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RESEARCH

Intensified exploitation of animal products in the Mediterranean Copper Age: isotopic evidence from Scaba 'e Arriu (Sardinia)

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Abstract
In this paper, dietary patterns are reconstructed across two phases represented at the Copper Age of Scaba 'e Arriu (Sardinia, Italy) via isotopic analysis of human and animal skeletal remains. Collagen carbon, nitrogen, and bioapatite carbon, and oxygen isotopes were used to infer diet, economic practices, and possibly different climatic conditions. Differential management of cattle, sheep/goats, and pigs was detected, with scarce animal products in the human diet in the Early Copper Age, followed by an increase in animal products identifiable in herbivore livestock, coincident with more rainy conditions in the Late Copper Age. Dietary information was then considered in light of the climatic periods already known for the period and compatible with the data presented. The study's outcome indicates generally sedentary and endogamous groups with only a few outliers in both phases.

Keywords Stable isotopes · Paleodiet · Animal management · Paleoclimate · Mediterranean

Introduction

Sardinian prehistory has attracted scholars for its monumental aspects, centered in the rock-carved tombs during the Neolithic and Copper Age (ca. 4200–2500 BC) and in the stone towers known as *nuraghi* in the Bronze Age (ca. 1700–1100 BC). Such a strong perception has led to the widespread use of the terms Nuragic and Pre-Nuragic to define two periods, based on the inception of the stone towers building tradition (Lilliu 1988; Webster 2016), with Pre-Nuragic encompassing several distinct cultural aspects from the Early Neolithic through the Early-Middle Bronze Age (ca. 5500–1700 BC). Much less is known, and much less has been investigated, of the economic practices and complex interaction between human groups and the natural and cultural landscape constituting the physical and social coordinates of their daily lives. Overall patterns of resource exploitation recorded up to the Bronze Age in Sardinia can be described as fully within the boundaries of general Neolithic tradition as concerns plants (Ucchesu et al. 2014) and animal species (Wilkens 2012) essential for daily subsistence, with some variation in relative proportions but within a remarkably consistent pool of resources that changed substantially only in the Iron Age. Among the notable facts highlighted by stable isotopy in the last two decades, it is essential to underline that the Neolithization process effectively led to the marginalization of marine resources in the Mediterranean (Craig et al. 2006; Richards 2003; Richards et al. 2003), and Sardinia, where this occurred ca. 5500 BC, was no exception (Lai et al. 2014; Lai 2016). Therefore, the relevant questions under the subsistence umbrella regard mainly the proportion of vegetal and animal resources, with all their social, cultural, and health implications, and the occurrence of the so-called secondary products revolution elements (Sherratt 1983). The latter have been shown not to

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co-occur but to be adopted step-wise and in varying degrees of intensity in the different components (Evershed et al. 2008; Greenfield 2010; Sherratt 1983).

Several other social aspects intersect in complex ways with practices such as plowing, grazing, milking, manuring, transporting, and wool shearing: the making of individual and collective identities and the relationships among them, involving gender, age, ethnicity, mobility, and social standing. The 3rd millennium BC in the Central-Western Mediterranean has been recognized as a period of heightened residential mobility (Furholt 2020; Price et al. 1998, 2004), accompanied by the gradual, patchy rise of generalized sources of authority and prestige through wealth accumulation and metals, although in diverse and experimental ways (Beck 2020; Costa Caramé et al. 2010; Waterman et al. 2014, 2016b). An increasingly distinct and uneven gender definition (Robb 1994) took shape, which fits local evidence (Hayden 1998). A novel emphasis on highlands has been documented (Melis 2000), likely connected with the use of marginal lands for grazing or farming, with continued use of collective burials, which suggests the absence or the disguise of intense social differentiation (Cámara Serrano and Spanedda 2002). The analysis of faunal remains has shown some incipient evidence for older bovines, pointing to varying degrees of utilization of their labor force (Lai et al. 2011; Wilkens 2012).

On the background of these processes are climatic conditions, which BC underwent profound changes in the 3rd millennium, making this fundamental to understanding paleoecology and historical developments in the Mediterranean. During this period, the present-day Mediterranean climatic pattern was established, with drier overall conditions, sharper rainfall seasonality, and summer droughts (Magri 1997, 1999; Magri and Sadori 1995; Ramrath et al. 2000; Tuccimei et al. 2003; Zielhofer et al. 2004), which interact with human practices leading to the establishment of plants that had been confined to refugia during the last glacial period and spread into the Corsica-Sardinia landmass (Lumaret et al. 2002; Reille 1992). Such climatic changes appear independent of human activities and are connected to the intensity of the westerlies that bring rain to the Mediterranean (Damnati 2000; Magny and Haas 2004; Weiss 1997). This long-term drier trend can also be articulated into two peaks separated by milder conditions (Jalut et al. 2000). The first, around 2900–2700 BC, corresponds to the sudden worsening identified in Tunisia (Zielhofer et al. 2004). The second, around 2300–2100 BC, is indicated by multiple proxies in the Western Mediterranean (Giraudi 2004; Magny et al. 2002; Rimbu et al. 2004) and seems correlated to evidence across the Northern hemisphere (Dalfes et al. 1997). These phases in Sardinia seem to coincide with radical shifts in settlement patterns and material culture. Stone architecture, new ceramic styles, and new burial rituals appear after the first event (Moravetti 2009; Webster and Webster 2017: 76–111), and the end of village life follows the second event. At Scaba ’e Arriu, the Early Copper Age phase (ECA hereafter: ca. 3400–2600 BC) overlaps with the first dry peak, the Late Copper Age phase (LCA hereafter: ca. 2700–2350 BC) with milder, wetter conditions.

Questions addressed in this study are as follows: (i) Was there was any dietary variation across the two phases? (ii) How can we describe it? (iii) Is there any evidence for climate change? (iv) How do these factors fit the overall evidence from the site toward a comprehensive understanding of economic dynamics? With these aims, stable isotopic analyses were applied to the bone remains from the burial at Scaba ’e Arriu (Siddi, Sardinia).

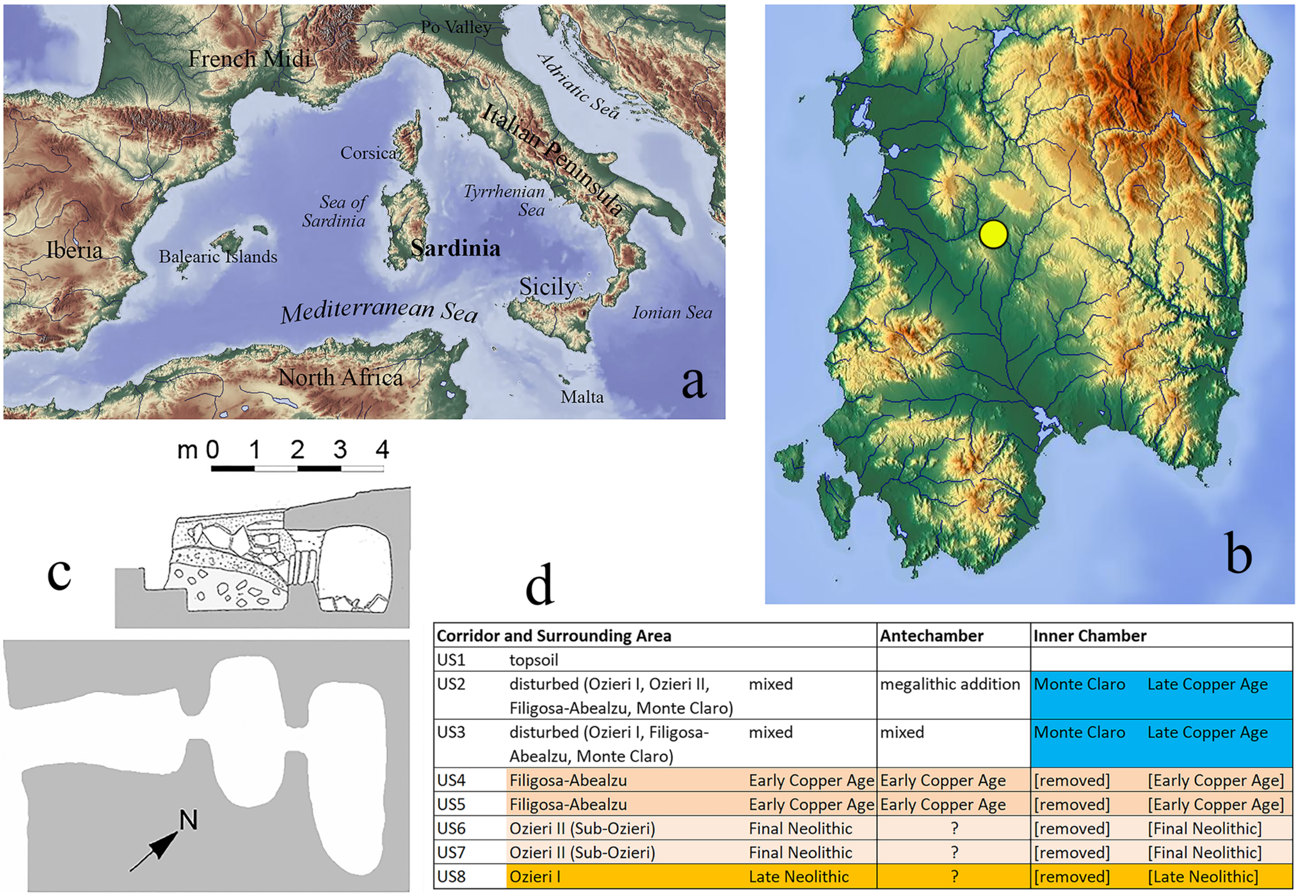
Archaeological context

The site of Scaba ’e Arriu lies at 200 m. a.s.l., approximately 60 km from the South coast and 30 from the West coast of Sardinia. It consists of a tomb carved in the local marly sandstone between a hilly landscape to the South and East and a narrow and elongated basaltic plateau to the West, from which small seasonal streams flow. The fertility of the soils in a radius of over 20 km made this area historically dedicated to cereal cultivation.

The tomb is articulated into the actual burial room and a small antechamber, preceded by a corridor/entryway. In the Late Copper Age (LCA hereafter: ca. 2700–2350 BC), the antechamber, whose roof had collapsed, was turned into a passageway flanked by upright slabs, after the clearing of earlier human remains from the chamber (see Fig. 1). Such slabs were laid on top of layers of soil, stones, animal bones, and human bones from earlier burials. The stratigraphy in the corridor and the surrounding area includes two thick layers (US4 and US5) characterized by human and animal bones, and by Early Copper Age (ECA hereafter: ca. 3400–2600 BC) cultural materials, resulting from ritual activity (Ragucci and Usai 1999; Usai 1998) and/or from emptying the earlier remains and grave goods. Thinner lower layers yielded Neolithic pottery dating to the early 4th millennium BC. The two main phases, the subject of this study, were radiocarbon dated (Lai 2009) (Table 1).

Preliminary averages of the isotopic values have been presented previously (Lai et al. 2011; Usai et al. 2011). Additional radiocarbon dates are now available (Olivieri et al. 2017), and analyses concerning pathologies and cross-sectional geometry of long bones have also been carried out (Chilleri et al. 2012; Murgia et al. 2021, 2020; Parkinson 2019; Parkinson et al. 2018). All isotopic values are presented here, with new data from FTIR measurements on bioapatite.

The two phases investigated are Filigosa (ECA, US4 and US5), dating to the early 3rd mill. BC, Monte Claro (LCA, inner chamber), mid-to-late 3rd mill. BC. The radiocarbon dates from the University of Arizona, Beta Analytics, and



Corridor and Surrounding Area			Antechamber	Inner Chamber	
US1	topsoil				
US2	disturbed (Ozieri I, Ozieri II, Filigosa-Abealzu, Monte Claro)	mixed	megalithic addition	Monte Claro	Late Copper Age
US3	disturbed (Ozieri I, Filigosa-Abealzu, Monte Claro)	mixed	mixed	Monte Claro	Late Copper Age
US4	Filigosa-Abealzu	Early Copper Age	Early Copper Age	[removed]	[Early Copper Age]
US5	Filigosa-Abealzu	Early Copper Age	Early Copper Age	[removed]	[Early Copper Age]
US6	Ozieri II (Sub-Ozieri)	Final Neolithic	?	[removed]	[Final Neolithic]
US7	Ozieri II (Sub-Ozieri)	Final Neolithic	?	[removed]	[Final Neolithic]
US8	Ozieri I	Late Neolithic	?	[removed]	[Late Neolithic]

Fig. 1 Top left (**a**): Sardinia in the Mediterranean. Top right (**b**): Scaba 'e Arriu in Sardinia—both elaborated based on maps from maps-for-free.com. Bottom left (**c**): section and plan of the rock-carved burial (elaboration L. Lai, permission from MiBAC – Soprintendenza Archeologia, Belle Arti e Paesaggio città metropolitana di Cagliari, provincie di Oristano e Sud Sardegna): left to right, the terminal part of the corridor and the antechamber, which together with the whole surrounding area contained the animal and human remains from the Filigosa phase (early 3rd mill. BC), and further right, the burial chamber with the remains from phase Monte Claro (mid-to-late 3rd mill. BC). Bottom right (**d**): outline of stratigraphy in the different areas

the University of Heidelberg agree on this overall chronology (Table 1, Fig. 2), corroborating the stratigraphic and behavioral break recorded in burial depositions. The clearing of the tomb chamber and the addition of the slabs in the antechamber from previous remains occurred between them.

Materials and methods

A total of 46 bone samples were analyzed, all except one representing different individuals: 15 humans and 18 animals from the outer corridor and surrounding area (ECA phase, except two animal specimens from the Neolithic layers) and 13 humans from the inner chamber (LCA phase). Human sample selection, aiming to optimize data on sex and age, targeted cranial and pelvic bones. No substantial systematic difference is expected between these elements (Fahy et al. 2017). Hydrological regimes must have been different across the site, with the former more exposed to rainwater but perhaps protected by soil and the latter protected from direct rainwater. This suggests different microenvironmental and taphonomic conditions for the two assemblages, which need to be considered in assessing signal preservation in bioapatite (Lee-Thorp and Sponheimer 2003; Wang and Cerling 1994). The ECA and LCA human remains had a similar taphonomic history for the first few hundred years after deposition but a different one for the last four millennia.

The animal remains, including *Bos taurus*, *Ovis aries/Capra hircus*, *Sus scrofa domesticus/ferus*, and *Canis familiaris*, residues of ritual meals or ritual offerings (Usai et al. 2011), appear to have been found in layers US5 and US6 in the antechamber, and US4 and US5 in the corridor and in the area facing it and surrounding it, parallel to a similar ritual elsewhere (Cocco and Usai 1988; Lai et al. 2017), but mixed with human remains, which may be the residue of special ritual activities or more likely of the clearing carried

Table 1 Radiocarbon dates from Scaba ’e Arriu (Siddi, Sardinia)

# excav./lab	Stratigraphic context	Cultural phase	USF lab. #	Dating lab. #	Date BP ± error [δ^{13}C ‰]	Range years cal BC	Prob. 95.4%	Range years cal BC	Prob. %
						Unmodeled		Modeled	
	Start phase							3079–2692 BC	(97.0%)
[SDD 83]	Outer corridor, Sq.V-South, cm − 105/ − 112 [Filig.Ab, US5]	ECA (Filigosa)		Beta- ?	?	2895–2485 BC			
4151	Outer corridor, sq. V-Northeast, cm − 95 [Filig.Ab, US5]	ECA (Filigosa)	7020	AA-72793	4278 ± 42 [− 19.3]	3016–2704 BC 3016–2862 BC 2804–2756 BC 2720–2704 BC	(84.6%) (9.1%) (1.7%)	2932–2675 BC	(99.6%)
6795	Outer corridor, sq. IXa-South-west, cm − 115/ − 145 [Filig.Ab, US5]	ECA (Filigosa)	6995	AA-64828	4202 ± 45 [− 19.8]	2902–2829 BC 2824–2662 BC 2652–2632 BC	(27.7%) (64.9%) (2.9%)	2901–2677 BC	(99.7%)
7686	Outer corridor, sq. 1-East, cm − 95/ − 110 [Filig.Ab, US5]	ECA (Filigosa)	7001	MAMS-39529	4128 ± 31 [− 23.6]	2870–2800 BC 2779–2580 BC	(27.7%) (67.8%)	2877–2674 BC	(99.5%)
	End phase							2867–2620 BC	(99.7%)
	Start phase							2755–2506 BC	(99.8%)
cr.b = JK2832	Inner chamber, cm -180	LCA (Monte Claro)	7003	MAMS-26890	4082 ± 23 [− 16.6]	2848–2811 BC 2744–2729 BC 2696–2568 BC 2524–2497 BC	(13.1%) (2.5%) (73.0%) (6.9%)	2667–2496 BC	(99.9%)
cr.8003	Inner chamber, inside situla 3	LCA (Monte Claro)	7012	AA-64829	3989 ± 41 [− 20.1]	2624–2432 BC 2426–2402 BC 2380–2348 BC	(89.6%) (2.5%) (3.3%)	2631–2461 BC	(99.5%)
								2651–2260 BC	(97.7%)

USF lab numbers refer to the University of South Florida Archaeological Science Laboratory. JK refers to Johannes Krause’s batch number (Max Planck Institute, Germany). *Beta*, Beta Analytics, Miami, FL; *AA*, University of Arizona, AZ; *MAMS*, University of Heidelberg, Germany. The Beta Analytics date for which only the calibrated range is provided is cited as such (Ragucci and Usai 1999)

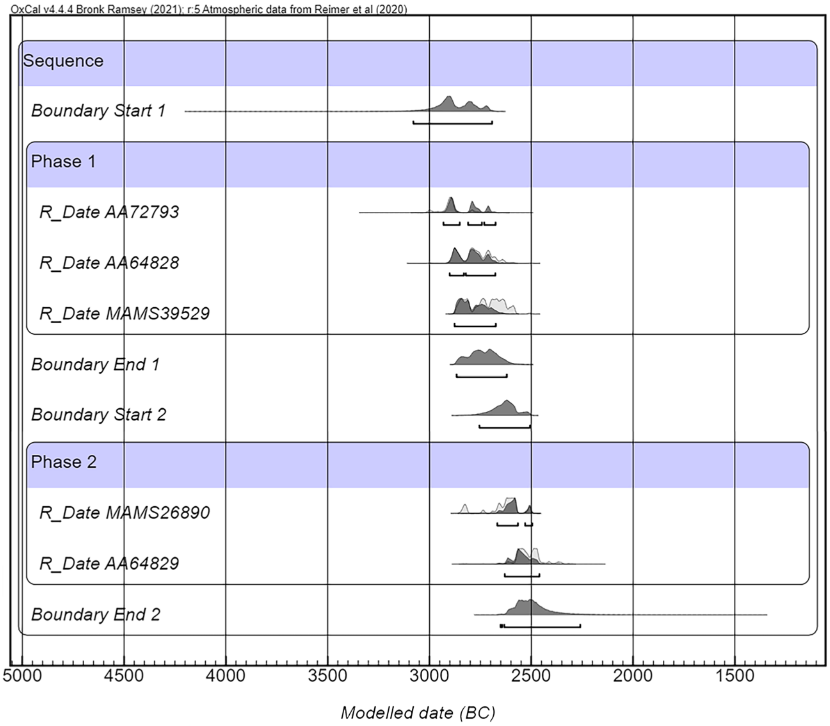


Fig. 2 Oxcal-generated chart of calibrated radiocarbon dates from Scaba 'e Arriu (see Table 1), both unmodelled (black filled) and modeled (grey filled). Raw dates (BP) are from three different laboratories (Lai 2008; Olivieri et al. 2017; Ragucci and Usai 1999), and the two phases were modeled according to evidence of a hiatus between them, with distinct end and start

out later. Therefore, their taphonomic history is expected to be consistent with the contemporary human remains after being cleared out, followed by soil accumulation. Two specimens, *Prolagus sardus* (ochotonid endemic to Sardinia and Corsica, now extinct) and *Vulpes vulpes*, are from levels compatible with the Neolithic layer US8. Since they are burrowers, they may be intrusive, but they have been included to strengthen the local faunal baseline.

To extract collagen, ca. 1 g of bone per individual was physically cleaned, ultrasonicated, and dried. Preparation (Tykot 2004) followed an established procedure (Ambrose 1990): humic acid contaminants were removed by soaking in 50 mL of 0.1 mol/L NaOH for ~ 24 h. Then, collagen was extracted by soaking in 50 mL of 2% HCl in two or more ~ 24-h baths, based on need. If necessary, samples were cut into small pieces to help the solution permeate the tissue. A further ~ 24-h bath in NaOH removes any contaminants not exposed to the reaction in the whole bone. Samples were finally soaked for ~ 24 h in 50 mL of a methanol-chloroform-distilled water solution (proportion 2:1:0.8) to remove lipids—a step that has consequences for results comparability (Liden et al. 1995). Samples were rinsed at every change of reagent. The extracted pellets were dried overnight at ~ 65 °C. Two replicates per sample were weighed into tin capsules and analyzed in continuous-flow mode with a Carlo-Erba 2500 Series II CHN analyzer, coupled with a Thermo Finnigan Delta + XL stable isotope ratio mass spectrometer, with precision (2σ) better than ± 0.3‰ for δ^{15}N and ± 0.2‰ for δ^{13}C, located at the Paleolab, St. Petersburg campus, University of South Florida.

To isolate the bioapatite carbonate (phosphate can also be extracted from bioapatite), ~ 10 mg of bone powder was treated with a ~ 72-h bath in 1.5 mL of 2% sodium hypochlorite to dissolve the organic portion. Non-structural carbonate was removed by soaking the sample for ~ 24 h in a 1.0 mol/L buffered acetic acid/sodium acetate solution. While preparation was ongoing, new studies showed that soaking times of ~ 4 h in less concentrated acetic acid (0.1 M) are sufficient and even better to prevent recrystallization, which introduces a possible differential fractionation (Berna et al. 2004; Garvie-Lok et al. 2004: 771–775; see also Nielsen-Marsh and Hedges 2000b; Zazzo and Saliège 2011). However, changing preparation times on route was considered less beneficial vs. losing comparability within the dataset, so the same method was employed for all samples. Later research appears to reach inconclusive results: short acid pretreatments may be unable to remove authigenic carbonate (Zazzo 2014), but long pretreatments in enamel may alter the isotopic signature significantly (Skippington et al. 2019), to the point that no pretreatment has more recently been suggested as potentially preferable (Pellegrini and Snoeck 2016; Snoeck and Pellegrini 2015). In any case, attention was paid to consistency with soaking times to ensure comparability (Garvie-Lok et al. 2004; Grimes and Pellegrini 2013; Koch et al. 1997; Lee-Thorp and Sponheimer 2003). One milligram per sample of the resulting bioapatite powder was analyzed on a Thermo Finnigan Delta + XL mass spectrometer, in dual-inlet configuration, equipped with a Kiel III individual acid bath carbonate system, with precision (2σ) better than ± 0.04‰ for $\delta^{13}C$ and ± 0.06‰ for $\delta^{18}O$.

Bioapatite has a specific turnover rate, estimated to be slightly faster than collagen, in the order of several years (Hedges et al. 2007). All macronutrients contribute to its synthesis, which makes it a unique proxy for overall diet, unlike collagen which records mainly the protein portion (Ambrose 2000; Jim et al. 2004; Tieszen and Fagre 1993), and unlike tooth enamel, which derives from all macronutrients but only during the few years of formation for each tooth type (Koch et al. 2009; Reid and Dean 2006). Therefore, considering that in the Western Mediterranean context, between the Mesolithic and the Bronze Age, there were no nutritionally significant C4 plants nor marine foods (Craig et al. 2006; Tafuri et al. 2009), bioapatite is extremely valuable. Unlike collagen, there are no precise indicators of preservation of the isotopic signature, but there is general evidence for better reliability in remains from dry climates compared to temperate areas (Zazzo and Saliège 2011). Concerns regarding the bone bioapatite ability to preserve its biogenic signal have emerged early (reviews in Lee-Thorp 2008; Lee-Thorp and Sponheimer 2003; Schoeninger and DeNiro 1982), and problems were recorded in several contexts (see Trueman et al. 2003), which made highly contentious its use as an archive of isotopic information (Kohn and Cerling 2002). However, confidence in the preservation of the isotopic signal has been supported by recent research using 14C: due to the different dynamics governing early diagenesis, for samples younger than 40,000 years, bone shows isotopic reliability similar to tooth enamel (Zazzo 2014).

Several indirect tools were employed to detect possible diagenetic trends and to estimate the reliability of the isotopic signal. Bioapatite yields were measured at each preparation step (Chesson et al. 2021; Nielsen-Marsh and Hedges 2000b), and parameters measured by FTIR, such as the Crystallinity Index or Splitting Factor (IR-SF) and Carbonate to Phosphate ratio (C/P), were explored, together with possible presence of calcite and fluorapatite peaks (Shemesh 1990; Weiner 2010: 286–292; Weiner and Bar-Yosef 1990; Wright and Schwarcz 1996). Different studies have shown the possibility of a moderate increase in crystallinity coupled with intense isotopic alteration or vice versa (Koch et al. 2000; Lee-Thorp and Sponheimer 2003; Pucéat et al. 2004; Trueman et al. 2008; White et al. 1998). These measurements are consequently to be taken as indirect tools to understand potential processes at play in specific taphonomic environments. Whereas acidity of the soil matrix appears to be the most prominent factor for bone degradation (Berna et al. 2004; Nielsen-Marsh et al. 2007), other elements should be considered in rocks from neutral to alkaline such as Scaba 'e Arriu's marly sandstone. FTIR-derived values may allow the identification of possible indicators of diagenetic processes.

Results: preservation

Preservation and diagenesis indicators are in Supplementary Materials 1, 2, and 3. Conditions of collagen were quite variable but overall acceptable. Most samples had C:N ratios and C and N concentrations within the range accepted as representative of well-preserved, isotopically reliable collagen (Ambrose 1990; DeNiro 1985). Some samples were considered for paleoecological reconstruction even though a single subsample represented them. Replicates excluded for possible instrumental detection errors were as follows: #8687; #8679, r. 1, which yielded normal C:N ratio, but N% = 36.35 and C% = 82.93; #6989, r. 1 (ECA phase), #7010, r. 2, and #7014, r. 2 (LCA phase). In one case (#8685, replicate 2), the C:N ratio was abnormal because N had no signal, but the value was retained since C% and isotopic values were very close to the replicate with all parameters within the acceptable range. Only sample #7020 had a C:N ratio of 2.4 and was not considered for discussion.

Bioapatite $\delta^{18}O$ and $\delta^{13}C$ (Fig. 3) ECA phase values show that, despite a central area of minimal overlap and the exception of one human outlier, the different species maintain the signal that is expected according to their physiology and diet (Kohn 1996): obligate drinkers such as humans and pigs have more negative $\delta^{18}O$, and moderately drought-tolerant taxa such as sheep and goats have more enriched values. The two samples of extinct *Prolagus* show the most distinct values, with very enriched $\delta^{18}O$ and depleted $\delta^{13}C$. The preservation of species-specific signals is the strongest argument

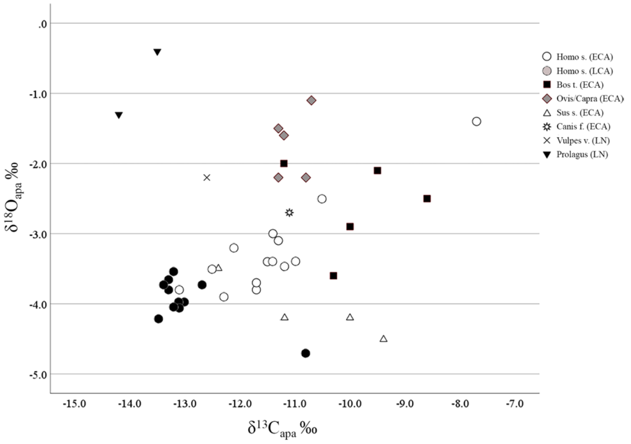


Fig. 3 Scaba 'e Arriu (Siddi). Plot of bone bioapatite $\delta^{18}O$ and $\delta^{13}C$, both human and animal samples from the Early Copper Age phase (Filigosa-Abealzu), with the indication of the species represented. The physiology-dependent biogenic signal across species is preserved

in favor of the reliability of the isotopic signal (Koch 1998; Kohn 1996; Sponheimer and Lee-Thorp 1999).

For the ECA phase, an ANOVA exploration of possible correlations between parameters that might suggest systematic diagenetic processes at work such as IR-SF and C/P and 1096 cm^{-1} shoulders, yields, and isotopic values themselves (Wright and Schwarcz 1996) did not lead to identifying any, except the expected one between IR-SF and C/P, which reflects some degree of diagenesis and recrystallization, since bone crystallinity generally co-varies inversely with preservation of organic matter (Hedges et al. 1995; Lee-Thorp and Sponheimer 2003; Person et al. 1995; Weiner and Bar-Yosef 1990; Wright and Schwarcz 1996). Some statistically significant correlations (between: $\delta^{13}C_{col}$ and IR-SF; $\delta^{15}N$ and bioapatite yield; $\delta^{18}O$ and both $\delta^{13}C_{apa}$ and the deriving $\Delta\delta^{13}C_{apa\text{-}col}$) were weak and likely caused by random effects of small numbers. Removing one observation, the p value is in the non-significant range. No significant correlations were found in IR-SF and $\delta^{18}O$ values (ANOVA), nor any significant difference in $\delta^{18}O$ associated with minimal presence vs. absence of a shoulder at 1096 cm^{-1} measured through FTIR (Mann–Whitney test). Furthermore, setting aside the one outlier (identified visually with a boxplot based on the interquartile method) with $\delta^{18}O = -1.4‰$, the two groups have an identical mean (−3.4‰). Whether the IR 1096 cm^{-1} peak is linked to fluorapatite uptake or reflects an overall increase in crystallinity (Weiner 2010: 288–289), such few and minimal shoulders and their lack of correlation with either IR-SF or $\delta^{18}O$ do not point to any significant isotopic alteration, so the recrystallization suggested by IR-SF and C/P must have been limited, and/or mainly from the bone matrix itself, with no meaningful contribution from exogenous carbonate.

Similarly, among the samples from the LCA phase, no significant correlation was found between the different measures related to possible diagenetic processes, or the correlation is weak and becomes non-significant by removing one of the extreme values ($\delta^{13}C_{col}$ and both $\delta^{15}N$ and the related $\Delta\delta^{13}C_{apa\text{-}col}$; $\delta^{15}N$ and $\delta^{18}O$; $\delta^{13}C_{apa}$ and collagen yield), except for the one between $\delta^{13}C_{col}$ and collagen yield, which is perhaps due to a random effect of small numbers, considering that the standard parameters for the collagen samples are entirely acceptable.

No detectable difference was noticed between the two specimens from individuals found inside ceramic vessels (#7005, 7012) and those from the remaining individuals. This further suggests no significant alteration of isotopic values, and it also probably reflects the sharing of a substantial portion of the taphonomic history before the secondary deposition of the remains inside jars. IR-SF and C/P in both human groups and the faunal samples can be compared with the intact context of Santa Caterina di Pittinuri (Lai et al. 2017), dating to the Filigosa ECA phase, contemporaneous to Scaba 'e Arriu's, where animal remains were recovered outside, and human remains still in their original burial chamber. Whereas domestic animal species are relatively consistent, FTIR-derived human values from both phases are closer to faunal ones at Scaba 'e Arriu, unlike at Santa Caterina di Pittinuri, where a much higher IR-SF in humans matches the concretions observed on the human remains: both can be read as outcomes of a different hydrological regime inside and outside the burial chamber. Notably, at Santa Caterina di Pittinuri, bioapatite $\delta^{18}O$ and $\delta^{13}C$ values clustered by species as at Scaba 'e Arriu. This examination points to the absence of overall diagenetic processes that could have substantially altered the isotopic signature of the samples analyzed from both phases.

Collagen yield ("concentration" in Ambrose 1990) of the two sets of human samples is broadly comparable: 4.8 ± 1.6% for ECA phase depositions and 5.7 ± 2.2% for LCA phase depositions. Bioapatite carbonate yields are also similar: 65.8 ± 4.7% for the former and 61.6 ± 6.5% for the latter. Recent assessments of such indicator (Chesson et al. 2021) would place these values across the upper limit of the acceptable range, but without similar significant correlations with other indicators as IR-SF and C/P. Such a slight difference points to similar diagenetic factors for both human collections, processes which must have been concentrated in the first centuries of their taphonomic history and then slowed significantly for the ECA group.

Collagen yields of faunal specimens (average 2.0 ± 1.3‰ for all animal specimens; 2.3% for *Ovis/Capra* sp.; 2.2% for *Bos* sp.; 1.5% for *Sus* sp.) are lower and more variable than humans, which can be connected to the following: (a) different pre-burial treatment, unlike humans (Jans et al. 2004; Nielsen-Marsh et al. 2007; Roberts et al. 2002); (b) different depositional history: Scaba 'e Arriu's animal remains may have lost their organic matter in the few centuries of exposure in the surrounding area, sharing the ensuing situation with the human remains for the next ~ 4500 years; (c) a combination of the two. Cooking is an analog of diagenesis since no method to differentiate their effect has been devised. If carried out before burial (for ritual consumption), it could help speed up the mechanical break-up of the bone structure, opening the way to microbial or chemical action (Roberts et al. 2002).

Bioapatite yields for animal samples are somewhat higher: 69.1 ± 4.3%, which fits the trend that where taphonomy, and not soil pH, is the primary diagenetic agent, animal bones are generally better preserved (Jans et al. 2004), showing prevalent fungus-related diagenesis, vs. human samples where microbial attack was dominant. This is compatible with animal bones undergoing faster diagenesis before being covered and mixed into compact soil layers when the inner room was cleared for reuse. The latter was protected from water, and such a consistently drier environment must have favored the preservation of collagen and of biogenic apatite along with it (Lee-Thorp and Sponheimer 2003; Zazzo and Saliège 2011). Moreover, the bedrock where the tomb was carved is marly sandstone, a calcium carbonate-rich sedimentary rock. The two combined factors are predictors of good overall preservation (Nielsen-Marsh and Hedges 2000a; Nielsen-Marsh et al. 2007) and bone mineral isotopic preservation (Lee-Thorp and Sponheimer 2003). Bone tissue from one cranium (n.8003) from the LCA phase recovered in the chamber inside a ceramic vessel showed collagen and bioapatite yield and δ^{13}C and δ^{18}O values fully consistent with the rest of the individuals, further supporting the inference that most diagenetic processes had already occurred before the discontinuity in burials. The microclimate inside the room probably caused the combination of slow collagen loss and fast increase in crystallinity suggested as conducive to preservation (Lee-Thorp and Sponheimer 2003). Similar conditions will likely have been in place for the ECA human remains that later continued their depositional history outside the tomb.

A smaller set of tooth enamel isotopic measurements (Tables 2 and 3; Fig. 4) shows that beyond some variability in the relationship between bone and tooth, the average values for δ^{13}C and δ^{18}O are fully comparable with bone (ECA phase: $n = 8$, $\delta^{13}C = -12.5 \pm 0.7$‰, $\delta^{18}O = -3.4 \pm 0.2$‰; LCA phase: $n = 3$, $\delta^{13}C = -12.0 \pm 0.4$‰, $\delta^{18}O = -4.4 \pm 0.2$‰). Furthermore, the average difference between bioapatite and enamel values is within instrumental precision range, and δ^{18}O values maintain their significant difference between the two phases (Mann–Whitney test: $p = 0.01783$), which suggests no significant contamination in bone apatite signature and corroborates the significance of variation between the two phases.

Results: isotopic values

Collagen isotope values (Tables 2, 3, and 4; Fig. 5) are generally within the expected range of fully terrestrial, C3-based ecosystems. The few wild species specimens from Late Neolithic layers show collagen isotope values similar to those at the contemporaneous site of Santa Caterina di Pittinuri (Lai et al. 2017). Relative to the diagonal line that should represent the vegetal-animal protein continuum within a C3-based domestic ecology, *Vulpes* sp. shows depleted δ^{15}N and enriched $\delta^{13}C_{col}$. The difference between *Vulpes* sp. and both humans and *Canis* sp.—the latter also sharing a similar physiology—suggests at both sites some wild resources so far unidentified. *Prolagus* shows at both sites significantly depleted values, to be associated with forest litter environments (at Santa Caterina, only one individual of *Cervus* had comparable values), which might indicate which ecosystem change eventually led to its extinction.

Among the herbivores, sheep/goats have the lowest δ^{13}C and δ^{15}N average values (-20.2 ± 0.3‰; 7.1 ± 0.3‰), reflecting their entirely herbivorous diet, likely a mix of grass and leaves, whereas cattle yielded more diverse and on average more enriched values (-19.7 ± 0.7‰; 8.4 ± 0.8‰). Plotting δ^{15}N for the two groups (Mann–Whitney test: $p = 0.02$) with the $\delta^{13}C_{apa\text{-}col}$ spacing (averages for sheep/goat 9.1 ± 0.6‰; for cattle 9.8 ± 0.5‰, Mann–Whitney test: $p = 0.06$) shows some overlap but a clear average difference (Fig. 6). The bioapatite values (sheep/goats: $\delta^{13}C = -11.1 \pm 0.3$‰ and $\delta^{18}O = -1.7 \pm 0.5$‰; cattle: $\delta^{13}C = -9.9 \pm 1.0$‰ and $\delta^{18}O = -2.6 \pm 0.7$‰) confirm the expected physiology-dependent variation among species, but also the difference between the two herbivorous groups, which points to the controlled management of cattle in smaller plots closer to the village, more fertile and progressively manured (Bogaard et al. 2007), for use as draft animals and perhaps for dairy products, unlike caprines. This is in line with the advanced age of many cattle specimens, which led to infer their use for secondary products (Usai et al. 2011). Also possible is an effect of the topographic difference in pasture location for sheep/goats and cattle, with sheep/goats feeding on ridges, slopes, or the nearby plateau of Pranu'e Siddi: higher nitrogen concentration as in rich, fertile soils can inhibit atmospheric N-fixing, leading to enriched values, whereas N-poor vegetal communities would uptake isotopically depleted N from the air (Garten 1993). This applies to cultivated fields, especially if manured (Amundson et al. 2003). Fire has also been shown to potentially enrich δ^{15}N values (Cook 2001; Saito et al. 2007). Whereas fires in a high-biomass primary forest would enrich δ^{15}N values of the young new plants, frequent fires in shrubby, dry vegetal communities as the Mediterranean lowlands near Scaba 'e Arriu would increase the need for bacterial N-fixing, leading to lower values. This, in turn, overlaps with the possibility of caprines feeding in distant fields periodically cleared by fire, unlike those closest to the village, plausibly employed for horticulture and pasture of draft animals. Such a dichotomy between caprines and draft oxen is historically and ethnographically documented in Sardinia in Medieval through Modern rural organization (Ferrante and Mattone 2004; Le Lannou 1941: 117): tame cattle, vegetable gardens, and tree crops were near the village. The outer area was divided into sections and alternatively cultivated with cereal grains, legumes, or left fallow. The farthest, marginal land was pasture for sheep and goats.

Concerning pig values, while average collagen δ^{13}C (-20.0 ± 0.4‰) is similar to the herbivores, average δ^{15}N is about half a trophic level above caprines (8.8 ± 0.7‰), as expected in omnivorous diets, but close to cattle (see above), possibly due to being kept near or in the village on a mainly plant-based diet. Bioapatite values ($\delta^{13}C = -10.8 \pm 1.3$‰; $\delta^{18}O = -4.1 \pm 0.4$‰) align with

Table 2 Identifiers and isotopic values for human samples from Scaba ’e Arriu (Siddi), antechamber and corridor (Early Copper Age)

Area	Stratigraphy (square, height)	Catalog #	Skeletal element	Species	Sex, age	USF # coll	USF # apat	USF # enamel	δ^{13}C bone coll ‰ PDB	δ^{15}N bone coll ‰ AIR	δ^{13}C bone apat ‰ PDB	δ^{13}C bone coll.-apat ‰ PDB	δ^{18}O bone apat ‰ PDB	δ^{13}C enamel ‰ PDB	δ^{18}O enamel ‰ PDB
Antechamber, corridor	q. Va-W, −112/−118	4628	L ischium	Homo s	Adult ♀	6988	7021		−19.2	9.6	−12.5	−6.7	−3.5		
Antechamber, corridor	q. Va-E, −118/−125	3747	R ischium	Homo s	Adult ♀	6989	7022		−18.9	10.3	−11.0	−7.9	−3.4		
Antechamber, corridor	q. IXa-S, −105/−112	5949	R ischium	Homo s	Adult ♂	6990	7023		−19.4	10.4	−7.7	−11.7	−1.4		
Antechamber, corridor	q. Va-S, −112/−118	4323 + 4324	R ischium	Homo s	Adult ♂	6991	7024								
Antechamber, corridor	q. Ib-N, −105/−112	5101	R ischium	Homo s	Adult ♂	6992	7025		−19.5	10.1	−11.7	−7.8	−3.8		
Antechamber, corridor	q. IXa-SW, −115/−145	6796	R ischium	Homo s	Young adult ♂	6993	7026		−18.8	11.8	−11.3	−7.5	−3.1		
Antechamber, corridor	q. Va-W, −112/−118	4631 + 4633	L ileus	Homo s	Adult ♂	6994	7027		−19.4	10.4	−11.5	−7.9	−3.4		
Antechamber, corridor	q. IXa-SW, −115/−145	6795	L ileus	Homo s	Adult ♂	6995	7028		−19.4	11.0	−11.7	−7.7	−3.7		
Antechamber, corridor	q. IXa-S, −105/−112	5950	R ileus	Homo s	Adult ♀	6996	7029		−19.3	9.3	−10.5	−8.9	−2.5		
Antechamber, corridor	q. I-S, −70/−76	1480	L ileus	Homo s	Adult ♀	6997	7030		−19.3	10.0	−12.3	−7.0	−3.9		
Antechamber, corridor	q. Ia-SE, −85 cm	4938	Mandible + M2	Homo s	Infant	6998	7031	7117	−19.3	9.9	−11.5	−7.8	−3.4	−12.6	−3.4
Antechamber, corridor	q. Va-S	4332	Mandible + P2	Homo s	Infant	6999	7032	7118	−19.3	11.2	−11.2	−8.2	−3.5	−11.9	−3.1
Antechamber, corridor	q. I-E, −95/−110 cm	7686	Mandible + M1	Homo s	Infant	7001	7033	7119	−19.3	10.1	−12.1	−7.2	−3.2	−12.3	−3.3
Antechamber, corridor	q. Va-S, −112/−118	4325 + 4327	R ileus	Homo s	Adult ♂	8697	8666		−19.1	11.9	−11.4	−7.7	−3.0		
Antechamber, corridor	q. V-NE, −95	4151	Mandible + M1 (?)	Homo s	Adult undet	7020	7052	7121	−19.0	10.9	−13.1	−5.9	−3.8	−13.1	−3.5
		3222	Mandible + M1	Homo s	Undet			7113						−13.3	−3.3
		2138	Mandible + M1	Homo s	Undet			7115						−12.5	−3.7
		4886	Mandible + M1	Homo s	Undet			7116						−13.0	−3.8
		1479	Mandible + M1	Homo s	Undet			7120						−11.2	−3.3
								Averages	**−19.2 ± 0.2**	**10.5 ± 0.8**	**−11.4 ± 1.3**	**−7.7 ± 0.6**	**−3.3 ± 0.6**	**−12.5 ± 0.7**	**−3.4 ± 0.2**

USF lab numbers refer to the University of South Florida Archaeological Science Laboratory. All collagen samples had acceptable C:N ratios except #7020

Table 3 Identifiers and isotopic values for human samples from Scaba 'e Arriu (Siddi), inner chamber (Late Copper Age)

Area	Stratigraphy (square, height)	Catalog #	Skeletal element	Species	Sex, age	USF # coll	USF # apat	USF # enamel	δ^{13}C bone coll ‰ PDB	δ^{15}N bone coll. ‰ AIR	δ^{13}C bone apat. ‰ PDB	δ^{13}C bone coll.-apat. ‰ PDB	δ^{18}O bone apat. ‰ PDB	δ^{13}C enamel ‰ PDB	δ^{18}O enamel ‰ PDB
Inner chamber	Outside stone cist in sq.3, −185	Cr.c	Occipital + M1	Homo s	Mature adult ♀	7002	7034	7122	−19.1	9.6	−13.5	−5.6	−4.2	−11.7	−4.2
Inner chamber	−180	Cr.b	R temporal	Homo s	Adult ♀	7003	7035		−19.3	11.0	−13.3	−6.0	−3.6		
Inner chamber	On the right of the cist	Cr.4	Occipital	Homo s	Mature adult ♀	7004	7036		−19.3	10.3	−13.0	−6.3	−4.0		
Inner chamber	Situla 1	Cr.8002	Occipital	Homo s	Mature adult ♂	7005	7037		−19.1	10.9	−13.1	−6.0	−4.0		
Inner chamber	Extreme left, along the wall to the left of situla, next to situla 3	Cr.5	R parietal + M3	Homo s	Young adult	7006	7038	7123			−10.9		−4.7	−12.4	−4.4
Inner chamber	Outside situla 1	Cr.2	R temporal	Homo s	Adult, ♂?	7007	7039		−19.2	10.8	−13.3	−5.9	−3.8		
Inner chamber	On the left, next to the cranium at –180 [cr. B?]	Cr.a1, 01/03/1983	Occipital	Homo s	Adult ♀	7008	7040		−19.2	10.9	−12.8	−6.4	−3.7		
Inner chamber	–190; midpoint of entrance	Cr.d	L parietal	Homo s	Adult ♀	7009	7041		−19.2	10.5	−13.4	−5.8	−3.7		
Inner chamber	Cist 3 in the area on the right of cist with cranium at –180	Cr.a	R parietal	Homo s	Infant ca. 6yy	7010	7042		−18.7	12.5	−13.2	−5.5	−3.5		
Inner chamber	Sq. 2 on left, −200"	Cr.z	Occipital	Homo s	Infant 6 yy+	7011	7043		−18.9	11.8					
Inner chamber	Inside situla 3 [left]	Cr.8003	L parietal	Homo s	Adult ♂	7012	7044		−19.0	11.3	−13.1	−5.9	−4.0		
Inner chamber	Extreme left of the cist, –180	Cr.8004	R parietal	Homo s	Young adult ♀	7013	7045		−19.3	10.6	−13.1	−6.2	−4.0		
Inner chamber	Cist (?) left part, −190 cm	Cr.8001	Mandible + M2	Homo s	Adult undet	7014	7046	7124	−19.2	10.3	−13.1	−6.1	−4.0	−11.8	−4.5
								Averages	**−19.1 ± 0.2**	**10.9 ± 0.8**	**−13.0 ± 0.7**	**−6.0 ± 0.3**	**−3.9 ± 0.3**	**−12.0 ± 0.4**	**−4.4 ± 0.2**

USF lab numbers refer to the University of South Florida Archaeological Science Laboratory. All collagen samples had collagen C:N ratios of 3.2 or 3.1

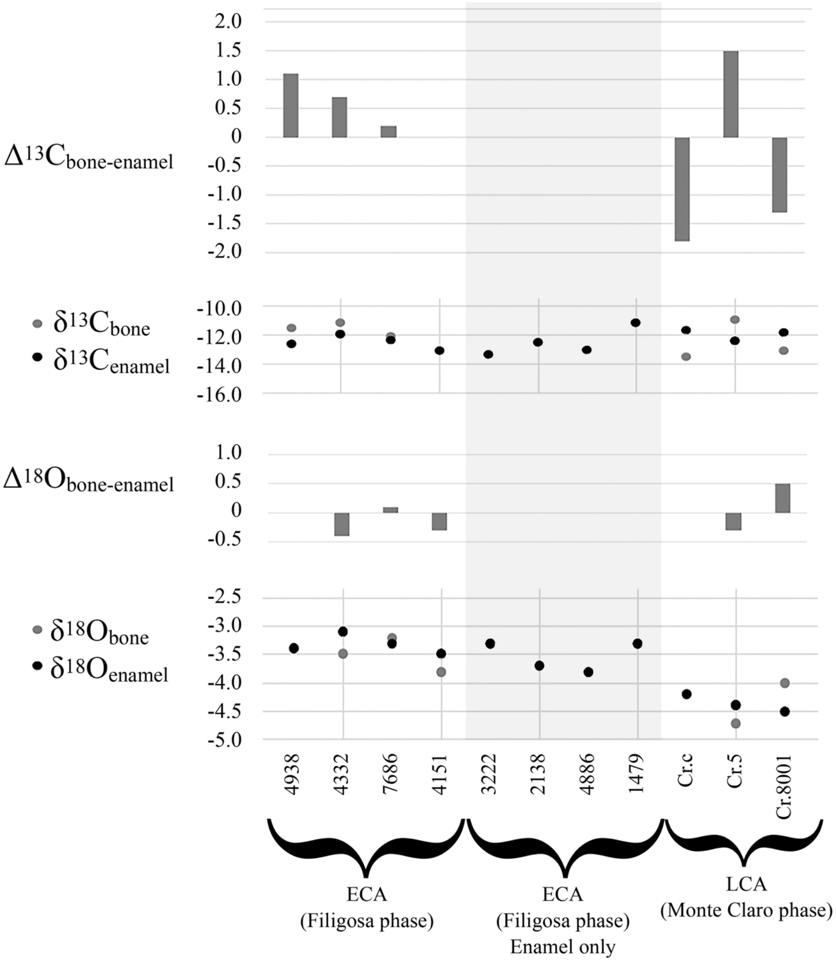


Fig. 4 Scaba ’e Arriu (Siddi). Chart showing all values of enamel $\delta^{13}C$ and $\delta^{18}O$, and values of bone bioapatite $\delta^{13}C$ and $\delta^{18}O$ for corresponding individuals. Beyond some degree of variation, especially in $\delta^{13}C$ from Monte Claro samples, the overall difference between the two sets is slight, and the difference in $\delta^{18}O$ values between the two phases remains significant, which corroborates the reliability of bone apatite values

water-related physiology and are closer to humans while not overlapping with any herbivore. The greater internal variation aligns with the blurred distinction between wild and domesticate (Albarella et al. 2006; Rowley Conwy et al. 2012), with part of the year spent in forested areas. However, no value is recorded at Scaba ’e Arriu, compatible with full forest environments as at Santa Caterina (Lai et al. 2017). This also fits the morphology-based identification of remains from the former as consistent with the domestic pig, unlike those from the latter (Usai et al. 2011).

Collagen values for humans are within overall expected ranges for C3-based ecosystems: ECA phase: $\delta^{13}C = -19.2 \pm 0.2‰$; $\delta^{15}N = 10.5 \pm 0.8‰$; LCA phase: $\delta^{13}C = -19.1 \pm 0.2‰$; $\delta^{15}N = 10.9 \pm 0.8‰$. Values of the two phases are similar (Mann–Whitney: $\delta^{13}C$: $p = 0.5195$; $\delta^{15}N$: $p = 0.548$) and would be attributed to a similar diet, other conditions being equal. However, despite our lack of direct indication from fauna for the LCA phase, we can infer different climatic conditions from $\delta^{18}O$ (see below). The baseline can be assumed to be more depleted for $\delta^{13}C$ and $\delta^{15}N$, and animal protein consumption can be assessed as higher for this phase. Bioapatite values are also within the expected overall ranges: ECA phase: $\delta^{13}C = -11.4 \pm 1.3‰$; $\delta^{18}O = -3.3 \pm 0.6‰$; LCA phase: $\delta^{13}C = -13.0 \pm 0.7‰$; $\delta^{18}O = -3.9 \pm 0.3‰$. Statistically, they are both significantly different: $\delta^{13}C$: $p = 0.003246$; $\delta^{18}O$: $p = 0.003175$. The former can be read in terms of dietary variation, per se and especially through the derived interval $\delta^{13}C_{apa\text{-}col}$ (ECA phase $= 7.7 \pm 0.6‰$; LCA phase $= 6.0 \pm 0.3‰$; $p = 0.00005$), whereas $\delta^{18}O$ values as reflecting variation in climatic conditions (see below).

At Scaba ’e Arriu, only a few outliers have been recorded, pointing to a low proportion of individuals who perhaps spent part of their lives far from the group: n. 5949 and possibly n. 5950 (adults), and cranium 5 (subadult). Whereas none of the cranial pathological markers in the LCA group, i.e., cribra orbitalia and trephinations (Chilleri et al. 2012) had any association with isotopic values, as concerns sex there is a statistically significant difference between males and females in $\delta^{15}N$ in the ECA phase (Mann–Whitney: $p = 0.02474$): males have more enriched values than females, suggesting that they may have consumed more animal products.

Table 4 Identifiers and isotopic values for animal samples from Scaba ’e Arriu (Siddi), corridor and surrounding area (Early Copper Age)

Area	Stratigraphy (square, height)	Catalog #	Skeletal element	Species	Sex, age	USF # coll	USF # apat	δ^{13}C coll ‰ PDB	δ^{15}N coll ‰ AIR	δ^{13}C bioap ‰ PDB	δ^{13}C coll.-bioap ‰ PDB	δ^{18}O bioap ‰ PDB
Corridor and surrounding area	q. V-S, – 70/– 76	F 37	Mandible	*Bos taurus*	6 mm ca	8679	8648	– 20.3	8.1	– 11.2	– 9.1	– 2.0
Corridor and surrounding area	q. Va-N, – 105	F 12 A	Mandible	*Bos taurus*	18 mm ca	8680	8649	– 19.5	8.8	– 10.0	– 9.5	– 2.9
Corridor and surrounding area	q. IX-N, – 112/– 118	F 735	Mandible	*Bos taurus*	2.5 yy ca	8681	8650	– 19.6	9.6	– 9.5	– 10.1	– 2.1
Corridor and surrounding area	q. V-E, – 50	F 22	Mandible	*Bos taurus*	4–6.5 yy ca	8682	8651	– 20.4	7.6	– 10.3	– 10.1	– 3.6
Corridor and surrounding area	q. Va-S, – 112	F 9	Mandible	*Bos taurus*	11.5 yy	8683	8652	– 18.7	8.1	– 8.6	– 10.1	– 2.5
Corridor and surrounding area	q. VI, – 42/– 30	F 566	Mandible	*Ovis/Capra*	6 mm ca	8684	8653	– 20.7	6.8	– 10.7	– 10.0	– 1.1
Corridor and surrounding area	q. I-W, – 80/– 100	F 142	Mandible	*Ovis/Capra*	12 mm ca	8685	8654	– 20.0	6.9	– 11.2	– 8.8	– 1.6
Corridor and surrounding area	q. Ia-NE, – 80/– 98	F 171	Mandible	*Ovis/Capra*	18 mm ca	8686	8655	– 20.1	7.1	– 10.8	– 9.3	– 2.2
Corridor and surrounding area	q. V-W, – 50/– 74	F 371	Mandible	*Ovis/Capra*	2–2.5 yy ca	8687	8656	– 19.9	7.6	– 11.3	– 8.6	– 1.5
Corridor and surrounding area	q. Ia-E, – 98	F 13 B	Mandible	*Ovis/Capra*	4 yy ca	8688	8657	– 20.1	7.2	– 11.3	– 8.8	– 2.2
Corridor and surrounding area	q. Va-E, – 112/118	F 522	Mandible	*Sus scrofa*	18 mm ca	8689-bis	8658	– 20.3	8.0	– 10.0	– 10.3	– 4.2
Corridor and surrounding area	q. Ia-E, – 98/– 105	F 189	Mandible	*Sus scrofa*	6–9 mm ca	8690	8659	– 19.4	9.6	– 9.4	– 10.0	– 4.5
Corridor and surrounding area	q. Ia-N, – 105	F 439	Mandible	*Sus scrofa*	18–24 mm ca	8691	8660	– 19.9	9.1	– 11.2	– 8.7	– 4.2

Table 4 (continued)

Area	Stratigraphy (square, height)	Catalog #	Skeletal element	Species	Sex, age	USF # coll	USF # apat	$\delta^{13}C$ coll ‰ PDB	$\delta^{15}N$ coll ‰ AIR	$\delta^{13}C$ bioap ‰ PDB	$\delta^{13}C$ coll.-bioap ‰ PDB	$\delta^{18}O$ bioap ‰ PDB
Corridor and surrounding area	q. Va-N, −95	F 921	Mandible	*Sus scrofa*	3yy+	8692	8661	−20.3	8.3	−12.4	−7.9	−3.5
Corridor and surrounding area	q. Va-NE, − 195/ − 215	F 60	Mandible	*Canis familiaris*	Adult	8693	8662	− 19.6	10.3	−11.1	−8.5	−2.7
Corridor and surrounding area	q. VI-W, − 110/ − 120	F 649	R femur	*Prolagus sardus*	Adult	8694	8663			−14.2		−1.3
Corridor and surrounding area	q. VI-E, − 110/ − 170	F 612	R femur	*Prolagus sardus*	Young	8695	8664	−21.9	8.4	−13.5	−8.4	−0.4
Corridor and surrounding area	q. V-W, − 215/ − 230	F 413	L radius	*Vulpes vulpes*	Adult	8696	8665	−19.0	7.9	−12.6	−6.4	−2.2
							Averages	**−20.0 ± 0.7**	**8.2 ± 1.0**	**−11.1 ± 1.4**	**−9.1 ± 1.0**	**−2.5 ± 1.1**

USF lab numbers refer to the University of South Florida Archaeological Science Laboratory. All collagen samples had collagen C:N ratios of 3.2 or 3.1

Since the $\delta^{18}O$ values in both phases do not cluster along sex lines, herding was not associated with pastoral seasonal mobility, at least the kind ethnohistorically documented in the Mediterranean (Ortu 1988), which men mostly carried out. The livestock was kept in the territory surrounding the village, without long-distance transfers to locations with sharp elevation gaps. This may have been unnecessary due to the area being a mid-point between the Sardinian highlands and the lowlands. On a local scale, the site is also a mid-point between the bottom valley and the Pranu'e Siddi plateau, with about 200-m elevation difference within a few miles radius. This aligns with findings from Late Neolithic-Copper Age Italy, suggesting generally sedentary communities (De Angelis et al. 2021), with only a few outliers to be explained as outsiders. Bioapatite $\delta^{18}O$ ratios show a statistically significant difference in $\delta^{18}O$ between the two phases (ECA: $-3.4 \pm 0.4‰$; LCA: $-3.9 \pm 0.3‰$; $p = 0.00318$, Mann–Whitney test), which can be tentatively connected to drier and/or colder conditions in the former vs. the latter.

Discussion

Discussion can be articulated in different strands as follows: (i) estimating protein consumption; (ii) estimating overall diet and the source of animal protein; and (iii) overall interpretation.

(i) The proportion of animal protein in the human diet is best estimated from the $\delta^{15}N$ interval between consumers and (likely) consumed animals, which for the ECA phase is 2.4‰ for all domestic animals, 2.7‰ for herbivores only. This appears to be the most solid basis, despite the many aspects that need to be clarified in this relationship (Hedges and Reynard 2007). Studies of Copper Age Mediterranean diets have mainly used linear mixing models between known potential protein sources, also using specific calculation tools (Fraser et al. 2013; Kellner and Schoeninger 2007), although the lack of faunal samples leads in some cases to comparisons with faunal or plant remains from the closest spatial and temporal approximation (De Angelis et al. 2019; Fontanals-Coll et al. 2015, 2017; Waterman et al. 2016b), introducing error in evaluating the different estimates, due to climate- and environment-derived variation (van Klinken et al. 1994). Based on the mass-balance linear model as used graphically by Fraser et al. (2013), with a 3‰ trophic level interval for $\delta^{15}N$, animal protein consumption at Scaba 'e Arriu, ECA phase could be estimated at approximately 90% (Fig. 7). However, recorded trophic level-related differences are far from consistent. Assuming a possible interval of up to 5.5‰ (Hedges and Reynard 2007; O'Connell et al. 2012; O'Connell and Hedges 1999), animal protein estimation turns out significantly lower (ca. 50%) (Fig. 7). Furthermore, a problem at the root of such procedure is the limitation of

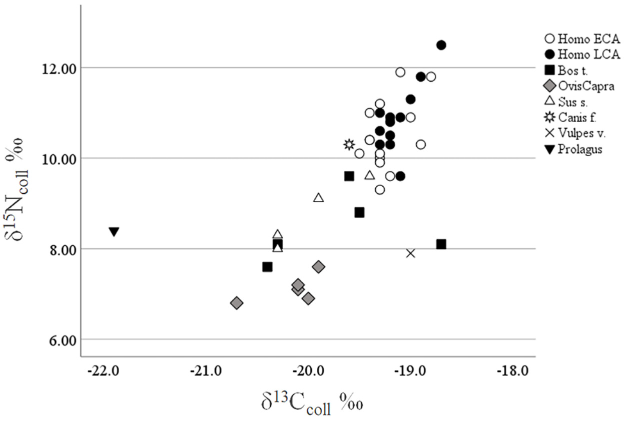


Fig. 5 Scatterplot of δ^{13}C and $\delta.^{15}$N collagen values from Scaba 'e Arriu (Siddi): animals from the Early Copper Age phase and humans from both Early and Late Copper Age (see Tables 2, 3, and 4)

the linear mixing model itself. In fact, concentration-dependent models fit more accurately the variability of protein content of different foods (Phillips 2012; Phillips et al. 2014; Phillips and Koch 2002): foods richer in protein (and among them, those richer in Nitrogen) will affect isotopic values proportionally more than the same amount of foods that are poorer in protein. Whereas this is particularly true between fish and plant foods, it holds significance also for diets that include cereals, animal products, and legumes. Rather than calculating specific numbers without a baseline for plants and legumes, we only propose a correction of the estimate considering the reported proportion in the quantity of nitrogen in plants (1%) vs. terrestrial meat (14%) (Phillips and Koch 2002), which can be converted in a reduction between 5 and 20% of estimates based on the standard model: the values for Scaba 'e Arriu, ECA phase, would therefore be lowered to between 50 and 65% (from 70% estimate), or between 30 and 45% (from 50% estimate), numbers more in line with averages in the majority of ethnographically recorded populations, whose proteins are primarily of vegetal origin.

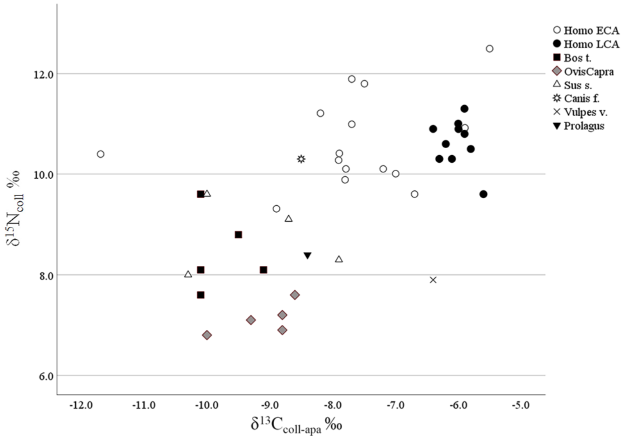


Fig. 6 Scatterplot of $\delta^{15}N_{col}$ and $\Delta.^{13}C_{col\text{-}apa}$ values from Scaba 'e Arriu (Siddi), animals from the Early Copper Age phase, and humans from both Early and Late Copper Age (ECA, LCA: see Tables 2, 3, and 4)

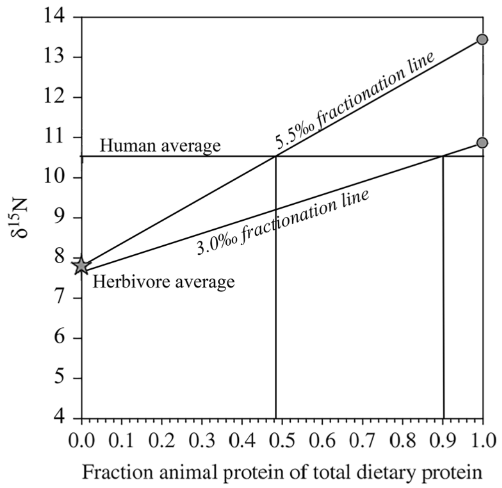


Fig. 7 Estimation of the fraction of animal protein at Scaba 'e Arriu, phase Filigosa, based on different fractionation models, using the graphic tool employed by Fraser et al. (2013). Human and herbivore averages are actual observed numbers

(ii) Estimating the origin of protein from δ^{15}N is complicated for the reasons discussed above. This problem is magnified if we have the goal of inferring diet and the source of animal proteins on collagen data alone due to the vast and often overlapping range of values for different species potentially consumed. Here, we argue for the usefulness of using $\delta^{13}C_{col\text{-}apa}$ spacing to infer the origin of lipids, which is deemed to partially overlap with the degree of carnivory (Katzenberg and Weber 1999; Schwarcz 2000). At Scaba 'e Arriu, there is a large $\delta^{13}C_{col\text{-}apa}$ spacing in the ECA compared to LCA (7.7 ± 0.6‰ vs. 6.0 ± 0.3‰: $p = 0.00005$, Mann–Whitney test, without outlier n.5949) (Fig. 6). Similar enriched bioapatite δ^{13}C values have been interpreted elsewhere as indicative of C4 plant consumption (Fontanals-Coll et al. 2015; Waterman et al. 2016a, 2014, 2016b), and elsewhere more explicit evidence for millet consumption has been highlighted at least in the Bronze Age (Masotti et al. 2017; Tafuri et al. 2009; Varalli et al. 2021, 2016a, 2016b), but no evidence of the presence of millet has been found so far on Sardinia through the Bronze Age (Ucchesu et al. 2018, 2014, 2017), which excludes any such source to explain enriched bioapatite δ^{13}C. Based on work on lipid residues isotopic values (Evershed et al. 1999, 2002), a difference in lipid isotopic signature was recorded between porcine and ruminant fats, which allows for their characterization and distinction. δ^{13}C values of porcine lipids are enriched and cause $\delta^{13}C_{col\text{-}apa}$ spacing to be wider since their signature does not affect collagen as much as bioapatite. Significantly δ^{13}C-depleted lipids in ruminants, on the contrary, reduce the $\delta^{13}C_{col\text{-}apa}$ spacing. Considering how minimal the amount of lipids present in cereals is (relative proportion of 2–3% in wheat and barley, less than 4% in bread, compared to protein and carbohydrates) vs. meat (10–15% in deer, goat, and wild boar; 30–40% and more in beef and lamb) and especially milk and cheese (30 to 50%) (USDA ARS 2022), and how in Copper Age Sardinia collection and consumption of lipid-rich wild olives and hazelnuts in large amounts is unlikely and unsubstantiated by any evidence, it is lipids from ruminants, together with a diet rich in cereal grains, the best explanation for depleted bioapatite δ^{13}C and low $\delta^{13}C_{col\text{-}apa}$ (see discussion in Herrscher et al. 2018).

In sum, consumption of dairy and ruminant meat must be considered limited in the ECA phase, whereas it appears to have been much higher in the LCA. While the importance of hunting cannot be estimated—only one faunal assemblage has been studied to date for the LCA (Carannante and Chilardi 2015), the most likely basis for such a significant difference across the two phases is the exploitation of milk. Since lactase persistence was still rare in the Mediterranean during this period (Leonardi et al. 2012; Plantinga et al. 2012), dairy products that enhance digestibility must be inferred. Such inferences based on bioapatite δ^{13}C highlight the limits of collagen alone in understanding significant paleoeconomic facts in agropastoral C3-based ecosystems and reveal a radical change in subsistence focus.

In terms of the overall interpretation of the factors at play in the change in economic patterns suggested by stable isotopic values, besides tradition and praxis that may have been affected by heightened mobility, more intense contacts, and possibly even immigration, climate change must be considered. A phase of increased rainfall around the mid-3rd millennium BC, preceded by a drier period around 2900–2700 BC, was identified in Tunisia (Zielhofer et al. 2004) and is followed by the well-established 4.2 kya event. On such grounds, it appears possible that during the LCA group's life, precipitation, if more intense than during the ECA period, could have provided greater agricultural outputs and possibly more profitable exploitation of land for pasture, including the expansion of pastoralism in lands previously unproductive. δ^{18}O values do not contradict such a connection at Scaba ‘e Arriu, which are compatible with drier conditions in the ECA (more enriched) and wetter conditions in the LCA (more depleted). δ^{18}O variation can be correlated with many variables with different intensities based on the circulation of air masses, seasonality, and other factors beyond simple amounts of rain (Longinelli and Selmo 2003; Rozanski et al. 1992) and could also derive from using different water sources and different mobility patterns. Therefore, while the data appear compatible with the scenario outlined here, the role of climate in the contexts examined requires further testing.

Conclusions

Isotopic analyses enabled the reconstruction of several aspects of the paleoeconomy at the Scaba ’e Arriu site and their evolution between the Early and Late Copper Age, concerning changes in both cultural and climatic patterns.

The ECA phase was characterized by a subsistence based on vegetal foods, with a small portion of the diet derived from animals. Whereas the protein component can be assessed through the interval of human and animal collagen δ^{15}N values, the overall diet reflected in bioapatite δ^{13}C indicates a limited amount of animal products. In the LCA phase, more depleted bioapatite δ^{13}C values are interpreted in terms of lipid signature, indicating a substantial proportion of ruminant-derived foods, which is to be read as the marker of an intensified exploitation of dairy products.

Previous data concerning climate based on several proxies, with the identification of a drier phase in the twenty-ninth to twenty-seventh century BC (e.g., Jalut et al. 2000; Zielhofer et al. 2004) and milder, wetter conditions afterward, is an essential element to understand the possible factors tied to dietary and economic dynamics. δ^{18}O values recorded in the two phases at Scaba ‘e Arriu are compatible with this possibility.

Whereas both groups appear largely sedentary, a few individuals may have been outsiders. Furthermore, in the ECA group, there is a statistically significant difference according to sex, possibly due to differential foods or food processing between males and females.

Finally, from the limited faunal sample, it appears that domestic species cluster separately, indicating distinct management practices and ecological niches for caprines, which grazed in the marginal areas, vs. tame cattle and pigs, more strictly controlled, which supports the finding of mature bovines (likely used for traction), and morphologically domestic pigs.

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Author contribution LL designed research, obtained funding, selected and obtained samples, processed samples to obtain analytes, assisted

in FTIR analyses, interpreted results, wrote the main manuscript text, created charts, and prepared figures. OF provided all osteological data and contextual information, assisted in obtaining samples, and contributed to interpreting the results. RT supervised the isotopic section of the research design and lab procedures, obtained funding, and contributed to interpreting the results. EG and DH managed the mass spectrometry analytical procedures and were responsible for the quality of the analytical results, contributing to interpretation. LM performed the FTIR analyses and processed the resulting data from the spectra. GT supervised FTIR analyses within the overall project. All authors reviewed and approved the final manuscript.

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Data availability All data are provided between tables in the text and in Supplementary Materials. There are no additional data.

Code availability Not applicable.

Declarations

Ethics approval All sampling procedures and analyses have been approved by the (then) Soprintendenza Archeologica per le Provincie di Cagliari e Oristano, Italian Ministry for Archaeological Resources.

Consent to participate Not applicable.

Consent for publication Publication of Figures from the Quaderni della Soprintendenza Archeologica per le Provincie di Cagliari e Oristano is permitted under the condition of citing the source: Fig. 1.c is a merger with the graphic elaboration of: "Le sequenze culturali e i riti funerari dell'ipogeo di Scaba 'e Arriu di Siddi (Cagliari)," in Quaderni della Soprintendenza Archeologica per le Province di Cagliari e Oristano, 15 (1998): 31–58, p. 51 (plan in TAV. I), and p. 53 (section of the dolmenic corridor in the antechamber and section of the chamber, in TAV. III).

Competing interests The authors declare no competing interests.

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