	Mixture N/R[a]
2	BYL-C-1322	702	F12	unknown	895	-26.1	-28.4	-2.3	Ruminant adipose
3	BYL-C-1323	702	F12	unknown	350	-24.8	-25.8	-0.9	Mixture N/R
4	BYL-C-1325	702	F4	unknown	498	-24.8	-25.8	-0.9	Mixture N/R
5	BYL-C-1329	1161	F5	unknown	822	-25.8	-27.9	-2.2	Ruminant adipose
6	BYL-C-1334	1246	F4	unknown	43	-26.4	-28.2	-1.7	Mixture N/R
7	BYL-C-1345	1161	F7	unknown	1975	-25.7	-25.4	0.2	Non-ruminant
8	BYL-C-1353	1246	F3	unknown	1245	-25.7	-25.1	0.6	Non-ruminant
9	BYL-C-1354	1246	F10	unknown	77	-26.4	-27.2	-0.8	Mixture N/R
10	BYL-C-1375	361	F10	18	11	-26.4	-28.1	-1.7	Mixture N/R
11	BYL-C-1376	361	F2	20	322	-26.2	-26.1	0.1	Non-ruminant
12	BYL-C-1383	619	F6	unknown	99	-26.1	-27.1	-0.9	Mixture N/R
13	BYL-C-1389	959	F10	25	61	-23.8	-22.9	0.9	Non-ruminant
14	BYL-C-1395	959	F12	16	298	-26.9	-29.3	-2.4	Ruminant adipose
15	BYL-C-1400	619	F11	12	99	-25.6	-24.7	0.9	Non-ruminant
16	BYL-C-1402	619	F10	28	33	-25.7	-26.6	-0.8	Mixture N/R
17	BYL-C-1408	619	F9	11	499	-24.9	-24.6	0.3	Non-ruminant
18	BYL-C-1411	619	F3	17	148	-24.9	-24.3	0.6	Non-ruminant
19	BYL-C-1416	959	F10	16	1634	-27.8	-30.6	-2.8	Ruminant adipose
20	BYL-C-1417	959	F10	19	600	-27.9	-28.5	-0.6	Mixture N/R
21	BYL-C-1419	959	F8	16	955	-25.3	-26.5	-1.2	Mixture N/R
22	BYL-C-1423	959	F6	20	77	-25.5	-24.1	1.4	Non-ruminant
23	BYL-C-1424	959	F6	20	53	-25.6	-24.7	0.8	Non-ruminant
24	BYL-C-1425	361	F1	9	558	-26.2	-28.2	-1.9	Ruminant adipose
25	BYL-C-1426	361	F2	26	40	-25.9	-26.1	-0.2	Mixture N/R
26	BYL-C-1427	361	F4	27	109	-25.7	-26.9	-1.2	Mixture N/R
27	BYL-C-1429	361	F10	24	232	-25.3	-24.3	1.1	Non-ruminant
28	BYL-C-1433	361	F12	16.1	1867	-25.6	-26.9	-1.3	Mixture N/R
29	BYL-C-1436	162	F1	unknown	202	-26.4	-28.4	-2.0	Ruminant adipose
30	BYL-C-1437	162	F1	unknown	49	-25.4	-24.9	0.5	Non-ruminant
31	BYL-C-1440	162	F5	unknown	43	-27.3	-30.1	-2.8	Ruminant adipose
32	BYL-C-1449	162	F14	unknown	33	-26.9	-28.8	-1.9	Ruminant adipose
33	BYL-C-1461	96	F3	13	17	-25.9	-25.7	0.2	Non-ruminant
34	BYL-C-1464	96	F5	10	824	-25.3	-26.3	-1.0	Mixture N/R
35	BYL-C-1470	96	F5	14	35	-27.6	-29.0	-1.4	Mixture N/R
36	BYL-C-1472	96	F6	20	126	-26.1	-25.9	0.2	Non-ruminant
37	BYL-C-1474	96	F6	20	166	-25.3	-28.4	-3.1	Ruminant adipose
38	BYL-C-1476	96	F7	unknown	78	-25.0	-23.9	1.1	Non-ruminant

[a] Mixture N/R - mixture of non-ruminant adipose and ruminant adipose fats

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