ISSN: 2687-8402

DOI: 10.33552/OAJAA.2023.04.000597

Open Access Journal of Archaeology and Anthropology

Iris Publishers

Research Article

A Petrographic and Multidisciplinary Study of Bronze Age Ceramics in Nuragic Sardinia, Italy. A Technological and Social Overview

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Received Date: May 01, 2023

Published Date: July 25, 2023

Abstract

Focusing on the relationship between ceramic technology and social organization, this research studied 488 ceramics from eight Bronze Age settlements (1800-950 BC) in south-central Sardinia, Italy. The multidisciplinary approach proposed represents an innovation with respect to the previous studies of pottery in Sardinia, that have mainly focused on stylistic attributes, and their use in assessing chronological typology. Considering fabric heterogeneity through time, it was demonstrated how the Bronze Age potters had a widespread appreciation of similar raw materials in the region. This indicates not only a shared technological tradition but also wider community interactions at an inter-site and inter-regional level.

Indeed, the evidence that local domestic plain ceramics could have been circulated by exchange since the Final Neolithic, and throughout the Bronze Age among settlements, is quite surprising and never argued before for nuragic Sardinia. Organic residues analysis on selected coarse fabric vessels demonstrated that Nuragic people used to cook ruminant, and non-ruminant meat simmered in red and white wine; make cheese, and cream; ferment wine, beer, and different vegetal beverages; extract cuticles wax from insects, maybe, for medical use; processed animal fat, raw honey, and castor oil; use pine resins, and beeswax to reduce vessels surface permeability. The number of samples studied, and the chronological interval covered (around 850 years) makes this study the broadest Bronze Age petrographic dataset produced up to now for Sardinia. These results constitute a firm basis for future analysis of ceramics technology in the region, and the whole of the Island.

Keywords: Petrography; Domestic ceramics; Raw materials; Provenance analysis; Ceramics exchange; Social organization and networks; Organic residue analyses; Sardinia

Abbreviations

Abbreviations are used to indicate the sites studied and their chronology, such as: BM, Brunku Madugui corridor nuraghe, Middle Bronze Age (MBA).

CSC, Conca 'e Sa Cresia corridor nuraghe, Middle Bronze Age (MBA). SF, Sa Fogaia corridor nuraghe, Middle Bronze Age (MBA).

NT, Nuraghe Trobas single tower nuraghe, Middle Bronze Age (MBA). GM, Genna Maria complex nuraghe, Middle Bronze Age (MA).

OC, Ortu Comidu complex nuraghe, Late-Final Bronze Age/Final Bronze Age-Early Iron Age (L-FBA/FBA-EIA). NA, Nuraghe Arrubiu complex nuraghe, Middle Bronze-Final Bronze Age (MBA/FBA).

BA, Barumini complex nuraghe with hut village, Final Bronze Age/Early Iron Age (FBA/EIA).

PN, pre-nuragic period, including Final Neolithic rock cut tombs, Chalcolithic (?) and Early Bronze Age open-air sites.

PP, indicates plane polarized light under the petrographic microscope. PX, indicates crossed polars under the petrographic microscope.

Introduction

This research focused on the relationship between ceramic technology, and social organization studying 488 ceramics selected from eight settlements located in a micro-region of the south-central Sardinia, in the Province of Cagliari. Sardinia is the second largest island of Italy, in the central part of the Western Mediterranean basin. These settlements refer to the time span, locally called 'Nuragic Culture', starting around the Middle Bronze Age, 1800-1350 BC, and continuing through the Late Bronze Age, 1350-1150 BC to the Final Bronze Age, 1150-950 BC/Early Iron Age,950-700 BC [1-6]. Its name derives from the island's most characteristic and unique buildings-nuraghi-truncated high round towers (Figure 1) built of large blocks of local rock set without mortar in regular horizontal rows, roofed by corbelled vaults.

The growing complexity of architectural structures can be observed in the course of time. During the Middle Bronze Age (1800-1350 BC) 'corridor nuraghi' and 'single-tower nuraghi' were both present: the former (Figure 1A) consist of low platforms of dry-laid cyclopean masonry with irregular plans, interior corridors, and flat upper surfaces accessed from interior or exterior stairs. The latter (Figures 1B and 1C) have a circular room at the ground floor which is entered through a passageway increasing in height, and width as it approaches the central chamber, closed by a corbelled vault. At the ground level, there is a spiral staircase climbing within the thickness of the wall to the upper floors [7-15].

In the Late Bronze Age (1350 - 1150 BC), often regarded as the apex of nuragic civilization, great developments in settlement organization occurred. Indeed, many former corridor- and single-tower nuraghi were expanded into larger multi-towered complexes with villages of stone walled huts (Figure 1D).

The Final Bronze Age (1150 - 950 BC), and the Early Iron Age (950-700 BC) were characterized by more complex settlement patterns. New nuraghi had not been built, and villages without nuraghi became dominant [16-21]. Temples for the cult of the waters proliferated, along with larger supra-regional sanctuaries having, perhaps, the function of associating wealth, and prestige (22) with proximity to villages (Figure 1 E).

1A

1B

1C

1D

1E

Figure 1: (A) Corridor nuraghe Sa Fogaia, Siddi, Middle Bronze Age. (B) Single tower nuraghe Goni, Middle- Recent Bronze Age. (C) Example of corbelled vault, Nuraghe Piscu, Recent/Final Bronze Age. (D) Barumini complex nuraghe with huts village, Final Bronze Age/Early Iron Age. (E) Sanctuary of 'Santa Vittoria di Serri' with sacred well, and huts, Final Bronze Age/Early Iron Age.

Photographs: Fabrizio Pinna, https://www.facebook.com/BibiPinna/.

Materials and Methods

The methodology used in this study considered, under a petrographic microscope, domestic ceramic fabric variability among selected common vessel forms, such as cooking, storage, and drinking vessels. These typologies were tested using the concept of 'technological style' and challenged in terms of social organization and chronological significance. A technological style [23-24] is the outcome of repetitive, and mundane activities associated with everyday domestic life, reflecting the potters' choices in selecting and transforming the raw materials in the way they were taught to in a particular community of practice [25].

The study principal research questions aimed at delineating an economic, and social reconstruction of ceramics production, distribution, and use in the Marmilla region in South-central Sardinia (Figure 2), considering raw materials use, their possible changes, and vessels exchange through time and space.

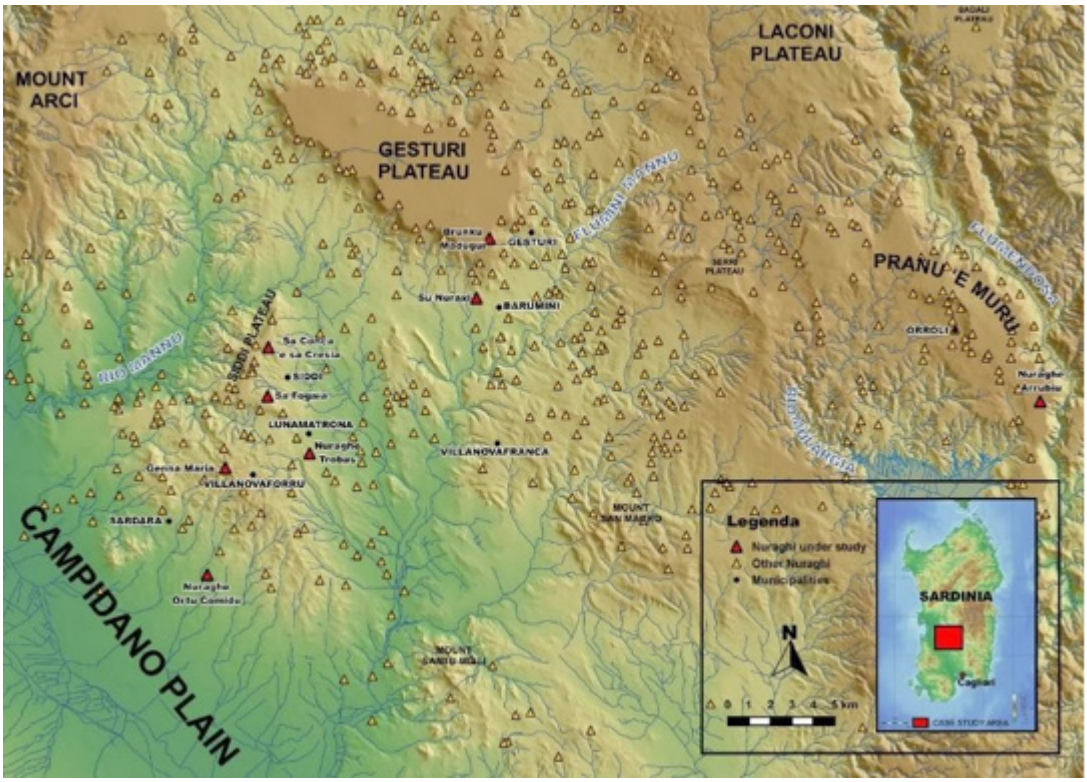


Figure 2: Map showing the nuraghi sampled as red triangles. Yellow triangles are the other nuraghi present in the area. From Gradoli 2020 [27].

The study was carried out considering:

a) Ceramic petrography, which is the systematic description of pottery materials, their compositions and organization in hand specimen, and prepared samples or thin sections, using a polarizing microscope.

b) The concept of 'chaîne opératoire', a sequence of technical and mental gestures that potters perform during the artefact manufacture, use, repair, and discard. Changes may occur at any stage of the process in response to a variety of constraints, and the same outcome can be produced in different ways, even though in presence of several functionally equivalent ways to operate, people seem to choose among those based on their cultural tradition [26].

c) The raw materials provenance study, based on the detailed knowledge of the local geology.

d) The experimental archaeology, in a laboratory and in the field.

The selected dataset and the case study area

The selected dataset was obtained by a preliminary large ceramic selection, which included all samples available for each cultural phase at each site, correlated with shape typology and granulometry. Diagnostic vessel parts, such as rims, bases, and handles with similar shapes, fabric granulometry, and possible function, were finally sampled from those first selected to undergo thin sectioning and petrographic study. This was carried out to verify whether different fabrics were used for different purposes or were preferentially associated with a special vessel shape, and to enhance the ceramic fabric variability within the site dataset.

Considering that all vessel parts recovered from an archaeological excavation are just a sample from an original but

unknown population, results and interpretations are here referred to fabric proportion occurrences in the selected dataset.

The Marmilla region was chosen as the case study area for its geographical position, which represents an intermediate zone linking the internal mountainous parts of the Island with the lowland of the Campidano plain on the one hand, and for the large presence of nuraghi of different architectural features and age, holding large quantities of pottery remains on the other hand. Ceramics were sampled (Figure 2, red triangles) from the Brunku Madugui, Sa Fogaia, and Conca e Sa Cresia corridor nuraghi (Middle Bronze Age), the single tower Nuraghe Trobas (Middle Bronze Age), and the Ortu Comidu, Genna Maria and Barumini complex nuraghi (Late Bronze Age to Early Iron Age). The nuraghe Arrubiu (Middle to Final Bronze Age) is not part of the Marmilla region but was chosen as an element for comparison with the region under study for two principal reasons: the first is its geographic setting on a basaltic plateau; the second is the presence of a great quantity of ceramics of all types and ages.

The selected sherds were described recording in a Microsoft Access database the relevant information on shape, inferred final vessel shape, firing color, surface treatment, decoration when present, signs of abrasion and use, inventory number, year of sampling, part of the site sampled, and brief description under the polarizing microscope.

Twenty samples from some Neolithic to Early Bronze Age sites of the region referred to as 'Pre-nuragic ceramics' were sampled from the Archaeological Museum at Villanovaforru for comparison to the Bronze Age fabrics.

The characterization study of the Bronze Age ceramics

The selected ceramics were characterized under a Brunel SP-300-P polarizing microscope, equipped with a Canon 1100D camera, using the method proposed by Whitbread [28]. Here, the term fabric refers to the arrangement, size, shape, frequency, and composition of components of the ceramic material, but it is also used to indicate groups of ceramics that have specific material properties in common. Characterization is, therefore, the process of defining groups or classes of similar ceramic fabrics that, combined with additional information, such as shape, decoration, possible function, and find context can help in detecting patterns of ceramic production, distribution, and use.

The fabric groups and classes identified are here denoted in the format: Group (class). Groups are based on broad geological characteristics, such as major rocks or mineral components, while classes constitute subdivisions based on secondary compositions or technological variations, such as grain size, sorting or frequency. A qualitative descriptive approach was adopted [28,29], sorting samples into fabric groups and classes by eye, and characterizing them using predefined descriptive terminology, visual estimations, and measurements. This method allowed recording of all features observed in a ceramic thin section, while incorporating significant elements of interpretation.

Following the petrographic characterization study, seven fabric groups divided into thirty-eight classes were identified from a total of 488 ceramic samples (Tables 1 and 2). The composition of the aplastic inclusions of each class is reported starting from the most frequent inclusions and continuing in diminishing frequency of occurrence.

Table 1: List of fabric groups, and classes identified. From Gradoli 2020 [27].

N.	FABRIC GROUPS	CLASSES	N. SAMPLES
1	VOLCANIC	17	207
2	SEDIMENTARY	6	116
3	PLUTONIC	6	80
4	GROG	4	37
5	PLUTONIC-METAMORPHIC	2	22
6	METAMORPHIC	2	21
7	MIXED	1	5
	TOTAL	38	488

Table 2: List of classes identified for each fabric group. From Gradoli, 2020 [27].

FABRIC GROUP		CLASS
1. VOLCANIC (V) (207 samples)	1.1	fine sand with basaltic rock (37 samples)
	1.2	weathered fine sand with weathered round basaltic rock (29 samples)
	1.3	very weathered coarse sand (25 samples)
	1.4	coarse sand with lapilli (24 samples)
	1.5	coarse sand with devitrified andesitic rock (15 samples)
	1.6	fine sand with weathered andesitic (?) rock (13 samples)
	1.7	weathered coarse sand with tuff (13 samples)
	1.8	coarse sand with andesitic rock (12 samples)
	1.9	well sorted fine sand with basaltic rock and polycrystalline quartz (8 samples)
	1.10	coarse sand with basaltic rock and porphyritic tuff (7 samples)
	1.11	coarse sand with lapilli and tuff (6 samples)
	1.12	coarse sand with porphyritic tuff (5 samples)
	1.13	weathered, quartz and plagioclase fine sand (3 samples)
	1.14	basaltic well sorted sand (3 samples)
	1.15	weathered, very fine sand (3 samples)
	1.16	fine sand with tuff (2 samples)
	1.17	weathered coarse andesitic (?) rock and tuff (2 samples)
2. SEDIMENTARY (S) (116 samples)	2.1	plagioclase and polycrystalline quartz well sorted fine sand (53 samples)
	2.2	plagioclase and quartz coarse sand (40 samples)
	2.3	plagioclase and polycrystalline quartz fine sand with rare basaltic rock (11 samples)
	2.4	plagioclase and quartz coarse sand with lapilli (6 samples)
	2.5	plagioclase and polycrystalline quartz very fine sand (4 samples)
	2.6	calcareous sand with microfossils (2 samples)
3. PLUTONIC (P)	3.1	fine sand with plutonic coarse grains (26 samples)
	3.2	coarse sand with plutonic coarse grains (21 samples)
	3.3	well sorted sand with coarse plutonic grains (21 samples)
	3.4	fine sand with rare plutonic coarse grains (10 samples)
	3.5	granitic porphyry (1 sample)
	3.6	muscovite laths (1 samples)
5. GROG (G) (37 samples)	4.1	basaltic weathered coarse sand (15 samples)
	4.2	basaltic and andesitic weathered fine sand (15 samples)
	4.3	plutonic coarse sand (5 samples)
	4.4	metamorphic coarse sand (2 sample)
6. PLUTONIC-METAMORPHIC (P-M) (22 samples)	5.1	fine sand (17 samples)
	5.2	coarse sand (4 samples)
6. METAMORPHIC (MT) (21 samples)	6.1	coarse sand (21 sample)
	6.2	very coarse sand (1 sample)
7. MIXED (MX) (5 samples)	7.1	mixed coarse sand (5 samples)

The Raw Materials Provenance Study

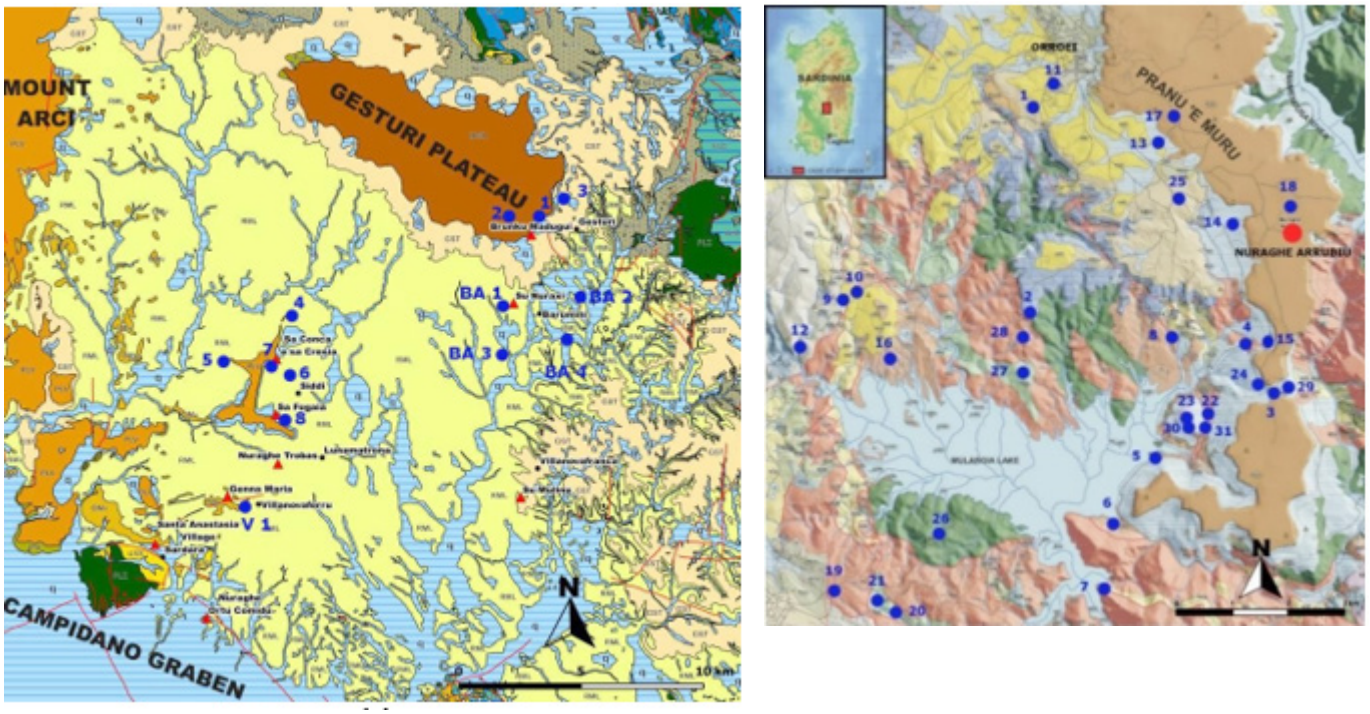
Ceramic provenance refers to the origin of the raw materials used to manufacture vessels as identified in chemical and mineralogical variation in ceramic fabrics. These studies inherit the limitations, and uncertainty of archaeological and geological provenance [30], and so are statements of probability based on 'the best analytical fit' for the samples analyzed. Petrographic analysis is effective for coarse ware in determining regions of resource

procurement because mineral inclusions may well be distinctive enough to permit identification of their parent geological rock. It is also, the most informative analytical method for differentiating local from non-local raw materials [31].

Both characterization (definition of fabric classes), and technological studies (differences in clay and temper preparation) are critical in determining the provenance of the raw materials used in ceramic manufacturing. The Marmilla region including the Gesturi, the Siddi volcanic plateau, the Barumini alluvial plain, and the volcanic plateau, and the valleys near the Nuraghe Arrubiu at Orroli (Figure 3A and B) were surface surveyed. Forty-three clays, linked to different local geological formations, were sampled (Figures 3A and B) with the aim of examining how clay sources were distributed within the modern landscape around the selected archaeological sites, assess their degree of natural variation, and which clay prehistoric potters selected most frequently, and for specific purposes.

The sampled clays were analyzed for their mineralogical composition, tested for their workability and linear shrinkage properties, fired in an electric kiln in oxidizing atmosphere at 700, 800, and 900°C, thin sectioned and compared, under the polarizing microscope, with the aplastic inclusions present in the archaeological vessels. The experimental results permitted to argue that the volcanic, metamorphic, and plutonic clays were the best materials used by Bronze Age potters to make ceramics in the region. Accessibility of raw materials from production sites is one of the most important factors in provenance studies. According to Arnold [32, 33] the distance that most potters travel to obtain their clays is 1 km or less ('preferred distance' or 'threshold distance'), while 4-5 km is the 'marginal distance', and 7 km is the 'maximum distance'.

In the Marmilla area (Figure 3A) the selected archaeological sites include, within a radius of 0-2 km, the most common raw materials present in the region, namely the volcanic rocks on the plateau, and the volcano- sedimentary formations in the lowlands. In the Orroli area (Figure 3B), the same raw materials are present, but extensive metamorphic rocks crop out around the Mulargia Lake, within a 4-5 km radius from the Nuraghe Arrubiu. This is what Arnold calls a 'marginal distance', in which the 'resource areas' of two different community of potters overlap, in this case the ones living on the plateau (of which only the Nuraghe Arrubiu is excavated) and the others living in the lowlands.



3A 3B

Figure 3: (A) Position of the twelve clay samples collected in the Marmilla area (bleu spots). Here the Pliocene volcanic formations are shown in brown color, while the volcano-sedimentary series are in yellow. (B) Position of the thirty-one clay samples collected around the Orroli-Mulargia Lake. The brown color indicates the Pliocene basaltic plateau. The other colors represent the Ordovician and Permian metamorphic rocks cropping out around the artificial lake. From Gradoli 2020 [27].

Temporal Patterns in Ceramic Production in The Dataset Related to Human Occupation in The Marmilla and Orroli Regions

Studying continuity and change in the use of raw materials improves our knowledge of the social dimensions of the past landscape, highlighting issues in resource exploitation, and detecting the range of human and environmental interactions affecting ceramic production in a region [34]. Temporal patterns in raw materials procurement are here investigated to determine whether the same resources were exploited throughout the Bronze Age for the eight nuragic settlements studied, and whether different material choices accompanied changes in settlement patterns (Table 3). The analysis is based on the results of the characterization study (seven fabric groups divided into thirty-eight classes, and 39 clays samples) to assess, under a polarizing microscope, the inclusions nature, degree of natural variation, and potters' potential choices. Imported vessels were identified as well.

Table 3: Principle trends in raw material use identified through time in the dataset. Grey lines indicate fabric classes showing continuity of use from the Pre-nuragic to the Final Bronze Age/Early Iron Age. From Gradoli 2020 [27]. Abbreviations are: PN, pre-nuragic period; BM, Brunku Madugui; SF, Sa Fogaia; CSC, Conca'e Sa Cresia, NT, Nuraghe Trobas; OC, Ortu Comidu; BA, Barumini; NA, Nuraghe Arrubiu nuraghi.

Fabric Group	Fabric Class	Pre-nuragic	Middle Bronze Age	Late Bronze Age	Final Bronze Age	Final Bronze Age / Early Iron Age	Early Iron Age	Site
1. VOLCANIC	V 1.1 Fine sand with basaltic rock	x	x	–	x	x	x	PN, BM, CSC, SF, NT, OC, BA
	V 1.2 Weathered fine sand with weathered round basaltic rock	–	x	x	x	–	–	Nuraghe Arrubiu
	V 1.3 Very weathered coarse sand	x	x		x	–	–	PN, BM, GM, NT, CSC, BA
	V 1.4 Coarse sand with lapilli	–	x	x	x	–	–	BM, BA, NA
	V 1.5 Coarse sand with devitrified andesite	x	–	x	x	x	x	PN, OC, BA, NA
	V 1.6 Fine sand with weathered andesitic? rock	–	x	–	x	–	–	BM, CSC, GM, OC, BA
	V 1.7 Weathered coarse sand with tuff	x	x	–	–	x	x	PN, CSC, NT, GM, OC, BA
	V 1.8 Coarse sand with andesitic rock	–	x	x	x	x	–	BM, SF, NT, GM, OC, BA, NA
2. SEDIMENTARY	S 2.1 Plagioclase and polycrystalline quartz well sorted fine sand	–	–	–	x	x	x	BA
	S 2.2 Plagioclase and quartz coarse sand	–	x	x	x	–	x	BM, SF, OC, BA, NA
	S 2.3 Plagioclase and polycrystalline fine sand with rare basaltic rock	–	x	–	x	x	–	NT, BA, OC
3. PLUTONIC	P 3.1 Fine sand with plutonic coarse grains	- -	x	–	x	x	x	BM, GM, NT, CSC, BA, OC, NA
	P 3.2 Coarse sand with plutonic coarse grains	x	x	–	x	x	–	PN, BM, CSC, BA, OC, NA
	P 3.3 Well sorted sand with plutonic coarse grains	- -	x	x	x	x	x	BM, GM, NT, CSC, BA, OC
	P 3.4 Fine sand with rare plutonic coarse grains	- -	x	–	x	x	–	BM, CSC, OC, BA, NA
4 GROG	G 4.1 Basaltic weathered coarse sand	–	x	x	x	–	–	BM, BA, NA
	G 4.2 Basaltic and andesitic weathered fine sand	- -	x	–	–	x	–	BM, SF, CSC, OC
5 PLUTONIC –	P-M 5.1 Mineral fine sand	- -	–	x	x	–	–	NA
	P-M 5.2 Mineral coarse sand	- -	x	–	–	–	–	NA
6 METAMORPHIC	MT 5.1 Coarse sand	- -	x	x	–	–	–	NA

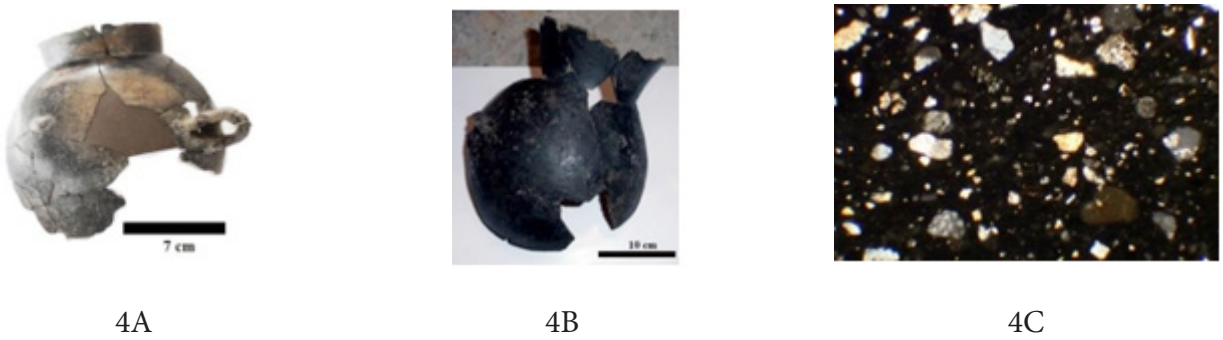
During the distinct Bronze Age cultural phases in the two areas, the regional geology probably remained unaltered, and potters' preference in exploiting the same geological resources could have been embedded, over time, in the local technological tradition producing vessels with a high degree of uniformity in raw materials.

Alternatively, the way potters exploited the two regions could have produced distinct differences in fabric composition, even when the range of geological resources was limited. Moreover, some raw materials now found within the modern landscape may not have been considered viable resources in the past, for broader social constraints, and clay access rights [34].

Grey lines in Table 3 indicate the Volcanic, and Plutonic fabric groups, and the five different fabric classes used since the Final Neolithic/Early Bronze Age, continuing to be utilized throughout the Bronze Age.

Another thirteen raw material classes (V1.2, V1.4, V1.6, V1.8, S2.2, S2.3, P3.1, P3.3, P3.4, G4.1 G4.2, P-M 5.2 and MT 5.1) appeared in the Middle Bronze Age and were used with continuity to the Final Bronze Age/Early Iron Age constituting long-lasting ceramic traditions. In examining the raw material classes use through time, a relationship with the main cultural phases of nuragic occupation can partially be detected. Spatially significant distribution (except for the Nuraghe Arrubiu region) was not evident, and fabric differences might therefore be attributed to potters' technical and personal preferences in raw materials use or restrictions in viability of specific raw materials at different times, or to imported ceramics.

Potters' preferences in raw materials show limited orientation toward specific functions, with the only exception being the Nuragic Burnished grey/black Wares, a specialized production manufactured using the Plutonic- Metamorphic group, found only at the Nuraghe Arrubiu (Figure 4). The ceramic fabrics identified are here discussed by cultural phase and trends in raw materials use.



4A 4B 4C

Figure 4: (A) Collared jar in 'Nuragic burnished grey ware' and (B) collared jar in 'Nuragic burnished black ware' from the Nuraghe Arrubiu. (C) XP, width of field is 0.85 mm. From M. G. Gradoli [27].

Neolithic/Eneolithic (?)/Early Bronze Age

For the pre-nuragic period no excavation was carried out in the two areas under study, and the few ceramics sampled at the Villanovaforru Museum (Figure 2) were, for the most part, unclassified vessel sherds; neither is any archaeological information available relating to the passage from the Early to the Middle Bronze Age. Nevertheless, these few pre-nuragic fabric groups indicate a broad trend in raw materials use in the Marmilla region, where sparse and intermittent occupation probably occurred [15] even if we have no secure information about it.

Middle Bronze Age

From a chronological viewpoint, this period represents the beginning of the Nuragic Culture on the island during which corridor nuraghi, and single tower nuraghi were built, surrounded by few rectangular [35] and/or circular huts. This settlement organization is reflected in the use of a wider range of raw materials as different parts of the landscape were progressively inhabited, in comparison with the pre-nuragic period.

Among the seventeen classes of the Volcanic group, seven (V 1.1, V1.2, V1.3, V1.4, V1.6, V1.7, and V1.8) dominate the sample of pans, platters, bowls, jars, and cups. Among the five classes of the Sedimentary group, two were the most represented (S2.1 and S2.2) in bowls and jars. The Plutonic classes P 3.1, 3.2, 3.3 and 3.4 were also used to manufacture pans, platters, bowls, jars, and cups even though there are no Plutonic rocks in the regions [36], thus indicating possible imports into the area. The Grog group includes fabrics with volcanic, and plutonic inclusions; some bowls and jars of the Plutonic group were rock tempered.

The Metamorphic group was only found at the Nuraghe Arrubiu, used to make bowls, jars, cups, and two imported samples in the Marmilla region, where there are no metamorphic rocks [36]. This evidence might indicate that social relationships within, and between sites of the area were fully developed from the Middle Bronze Age on. Assuming 25 years for a generation, around 20 generations of people might have been manufacturing these vessels, which do not represent contemporary alternatives but possible variations in practices over time within the Middle Bronze Age, which lasted around 450 years [2].

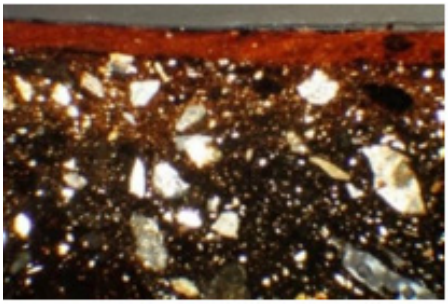
Preferential selection of resources in the Marmilla region can be seen in the recurrent use of the Volcanic Group, Class V1.1 fine sand with basaltic rock at the Conca 'e Sa Cresia, Brunku Madugui,

and Sa Fogaia corridor nuraghi and Class V1.3 very weathered coarse sand at Conca 'e Sa Cresia, Brunku Madugui, Genna Maria, Nuraghe Trobas used to make pans, platters, bowls, jars, and cups. The Plutonic group, Classes P3.1 fine sand with plutonic coarse grains, and P3.3 well sorted sand with coarse plutonic grains were used to manufacture pans, platters, bowls, jars, and cups at Conca 'e Sa Cresia, Brunku Madugui, Genna Maria, and Nuraghe Trobas sites. This means that mainly the volcanic clays, sometimes grog tempered, were those most preferred for manufacturing all the different domestic vessels in the Marmilla region. Plutonic fabrics were, instead, imported. At the Nuraghe Arrubiu, other local raw materials were used according to the geological nature of the territory, that might represent different technological styles, indicating greater complexity, and interaction in this area, though it may be difficult to fully interpret it within the confines of the dataset.

Late Bronze Age

The Late Bronze Age corresponds to the expansion phase of the Nuragic Culture. The progressive addition of ancillary towers to the first nucleated settlements is attributed to a demographic increase, perhaps linked to a rapid expansion in agricultural activity in the lowlands, and alluvial plains of the region. This is not clearly reflected in the dataset in terms of number of vessels, which come only from the complex nuraghi Ortu Comidu, and Arrubiu, but it can be appreciated in the higher number of raw material classes used. In the former, the excavators [37] did not separate the Late from the Final Bronze Age, but preferential selection of local resources is evident in the use of the Volcanic Group, Classes V1.5 *coarse sand with devitrified andesitic rock, and V1.6 fine sand with weathered andesitic (?) rock.*

At the Nuraghe Arrubiu new vessel shapes, and raw material classes were used showing how this expansion phase of the Nuragic Culture intensified movements in the landscape for different activities, which brought raw materials located in other parts of the region into use. Here, the use of the local Plutonic-Metamorphic group increased for bowls, jars and cups showing how, during the expansion phase of the nuragic society, these shiny- looking vessels (Figure 5) might have been very appreciated.



5A 5B

Figure 5: Large bowl from the Nuraghe Arrubiu, Final Bronze Age, manufactured using metamorphic sand. XP, width of field is 0.85 mm. A red slip, covered by burnt material, is visible on the external surface of the vessel. Photograph and photomicrograph: M. G. Gradoli [27].

Final Bronze Age/Early Iron Age

The Final Bronze Age continued to follow ceramic traditions from the previous cultural phases at the Nuraghe Arrubiu, Barumini, and Ortu Comidu, especially during the second part of the Final Bronze Age, considered as the crisis period before final collapse of the Nuragic Culture. At the Nuraghe Arrubiu all the raw material classes used during the Late Bronze Age were still in use but in the dataset more pans, platters, bowls, jars, cups, and necked vessels were manufactured from Class S 2.2 weathered fine sand with weathered rounded basaltic rock, showing how ceramic traditions continued with an expansion trend. Moreover, a new vessel shape- the askos-appeared, made from raw materials that were previously used (Plutonic-Metamorphic, Plutonic, and Sedimentary).

At Barumini site during the Final Bronze Age, principal towers and huts were all still in use to judge by the ceramics analyzed. The Sedimentary group was the most used raw material for cooking, storing, drinking, and lighting. The Volcanic, and Plutonic Groups, the latter imported since there are no plutonic rocks in the Marmilla region [36], were also used in minor quantities for bowls, jars, necked vessels, cups, and askoi.

At the Ortu Comidu nuraghe even if vessel shapes are unknown (52 thin sections were provided for re- examination by Prof. Paul Nicholson, Cardiff University), a preferential use in raw materials is attested for the Volcanic, and Plutonic Groups.

In the Final Bronze Age/Early Iron Age the raw materials used were the same as the previous period, except for the presence of the Sedimentary Group, which is missing from the dataset during the other periods, perhaps due to the sampling methodology adopted. The same ceramic categories at the Nuraghe Arrubiu, were manufactured using the Metamorphic (Figure 6), and the Sedimentary (plagioclase and quartz coarse sand) classes for vessels that look different in manufacture, surfaces treatment, and firing atmosphere. They might have been easily recognized by the people who might have been exchanging vessels and other commodities during their daily, and seasonal movements across the landscape.

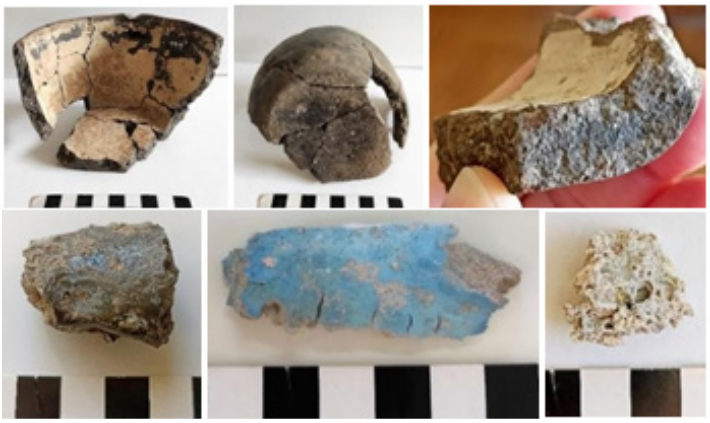


Figure 6: The crucible, and the other vitreous materials analyzed from the Nuraghe Conca 'e Sa Cresia. Photographs: M. G. Gradoli [41].

Results and Discussion

In this study, the main research questions posed were related to patterns of pottery production, consumption, and exchange at an inter-site level among the archaeological settlements in the Marmilla region, and the Nuraghe Arrubiu, in central-south Sardinia. The main results are here summarized and discussed, considering:

Raw material selection and pottery production

The characterization study demonstrated that in the Marmilla region similar local raw materials of volcanic and volcano-sedimentary origin were used in the sites studied. Plutonic, and some metamorphic fabric vessels were imported.

The practice of rock, and grog tempering was used from pre-nuragic times throughout the Bronze Age. Two types of plutonic temper were used:

a) angular to subrounded inclusions for bowls, jars, and cups at the Barumini, Genna Maria, and Conca 'e Sa Cresia nuraghi;

b) rounded inclusions, perhaps taken from a stream bed, from the Final Neolithic throughout the Bronze Age for cooking, storage, and drinking vessels. These two non-local temper types, at the same sites, highlight inter-regional ceramic exchange networks among different parts of the island.

The grog tempered vessels were used for cooking, and storage. Since these fabrics contain coarse rocks and mineral grains, the addition of grog would probably have made no significant difference to the physical properties of the clay or fired ceramic, leading one to think that it was a social choice rather than a technological necessity. By way of contrast, at the Barumini site, the choice of tempering or acquiring coarse plutonic fabric ceramics was, perhaps, a necessity due to geological constrains (presence of fine alluvial sand) for producing cooking vessels able to better counteract thermal shock over the fire. Standardization and specialization were not observed within the region where pottery production appears to have been small-scale, and probably intended for internal consumption.

Technological characterization considering vessel macroscopic and typological attributes.

From observation of the ceramics by naked eye and the lack of any wheel riling, these vessels seem to have been hand-made. Under the polarizing microscope possible coil joints, in a few samples, were detected by the concentrically arranged distribution of inclusions.

A domestic way of production [38], perhaps subsidiary to other activities such as farming, and linked to several episodes of production throughout the use of the site, could be proposed. Since no kilns have been found during excavations in Bronze Age Sardinia, vessels might have been fired in pits or open bonfires which, unfortunately, rarely leave traces in the archaeological record [38]. Firing conditions ranged from oxidizing to reducing atmospheres, showing how potters were able to make specific color choices. Notwithstanding this, around one third of the sampled vessels were fired in mixed oxidizing-reducing conditions which may reflect less control over firing atmospheres or that the latter were not the potters' primary concern.

Cooking pots (pans, platters, and coarse fabric hemi-spherical cups) from the Middle Bronze Age on, always have corrugated external surfaces, thought to be better at transmitting heat but also to be easily grasped and moved around [34], and burnished internal surfaces to reduce permeability. In the Late-Final Bronze Age, more effective heat-transmitting thin-walled cooking pots appeared, having burnished internal, and external surfaces.

Carinated and simple bowls used for cooking, consumption, and food transformation, such as wine, beer fermentation, and dairy products [39, 40], also have well burnished internal, and external surfaces to reduce permeability. Sometimes, they have carbon-coated external surfaces which suggest the use of firing conditions (bonfires) in which the fuel was in contact with the pottery or the addition of fresh vegetal materials producing carbon particles which, sealing the pores, reduced permeability [34].

Jars and cups, used to contain and serve liquids, have well-burnished external surfaces in the former case and well-burnished

external and internal surfaces in the latter. Whereas askoi and pitchers, also used to serve liquids, have well burnished external surfaces, and plain internal walls, due to the necessity of having a porous surface which could contribute to keeping the liquid inside of them fresh [34].

In the Marmilla region, vessels fired in a reducing atmosphere to produce grey and black carbon-coated surfaces were used since the Middle Bronze Age and were not linked to any special type of raw material nor vessel shape. At the Nuraghe Arrubiu, on the contrary, these vessels were linked to some geological localized clays, producing the 'Nuragic Burnished Grey and Black Wares' (Figure 4).

In the Marmilla region, at the corridor nuraghe Conca'e Sa Cresia, Middle Bronze Age, the only non-domestic vessel identified during the study was a coarse-ware crucible, lined in the internal surface by a whitish layer (Figure 6) which analyzed by SEM-EDS at the University of Cagliari, showed the presence of quartz, Na and K alkali, Ca, P, and Cu. Other nineteen crucible sherds, one greenish glass slag, a turquoise vitrified animal jaw, glass porous white material, and powder were analyzed as well. They come from the excavation of a round structure closed by a wall, in which quartz pebbles and pestles, granitic querns, animal bones, and a small bronze rod were recovered in association. This might be the first time that a primary glass production is identified in Bronze Age Sardinia [41].

Fabric variation according to functional vessel categories

The three categories of ceramics considered, cooking, storage and drinking vessels, reflect the same trends in raw materials use, and technological characteristics throughout the Bronze Age. Cooking vessels appear to have been manufactured locally using mostly the Volcanic group fabrics from the Middle to the Final Bronze Age/Early Iron Age. During the Late and Final Bronze Age, the expansion, and the crisis period of the Nuragic Culture, changes in shape of the cooking pots but not in raw material occurred at the Barumini site. Indeed, even if the Volcanic raw materials were still used for pottery production, the use of the Sedimentary classes for pans, platters, and cooking pots might have been a conscious choice of alternative good raw materials for the same vessel types, and the new forms alike. Alternatively, they could represent the establishment of additional pottery production sites or imported ceramics from neighboring settlements.

In social terms the lack of change in fabrics might indicate that during the transitional and crisis periods, potters continued their day-to-day living, and any social change does not appear to be reflected in pottery manufacturing. At the Barumini nuraghe, in the Final Bronze Age, pitchers and askoi were made of the Sedimentary, and the imported Plutonic fabric groups, while richly decorated lamps with impressed circles and crossed lines continued to be produced using the same raw materials to the Early Iron Age. Thus, during the full crisis of the Nuragic Culture, at the Barumini site, instead of having a drastic reduction of pottery production, day-to day life in ceramic terms, continued unchanged.

Provenance and vessel function over time

From the provenance analysis it seems that there were no appreciable changes in raw materials provenance through time. New shapes were introduced passing from the Middle to the Late Bronze Age, reflecting a demographic increase during the expansion phase of the Nuragic Culture, which brought to intensification of culinary practices, and new vessel functions into use. According with this dataset, a limited set of vessels were in use, such as pans, platters, jars, bowls, and cups. Three types of new vessel shapes, previously unknown, appear from the Late Bronze Age, and continue to be used to the Final Bronze Age a) thin-walled deep cooking pots b) large necked and storage vessels c) pitchers, askoi, grey/black bowls, and cups.

At the Barumini site, in the Final Bronze Age, new shapes appear too: d) thin-walled pans and platters, perhaps used for oven cooking for which a minor resistance to thermal shock is needed or as serving plates. Twenty-three coarse cooking vessels from the Nuraghe Arrubiu were selected among those studied under the petrographic microscope and analyzed by Gas Chromatography and Mass Spectrometry to identify soluble biomarkers (fat, oil, wax, resin, and vegetables), and an acid-catalyzed extraction to detect the insoluble biomarkers (fruit, wine, and polymerized tannins). Results were quite unexpected considering previous local authors' interpretations. It was, thus, demonstrated [39,40] that people inhabiting the Nuraghe Arrubiu used to:

a) Cook ruminant, and non-ruminant meat simmered in red, and white wine in pans, platters, and large bowls.

b) Ferment wine, beer, and different vegetal beverages in large bowls.

c) Make cheese and cream from boiling milk in large carinated platters (Figure 7).

d) Cook insects for extracting cuticles wax, maybe, for medical use.

e) Processed animal fat.

f) Collected raw honey.

g) Use pine resins, and beeswax to reduce vessels surface permeability.

h) Extract castor oil, even though its real use during Bronze Age is still unknown.

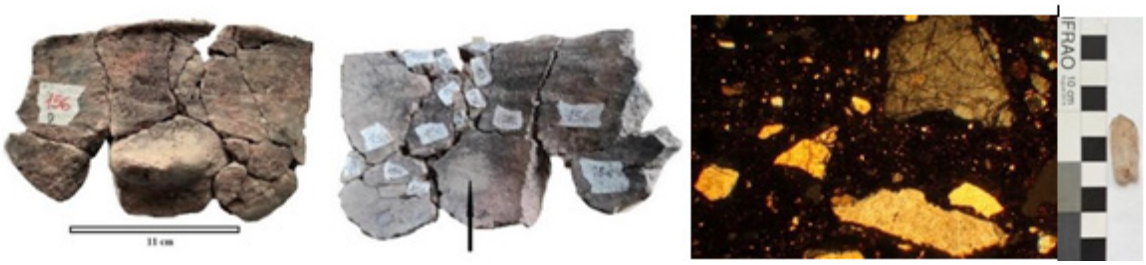


Figure 7: Large carinated platter used to prepare dairy products, part of the Plutonic Group, showing angular quartz crystals added intentionally as temper (see quartz crystal found in the main hearth, mixed with other ceramics sherds). Black arrow indicates where the powder for organic residues analysis was sampled. Photographs: M. G. Gradoli [39, 40].

Acknowledgment

None.

Conflict of Interest

No conflict of interest.

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