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The role of pottery in Middle Neolithic societies of western Mediterranean (Sardinia, Italy, 4500-4000 cal BC) revealed through an integrated morphometric, use-wear, biomolecular and isotopic approach

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Abstract

The use of pottery in the Early Neolithic communities of Western Mediterranean has begun to be addressed by recent studies concerning the residues of dietary commodities in potsherds. In order to contribute to a broader perspective on the issue of pottery function, we investigate pottery assemblages through an integrated methodology, combining the study of vessel morphology and morphometry, use-wear analysis, biomolecular and compound-specific carbon isotopic analysis of residues. We focus on the use of pottery containers by advanced Middle Neolithic societies of Sardinia (Italy, 4500-4000 cal BC), protagonists of significant technical, economic and cultural changes in the completion of Neolithisation in this island. The aims are to elucidate the role of whole pottery assemblages in technical and socioeconomic systems of Middle Neolithic communities and to provide data on animal and plant resources exploitation during this phase.

Based on the integrated combination of data, six categories of vessel use are identified. The results reveal a differential integration of vessels in activities related to the exploitation of distinct kinds of resources (ruminant adipose/dairy fats and plant foods vs. non-ruminant and aquatic products) and highlight specific behaviours of Middle Neolithic societies in selecting pottery morphotypes for different uses, notably in processing products with heating.

Keywords:

Neolithic, Western Mediterranean, Pottery use, Use-wear, Organic residues, Dairy products

Highlights

- An integrated approach of whole pottery assemblages reveals specific use-behaviours.
- Six categories of vessel use are identified in Sardinian Middle Neolithic B (MNB).
- Pottery is differentially embodied in technical subsystems of MNB societies.
- Vessels are mainly used for processing and consuming ruminant fats and plant foods.
- A morphometric specialisation characterises MNB cooking pots.

1. Introduction

In the last twenty years, research on the use of pottery by Neolithic societies has been strongly based on the chemical analysis of visible “foodcrusts” and/or absorbed residues, in order to address crucial issues: the origin and diffusion of dairying (Dudd and Evershed, 1998; Evershed *et al.*, 2008; Salque *et al.*, 2013), the relationships between the introduction of pottery and culinary innovations during the spread of the Neolithisation process, the dietary changes or continuity across the Mesolithic/Neolithic transition (Debono Spiteri *et al.*, 2016; Craig *et al.*, 2007a, 2011; Cramp *et al.*, 2014a-b; Heron *et al.*, 2015; Isaksson and Hallgren, 2012; Oras *et al.*, 2016), the exploitation and use of specific resources and products, such as beeswax or birch bark tar (Regert *et al.*, 2000; Roffet-Salque *et al.*, 2015). In Europe, research about residues of commodities preserved in Neolithic pottery has been conducted mainly in central and northern regions (Copley *et al.*, 2005a-b; Craig *et al.*, 2005a-b, 2007a-b, 2011; Cramp *et al.*, 2014a-b; Heron *et al.*, 2015; Matlova *et al.*, 2017; Mirabaud *et al.*, 2007; Isaksson and Hallgren, 2012; Regert *et al.*, 1999; Salque *et al.*, 2012, 2013), and only recently extended to some western Mediterranean regions (Debono Spiteri *et al.*, 2016; Salque *et al.*, 2012; Šoberl *et al.*, 2008, 2014). Nonetheless, the relationship between residues and typological/morpho-dimensional features of vessels has been rarely investigated in an integrated approach so far (Copley *et al.*, 2005a; Debono Spiteri *et al.*, 2016; Heron *et al.*, 2015; Matlova *et al.*, 2017; Nieuwenhuys *et al.*, 2015; Salque *et al.*, 2012, 2013; Šoberl *et al.*, 2014). Indeed, the potential of the functional analysis, as a means to develop a broader perspective on the role of whole pottery assemblages made and used in technical systems by Neolithic societies, remains poorly exploited. Particularly, the systematic recording of all range of use-wear alteration (Skibo, 1992, 2012), providing direct evidence of use and pottery functioning (Regert, 2011; Regert and Mirabaud, 2014; Vieugué *et al.*, 2008; Vieugué, 2014), is still underestimated or neglected.

In this context, we focus our attention on the uses of pottery during Middle Neolithic B (MNB - *San Ciriaco* culture, 4500-4000 cal BC) in Sardinia, Italy (fig. 1,a-b). This island is mainly known for housing one of the four obsidian sources in central-western Mediterranean, the Monte Arci (Lugliè *et al.*, 2006; Tykot, 1992;). Specifically, the MNB-*San Ciriaco* phase is of great interest, due to the role of these societies in developing technical, economic and cultural changes during the second half of 5th millennium BC. *San Ciriaco* culture was first identified on the basis of pottery morpho-typology as a subsequent phase of the original all-embracing Middle Neolithic *Bonu Ighinu* culture (Lugliè, 2003; Santoni, 1982a-b; Santoni *et al.*, 1997; Ugas, 1990), which actually constitutes the first phase of Middle Neolithic in Sardinia (MNA: 4800-4500 cal BC, fig. 1,b; Sebis *et al.*, 2012). MNB phase corresponds to the full development of Neolithic economy in the island, with an increased number of open-air settlements, possibly linked to farming expansion (Usai, 2009). Faunal remains include ruminant (ovicaprids, *i.e.* sheep or goat, cattle) and non-ruminant (wild boar/pig) species, less frequently aquatic (mollusc shells, fish) resources (Boschian *et al.*, 2001; Lugliè *et al.*, forthcoming; Santoni *et al.*, 1997). Botanical analyses revealed the exploitation of free threshing wheat, naked barley, legumes and wild fruits (Ucchesu *et al.*, 2017). Interestingly, crucial transformations appear in technical and symbolical behaviours during this phase. Monte Arci obsidian exploitation systems shift from a household procurement strategy towards a craft production in workshops close to distinct outcrops, expanding the diffusion of this lithic material in north-western Mediterranean networks (Binder *et al.*, 2012; Lugliè, 2009, 2012). The appearance of the first burials in hypogea from MNA reflects an increasing complexity in MN societies (Santoni,

1982a-b, 2000), which is also suggested by the circulation of prestige goods (ornaments, stone vessels, axes) during MNB. This phase is also marked by symbolically invested practices such as “structured deposition” of objects (*i.e.*, stacked pottery vessels) in pits (Fanti, 2015; Fanti *et al.*, 2017).

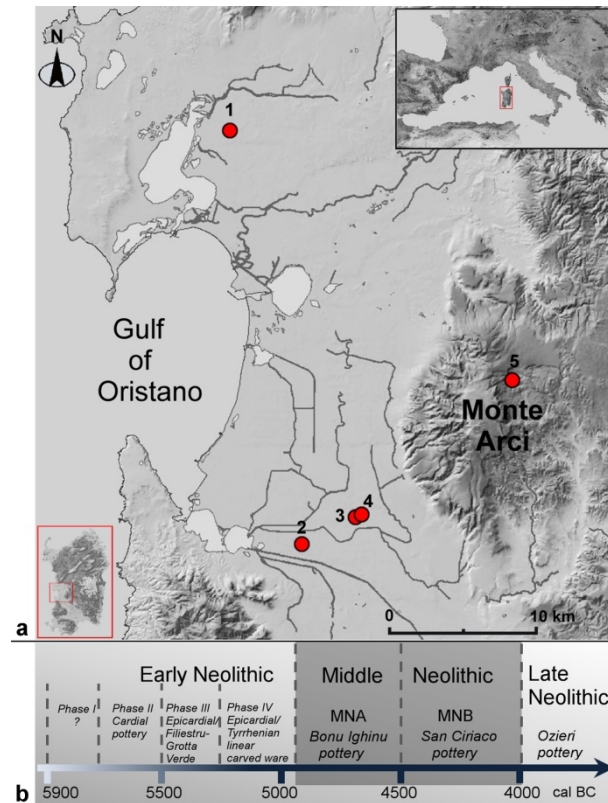


Fig. 1: Geographical and chronological overview on the context of this study: a, location of Middle Neolithic B sites in Central-western Sardinia, in relation with Monte Arci obsidian source: 1, Gribaia-Nurachi (OR); 2, Bau Angius-Terralba (OR); 3, San Ciriaco-Terralba (OR), eponym site of the MNB pottery; 4, Su Mulinu Mannu-Terralba (OR); 5, Su Forru de is Sinzurreddus-Pau (OR); b, chronology of Sardinian Neolithic (Fanti *et al.*, 2017; Lugliè, 2014, in press; Sebis *et al.*, 2012).

Pottery production is dominated by undecorated fine ware with depurated and compacted pastes, thin walls (<5 mm), burnished to polished surfaces; sand-tempered coarser pottery is less frequent (Lugliè, 1998; Ugas, 1990). Emblematic zoomorphic decorations on stone and pottery vessels (Lugliè, 2003) suggest the increased importance of ruminants in economy and symbolical realm of MNB societies. Extraordinarily for Early/Middle Neolithic phases, in several MNB assemblages the vessels profiles and surfaces are exceptionally well-preserved: this encourages the application of a broad-spectrum approach, taking into consideration all the evidences inherent in and preserved by containers, *i.e.* dimensional features like capacity and use-wear alteration on surfaces, in relationship with residues analysis.

The specific aims of this study are:

- to elucidate pottery use in MNB societies, by outlining implication of pottery containers in subsistence systems, *i.e.* in the activities linked to processing, storing and serving different kinds of food, whose variety is observed in the faunal and botanical record;

- to assess the importance of ruminant products, apparently reflected in the symbolic realm;
- to obtain data on MNB economy, in order to contribute to the knowledge of the wealth of those societies that played a leading role in the increased diffusion of obsidian in western Mediterranean.

A broader goal is to contribute to the construction of a more detailed scenario on the topic of vessels function during the Neolithic, by outlining specificities in the use of pottery at regional scales.

In order to address these issues, we follow an integrated interdisciplinary methodology, on the basis of previous studies in different scientific domains (archaeology, traceology, chemistry: Vieugué *et al.*, 2008; Vieugué, 2014). Simultaneously, we combine the archaeological analysis of morphometric and morphological characteristics of vessels, the observation of use-wear on pottery surfaces and the biomolecular and compound-specific carbon isotopic analysis by HT GC-FID (High Temperature Gas Chromatography-Flame Ionisation Detector), GC-MS (Gas Chromatography-Mass Spectrometry) and GC-C-IRMS (Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry).

2. Middle Neolithic B in central-western Sardinia: environment, contexts and pottery assemblages

Paleoenvironmental studies have shown that the landscape of central-western Sardinia, surrounding the Oristano Gulf (fig. 1,a), was characterised by alternating alluvial terraces, sand dunes and interdunal wetlands, modeled by stream channels linked to the Tirso, Rio Mogoro, Flumini Mannu and Rio Sitzerru rivers system (Bertorino *et al.*, 2000; Pittau *et al.*, 2012).

Several MNB sites appear to gravitate towards this coastal and wetland environment, near to the Monte Arci (Lugliè, 2009, 2012; Usai 2009), but few of these have been fully investigated thus far.

In the Gribaia site (Nurachi, OR), known from surface finds since 1950s (fig. 2,a; Atzeni, 1978; Lugliè, 1998), a preventive excavation uncovered an area with 30 small pits (20-40 cm diameter and 20-30 cm depth), filled with selected objects or faunal remains (Fanti *et al.*, 2017; Soro and Usai, 2009). Ten pits held “sets” of exceptionally well-preserved almost complete MNB vessels, stacked and sometimes overturned one on top of each other.

Similar “groups” of well-preserved MNB vessels have also been recovered in the open-air site of Bau Angius-Terralba (fig. 2,b; Lugliè, 2003). Unfortunately, no faunal/botanical data were documented in this site.

The open-air site of Su Mulinu Mannu (TMM)-Terralba, near Bau Angius and the eponym site of San Ciriaco (fig. 2,c), is a MNB household settlement. There, many typical structures are irregular pits filled with household waste: abundant pottery sherds, lithics (mainly obsidian), ground-stone and bone tools, together with faunal (cattle, ovicaprids, boar/pig, fish) and botanical remains (Lugliè *et al.*, forthcoming).

The assemblage from the only one excavated MNB inland site in central-western Sardinia (Su Forru de is Sinzurreddus-Pau, OR) being unavailable for sampling thus far, we focus our investigation on the previously described three sites.

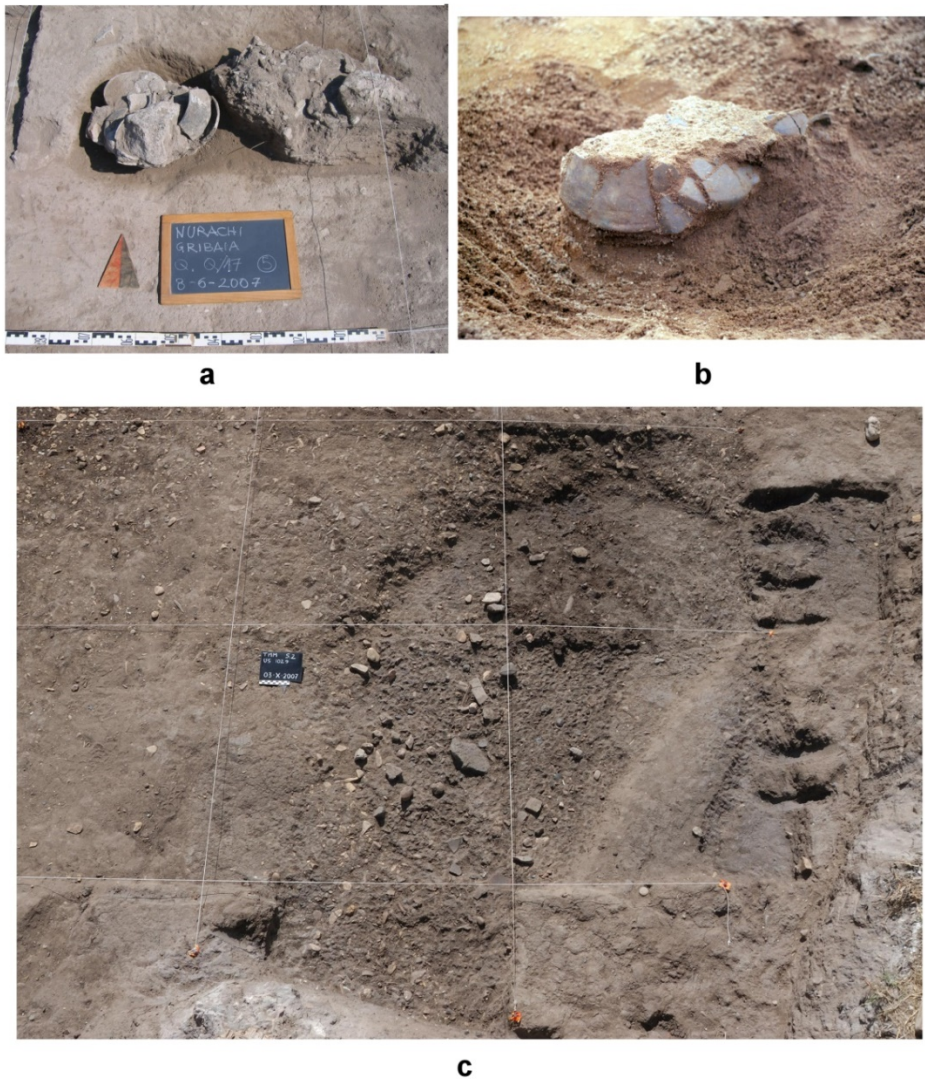


Fig. 2: MNB sites: a, excavation of small pits at Gribaia-Nurachi (photo courtesy: A. Usai); b, pottery *in situ* at Bau Angius-Terralba (photo: C. Lugliè), c, Su Mulinu Mannu-Terralba, S2 structure (photo: C. Lugliè).

3. Materials and methods

3.1 Materials and post-excavation protocol

All the sherds from the three MNB assemblages were firstly observed before washing, in order to recognise and preserve visible residues, document them by photography, and take samples. At that time, a first phase of refitting was conducted to determine the number of vessels, to obtain vessel profiles as complete as possible for morphometric analysis, and to select sherds for chemical analyses before cleaning and restoration. Nitrile gloves were systematically used to minimise contamination during the handling for refitting and sampling. Afterwards, sherds with no evidence of visible residues were washed under gentle streams of demineralised water and cleaned with very soft brushes. All the phases of sherd cleaning and storage were meticulously controlled in order to preserve the ceramic surfaces and use-wear traces against post-excavation alteration. A second phase of refitting and an additional sampling of sherds were made after cleaning, which also included two vessels from Bau Angius site previously reconstructed and published (Lugliè 2003). A total of 198 vessels have been identified through the refitting of around 8000 sherds from the entire assemblages of the three MNB sites, and studied (table 1).

Table 1: General assessment on MNB pottery assemblages investigated in this study.

Site	Total <i>n</i> of vessels identified	<i>n</i> of vessels with totally preserved profile	<i>n</i> of vessels classified by morphometric analysis	<i>n</i> of vessels studied by use-wear analysis	<i>n</i> of vessels sampled for organic residues analysis
Bau Angius	89	25	43	59	23
Gribaia	73	50	55	67	50
Su Mulinu Mannu	36	1	21*	36	26
Total	198	76	119	162	99

*except volume calculation, due to incomplete profile

3.2 Methods

3.2.1 Morphological and morphometric analysis

The study of vessel morphology and morphometry, together with patterns of use-wear and biochemical analyses of contents, can provide information about use habits (*i.e.*, the quantity of food prepared and stored, the selection of some types of vessels for specific purposes), pointing to economic and social behaviours linked to the consumption and conservation of food (Arthur, 2002; Skibo, 1992, 2013; Vieugué *et al.*, 2008). MNB pottery classification is based on morpho-dimensional features: type of profile (simple, inflected, high/medium/low carinated, “stepped-wall”, necked), openness (rim diameter/maximum diameter ratio: =1: open, 0.99-0.76: restricted, 0.75-0.50: closed, < 0.50: very closed), depth (height/maximum diameter ratio: = 0.25-0.50: shallow, 0.51-0.75: medium-deep, 0.76->1: deep), volume¹, presence of handles.

3.2.2 Use-wear analysis

Use-wear analysis provides evidence on pottery use in relation with fire exposure, ways of moving/placing vessels, and modalities of food processing, serving or storing (Arthur, 2002; Kobayashi, 1994; Skibo, 1992; Vieugué, 2014). As shown by ethnoarchaeological and experimental studies, use-related alterations can be better understood by the study of (almost) complete or refitted containers; particularly, use-wear can be discriminated from non-use alteration (Skibo, 1992) by characteristic patterns of occurrence and concentration on specific vessel parts (e.g., rim, lugs, bottom), whereas non-use alteration accidentally and/or completely covers ceramic surfaces and also edges/sections of sherds (Dugay, 1996; Nielsen, 1991; Skibo and Schiffer, 1987; Vieugué, 2014). Use-wear of ceramic surfaces is examined macroscopically and through a binocular microscope with low-magnification (10-40x), then identified by comparison with ethnoarchaeological, experimental and archaeological references (Arthur, 2002; Reid and Young, 2000; Regert *et al.*, 2003; Skibo, 1992; Vieugué *et al.*, 2008, 2014). Following J. Skibo’s methodology, the traces on MNB assemblages have been recorded and described by type, distinguishing between attritions (scratches, abraded areas, pits, spalls, chips) and accretions (visible residues and soot), and by position on vessel profile: rim, exterior/interior upper, mid-, lower body, (exterior) base and (interior) bottom (Skibo, 1992; Vieugué, 2014). Furthermore, absorbed residues constitute a particular category of use-related traces, invisible to the naked eye, which provide information about not only vessel content(s) but also specific modalities of use, if

¹ Volume is calculated from drawings of profiles, by dividing the area described by vessels walls in summed slices corresponding to geometric shapes -mainly cylinders and truncated cones- and by calculating geometric solid volume, then converting cc volume to liters (Nelson 1985; Vieugué *et al.* 2008).

characteristic patterns of distribution and concentration of residues are detected in the vessel profile (Charters *et al.*, 1993; Evershed, 2008).

3.2.3 Biomolecular and isotopic analyses of organic residues: sampling strategy and sample preparation

A total of 116 sherds and 12 visible residues corresponding to 99 of the 198 vessels identified at the three sites were sampled for organic residues analysis (table 2). When possible, vessels were sampled at different points of their profile, in order to investigate patterns of residue concentration (see 3.2.2; Supplementary tables A.1-A.3). Visible residues (5-50 mg) and sherds (about 2x2 cm², 2 g) were prepared for analyses by HT GC-FID, GC-MS and GC-C-IRMS following the established protocol for lipid residues analysis of archaeological pottery (Evershed *et al.*, 1990, 1994; Copley *et al.*, 2003; Regert, 2011), fully detailed in Supplementary data A.1.

4 Results

4.1 Morphological and morphometric classification of vessels

The classification of MNB vessels is summarised in fig. 3. Bowls have a broad morphological and morphometric variability, with different types of profile, open to low-restricted orifice, shallow to medium-deep height, little to medium sizes (<4 L). At the opposite, “ladle-bowls” have very distinct morphometric characteristics (open shallow/medium-deep simple profile and a robust handle), as well as pots, being restricted medium-deep carinated big-size vessels, mainly double-handled (rim diameter: 20-30 cm, capacity: 4-9 L). Finally, “stepped-wall” and necked jars, sometimes handled, have closed orifice and deep body. Fragmentary big-size vessels with unidentifiable profiles are also documented from Bau Angius and Su Mulinu Mannu sites. Although almost all the vessel morphologies appear in the three sites, jars are absent in the Gribaia pits.

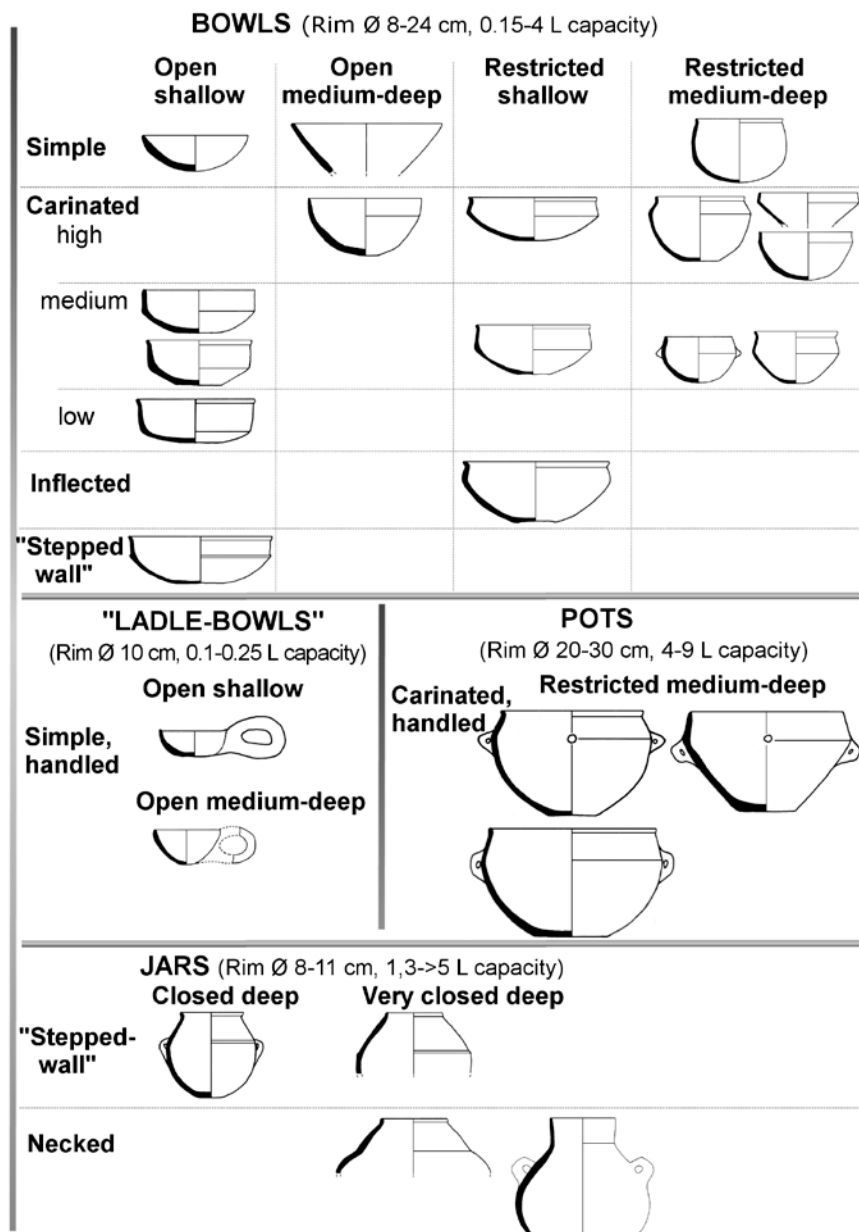


Fig. 3: Morphological and morphometric classification of MNB pottery from Bau Angius, Gribaia and Su Mulinu Mannu sites (adapted from Fanti, 2015). Drawings: L. Fanti.

4.2 Use-wear traces

We observe carbon deposits both on exterior (ECD) and interior (ICD) pottery surfaces. According to the ethnographic, experimental and archaeological literature, the ECD can be related to soot deposition caused by fire exposure or to the carbonisation of vessel content that boiled over (Craig *et al.*, 2013; Duplaix-Rata 1997; Hally, 1983; Pétrequin and Pétrequin 1989; Saul *et al.*, 2011; Skibo, 1992; Skibo and Blinman 1999). Based on their macro-/microscopic appearance and distribution on vessel surfaces, the ECD on MNB vessels are consistent with soot (fig. 4,a-d), partly affected by post-depositional alteration (Beck *et al.*, 2002; Kobayashi, 1994; Skibo, 1992). Moreover, no lipids were detected in samples from these deposits by HT-GC-FID analysis (see 4.3 and Supplementary tables A.1-A.3). ICD are produced by charring of vessel content: on MNB vessels, they are fine charred layers usually associated to black patches, which correspond to carbon deposits penetrated below the ceramic surface (fig. 4,e-f; Kobayashi, 1994: 144; Skibo, 1992: 148).

Carbon deposits on exterior surfaces and/or interior body and bottom appear only on one category of MNB vessels: big-size handled pots (fig. 3 and 4,a-d). This reflects a selection of specific vessels for processing products with heating.

Two patterns of use-wear can be distinguished on interior surfaces: a) intense abrasion stopping at lower body, and no abrasion of bottom, which is covered by a black patch and/or fine carbonised residues, in the pots (fig. 4, e-f); b) fine scratches with variable orientation in a few bowls and one jar, possibly related to cutting and/or mixing contents (fig. 5, a-b). Exterior base attrition appears on both pots and bowls with different shapes and sizes, as peripheral (fig. 5, c) to covering abrasion (fig. 5, d). These different patterns of base abrasion are not strictly correlated with base morphology, but could be linked to several factors: the intensity, frequency and duration of use, the different ways of moving and placing vessels (*i.e.*, in the case of peripheral alteration, inclining the containers to facilitate processing or removing content), or the use of different kinds of supports (Skibo, 1992; Vieugué, 2014). Rim abrasions are rare, possibly due to covering or upturning the vessels (Skibo, 1992; Vieugué, 2014). Altogether, these patterns of use-wear are comparable in all sites.

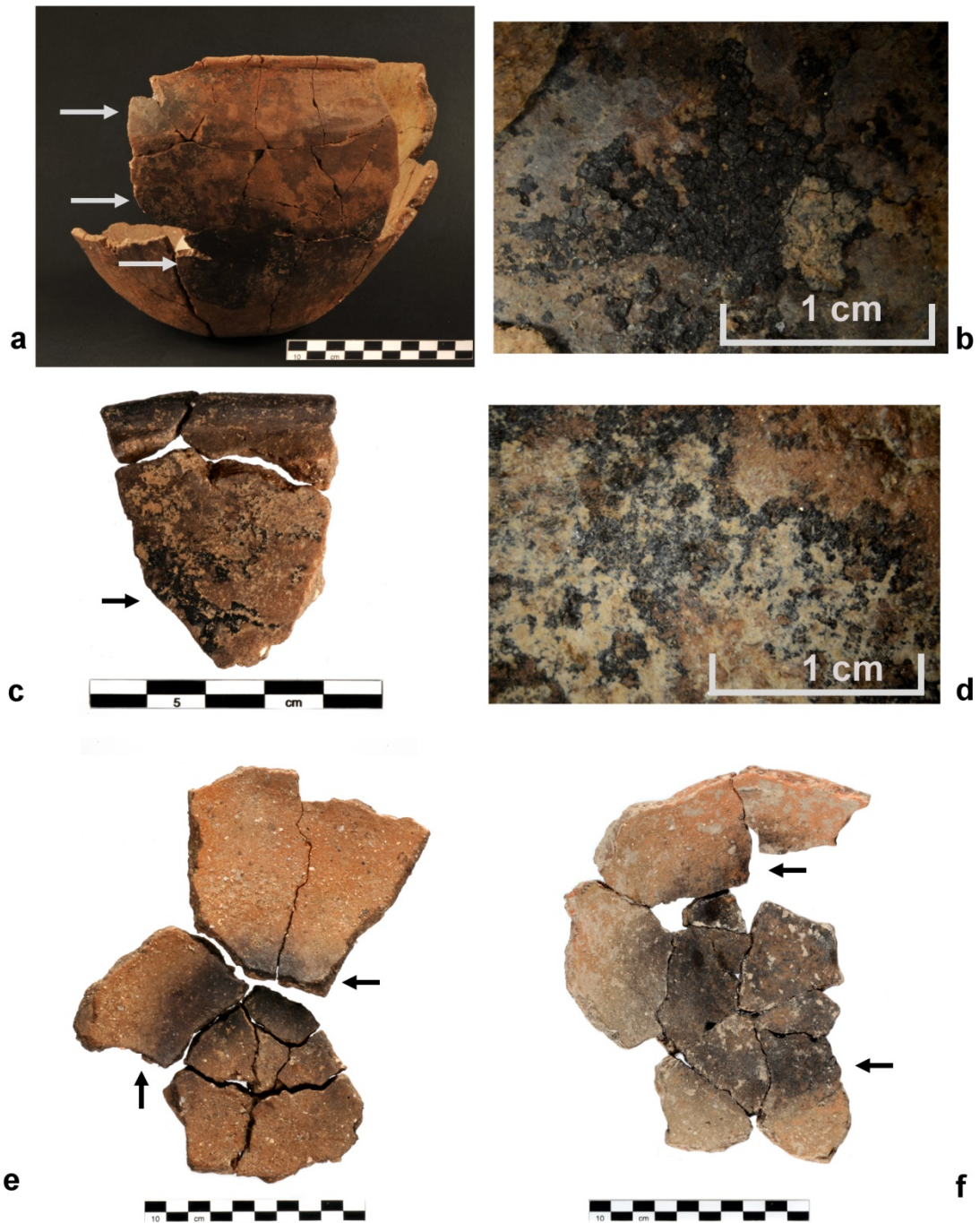


Fig. 4: Use-wear on MNB vessels: soot on exterior surfaces of pots BANG204 (a) and BANG178 (c); details of the soot on the same vessels BANG204 (b) and BANG178 (d), photographed at binocular microscope (10x); abrasion of interior surfaces stopping near black patches/carbonised residues (indicated by arrows) on bottom of pots BANG204 (e) and NG-G20/06 (f). Photo: L. Fanti, C. Lugliè.

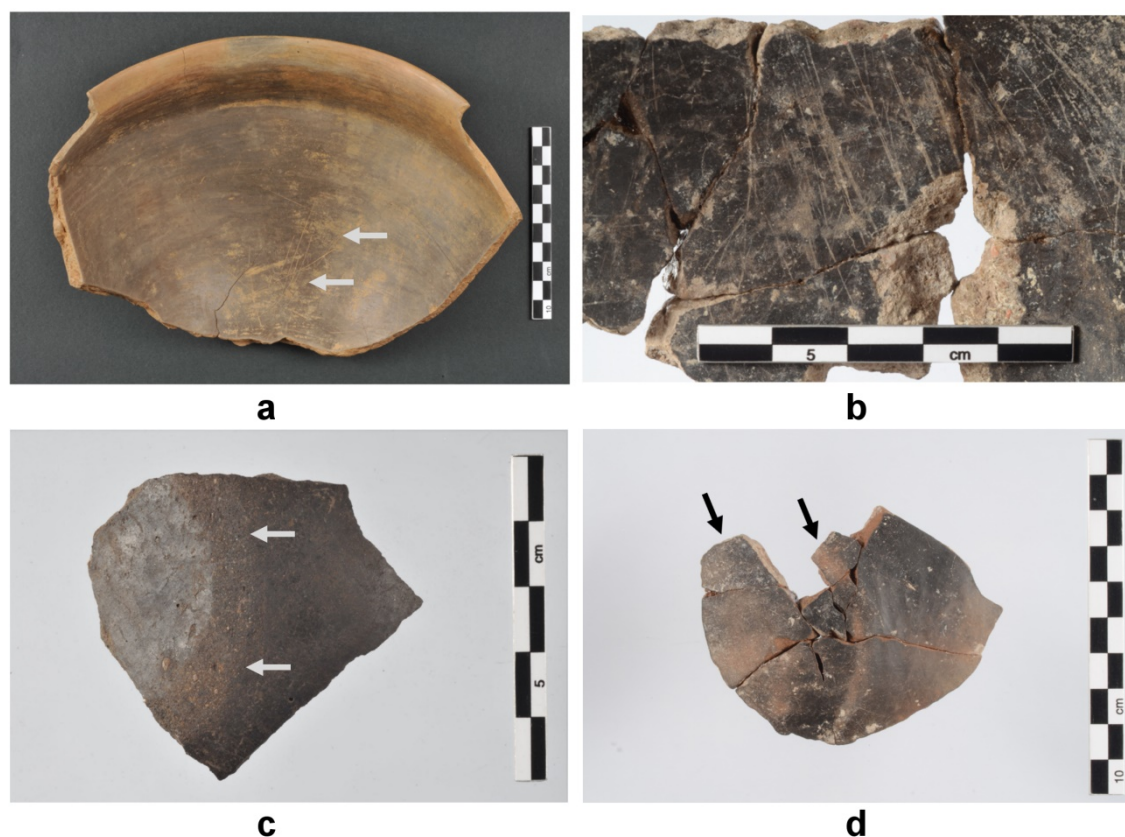


Fig. 5: Use-wear attritions on MNB vessels: scratches on interior surfaces of bowls BANG704 (a) and NG-G9/03 (b); and peripheral exterior base abrasion on sherd TMM2182 (c); peripheral to covering exterior base abrasion on vessel NG-G03/01 (d). Photo: L. Fanti.

4.3 HT GC-FID, GC-MS and GC-C-IRMS results

Molecular and isotopic results are fully presented in Supplementary tables A.1-A.3. Only potsherd extracts held organic material, whereas visible residues did not provide any exploitable signal. 27 of the 128 samples analysed by HT GC-FID (23%) retained a lipid concentration higher than 5 $\mu\text{g/g}$, meeting the accepted criteria of Evershed (2008), with the greatest conservation in pottery from Bau Angius site (table 2).

Table 2: Sampling for organic residues analysis (ECD: carbonised deposit on exterior surface (“soot”), ICD: carbonised deposit on interior surface, INCD: non-carbonised deposit on interior surface).

Site	Total <i>n</i> of samples	Type of sample*	<i>n</i> of samples analysed by GC-FID / GC-MS	<i>n</i> of samples with TLE concentration > 5 $\mu\text{g/g}$ (%)	TLE $\mu\text{g/g}$ concentration		<i>n</i> of samples analysed by GC-C-IRMS
					max	mean	
Bau Angius	31	30 sherds 1 ECD	31 (6: polluted)	9 sherds (36%) 0 ECD	2438	149	5
Gribaia	68	60 sherds 4 ECD 4 ICD	68 (4: polluted)	13 sherds (20%) 0 ECD 0 ICD	21	4	8
Su Mulinu Mannu	29	26 sherds 1 ICD 2 INCD	29 (2: polluted)	5 sherds (18%) 0 ICD 0 INCD	65	6	3
Total	128	116 Sherds 5 ECD 5 ICD 2 INCD	128 (12: polluted)	27 sherds (23%) 0 ECD 0 ICD 0 INCD	2438	53	16

This percentage is coherent with the average conservation of lipids in pottery from Mediterranean contexts (Debono Spiteri *et al.* 2014, 2016; Evershed *et al.*, 2008; Salque *et al.*, 2012). Samples with modern contamination markers (squalene, restoration glue components) are excluded from any further discussion.

Chromatograms are dominated by saturated fatty acids, mainly C_{16:0} and C_{18:0}, sometimes with mono- and diacylglycerols, animal or plant sterols (fig. 6). Considering the palmitic/stearic ratio (P/S), the very high abundance of C_{18:0} in samples from Bau Angius (P/S: 0.03-0.25) suggests an animal origin for the lipids (fig. 6,a). Conversely, in several vessels from Gribaia, high concentration of C_{16:0} compared to C_{18:0} (P/S >1.4, even >5 in NG-G03/02 sample), presence of unsaturated fatty acids (C_{16:1}, C_{18:1}-C_{18:2}), series of odd-numbered long-chain alkanes (C₂₁-C₃₅), even-numbered linear alcohols (C_{22OH}-C_{34OH}), and sometimes plant sterols (mainly β-sitosterol) are consistent with plant products (fig. 6,b and 7,a, Supplementary table A.2; Dunne *et al.*, 2012, 2016).

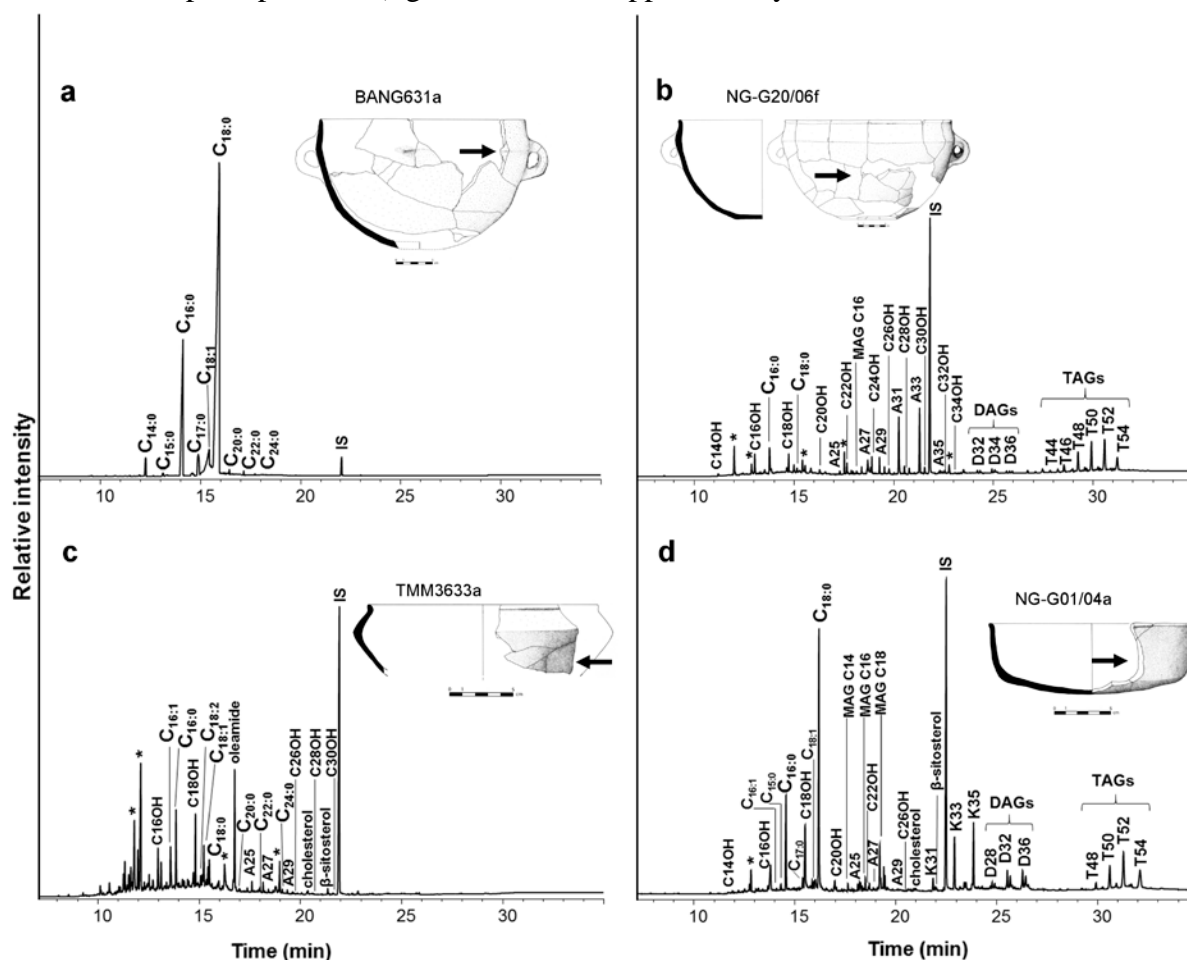


Fig. 6: Partial high temperature gas chromatograms of total lipid extracts of MNB samples. C_{n:0}: saturated fatty acids with *n* carbon atoms; C_{n:x} unsaturated fatty acids with *n* carbon atoms; A_x: *n*-alkanes containing *x* carbon atoms; C_xOH: mid-chain and long-chain alcohols containing *x* carbon atoms; MAG C_x: monoacylglycerol containing *x* carbon atoms; DAGs D_x: diacylglycerols containing *x* carbon atoms; TAGs T_x: triacylglycerols containing *x* carbon atoms; K_x: mid-chain secondary ketones containing *x* carbon atoms; IS: internal standard, C₃₄ *n*-tetratriacontane; *: phthalates. Arrows indicate the position of sampling. Vessel drawings: L. Fanti.

Triacylglycerols are preserved in 8 samples from Gribaia, with different patterns of distribution (fig. 6,b,d and 7,a-b):

- 1) TAGs C₄₄/C₄₈-C₅₄, max C₅₂ (NG-G01/04a, NG-G06/05b, NG-G20/06f), typical of animal adipose fats (Mukherjee *et al.*, 2007, fig. 2);
- 2) TAGs C₄₈-C₅₄, largely dominated by C₄₈ (NG-G6/05at, NG-G15/03b, NG-G09/03a). The close analysis of the mass spectrum of peak C₄₈ in samples NG-G15/03b and NG-G06/05at reveals that it is mainly constituted of palmitolein (TAGs composed of 3 palmitoleic acid moieties), an infrequent signature in archaeological residues, which suggests an aquatic or vegetal origin, perhaps an unknown plant residue (Evershed *et al.*, 2003: 6; Jones *et al.*, 2011; Regert *et al.*, 2005; Skibo *et al.* 2016; Šoberl and Evershed, 2011). The TAGs distribution in sample NG-G09/03a is similar but TAGs are present in much smaller quantities, making the close analysis of their mass spectra impossible;
- 3) “Mixed” patterns: TAGs C₄₈-C₅₄, max C₅₀ (NG-G01/03a), TAGs C₄₂-C₅₄, max C₄₈ (NG-G03/02a), possibly resulting from multiple episodes of use/mixed foodstuffs (Mukherjee *et al.*, 2008, fig. 5).

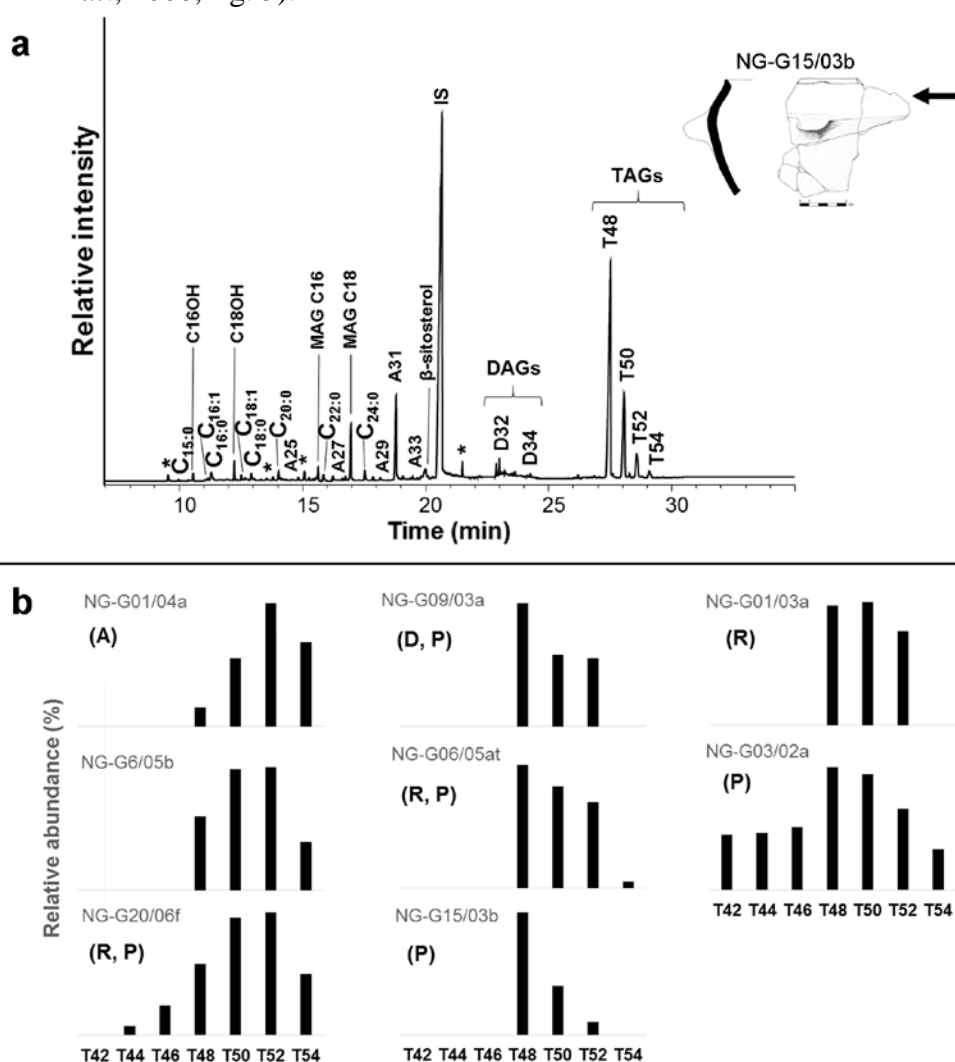


Fig. 7: Triacylglycerols in total lipid extracts from Gribaia pottery vessels: a, Partial high temperature gas chromatograms of total lipid extracts of sample NG-G15/03b. C_{n:0}: saturated fatty acids with *n* carbon atoms; C_{n:x} unsaturated fatty acids with *n* carbon atoms; Ax: *n*-alkanes containing *x* carbon atoms; C_xOH: mid-chain and long-chain alcohols containing *x* carbon atoms; MAG C_x: monoacylglycerol containing *x* carbon atoms; DAGs D_x: diacylglycerols containing *x* carbon atoms; TAGs T_x: triacylglycerols containing *x* carbon atoms; IS: internal standard, C₃₄ *n*-tetratriacontane; *: phthalates. Arrow shows the position of sampling; b), distributions of triacylglycerols in total lipid extracts from Gribaia pottery vessels. Letters between parentheses: A (animal fat), R (ruminant adipose fat), D

(ruminant dairy fat) denote the identification of residue on the basis of GC-C-IRMS results; P indicates the presence of plant markers detected by GC-MS analysis. Vessel drawing: L. Fanti.

16 of the 27 samples with TLE concentrations $>5 \mu\text{g/g}$ were directly analysed by GC-C-IRMS (Supplementary tables A.1-A.3).

Fatty acid extracted from the vessels were not noticeably enriched in ^{13}C ($\delta^{13}\text{C}_{\text{C}_{16:0}}$ values usually under -25‰ and $\delta^{13}\text{C}_{\text{C}_{18:0}}$ under -27‰), which suggests that they are terrestrial in origin, except for sample TMM1973a (fig. 8).

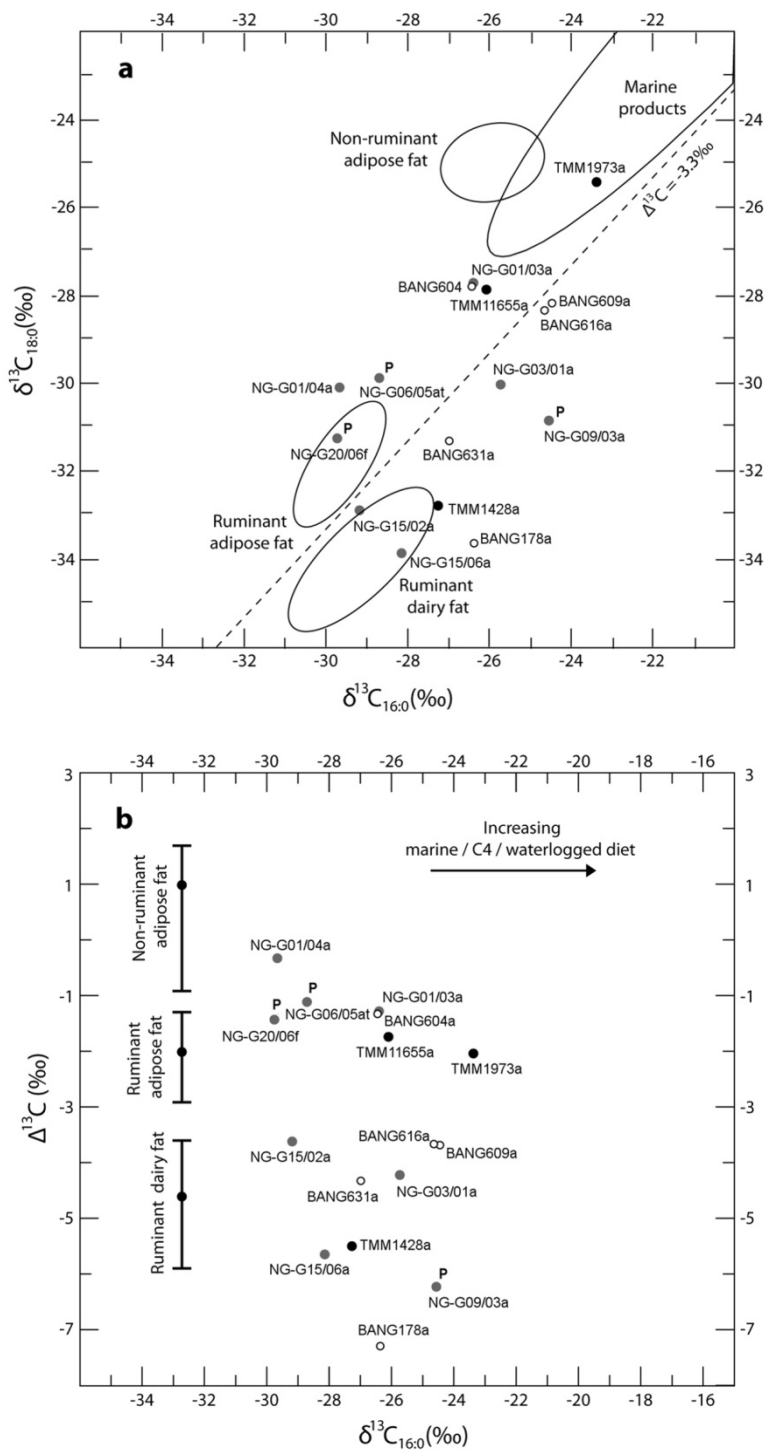


Fig. 8: Results of the GC-C-IRMS analysis of MNB pottery samples: a, $\delta^{13}\text{C}$ values of the FAMES of $\text{C}_{16:0}$ and $\text{C}_{18:0}$ prepared from lipid extracts from the three pottery assemblages; b, $\Delta^{13}\text{C}$ values ($= \delta^{13}\text{C}_{18:0} - \delta^{13}\text{C}_{16:0}$) of the extracts

plotted against their $\delta^{13}\text{C}_{16:0}$ values. White circles: Bau Angius, grey circles: Gribaia, black circles: Su Mulinu Mannu. P indicates the presence of plant markers detected by GC-MS analysis. The reference materials are represented by their ranges and mean $\Delta^{13}\text{C}$ values, according to Copley *et al.*, 2003.

Most of the $\delta^{13}\text{C}$ values of fatty acids (9 samples: BANG178a, BANG609a, BANG616a, BANG631a, NG-G03/01a, NG-G09/03a, NG-G15/02a, NG-G15/06a, TMM1428a) plot under the line $\Delta^{13}\text{C} = -3.3\text{‰}$, within the range of dairy products (Copley *et al.*, 2003). Some studies cautioned against the risk of misinterpretation of residues in the case of compresence of wild ruminants like deer, because $\delta^{13}\text{C}$ values of domesticated ruminant (i.e. dairy) products and deer adipose can be partially superposed (Craig *et al.*, 2012). Favourably, the absence of wild ruminants in Early and Middle Neolithic faunal assemblages in Sardinia (Wilkens, 2012) rules out the possibility of a misinterpretation of MNB residues.

The ^{13}C values of five samples (BANG604a, NG-G01/03a, NG-G06/05at, NG-G20/06f, TMM11655a) are consistent with the reference established for ruminant adipose fat ($\Delta^{13}\text{C}$ between -0 and -3.3 ‰), while an unidentified terrestrial animal fat is present in sample NG-G01/04a (Copley *et al.*, 2003; Mukherjee *et al.*, 2008).

One sample (TMM1973a) plots in the ellipse of marine fats, but we did not detect any aquatic biomarker, such as isoprenoid fatty acids (phytanic and pristanic acids, 4,8,12-trimethyltridecanoic acid) and heating markers (ω -(*o*-alkylphenyl) alkanolic acids; Craig *et al.*, 2007a, 2011, 2013; Cramp *et al.*, 2014a; Hansel *et al.*, 2004). Furthermore, the calculation of $\Delta^{13}\text{C}$ indicates that it is more likely a ruminant adipose fat. The slight enriched $\delta^{13}\text{C}$ values of palmitic acid extracted from this sample and three others (BANG609a, BANG616a and NG-G09/03a) could result of the contribution from C₄, marine or waterlogged plants in the diet (Craig *et al.*, 2005a; Copley *et al.*, 2003; Salque *et al.*, 2012; Šoberl *et al.*, 2014). Feeding livestock with marine products such as seaweed is mainly observed in northern areas with limited resource during winter (Craig *et al.*, 2005a); for Sardinian Neolithic sites, enriched $\delta^{13}\text{C}_{16:0}$ values are more likely related to the waterlogged environment. Indeed, this flat region crossed by stream and rivers and covered by wetland vegetation is ideally suited for domestic animal grazing (Pittau *et al.*, 2012). More generally, the large differences in $\delta^{13}\text{C}_{16:0}$ values could be explained by the diversity of the fodders and pastures.

Large amount of hexadecenoic acid (C_{16:1}), in concentration almost equal to C_{16:0} and higher than C_{18:0} and C_{18:1} have been detected in samples NG-G01/02a and TMM03633a (fig. 6, c). This molecular profile does not fit with the fatty material usually identified in archaeological ceramics.

High amount of C_{16:1} has been highlighted in fat from archaeological seal bones (Heron *et al.* 2015) and in some modern seals (Ackman, 1989). The presence of monk seals (*Monachus monachus*) during 5th millennium cal BC is attested in the Bel Torrente submerged costal cave, central-eastern Sardinia (De Waele *et al.*, 2009). Nevertheless, none of the Sardinian Neolithic faunal assemblages displayed evidence of marine mammal exploitation thus far (Wilkens, 2012). Furthermore, no aquatic biomarkers have been identified in the Sardinian vessels.

High concentration of hexadecenoic acid is rare in the plant kingdom, but it has been identified in oil extracted from sea buckthorn (*Hippophae rhamnoides* L.) berries (Dubois *et al.*, 2007; Yang and Kallio, 2001). Nevertheless, this shrub is not documented in the environment of the island during Neolithic (Bartish *et al.*, 2006; Pittau *et al.*, 2012). The presence of the C_{16:1} might be related to the TAGs profiles dominated by unsaturated C₄₈, as attested in samples NG-G6/05at and NG-G15/03b (fig. 7, a). A triacylglycerol's distribution dominated by C₄₈ is typical of kernels of sumac plants

(*Rhus* genus), known as Japan wax (Regert *et al.*, 2005). Nevertheless, in this product, C₄₈ is saturated (tripalmitin); furthermore, *Rhus* genus does not seem to be characteristic of Neolithic botanical assemblages in Italy (Mercuri *et al.*, 2015), while some species (i.e., *Rhus coriaria*) are attested during Neolithic in Greece (Ntinou and Badal, 2000). As a hypothesis, the residues in our samples could be attributed to a fatty material of vegetal origin, whose source in Sardinia must be assessed by further analyses. Because C_{16:1} is abundant in skin lipid composition and a common component of cosmetics, as well as tripalmitolein, it has been also considered as a potential modern contamination marker (Šoberl and Evershed, 2011). In consequence, these residues could be tentatively assigned to unknown plant oil or a modern contamination.

Nonetheless, other plant biomarkers (odd-numbered long-chain alkanes C₂₁-C₃₃ and even-numbered linear alcohols C_{22OH}-C_{34OH}) point to vegetal products at Gribaia (Supplementary table A.2). One sample seems to be only characterised by these plant biomarkers (NG-G03/06a) while some others have also evidences of dairy products (NG-G09/03a) or adipose fat (NG-G03/02a, NG-G06/05a, NG-G20/06f: fig. 6,b).

In the sample NG-G03/02a, the singular pattern of triacylglycerol distribution can be explained by mixtures of vegetal and animal products (fig. 7,b). Then, on the basis of GC-MS and GC-C-IRMS data, some vessels from Gribaia contained ruminant adipose or dairy fats with plant products, which could result from multiple episodes of use or from “recipes” combining different kinds of foodstuffs.

Mid-chain secondary ketones (C₃₁-C₃₅), markers of anthropogenic transformation of fats (heated at a temperature > 350°C: Evershed *et al.*, 1995; Raven *et al.*, 1997; Regert, 2007), have been detected in only one carinated bowl from Gribaia (NG-G01/04a, fig. 6,d).

Considering the relative proportion of the types of contents in vessels from the three sites, some differences emerge (table 3, fig. 9). In Bau Angius, only animal fats, ruminant adipose and dairy products were processed in the vessels, whereas Su Mulinu Mannu and Gribaia pottery held a broader range of commodities, such as plant products. Despite accurate flotation and sieving, no macro-botanical evidence was found at Gribaia, while cultivated cereals, legumes, gathered and wild plants (notably, *Malva* sp.) are documented at Su Mulinu Mannu (Ucchesu *et al.*, 2017). Nevertheless, the absence of carpological remains at Gribaia fits into the general lack of carbonised (e.g., charcoal) remains in the sediment. On the other hand, carbonised deposits appear on vessel surfaces. This divergence between data on pottery use and context could be explained in terms of spatial differentiation (the activities involving fire, e.g. cooking with and without pots, were performed elsewhere in the site) and/or by the particular status of this site, characterised by the deposition of vessels (brought from elsewhere?) in pits (Fanti *et al.*, forthcoming).

Table 3 – Synopsis of vessel content in the samples from the three sites, on the basis of biomolecular and isotopic results.

Site	Dairy fat	Dairy fat + plant residue	Ruminant adipose fat	Ruminant adipose fat + plant residue	Animal fat	Animal fat + plant residue	Plant residue	Unassigned/undetermined fat	Total
Bau Angius	4	0	1	0	4	0	0	0	9
Gribaia	3	1	1	2	2	1	2	1 (plant oil?)	13
Su Mulinu Mannu	1	0	2	0	0	0	1	1	5
Total	8	1	4	2	6	1	3	2	27

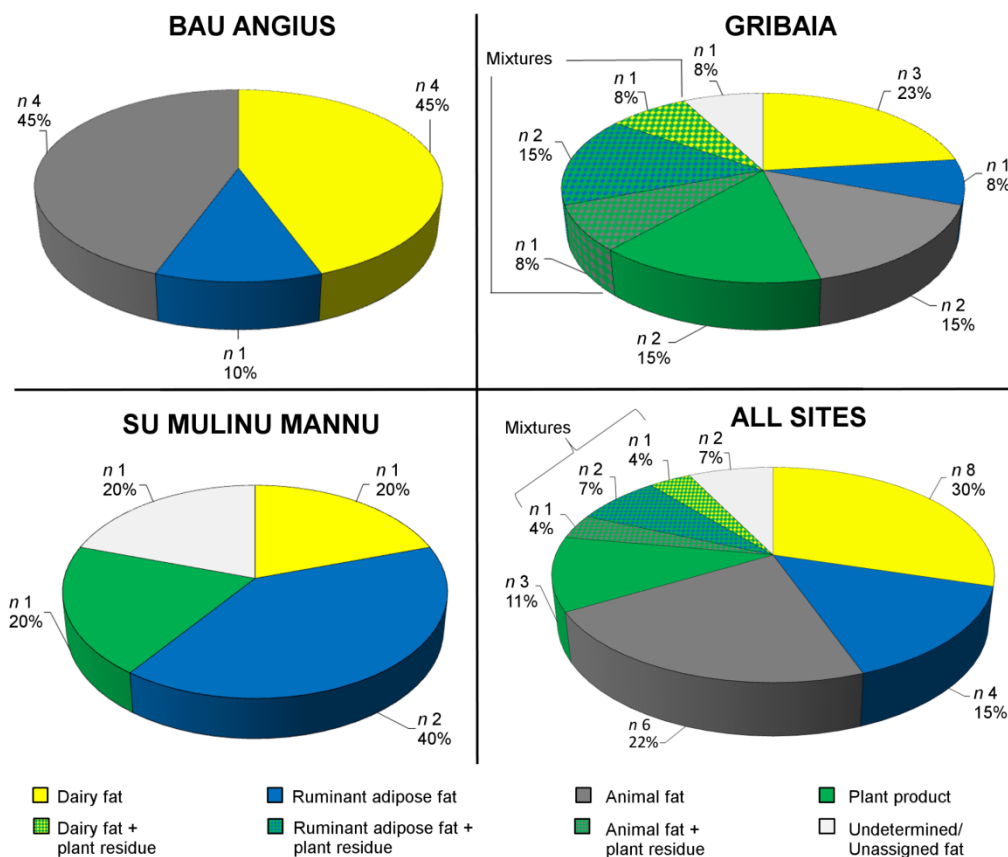


Fig. 9: Inter-site differences on the contents of MNB pottery vessels from Bau Angius, Gribaia and Su Mulinu Mannu sites.

5 Discussion: identifying functional categories in MNB pottery

By combining all morphological, morphometric, use-wear and chemical data, we identified six categories of vessel use (table 4, fig. 10), arising from three broader functional realms (Rice 1987): processing (categories 1-Processing with heating, 2-Processing without heating); consumption (categories 4-Drawing/distribution, 5-Serving/eating); storing (category 6-Storing). The minor cross-category 3-Processing/storing perhaps reflects a secondary use of the vessel.

In category 1-Processing with heating, cooking vessels are identified through the presence of soot on the exterior surfaces, black patches and/or fine carbonised residues on the interior bottoms, sometimes associated to interior body abrasion. Several assemblages in central-northern Europe bear traces of sooting (Craig *et al.* 2007b; Cramp *et al.*, 2014a; Isaksson and Hallgren 2012; Heron *et al.* 2015; Müller and Peterson 2015), while the conservation of soot is not systematically documented in the studies about pottery use in southern Europe (Debono Spiteri *et al.*, 2016; Salque *et al.*, 2012; Vieugué *et al.*, 2008; Vuković, 2011). This absence could be due to the loss of soot in post-depositional contexts (Beck *et al.*, 2002) or to cleaning, restoration and conservation practices (Kobayashi, 1994; Stacey, 2009). In MNB assemblages, the conservation of soot is probably enhanced by the exceptional depositional characteristics (*i.e.*, deposits of stacked vessels in pits) and by controlled post-excavation protocol. MNB cooking pots are very homogeneous in morphology and morphometry, being restricted medium-deep and handled vessels with a capacity of ca. 4 to 9 L. Thus, cooking activities had to involve a quantity of food shared by several persons

or prepared to be stored over a period of time. These vessels were generally used to cook ruminant fats, dairy products at Bau Angius and/or plant materials at Gribaia. At that site, the plant biomarkers could suggest a recipe combining animal fats and vegetables or multiple episodes of cooking. Only one open shallow carinated vessel from Gribaia (fig. 10, NG-G01/04) contains animal fat and mid-chain secondary ketones, heating markers (fig. 6,d). Interestingly, the ketones are not associated to visible soot in the bowl surface and, conversely, no cooking pot having exterior soot retains residues with ketones. This confirms the lack of a strict correlation between the two kinds of traces, already observed in other archaeological contexts (Heron *et al.*, 1991; Craig *et al.*, 2007b). Furthermore, heating of fatty substances could occur during pottery use (*i.e.* successive cooking events; Evershed *et al.*, 1995; Raven *et al.*, 1997) but also in the final phase of pottery production (Drieu, 2017; Drieu, Lepère and Regert, unpublished data). As a consequence, NG-G01/04 bowl is dubitatively assigned to this use-category.

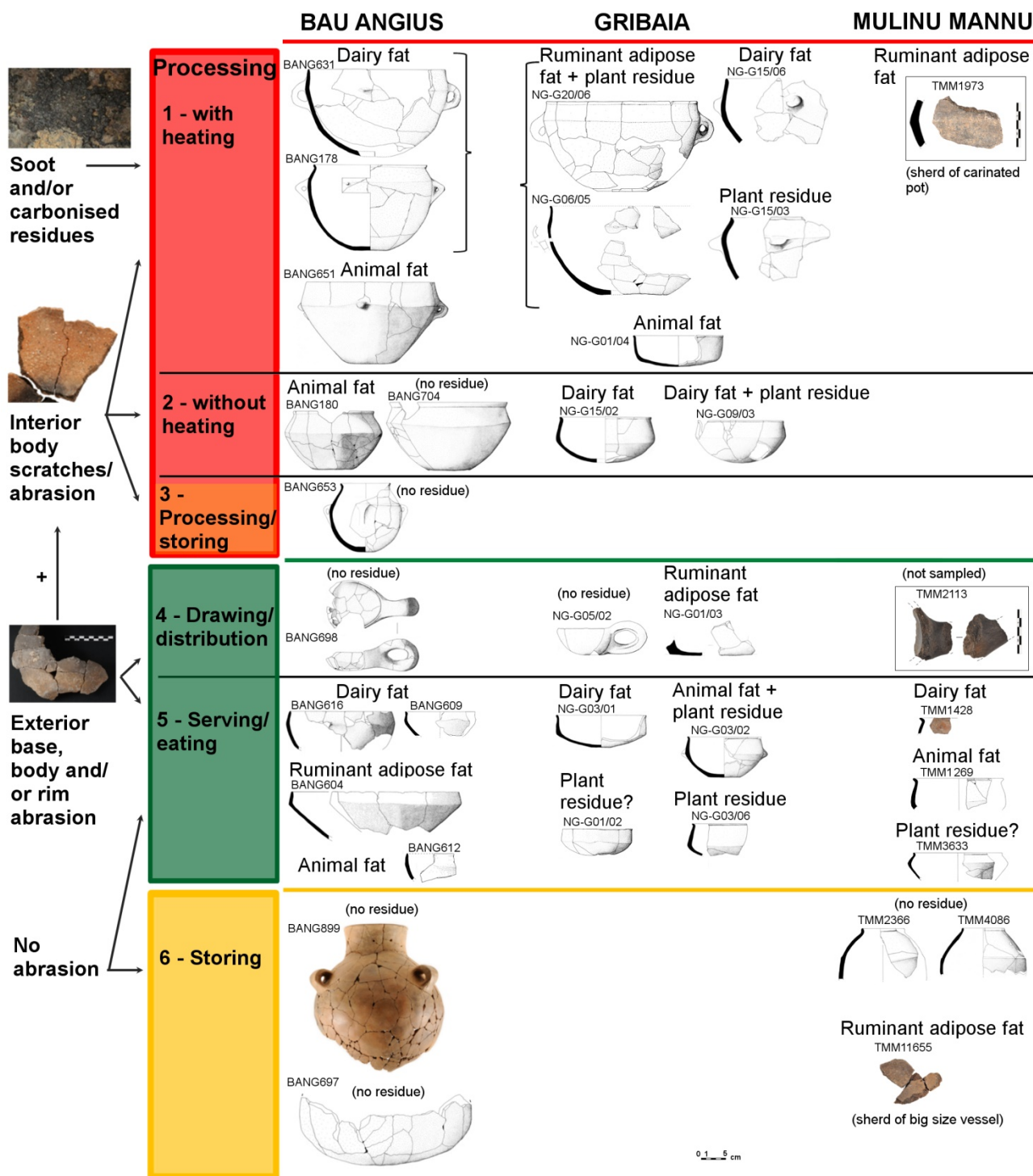


Fig. 10: Functional categories identified in MNB pottery assemblages from Bau Angius, Gribaia and Su Mulinu Mannu sites by combining morphological, morphometric, use-wear, biomolecular and isotopic data. Vessel drawings and image processing: L. Fanti.

Table 4 – Relations among morphological/morphometric features (rim diameter, height, volume), use-wear traces, GC-MS and GC-C-IRMS identification of residues of contents, and assignment to functional categories of the main MNB vessels analysed by the integrated approach (Rim Ø: rim diameter, h: height of the vessel from rim to bottom; V: vessel volume; n.a.: not attributed to a specific morphotype, n.d.: not determined, due to incomplete conservation of vessel profile).

Vessel number	Sample numbers	Morpho-type	Morphometric features	Use-wear	Contents	Functional category
BANG178	BANG178/	Restricted medium-	Rim Ø 227 mm	Soot on exterior body,	Dairy fat (lipid	1-Processing

	01-04a	deep pot with handles	h 172 mm V 5,5 L	base abrasion; interior body abrasion, black patch and carbonised residues on bottom	concentration decreasing from rim to bottom)	with heating
BANG180	BANG180a	Restricted medium-deep carinated bowl	Rim Ø 162 mm h 117 mm V 2 L	Exterior base abrasion, interior body and bottom abrasion	Animal fat	2-Processing without heating
BANG204	BANG204/01-02, BANG204e	Restricted medium-deep pot with handles	Rim Ø 223 mm h 163 mm V 4,1 L	Soot on exterior body, base abrasion; interior body abrasion stopping at bottom; black patch on bottom	-	1-Processing with heating
BANG445	BANG445/01-02a	Restricted medium-deep pot with handles	Rim Ø 244 mm h 180 mm V 6,7 L	Soot on exterior body, base abrasion; interior body abrasion stopping at bottom; black patch on bottom	-	1-Processing with heating
BANG604	BANG604a	Restricted medium-deep carinated bowl	Rim Ø 221 mm h, V n.d.	Rim abrasion/chips	Ruminant adipose fat	5-Serving/eating
BANG609	BANG609a	Restricted carinated bowl	Rim Ø 140 mm h, V n.d.	Rim abrasion	Dairy fat	5-Serving/eating
BANG612	BANG612a	Restricted carinated bowl	Rim Ø , h, V n.d.	Rim abrasion	Animal fat	5-Serving/eating
BANG616	BANG616a	Restricted medium-deep carinated bowl	Rim Ø 200 mm h, V n.d.	Rim abrasion	Dairy fat	5-Serving/eating
BANG631	BANG631a	Restricted medium-deep pot with handles	Rim Ø 300 mm h 170 mm V 8,4 L	Soot on exterior body; interior body abrasion	Dairy fat	1-Processing with heating
BANG651	BANG651a	Restricted medium-deep pot with handles	Rim Ø 260 mm h 168 mm V 5,8 L	Soot on exterior body, rim and base abrasion	Animal fat	1-Processing with heating
BANG653	BANG653a	Closed deep stepped-wall jar	Rim Ø 101 mm h 129 mm V 1,3 L	Exterior base abrasion, scratches on interior mid-lower body and bottom	-	3-Processing/storing
BANG697	BANG697a	Big size vessel (n.a.)	Rim Ø , h, V n.d.	-	-	6-Storing
BANG698	BANG698a	Ladle-bowl	Rim Ø 108 mm h 38 mm V 0,2 L	Exterior body and rim abrasion	-	4-Drawing/distribution
BANG704	BANG704	Restricted medium-deep carinated bowl	Rim Ø 236 mm h 138 mm V 4 L	Exterior base abrasion, scratches on interior lower body and bottom	-	2-Processing without heating
BANG899	BANG899/01-03a	Very closed deep necked jar	Rim Ø 112 h n.d. (V > 5L?)	-	-	6-Storing
NG-G01/02	NG-G01/02a	Open shallow carinated bowl	Rim Ø 141 mm h 54 mm V 0,5 L	Exterior base abrasion	Unknown plant oil/pollution?	5-Serving/eating
NG-G01/03	NG-G01/03a	“Ladle-bowl”	Rim Ø, h, V n.d.	-	Ruminant adipose fat	4-Drawing/distribution
NG-G01/04	NG-G01/04a	Open shallow carinated bowl	Rim Ø 176 h 63 V 1 L	Exterior base and rim abrasion	Terrestrial animal fat; mid-chain ketones	1-Processing with heating?
NG-G03/01	NG-G03/01a	Open shallow carinated bowl	Rim Ø 180 mm h 65 mm V 1 L	Exterior base abrasion	Dairy fat	5-Serving/eating
NG-G03/02	NG-G03/02a	Restricted medium-deep bowl with lugs	Rim Ø 120 mm h 81 mm V 1,2 L	-	Animal fat, plant residue	5-Serving/eating
NG-G03/06	NG-G03/06a	Restricted shallow carinated bowl	Rim Ø, h, V n.d.	-	Plant residue	5-Serving/eating
NG-G06/05	NG-G06/05a-c	Restricted medium-deep pot with handles	Rim Ø , h, V n.d.	Soot on exterior body, exterior lower body and base abrasion; abrasion on interior body stopping at bottom, black patch on bottom	Ruminant adipose fat, plant residue	1-Processing with heating
NG-G09/03	NG-G09/03a	Restricted shallow carinated bowl	Rim Ø 170 mm h 85 mm V 1,4 L	Scratches on interior lower body and bottom	Dairy fat, plant residue	2-Processing without heating
NG-G12/06	NG-G12/06ae-at	Restricted medium-deep pot with handles	Rim Ø 230 mm h 149 mm V 5,6 L	Soot on exterior body, base abrasion; abrasion on interior body stopping at bottom, fine carbonised residues on bottom	Ruminant adipose fat, plant residue	1-Processing with heating

NG-G15/02	NG-G15/02a	Restricted shallow carinated bowl	Rim Ø 182 mm h 91 mm V 2,3 L	Exterior base abrasion; scratches on interior lower body	Dairy fat	2-Processing without heating
NG-G15/03	NG-G15/03a-d	Restricted medium-deep pot with lugs	Rim Ø 260 mm h, V n.d.	Soot on exterior body	Plant residue (concentration decreasing from rim to mid-body)	1-Processing with heating
NG-G15/06	NG-G15/06a	Pot with lugs (n.a.)	Rim Ø, h, V n.d.	-	Dairy fat	1-Processing with heating
NG-G20/06	NG-G20/06ae-ht	Restricted medium-deep pot with handles	Rim Ø 230 mm h 180 mm V 8,8 L	Soot on exterior body; abrasion on interior body, stopping at bottom, black patch and carbonised residues on bottom	Ruminant adipose fat, plant residue	1-Processing with heating
TMM01269	TMM01269a	Restricted carinated bowl (=TMM1428?)	Rim Ø 180 mm h, V n.d.	-	Undetermined fat (=TMM1428?)	5-Serving/eating
TMM01428	TMM01428a	Rim of a bowl (=TMM1269?)	=TMM1269?	-	Dairy fat	5-Serving/eating
TMM01973	TMM01973a	Sherd of carinated pot	Rim Ø, h, V n.d.	-	Ruminant adipose fat	1-Processing with heating
TMM2113	Not sampled	Sherd of "ladle-bowl"	Rim Ø, h, V n.d.	-	-	4-Drawing/distribution
TMM02366	TMM02366a	Very closed deep stepped-wall jar	Rim Ø 80 mm h, V n.d.	-	-	6-Storing
TMM3330	TMM3330a	Restricted shallow inflected bowl	Rim Ø 240 mm, h 97 mm, V 2,5 L	Base abrasion	-	5-Serving/eating
TMM03633	TMM03633a	Restricted carinated bowl	Rim Ø 180 mm h, V n.d.	Rim abrasion	Plant residue?	5-Serving/eating
TMM4086	TMM4086a	Very closed stepped-wall jar	Rim Ø 80 mm h, V n.d.	-	-	6-Storing
TMM11655	TMM11655a	Sherd of big size vessel with thick walls (n.a.)	Rim Ø, h, V n.d.	-	Ruminant adipose fat	6-Storing

The scarcity of molecular heating markers in MNB vessels can be due to low-temperature cooking process (< 350°C) of fats not allowing the formation of ketones and ω -(*o*-alkylphenyl) alkanolic acids. Then, cooking in MNB pottery has involved usually low-temperature processes such as simmering or boiling, rather than frying (Skibo, 2013: 85-88).

Interestingly, one vessel from Bau Angius (BANG178), sampled at different points of profile, retained a very high lipid concentration, decreasing from rim to bottom (Supplementary table A.1). As demonstrated by experimental and archaeological data, this pattern of lipid concentration is coherent with the use of vessels in boiling foodstuffs (Charters *et al.*, 1997), in this case dairy products. Less clearly, a lipid concentration decreasing from upper to mid-body seems to appear in the vessel NG-G15/03 from Gribaia, whose samples held plant biomarkers (upper body) and a mixed signal (mid-body). This variation of content at different points of the vessel profile is also documented in NG-G06/05, and could reflect multiple uses (filling the vessel at different levels) or mixing products with different density (Charters *et al.*, 1995).

Some cooking pots bear an intense abrasion of interior surfaces stopping near their bottoms, which are covered by a black patch and/or fine carbonised residues (BANG204, BANG445, NG-G06/05, NG-G20/06: Table 4, fig. 4, e-f). This abrasion of interior surfaces may have been caused by strong or repeated mixing of food. Interestingly, this pattern of use-wear compares with an ethnographic record of vessel use for processing grains (Reid and Young, 2000). This kind of alteration is correlated with very low or no lipid signal at Bau Angius, whereas at Gribaia residues from these vessels show "mixed" signals of animal fats with plant materials (fig. 6-7).

Dairy fats, in one case mixed with plant products, were also detected in mid-size shallow or slightly restricted carinated bowls, with scratches on interior surfaces but without exterior sooting (fig. 5, a-

b). This use-wear pattern characterises the functional category 2-Processing without heating (fig. 10) and could be related to stirring milk products in fermenting (Lugli and Vidale, 1996). In this case, the presence of plant biomarkers could also derive from adding a vegetable coagulant (Atzei, 1989; Gouin, 1990). This practice would not be an isolated case in Neolithic, being also suggested from vessel residues in continental site of Clairvaux XIV-Jura, France (Drieu *et al.*, submitted).

The abrasion of interior surfaces is quite infrequent, which suggests that bowls were not systematically involved in activities implying intense mechanical transformation of products (cutting, grinding, stirring). Most of the bowls, having a wider morphological and morphometric variability (0.15-4 L volume), often showing only exterior base abrasion, were probably used in consumption of food and drinks (category 5-Serving/eating). The identified contents are ruminant adipose fats, dairy fats, plant products or undetermined animal fats sometimes with plant biomarkers. Rim abrasions on some vessels from categories 1 and 5 (table 4) is perhaps due to covering, respectively during heating and serving foods, or placing upturned (Skibo, 1992; Vieugué, 2014).

Transfer was achieved by drawing products through a specific-designed pottery tool, the “ladle-bowl” (0.15 to 0.25 L capacity), equipped with a big handle that counterbalanced the weight of contents during activity (category 4-Drawing/distribution). As revealed by residues analysis, one ladle-bowl from Gribaia was used to transfer foodstuffs containing ruminant adipose fats (perhaps, a soup?).

Storing (category 6-storing) was performed in closed-deep necked jars having a capacity of about 5 L, where lipids were not detected, then possibly used for liquids, as water; incomplete big size vessels, whose morphology cannot be reconstructed, were used to store animal fats at Su Mulinu Mannu. Nevertheless, some big size vessels could have been also used to store other kinds of low-fat foodstuffs like grains or pulses.

No precise correlation between the kind of foodstuffs and vessel morphology is evident, but two opposed behaviours emerge in the relationship between morphometry and use category, with a strong specialisation of a particular type of vessel for cooking (“specialized” handled pots with > 4 L capacity, except for only one bowl), while serving/eating is performed in bowls with a broader morphological and morphometric (< 4 L volume) variability.

Although boar/pig bones and teeth appear in faunal remains from Su Mulinu Mannu and Gribaia, $\delta^{13}\text{C}$ values of non-ruminants fats (*i.e.*, porcine fats) are lacking in MNB vessel residues. This suggests that different technical subsystems (Vigne, 1998) were carried out by MNB groups in processing resources from different terrestrial species. Perhaps, non-ruminant products were preferably processed without pottery (*i.e.*, by roasting, smoking, salting). Furthermore, perishable containers could have been used in order to serving roasted meat and, eventually, storing dried and/or smoked porcine products.

No evidence of processing marine resources in MNB pottery has been provided by organic residue analysis. Nevertheless, fish are attested among faunal remains of Su Mulinu Mannu (Lugliè *et al.*, forthcoming), and piles of shells were separately discarded in specific pits near the vessels deposits at Gribaia (Fanti *et al.*, 2017; Soro and Usai, 2009). In the case of Middle Neolithic in Sardinia, the faunal and pottery data could suggest a particular behaviour, *i.e.* the (occasional? seasonal?) consumption of aquatic products, apparently without using pottery vessels.

6 Concluding remarks

This study showed the fruitful application of a combined approach in addressing functional analysis of pottery, in order to recognise specific behaviours of Neolithic societies in the activities aimed at processing, consuming and storing resources, and in the way of embodying vessels within their socioeconomic systems. Six functional categories have been identified in *San Ciriaco*-MNB assemblages, where distinctive patterns of wear reflect precise habits on the use of pottery.

Our research provided evidence of dairy products in Sardinian Neolithic and underlined the importance of ruminant products in the economic systems of MNB societies (notably, in Bau Angius), also reflected in the symbolic realm by emblematic zoomorphic vessels and decorations (Lugliè, 2003). Nevertheless, inter-site dissimilarities emerge, with a stronger importance of vegetal products in Gribaia, where plant biomarkers appear in 46% of samples. These first results should be completed with additional analysis on other MNB sites to establish if this reflects an economic (perhaps, sub-regional?) diversification in the use of resources or differential preservation contexts. Placing our data in a Mediterranean perspective, the results about Sardinian MNB residues are strictly coherent with available data from Early and Middle Neolithic sites in central-western Mediterranean, showing the importance of ruminant products (Debono Spiteri *et al.*, 2016). Indeed, as in the rest of Italian sites studied thus far, the lacking of beeswax biomarkers in pottery vessels has to be highlighted (Roffet-Salque *et al.*, 2015). Contrariwise, vegetal residues in pottery vessels from central-western Mediterranean being almost unknown (Debono Spiteri *et al.*, 2016), but documented in western Slovenia (Šoberl *et al.*, 2014) and northern Africa (Dunne *et al.*, 2012, 2016), the site of Gribaia provides an exceptional direct evidence of processing plant products in Neolithic pottery vessels from this region.

Aquatic biomarkers are absent in MNB vessels, as in pottery from other sites in central-western Mediterranean (Debono Spiteri *et al.*, 2016; Salque *et al.*, 2012). This behaviour seems to be characteristic of Mediterranean Neolithic groups, which are thought to have culturally preferred terrestrial food avoiding aquatic products (Debono Spiteri and Craig, 2015). On the contrary, pottery vessels were used for processing aquatic products in several regions of northern Europe (*e.g.*, Southern Scandinavia and Baltic region: Craig *et al.*, 2011; Heron *et al.*, 2015; Isaksson and Hallgren, 2012; Oras *et al.*, 2016). Notwithstanding, in MNA and MNB sites, mollusc shells and fish are part of the faunal remains (Bignon *et al.*, 2008; Fanti *et al.*, 2017; Lugliè *et al.*, forthcoming), although their relative importance in Sardinian MN economy have to be assessed by archaeozoological analyses. Given our findings, the dissimilarity between MNB pottery contents and faunal record reflects specific behaviours and different technical and/or symbolic subsystems in the use of distinct kinds of resources (ruminant and plant foods vs. non-ruminant and marine products), with a differential integration of vessels in the activities aimed at processing, consuming and storing these products. The regional outlines and diachronic evolution of this differentiation in central-western Mediterranean deserve further investigation.

Moreover, even if data on the function of different types of vessels during Neolithic in Europe are far to be systematically known, it seems that two diverging tendencies act on cooking habits, opposing sites in which cooking vessels have a broader morphological and morphometric variability (Vieugué *et al.*, 2008, Vuković, 2011) to sites with more “specialised” vessels for cooking (Drieu *et al.*, submitted; Salque *et al.*, 2013; Šoberl *et al.*, 2014). The MNB cooking vessels from Sardinia seem to fit into this second tendency. Nevertheless, further research on the relationship among pottery morphologies, use-wear and contents is needed to outline this embryonic scenario. The behaviours linked to pottery use remain to be fully explored in a broader scale, by extending the use

of integrated approaches on the analysis of Neolithic pottery from a more consistent number of sites in Mediterranean regions, with the purpose of identifying diachronic change or continuity and cultural affinities in the use of pottery among different Neolithic groups.

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