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1 This paper's aim is to present the first isotopic data available on Sardinian Bronze Age diet, and provide a tentative assessment of how they match some of the current models suggested by archaeological literature. The Bronze Age of Sardinia is mostly known for the monuments, called *nuraghi,* single or grouped stone towers which have attracted scholarly attention in the attempt to understand when, why and who invested labor and organizational skills for these buildings that are still part of Sardinian landscape. Still little, however, is known about the economy and lifestyle of the builder's society; this paper addresses this gap by stable isotope analysis. However, only the Early Bronze Age data are the outcome of a deliberate project; the other skeletal assemblages were a byproduct, either due to their unexpected identification as Bronze Age sites where previously considered Neolithic, or due to the restriction in the project's temporal goal. Nevertheless, they provide a first glimpse into Bronze Age diet.

2 Sardinia is an island about 24,090 km^2 large, located in the W Mediterranean, surrounded by the Italian peninsula, Tunisia, the Balearic Islands, Sicily, S France and very close to Corsica. The majority of the landscape is hilly, with limited plains in the S and W and highlands in the E up to ~1800 m. a.s.l. Climate is presently characterized by mean annual temperatures between 10°C to 18°C and precipitation of 400-1000 mm (Pracchi & Terrosu Asole 1971), long and dry summers, and prevalent winds from the NW. Vegetation is characterized by typical Mediterranean trees and shrubs, with limited deciduous forests; alluvial plains are mainly cultivated, and pasture dominates in the highlands.

3 After the final Copper Age cultures Filigosa-Abealzu and Monte Claro, the Bronze Age begins with the abandonment of settlements occupied for centuries. With a sharp break in landscape occupation patterns after the 2nd third of the 3rd mill. BC: Bell Beaker and Early Bronze Age (EBA hereafter) cultures are known mainly from burials, reflecting a transition toward different forms of social and economic organization, detected in different forms at the same time in several areas of the Mediterranean. The EBA (ca. 2300-1800 BC) is characterized by continuity with Bell Beaker tradition and slow change in material culture, which shows similarity with mainland Europe. Compared with the Copper Age (CA hereafter), detectable presence in the landscape drops, except from burials, mostly natural caves and reused rock-carved tombs. Recent research underlined that the island experiences its monumental phase, including both nuraghi and chambered tombs, only in the Middle Bronze Age (MBA hereafter) (Lo Schiav*o et al.* 2010). This leaves the EBA virtually without stone architecture, except for a few isolated houses (es. Usai 1994). This is to be highlighted because not all of the models proposed to describe and interpret material culture change share these acquisitions. The MBA (ca. 1800-1350 BC) shows innovations and continuity in material culture; it also experiences the diffusion of the chambered tombs and especially of *nuraghi*, pieces of the canonical Nuragic 'locale' as long known and recently defined by Blake (2001), which by the end of the Late Bronze Age (LBA hereafter) fill most of the available land on the island. The intensification of external contacts is clearly traceable in the LBA (ca. 1350-1150 BC), when Aegean pottery and metal items are found at several sites (Knapp 2000; Lo Schiavo 1995), and Sardinian pottery finds its way up to Crete. The Final Bronze Age (FBA hereafter, ca. 1150-1000 BC) is marked by several symptoms of discontinuity and conflict. Several sites are abandoned, some show traces of destruction, whereas others are fortified and grow considerably into large villages, and new types of sites replace the chambered tombs as power and ritual centers (Lo Schiav*o et al*. 2010).

4 The study of Sardinian dietary patterns – and therefore isotopes – in the Bronze Age is important for the whole Western Mediterranean to understand the economic basis underlying the development of a unique society that from a marginal reflection of the European mainland cultural patterns results in a dynamic exchange partner in Cypriot Copper trade and one of the areas with the most remarkable and dense architectural complexity. The transition from an organization that did not have tight connections overseas to one with long-distance ties must have been also economic in nature: disentangling the interaction between natural, economic and cultural factors involved can also be of interest for broader anthropological issues.

5 Botanical data for the Bronze Age are scarce and not quantitative, amounting to lists of species represented by remains at the site of Duos Nuraghes, Borore. The record from this site is important for the first record, in the Middle Bronze Age layer, of olive potentially not wild, and in the Late Bronze Age layer, of *Avena* sp. and of several fruits (*Ficus, Prunus, Vitis* and *Rubus*, also not necessarily cultivated (Bakels 2002). All other main staples (cereal grains and legumes) were present in Sardinia from Neolithic times. Faunal studies are also few and chronological phases are not well distinct, often well into the Iron Age; a recent review (Wilkens 2004) indicates high variability among the proportion of the main domesticates, with frequent ovicaprines, and the highest recorded presence of bovines at one FBA site (Nuraghe Miuddu). Cattle and deer are more frequent in FBA-Iron Age contexts, although when remains are found at nuraghi feasting and ritual may create a bias relative to domestic every-day consumption at village sites. Additionally, there remains the problem of excavation projects that never involve both burial and habitation sites, so that human and faunal bone remains from the same ecosystem are never associated.

6 Several models of development, more or less specific on the economic basis for social changes, have tried to make sense of the material evidence. Among them, Lilliu (1988) suggests a rise of pastoralism in the Final CA, opposed to a mostly agricultural Neolithic, with a stable pastoral society in the Bronze Age, characterized by king-shepherds, the use of the plow, and specialization of labor. Lazrus (1999), challenging this canonical view, identifies similar economic practices from the Neolithic to the Iron Age, with higher social complexity beginning in the (undifferentiated) LBA-FBA with an unchanging economic basis. A well-balanced mixed farming economy with no specialized pastoralism would have been so successful as to be maintained over millennia; the potential exploitation of secondary products (Sherratt 1983) is not considered. According to Webster (1996), starting in the MBA a gradual intensification both in agricultural outputs and secondary animal products – due to population growth and occupation of available land – would have characterized economy, with plow agriculture common only in the EIA. Perra's model (1997) finally identifies the true break in the economic system within the EBA, with an EBA1 characterized by bare subsistence based on cereal monocropping, and first moves towards intensification already in the EBA2; such moves would have been carried out by the elites, during the MBA-FBA, in order to strengthen their hold on power, with inputs from Aegean ideologies.

Principles, Materials and Methods

Principles

7 Stable isotopy has been used for several decades now to explore ancient diets, since the discovery of the dynamics underlying ^{13}C distribution in plants, and their first applications (for a review see Tykot 2006). Today, both C and N isotopic ratios of collagen are widely used, providing insights into different dietary transitions through time and variation through space. The macronutrients we consume (protein, lipids and carbohydrates) are metabolized and used by the body to build tissues, and through this process they carry along the isotopic signature of their origin, since C and N isotope ratios in all organic tissues change predictably from source diet to tissues because of differential fractionation. This term refers to the process whereby chemical reactions involving these elements determine the selective uptake of heavier and lighter isotopes in specific ratios. This is due to different atomic mass, which causes the reactions to occur at different rates. The isotopic signature of different tissues is unique, and so is each tissue's turnover: while bone is constantly replaced (Hedges *et al.* 2007), reflecting

diet over several years *ante mortem*, other tissues are not replaced after formation or are replaced much faster. Consequently, different tissues answer different questions: bone (both collagen and apatite) has the advantage of enabling to assess the components of an average diet over a long period of time, reflecting a practice as opposed to a temporary behavior or an occasional act. Furthermore, bone collagen is mainly an expression of the protein portion of the diet, because it is mainly synthesized from ingested protein, whereas bone apatite is a more comprehensive indicator of diet since it is produced from all macronutrients (Ji*m et al.* 2004). If there is no severe protein shortage (Schwarcz 2000), collagen in humans will mostly reflect foods of animal origin, which are much richer in protein; it will reflect vegetal foods only if alternative sources of protein were so scarcely available that the organism uses plant proteins to build tissues.

8 Carbon has two main stable isotopes: ^{12}C and ^{13}C, of which the former is most common (98.89%). Similarly, nitrogen is mostly found as ^{14}N and ^{15}N, where the former represents 99.63% of all nitrogen (Sharp 2007: 8). Due to this conspicuous difference, in order to express minute quantities in ratios that can be accurately recorded and intuitively grasped, the conventional quantity used is the difference (δ) from a standard value in the ratio of the of the least vs. most frequent isotope. Standards are agreed upon by the scientific community: the Pee Dee Belemnite (PDB) for C and the air (AIR) for N (Hoefs 1997: 22-24; Sharp 2007: 28-29); the measurement unit is the part per thousand (‰):

$\delta^{13}C_{PDB}$ ‰= $[(^{13/12}C_{sample} / ^{13/12}C_{PDB}) - 1] \times 1000$

$\delta^{15}N_{AIR}$ ‰= $[(^{15/14}N_{sample} / ^{15/14}N_{AIR}) - 1] \times 1000$

9 Since both standard material and measurement unit are established and implied, it is common to omit them, so that the typical notation for stable isotope ratios turns out to be simply δ^{13}C, δ^{15}N.

10 To trace a human organism's position within the food chain it occupied while living, nitrogen represents the best choice, since differences between consumed and consumer are considerable, between 2.5 to 4.5‰ (Hedges & Reynard 2007) or perhaps greater (O'Connel*l et al.* 2012), and therefore fairly detectable. N is fixed or absorbed by plants, and their isotopic ratios are also passed on up the food chain with this interval. Since there is no fractionation in nitrate absorption, values for plants are quite similar to those in the atmosphere, δ^{15}N = -5 to + 5‰. The main relevant difference in plant physiology is for N the one between fixers and non-fixers. The former, represented mainly by legumes, show depleted (lighter) δ^{15}N values, whereas non-fixers as cereal grains and most other plants are more enriched and, within the same ecosystem, non-overlapping with fixers (DeNiro & Hastorf 1985). Carnivores will be about 4‰ enriched compared to their herbivore prey, and this means that due to long food chains that increase the enrichment at every step, the most detectable protein origin is from seafood (Richards & Hedges 1999; Schoeninger & DeNiro 1984). Environmental factors, however, affect N isotopic ratios in soils and plants, and so in the whole food chain. Since early work documented variation linked to elevation (Ambrose 1991), much work has documented climatic effects on a global scale: both temperature and precipitation are correlated with δ^{15}N (Amundso*n et al.* 2003). Geology, topography, cultivation, all affect δ^{15}N, with variation transferred to the rest of the food chain. Cultivation depletes soils of nitrates and leaves them ^{15}N-enriched; manure addition also enriches ^{15}N (Bogaar*d et al.* 2007). Additionally, physiological responses to nutritional or temperature stress also enrich δ^{15}N values (Ambrose 2000).

11 As concerns δ^{13}C, the largest difference observed among foodstuffs worldwide is related to two plant groups: C3 and C4. Such interval is then maintained up the food chain. These groups differ in their photosynthetic pathways, which translates into two distinct signatures, averaging about -26‰ in the former and -12‰ in the latter (Ambrose & Norr 1993). C3 plants are the most common type in temperate areas. C4 plants are generally grasses adapted to tropical climates, some of which have been domesticated and spread elsewhere. Additional variation in δ^{13}C is due, as for δ^{15}N, to factors as latitude, altitude, and geomorphology; in fact, significant δ^{13}C variation has been recorded on a large scale (van Klinke*n et al.* 2000), and on a small scale,

due to several micro-environmental and physiological factors. Marine $\delta^{13}C$ values are usually enriched, resulting in an overlap with the C4 plants' range, so that the way of setting them apart is by plotting $\delta^{13}C$ and $\delta^{15}N$ (which is the standard way of presenting all such collagen values): high $\delta^{13}C$ and low $\delta^{15}N$ indicates C4 plant-based diets, while high $\delta^{15}N$ indicates marine protein-based diets.

Materials

12 The number of individuals per site is in Table 1; location in Fig. 1). Iscalitas, located some 25 km NNE of Cagliari, is a shallow pit grave dug on a low hillock. Excavation in 1995 (Manunza 1998) yielded EBA materials and human remains, pertaining to at least 79 individuals, found mostly as disarticulated elements (Usa*i et al.* 2005); of these, 29 were sampled. Two AMS dates on bone are available (23rd-19th cent. BC, 2σ range). The relatively low caries (3%) and frequent tooth wear also provide an indication of diet (Usa*i et al.* 2005), which would involve a low degree of processing for starch and carbohydrates sources. Concali Corongiu 'Acca is a location with two natural caves, located in the Sardinian southwest, where human remains and pottery were recovered; the caves were used most intensively in the EBA (Ferrarese Ceruti 1974), and one AMS date on bone (23rd-20th cent. BC, 2σ range) confirmed the assessment. Among the five cranial specimens sampled, there was a high occurrence of hyperostosis (Maxia & Floris 1961), a condition commonly associated with metabolic or nutritional deficiencies, or parasitic infections (Ortne*r et al.* 1999). Montessu is a large rock-carved necropolis, established in the Late Neolithic (LN hereafter) and reused up to the MBA; from tomb 10, one individual was available for sampling and AMS dated to the 18th-15th cent. BC, 2σ range (confirming the MBA chronology). Is Aruttas, on the West coast of Sardinia, according to the little information published, is a modified natural cave a few hundred meters from the seashore and a few miles from the brackish water Cabras Lagoon. The context, damaged by looters, was originally attributed to the LN for the few potsherds recovered near the 25 individuals, of which 11 were available for sampling. One of them was AMS dated (15th-12th cent. BC, 2σ range), yielding a date compatible with the MBA to FBA. This calls for caution in considering this collection; however, several AMS dates in the last two decades (Cosseddu *et al.* 1994; Sann*a et al.* 1999) have consistently shown that burial in natural caves was frequent in the Middle through Final Bronze Age, whereas cave burials in the LN remain rare and never directly dated, so that it seems likely, though not certain, that the remains actually belong to the last phase of use in the Bronze Age. Despite a quite homogeneous preservation, also morphological traits (Germanà 1980) and $\delta^{18}O$ isotopic values (not presented here) appear diverse, pointing to some kind of intra-group heterogeneity. The remains of at least 25 individuals included both sexes and both adult and subadults (Germanà 1980; 1982). *Cribra orbitalia*, tooth wear (25%) and caries (3.7%) were recorded. Faunal remains found at the site were impossible to locate. Sedda sa Caudela, tomb B, is a chamber tomb, part of a complex of two megalithic collective burials dating to the advanced MBA and still used up until the FBA. They belong to the *giants' tomb* type, but without the marked forecourt characterizing the majority of them. Chronology is not detailed to the layer, so that attribution of single remains to a single phase is mostly impossible with no absolute dates. The skeletal remains, studied by Fonzo (Atzen*i et al.* 2012) represent at least 239 individuals of both sexes and all ages (with an unusual distinction of subadult human remains), of which 10 were sampled but only 2 yielded collagen;. Dental health shows low caries (2.5%) and high tooth wear (75%); T. Setzer ascertained that cribra orbitalia and cranii affected roughly half the cranial fragments (Atzen*i et al.* 2012). No faunal remains were recovered or available to build an isotopic baseline; this is why the tentative approach of climate-based corrections was taken.

1. Map of Central-southern Sardinia with the sites considered in the isotopic study (circle size proportional to number of sampled individuals)

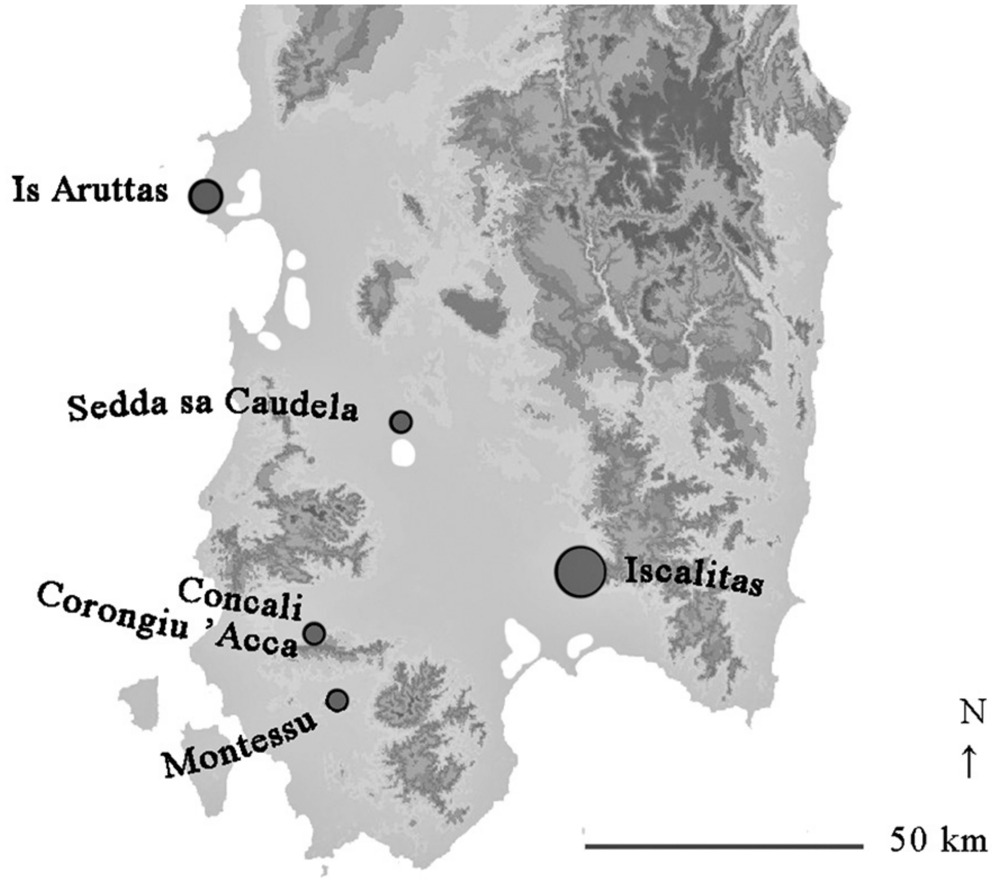


Table 1. Climatic data, average isotopic values and AMS dates per site

site	*burial type*	*phase*	*n. indiv.*	Avg. precipit. mm/year	Avg. temp. °C	Avg. coll. $\delta^{13}C$‰	St. dev. coll. $\delta^{13}C$	Avg. coll. $\delta^{15}N$‰	St. dev. coll. $\delta^{15}N$	AMS lab #	Date BP
Concali Corongiu 'Acca	Cave	EBA	4	800	17.5	-18.9	0.2	11.4	0.8	AA72150	3699 ± 42
Iscalitas	Pit	EBA	29	500	15.0	-19.1	0.3	10.4	0.9	Beta-107558 AA72149	3700 ± 70 3738 ± 42
Montessu t. 10	Rock-carved tomb	MBA	1	700	17.5	-20.3		9.1		AA64836	3291 ± 59
Is Aruttas	Cave	MBA-FBA	11	500	16.0	-18.7	0.3	10.5	0.9	AA64824	3054 ± 55
Sedda sa Caudeba t. B	Chamber tomb	MBA-FBA	2	600	17.0	-19.0	0.1	9.3	0.3		

Methods

13 Ca. 1 g of bone was selected per individual, cleaned from soil or concretions, ultrasonicated and dried. Preparation is a variation (Tykot 2004) of a procedure that is less common than the standard, but proved to yield results of comparable quality (Ambrose 1990), with the practical advantage of being low-tech – not requiring hot plates and freeze-drying – and allowing visual assessment throughout the process: after soaking the sample ~24 h in 50 ml of 0.1 mol/L NaOH aq. to remove humic acid contaminants, collagen was extracted by soaking in 50 ml of 2% HCl aq. in two or more ~24-h baths, based on need. Whenever appropriate, samples were cut into smaller pieces to help the solution permeate the tissue. After demineralization, another ~24 h in NaOH removed further contaminants that were not exposed to reaction when the bone was whole. Demineralization is visible from the coloring of the solution and often from the bubbles on the surface. Samples were then soaked for ~24 h in 50 ml of a methanol-chloroform-distilled water solution (proportion 2:1:0.8) to remove lipids. Samples were rinsed at every step involving the change of reagent. The extracted material, consisting of pellets, was dried overnight in vials at ~65°C. Two 1-mg replicates per sample was weighed, placed in tin capsules, and analyzed in continuous-flow mode with a Carlo-Erba 2500 Series II CHN

analyzer, coupled with a ThermoFinnigan Delta+XL stable isotope ratio mass spectrometer, with precision (2 sigma) better than ±0.3‰ for $\delta^{15}N$ and ±0.2‰ for $\delta^{13}C$, located at the Paleolab, St. Petersburg campus, University of South Florida.

Results

14 Collagen preservation was quite different among the five populations (Table 2): at Concali Corongiu 'Acca, one sample did not yield sufficient collagen for analysis, whereas the other four had yields between 2.1 and 10.7%, with an average of 3.5 ± 4.1%. Iscalitas had low and more homogeneous yields (average 1.6 ± 0.8%), and a small range (0.4-3.8%) reflecting similar taphonomic conditions in the shallow pit. The yield of the single sample from Montessu, t. 10 was 2.5%. Is Aruttas shows consistently high collagen yields: average 14.5 ± 1.4%, range 12.1-15.8%. Sample 6880, reexamined after unusual apatite $\delta^{13}C$, turned out to be burnt, is the only one below 13.3%, and is not considered for dietary reconstruction. Samples from Sedda sa Caudela, tomb B, as those from tomb A, had very poor collagen preservation (average 1.5 ± 0.6%, range 1.1-1.9%); in fact, only two out of ten had enough to be measured: probably the basalt used for construction was too acid to allow good preservation. Stemming from the preparation method, collagen preservation was assessed first by visual means: abnormal features (texture, color) can be observed during the process; yields lower than 1% are commonly a symptom of potentially bad preservation when milling the bone to powder and keeping in a closed system (Ambrose 1993); in this case, manual rinsing makes likely the loss of small amounts of sample, so that yields are to be considered approximations rounded down, and even when less than 0.5% they are regularly associated with normal C and N concentrations – which should be respectively higher than 13% and 4.8% in well preserved collagen, as in Ambrose (1990).

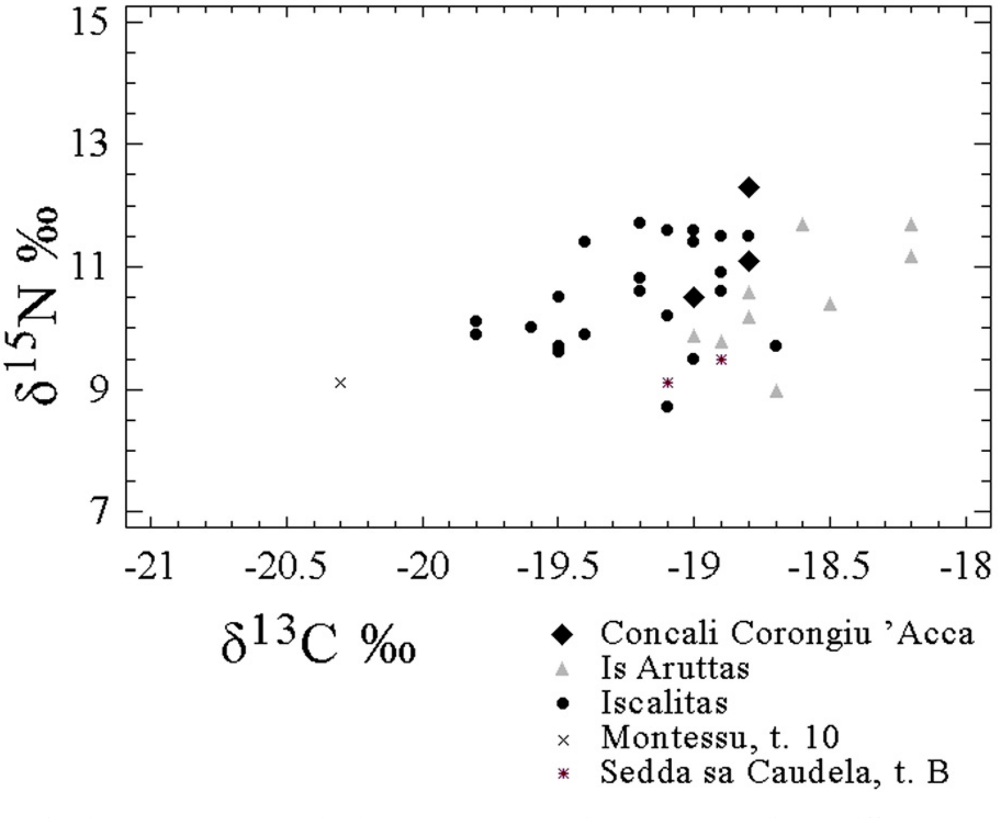
Table 2. All individual isotopic values and preservation indicators

# indiv.	USF#	site	*Age sex*	*burial type*	*phase*	*skeletal district*	% yield	% C	% N	C:N	Coll. $\delta^{13}C$‰	Coll. $\delta^{15}N$‰
Cranio 1	6978	Concali Corongiu 'Acca	adult M	Cave	EBA*	Cranium	2.5	37.0	15.8	3.1	-18.8	11.1
Cranio 2	6979	Concali Corongiu 'Acca	adult F	Cave	EBA	Cranium	10.7	39.1	16.7	3.1	-19.0	10.5
Cranio 3	6980	Concali Corongiu 'Acca	adult ind.	Cave	EBA	Cranium	2.2	38.4	16.2	3.2	-19.1	11.7
Cranio 5	6982	Concali Corongiu 'Acca	adult ind.	Cave	EBA	Cranium	2.1	38.9	16.6	3.1	-18.8	12.3
I.1* = Cr. C29	8607.2	Iscalitas	senile M	Pit	EBA	Tibia	2.1	37.0	17.0	2.9	-18.9	10.9
I.2 = Cr. C11	8608	Iscalitas	adult M	Pit	EBA	Cranium	0.9				-19.5	9.7
I.3 exc = ind. a.3 = Cr. C19	8609	Iscalitas	adult M	Pit	EBA	Cranium	0.8				-18.7	9.7
I.4 exc. = inf. 1* = ind. sa.7	8610	Iscalitas	infant	Pit	EBA	Cranium	1.0				-19.3	8.7
I.5-bis* = Ind. sa.6	8611	Iscalitas	juvenile	Pit	EBA	Long bone	1.7				-18.8	10.7
Cr. C38 box 7502	8612.2	Iscalitas	adult F	Pit	EBA	Cranium	1.9	31.4	14.3	2.9	-19.6	10.0
Cr. C35	8613	Iscalitas	adult M	Pit	EBA	Cranium	2.0				-19.1	8.7
Cr. C32	8614	Iscalitas	adult F	Pit	EBA	Cranium	0.5				-19.8	10.1
Cr. C46	8615	Iscalitas	adult F	Pit	EBA	Cranium	2.6				-19.1	11.6
Cr. C21 box 7490 = cr. 37	8616	Iscalitas	adult M	Pit	EBA	Cranium	1.4				-19.8	9.9
Cr. C24	*8617.b*	Iscalitas	juvenile	Pit	EBA	Cranium	1.4	38.4	22.0	2.3	-19.0	9.5
Cr. C61	*8618.b*	Iscalitas	senile F	Pit	EBA	Cranium	1.3	38.4	23.1	2.2	-19.0	10.5
Cr. C7	8619	Iscalitas	adult M	Pit	EBA	Cranium	2.4				-19.5	10.5
Inf. 8 = sa.15	8620.2	Iscalitas	infant	Pit	EBA	Humerus	0.8	40.0	16.3	3.3	-19.2	8.8
Cr. C22	8621.2	Iscalitas	adult F	Pit	EBA	Cranium	2.2	37.9	16.7	3.1	-19.2	10.6
Cr. C42	8622.2	Iscalitas	adult M	Pit	EBA	Cranium	0.4	35.8	14.5	3.3	-19.5	9.6
Cr. C28 box 7492	*8623.b*	Iscalitas	adult M	Pit	EBA	Maxilla	1.4	35.6	15.2	3.1	-19.0	11.4
Cr. C40 box 7492	8624	Iscalitas	senile M	Pit	EBA	Cranium	1.8				-18.9	11.5
Cr. C18	8625	Iscalitas	adult M	Pit	EBA	Cranium	2.1				-19.4	11.4
Cr. map.64 = I.5 with Sa.6 = I.5bis	8626	Iscalitas	senile F	Pit	EBA	Cranium	1.2				-19.4	9.9
Cr. C43	8627	Iscalitas	adult M	Pit	EBA	Cranium	3.0				-19.0	11.6
Inf. 10 = sa.16	8628	Iscalitas	infant	Pit	EBA	Femur	0.7				-19.1	10.1
Inf. 11 =sa.17	8629	Iscalitas	infant	Pit	EBA	Femur	2.3				-18.4	9.9
Cr. C30 box 7490	8630	Iscalitas	adult M	Pit	EBA	Cranium	1.4				-18.9	10.6
Cr. C54	8631.2	Iscalitas	adult M	Pit	EBA*	Cranium	3.8	38.8	16.3	3.2	-19.2	11.7
Sa.2	8632	Iscalitas	juvenile	Pit	EBA	Tibia	0.6				-18.5	10.5
Cr. C53	8633	Iscalitas	senile M	Pit	EBA	Cranium	2.6				-18.8	11.5
Cr. C36	8634	Iscalitas	senile M	Pit	EBA	Cranium	1.4				-19.2	10.8
Cr. C2	8635	Iscalitas	adult F	Pit	EBA	Cranium	2.1				-19.1	10.2
Ind. Y	9552	Montessu, t.10	adult ind.	Rock-carved tomb	MBA*	Cranium	2.5	40.7	17.1	3.2	-20.3	9.1
Cr. 8	6878	Is Aruttas	adult M	Cave	MBA-FBA	Cranium	14.4				-18.6	11.7
Cr. 2	6879	Is Aruttas	adult M	Cave	MBA-FBA	Cranium	15.8				-18.2	11.7
Cr. 5	6880	Is Aruttas	senile M	Cave	MBA-FBA	Cranium	12.1				-18.5	10.4
Cr. 14	6881	Is Aruttas	infant	Cave	MBA-FBA	Cranium	13.4				-18.2	11.2
Cr. 3	6882.b	Is Aruttas	adult M	Cave	MBA-FBA	Cranium	17.1	41.6	17.8	3.1	-18.8	10.6
Cr. 4	6883	Is Aruttas	senile M	Cave	MBA-FBA	Cranium	13.9				-18.7	9.0
Cr. 10=12	6884	Is Aruttas	senile F	Cave	MBA-FBA*	Cranium	15.1				-18.9	9.8
Cr. 9	6885	Is Aruttas	senile F	Cave	MBA-FBA	Cranium	13.8				-19.0	9.9
Cr. 11	6886	Is Aruttas	adult F	Cave	MBA-FBA	Cranium	14.9				-18.8	10.2
Cr. 7	6887	Is Aruttas	adult M	Cave	MBA-FBA	Cranium	13.3				-18.2	11.2
Cr. 13	6888	Is Aruttas	juvenile	Cave	MBA-FBA	Cranium	15.3				-19.1	9.2
n/15	7057	Sedda sa Caudeba t. B	adult F	Chamber tomb	MBA-FBA	Pelvis	1.9	42.1	15.2	3.2	-19.1	9.1
p/15	7059	Sedda sa Caudeba t. B	adult M	Chamber tomb	MBA-FBA	Pelvis	1.1	52.9	19.2	3.2	-18.9	9.5

Not all samples could be assessed through C:N ratios since the analyzer became available only after the the first batch of analyses; the lack of this parameter, surely not an ideal situation, does not undermine the validity of the overall results: in fact, those measured were all except two between 2.9 and 3.2, therefore within the range expected for well preserved samples (DeNiro 1985). The only two samples off the range are from Iscalitas (8617.b and 8618.b), for measurements of N % systematically off due to instrumental error, as detected on several samples belonging to other collections from diverse contexts, whereas C% were instead accurately measured; therefore, C:N ratio resulted out of the range. Considering this, and the fact that isotopic values are fully within the range of the remainder, the choice was made to include these two results into the pool of values for dietary reconstruction. Sample 9552 from Montessu had only one replicate measured, and must therefore be considered cautiously as an indication of diet despite having C%, N% and C:N ratio within the acceptable range. Finally, both δ^{13}C results from Sedda sa Caudela t. B are used for dietary reconstruction until more analyses will be performed, but they too must be considered with caution: one (7057.b) because the two replicates yielded quite different values (-20.1 and -18.1‰), the other (7059.b) because due to an istrumental error only one replicate was measured. δ^{15}N results are, however, very consistent. Finally, a possible symptom of instrumental and/or preparation problems for Is Aruttas lies in that δ^{13}C of sample 6884 (= cr.10), when analyzed for AMS dating at the University of Arizona, yielded a quite different value compared to the measurement from the University of South Florida (USF = -18.8‰ vs. UA = -19.8), which casts a doubt on the consistency and reliability of the results pertinent to this site.

16 Isotopic results (Tables 1 and 2, Fig. 2) are largely overlapping with most isotopic results from W and Central Mediterranean sites, all indicating diets within terrestrial, C3 ecosystems. A few values from Is Aruttas may be compatible with some limited consumption of aquatic food and/or C4 plants, whereas the single δ^{13}C value from Montessu, t. 10 appears definitely different from the rest, indicating probably a diet heavily based on vegetal foods, and relying more on grains than legumes compared to the rest, or an outsider to S Sardinia. Any other assessment would be speculative based on these data, since without clear C4 or aquatic signal, nor faunal baseline data, isotopic differences due to environmental/ ecosystem-wide variation are potentially larger than variation due to diet.

2. Scatterplot of adults' δ^{13}C and δ^{15}N isotopic values of the five Bronze Age sites analyzed



17 Considering the two groups with large sample populations, sex-based dietary difference was examined; difference in δ^{15}N values was not found statistically significant with the T-test nor

with the Mann-Whitney test for either Iscalitas (F = 7; M = 15) nor Is Aruttas (F = 3; M = 6), nor was it in $\delta^{13}C$ values for Iscalitas; Is Aruttas instead did show a statistically significant difference (T-test: $p = 0.04$; Mann-Whitney: $p = 0.04$). The small sample size and the p value barely within the significance range, of course, suggest caution in drawing conclusions.

Discussion

18 A correct interpretation of the isotopic values in dietary terms, in the specific context of post-Mesolithic W Mediterranean prehistory, requires consideration of the specific resources available, archaeologically documented as food items. There is evidence that, in the Mediterranean, reliance on fishing never approached the importance it had in the Atlantic coasts and the Baltic; based on evidence in material culture and a growing body of isotopic measurements (Craig *et al.* 2006), it seems that until the advanced Bronze Age exploitation of seafood was nutritionally negligible. $\delta^{13}C$ and $\delta^{15}N$ as documented in present-day W Mediterranean marine ecosystems appear to be variable but comparable to those in the Atlantic Ocean (Richards & Hedges 1999), ranging from human-like to values up to $\delta^{13}C = -16‰$. Thus, if marine food consumption was significant, it would be reflected in much more enriched values, due to trophic level effect, as documented elsewhere. This seems to hold not only inland, but also on islands and coasts, as recorded in the Aegean (Richards & Hedges in Martlew & Tzedakis 1999), with the exception, at LBA Mycenae, of a few members of the elite whose distinct burial context matched a diet that likely included some fish. Similar data have produced samples from the Balearic islands, where some fish consumption seems to appear only after 500 BC (Davis 2002; Van Strydonck *et al.* 2002). In conclusion, the contribution of marine food to prehistoric Mediterranean nutrition seems to have been, in the Bronze Age, fairly marginal, and the data from Sardinia, despite their diversity in reliability of contexts and of preservation, seem aligned with such findings. The other sharply different signature is from C4 plants, which do not appear to be used in earlier prehistory, whereas millet was possibly introduced in N Italy by the MBA-LBA (Tafuri *et al.* 2009).

19 Environment-related ecosystem-wide changes cannot obliterate the clear signature of seafood and C4 plants, but can prevent detection of variation within C3 food chains. To do this, faunal and botanical remains coming from the same context are the ideal situation, but also a very rare occurrence. Only when burial ritual involves the offering of foodstuffs or their contextual consumption can we reasonably assume that we deal with interconnected rings of the same food chain. Otherwise, habitation sites that can be associated with the burials could help. Without any such combinations, biotic remains from contexts reasonably close (temporally, geographically) can be used to build the local isotopic baseline. Using $\delta^{15}N$ data from the available collections recovered at the closest sites (Table 3), ranging from ~5km to ~ 35km, the groups of Concali Corongiu Acca, Iscalitas and Is Aruttas show the largest offsets, between 4.2 and 5.0‰, which would imply higher consumption of animal proteins, whereas the human-animal interval between Montessu t.10 and the fauna of Monte Meana, about 10km apart, is only 2.1‰, confirming the general impression of a low trophic level. The individuals from Sedda sa Caudela t.B show an intermediate value, 3.6‰, which would reflect an intermediate diet. Despite the good correlation between $\delta^{15}N$ values and the $\delta^{15}N$ humans-animals offset, much caution is needed: the faunal data are few in number (range is from 4 to 16 individuals per site), they do not match temporally nor spatially with the human data, and even though all groups are dominated by ovicaprines, they are uneven in species representation and the different species do not show similar intervals among them.

Table 3. Average δ15N isotopic values, human-domesticated fauna offsets, and distances from sites were human skeletal materials are from. Data marked with * are after Lai, 2008. The rest from unpublished data.

Human remains site	*phase*	Avg. coll. $\delta^{15}N$‰ humans ± SD	Faunal remains site	*phase*	Avg. coll. $\delta^{15}N$‰ faunal ± SD	Distance rounded to 1Km	Offset avg. $\delta^{15}N$‰ human-faunal
Concali Corongiu 'Acca	EBA	11.4 ± 0.8	Monte Meana	EBA	7.0 ± 1.9	22	4.4
Iscalitas	EBA	10.4 ± 0.9	Padru Jossu	Bell Beaker	6.2 ± 0.8	34	4.2
Montessu t. 10	MBA	9.1	Monte Meana	EBA	7.0 ± 1.9	10	2.1
Is Aruttas	MBA-FBA	10.5 ± 0.9	S. Caterina di Pittinuri*	ECA	5.5 ± 1.7	19	5.0
Sedda sa Caudeba t. B	MBA-FBA	9.3 ± 0.3	Bingia 'e Monti	EBA	5.7 ± 0.8	3	3.6

20 Considering the lack of faunal remains directly associated with the human remains, another tentative way to peel off a layer of environmental variability has been explored, based on previous studies on the consistent correlation between climatic parameters and isotopic values (Amundso*n et al.* 2003), in order to remove some of the isotopic shifts affecting the whole system and enabling a more reliable comparison among diets in different populations. Surprisingly, despite the theoretical and empirical evidence and the available quantification of such correlations into equations, there has not been so far an attempt to practically use it. Regarding collagen $\delta^{15}N$, Schwarcz *et al.* (1999) documented a correlation with average precipitation that is here used as a predictive line of expected values. Similarly, van Klinken *et al.* (2000; 1994) have documented similar correlations of collagen $\delta^{13}C$ with several climatic parameters, of which average July temperature was selected as the one that explains most of the variation. The equations below were therefore used to calculate predicted values:

$^{15}N = (16.37 \pm 1.23) + (-0.01108 \pm 0.0011) * \text{average mm/year}$

$^{13}C = -22.7 + (-0.181 \pm 0.039) * \text{average annual T°C}$,

21 where average precipitation and average temperature (annual average, since July average was not available) are after Pracchi & Terrosu-Asole (1971). The difference between predicted values and measured values was then calculated, and such interval was added to a number which for the sake of immediate readability was chosen as the average of all 152 measurements performed ($\delta^{15}N = 9.43$‰, $\delta^{13}C = -19.83$), which include a large majority of collections from the period 4000-1000 BC (Lai 2008). There are admittedly several assumptions behind this procedure: a) that rainfall and temperature's spatial distribution at any considered time in prehistory was similar to the present one; b) that rainfall and temperature from year to year at any considered time in prehistory was similar to the present one; c) that geomorphology, latitude, altitude were consistent; d) that vegetation cover, which affects isotopic values, was similar. While c) can be safely assumed to be true, the rest have unquantifiable ranges of possibility and probability, which future studies may narrow.

22 All other sources of isotopic variation remain in place: manuring, livestock management, forest burning, food processing, which can be partially accounted for if faunal remains were available (a review in Murphy & Bowman 2006). Finally, a limitation not to be neglected is that the large error in the terms of the equations generate a very large error in the transformed value, which makes all results potentially overlapping; of course it is hoped that more work and data in the future will enable a refinement of these predictive equations, and/or that more complex models will be created that take into account these and other variables; anyway, the error reflects the data on which the model was constructed, but does not need to be applied to the transformed values.

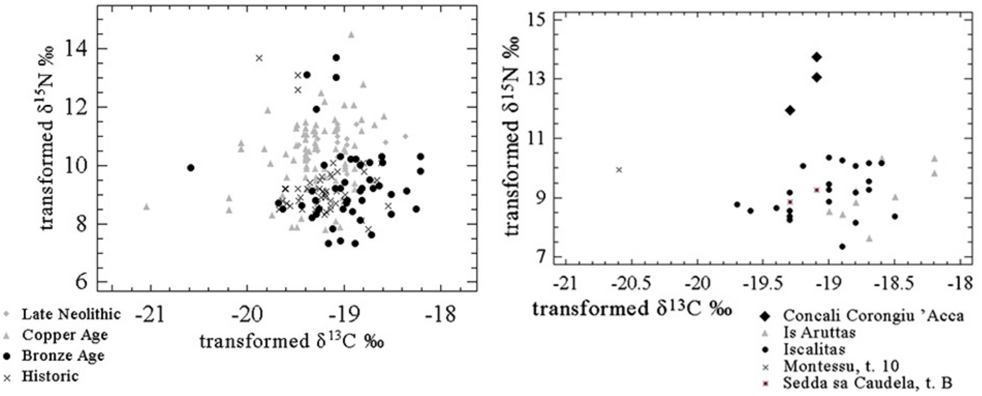
23 The elimination of a portion of climate-related variation produced the expected outcome on the correlation of different isotopic values: concerning the correlation $\delta^{15}N_{col}$-$\delta^{13}C_{col}$, which is assumed to depend on common climatic effects, R^2 decreases from 23.49% to 0.57%, and *p* value becomes non-significant (from 0.00 to 0.36). Conversely, the correlation between $\delta^{15}N_{col}$ and the spacing $\delta^{13}C_{col-apa}$, expected to exist based on common roots (degree of animal products' consumption: Hedges 2003; Lee-Thorp, *et al.* 1989), obscured by ecosystem-wide variation

before transformation, reappears at a statistically significant level: R^2 from 0.04 to 24.94%, *p value* from 0.82 to 0.00. It can therefore be inferred that the goal of making the results a closer reflection of dietary values was achieved.

24 After this transformation, results can be used more reliably to compare dietary variation among groups, both among the Bronze Age ones and between Bronze Age and other phases. The scatterplot of corrected values (Fig. 3, left) shows that most Bronze Age individuals belonging to the groups of Iscalitas, Is Aruttas and Sedda sa Caudela t. B cluster in a cloud partially overlapping with the CA, but is clearly centered on lower δ^{15}N and less negative δ^{13}C. This could reflect several factors, which are complex to disentangle and assess (especially without faunal and botanical samples). If we attribute it to diet, it would seem that on average Bronze Age groups relied on sources of protein that are lower in δ^{15}N – so more plant protein than in LN-CA groups – but similar, or slightly less negative, in δ^{13}C. The simplest explanation could be the presence in the Bronze Age of small amounts of C4 plants, perhaps millet, introduced in the diet; this matches also the possible dating of Is Aruttas and Sedda sa Caudela and the first isotopic record of millet consumption in N Italy (Tafur*i et al.* 2009). Otherwise, assuming that a mix of vegetal and ruminant-derived protein made up the bulk of the protein intake, keeping as an end point the ruminant values (higher δ^{15}N and δ^{13}C), such variation could be due to differential average intake of grains vs. legumes, which are depleted in ^{15}N: less legumes in the LN-CA, more in the Bronze Age (and especially MBA-FBA). It seems anyway unlikely the opposite, a higher animal protein consumption in the Bronze Age. The group of Is Aruttas, AMS dated to the MBA-FBA, is the best candidate, due to its coastal location, for the early reception of millet from elsewhere in the Mediterranean. Alternatively, its enriched δ^{13}C values might reflect some specific lagoon adaptation (the site is today close to brackish-water bodies), although based on currently available data an even limited consumption of protein-rich foods as fish and mollusks would also have enriched δ^{15}N values.

25 Finally, the two groups of Concali Corongiu ‘Acca and Montessu t. 10 are outliers (Fig. 3 right), and they might reveal very different subsistence patterns, apparently indicating the former a high consumption of animal protein, the latter a very unique diet that seems incompatible with the context, suggesting that the individual may have been an outsider to S Sardinia. The pathological diploïc thickness of the remains from Concali Corongiu ‘Acca, however, calls for caution: values may be affected by physiological responses to disease, as shown experimentally and empirically (Reitsema & Crews 2011; Whit*e et al.* 2006).

3. Scatterplots of collagen δ^{13}C and δ^{15}N isotopic values after transformation (see text). Left: Comparison of Late Neolithic, Copper Age, Bronze Age and Historic groups analyzed. Right: Comparison of the five Bronze Age sites analyzed

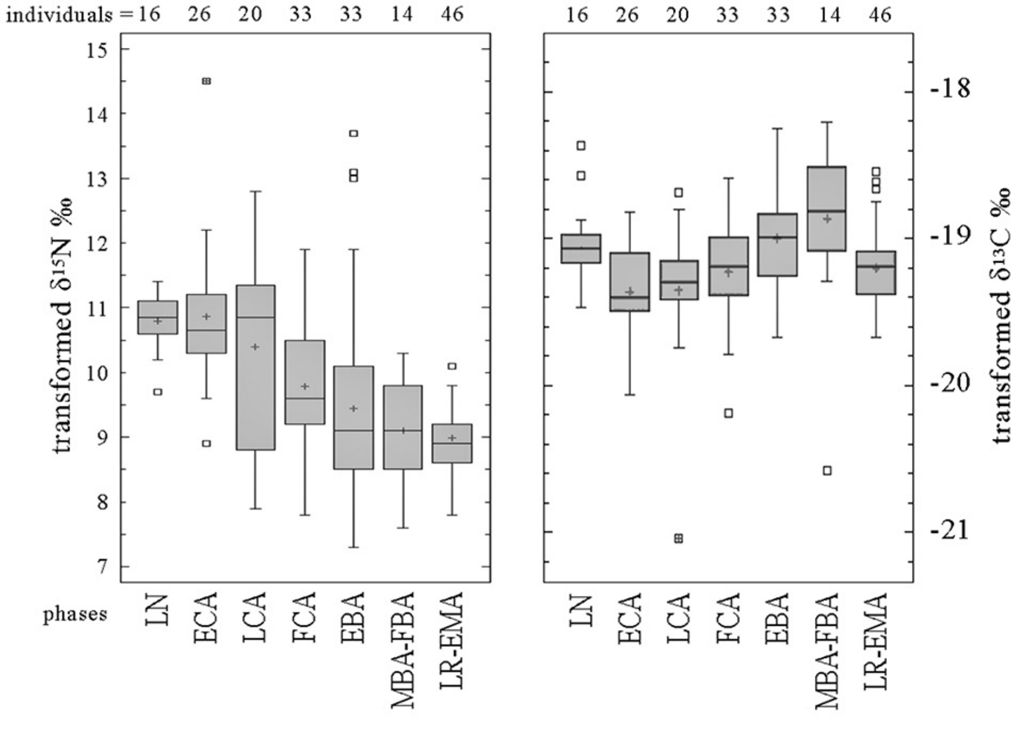


26 A comparison of δ^{15}N values (after transformation) with Fisher Least Significant Difference (LSD) test for different phases shows that EBA and MBA-FBA are significantly similar to each other; furthermore, they are both significantly different from the LN, ECA and LCA groups, previously analyzed (Lai 2008); the EBA, though, is actually close to FCA Bell Beaker, confirming in the nutritional/environmental domain a strong continuity recorded in most aspects of material culture. The box-and-whisker plot (Fig. 4, left), contrary to the few

data on offsets between fauna and humans, would indicate a trend of decreasing animal protein consumption from the 4th-early 3rd mill. BC – when average values are constant – to the 3rd mill. BC onwards – when values are compatible with a low consumption of animal protein. In between, with intermediate values, is placed the FCA Bell Beaker sample. Smaller variation over time is recorded for δ^{13}C (Fig. 4, right), most within 1‰, which is not reliable for dietary reconstruction; it is to be noted, however, the apparently regular trend of isotopic enrichment that accompanies the depleting δ^{15}N values from the LCA to the MBA-FBA. Considering that both use of marine foods and relevant C4 plants consumption are unlikely causes on their own, a combination of varying marginal contribution of either or both, and/or some of the other possible environmental factors are all potentially acceptable explanations.

27 In order to apply more accurate data corrections, it is planned to use δ^{18}O to complement the spatial information extracted from present-day precipitation patterns with a climate-change sensitive, direct isotopic indicator, as attempted in the past (Lai *et al*. 2007). However, some concerns with signal alteration – in this case especially relative to the site of Iscalitas – have prompted a reconsideration of the δ^{18}O dataset, with the application of FT-IR spectroscopy in order to investigate traces of diagenetic processes.

4. Box-&-whisker plots of collagen δ^{15}N (left) and δ^{13}C(left) isotopic values after transformation (see text) across different time periods



LN = Late Neolithic; ECA = Early Copper Age; LCA = Late Copper Age; FCA = Final Copper Age, Bell Beaker; EBA = Early Bronze Age; MBA-FBA = Middle to Final Bronze Age; LR-EMA = Late Roman-Early Middle Ages

28 Environments and soils cannot be used to infer possible variation in dietary habits: all sites are located in or near potentially good agricultural areas; the Southwest has had in the last centuries a strong pastoral connotation unlike the Southern-Central plains and hills, but this was due to historical dynamics that left uninhabited vast extensions of land.

29 These first data allow a tentative evaluation of the models outlined above; the traditional model depicting a pastoral Bronze Age society (Lilliu 1988), would not find isotopic confirmation if considering the transformed human data since precisely between Copper and Bronze Age there are values compatible with higher reliance on vegetal foods; however, the tentative comparison with faunal data from closest location is not incompatible with it, due to the larger offset between consumed and consumers. The continuity model (Lazrus 1999) is not supported either: the data, using both interpretive methods, show important variation in the amount of animal proteins both between the Bronze Age and other phases, and within the Bronze Age.

Webster's model of slow and gradual change towards intensification (Webster 1996) might be partially confirmed by an increase in plant proteins potentially visible between the EBA site Iscalitas and the few MBA-FBA individuals at Montessu, t.10 and Sedda sa Caudela B (Is Aruttas and Concali Corongiu Acca, as discussed, appear more problematic). Perra's (1997) model seems partially confirmed in the possible agricultural intensification in the MBA-FBA period that he proposes, but not in his scenario of cereal-based EBA economy.

30 These attempts to interpret the data are clearly tentative; the specific variation in the animal-human offset (Hedges & Reynard 2007), in the consumed animals' species-specific potential differences, and the many ecosystem-wide sources of error makes this reading provisional.

Conclusions and Perspectives

31 First isotopic ratios of collagen C and N have shown that diet in Sardinian Bronze Age is not different from what has been already recorded in most of the Mediterranean: it was based on terrestrial C3 products, with negligible or limited presence of aquatic foods and C4 plants. An assessment of the contribution of animal vs. vegetal protein, and a comparison among the five considered groups and with other groups is at the moment difficult due to lack of a faunal isotopic baseline. However, a method has been illustrated that takes into account the correlation of isotopic values with climatic factors in order to help improve inter-site comparability, by using present-day climatic data to account for geographic variation, and so improve the readability of dietary data. Applying such transformation, the data show that while still partially overlapping, Bronze Age groups may have been less reliant on animal products than those in LN and CA. After the Bell Beaker phase, average contribution of vegetal vs. animal protein was probably consistent through the Bronze Age, with no reflection of intensification in either agriculture or animal husbandry.

32 Considering that the majority of prehistoric Mediterranean contexts show similar C3 terrestrial dietary basis and that most of them do not have contextual association of different food chain rings (humans, animals and vegetals together), a few points need to be made. One is the scarce efficacy of collagen alone in detecting significant dietary variation; for this, despite its higher risk of contamination, coupling collagen and apatite measurements can refine nutritional interpretation by allowing a better assessment of whole diet (Hedges 2003; Ji*m et al.* 2004), and especially the components not represented in collagen, particularly lipids, since C3 grains have relatively similar isotopic signatures. Furthermore, there is a need for more theoretical modeling on how to exploit climatic correlations to create more powerful equations that can purify the dietary signal from such sources of error. Finally, an important challenge is to refine our knowledge of alternative sources of variation (see above: geographic location within a given radius from settlement; use of fertilization, fire, arboreal fodder etc: Bogaar*d et al.* 2007; Garten 1993; Leavitt & Long 1986) and to devise biochemical ways to assess them. One way could utilize an "ethno-biochemistry" approach, analyzing present-day controlled cultural ecosystems to better understand how and to which degree such practices can affect isotopic values. Without this, it appears that accumulating collagen data alone produces the likely wrong impression of a virtually homogeneous Mediterranean prehistoric diet. Regarding Sardinia, research in progress is going to document isotopic variation in humans and as much as possible faunas, filling the gaps in the record between the Neolithic and the Iron Age (4700-600 BC), in the attempt to pinpoint long-term continuity and change through integration of collagen and apatite.

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À propos des auteurs

Luca Lai
Department of Anthropology, University of South Florida, 4202 E. Fowler Ave., SOC107, Tampa, FL 33620, USA - melisenda74@yahoo.it

Robert H. Tykot
Department of Anthropology, University of South Florida, 4202 E. Fowler Ave., SOC107, Tampa, FL 33620, USA - rtykot@usf.edu

Elena Usai
Dipartimento di Biologia Sperimentale, Sezione di Scienze Antropologiche, Università degli Studi di Cagliari, Cittadella Universitaria S.P. Monserrato - Sestu Km 0,700 09042 Monserrato (CA), Italia -

Jessica F. Beckett

Department of Archaeology, University of Cambridge, Cambridge, United Kingdom – jfbeckett@googlemail.com
Rosalba Floris
Dipartimento di Biologia Sperimentale, Sezione di Scienze Antropologiche, Università degli Studi di Cagliari, Cittadella Universitaria S.P. Monserrato - Sestu Km 0,700 09042 Monserrato (CA), Italia - floris@unica.it
Ornella Fonzo
Laboratorio di Archeologia, Villanovaforru, Italy - ornellafonzo@virgilio.it
Ethan Goddard
Department of Chemical Oceanography, University of South Florida, St. Petersburg, FL 33701 - egoddard@mail.usf.edu
David Hollander
Department of Chemical Oceanography, University of South Florida, St. Petersburg, FL 33701 - davidh@usf.edu
Maria Rosaria Manunza
Soprintendenza per i Beni Archeologiciper delle province di Cagliari e Oristano, Piazza Indipendenza, 709124 Cagliari, Italia - mariarosaria.manunza@beniculturali.it
Alessandro Usai
Soprintendenza per i Beni Archeologiciper delle province di Cagliari e Oristano, Piazza Indipendenza, 709124 Cagliari, Italia – alessandro.usai@beniculturali.it

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Résumés

Traditional reconstructions depict Sardinian Bronze Age economy as a mixed one characterized by a remarkable importance of pastoralism, opposed to a more ‘agricultural’ Neolithic. The first few isotopic data, though not unambiguously, seem to indicate quite the opposite compared with earlier times, reflecting possibly a higher dependence on vegetal foods, with possible marginal contributions of aquatic foods and/or C4 plants at one coastal site. However, the importance of ecosystem-wide shifts in interpreting collagen data for comparative purposes is underlined, with specific examples from Sardinia, and so is the rarity of collections including faunal and botanical specimens alongside humans, which would help establish a local isotopic baseline. Efforts to discriminate animal vs. vegetal contributions in Bronze Age diets that are fully based on C3 ecosystems, therefore, remain tentative. Isotopic research in progress on Sardinian diet and climate from the Copper Age up to the Nuragic Late Bronze (2800-1100 BC) is expected to provide a better grasp on temporal and geographic variation.

La diète à l’âge du Bronze en Sardaigne : modèles, donnés isotopiques du collagène, problèmes et perspectives

Les reconstitutions alimentaires traditionnelles dépeignent l’économie de l’âge du Bronze en Sardaigne comme une économie mixte caractérisée par une grande importance de l’élevage des moutons, juxtaposée à une période néolithique plus agricole. Les premières données isotopiques, bien que peu nombreuses encore, semblent, d’une façon ambigüe, plutôt indiquer le contraire lorsqu’on les compare aux données des périodes précédentes. Elles montrent une plus grande dépendance des aliments végétaux avec peut-être la contribution marginale d’aliments aquatiques et/ou des plantes issues du milieu côtier. Afin de palier le manque d’études sur les restes fauniques et botaniques et dans le but de réaliser des comparaisons à l’échelle de la Sardaigne, une analyse détaillée des données isotopiques des collagènes a été réalisée pour cerner l’importance de modifications isotopiques de l’écosystème tout entier. Une recherche en cours sur la diète et sur le climat dans la Sardaigne à partir du Néolithique jusqu’à l’âge du Fer (4700-500 avant J.C.) devrait permettre une meilleure interprétation de la variabilité isotopique d’un point de vue chronologique et géographique.

Entrées d'index

Mots-clés : isotopes stables, régime alimentaire, Sardaigne, âge du Bronze, Méditerranée, collagène
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