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Analysis of seasonal mobility of sheep in Iron Age Catalonia (North-Eastern Spain) based on Strontium and Oxygen isotope analysis from tooth enamel: first results.

Valenzuela-Lamas, S. [1,2], Jiménez-Manchón, S. [3,4], Evans, J. [5], López, D. [2], Jornet, R. [2], Albarella. U. [1]

[1] University of Sheffield, Department of Archaeology, Northgate House, West Street, S1 4ET Sheffield, UK

[2] University of Barcelona, GRACPE, C/Montalegre 6-8, 08001 Barcelona, Spain.

[3] Universitat Rovira i Virgili (URV), Avinguda de Catalunya 35, 43002 Tarragona, Spain

[4] IPHES, Institut Català de Paleoecologia Humana i Evolució Social, Zona Educacional 4 - Campus Sescelades URV (Edifici W3) ES 43007 Tarragona, Spain

[5] NERC, Geosciences Laboratory, Keyworth, UK

Abstract (modified)

This pilot study investigates the existence of seasonal movements of sheep –transhumance– in Iron Age Catalonia (North-Eastern Spain). The occurrence of seasonal movement of livestock between the coast and the interior, perhaps in relation to the Mediterranean market, was suggested for this area based on landscape and palynological studies. This hypothesis was tested on the basis of strontium, carbon and oxygen isotope analysis from seven sheep lower third molars. The evidence obtained suggests that the animals did not move across geological areas during the time of enamel mineralization. In addition, the paper provides valuable isotopic evidence that can be used in further studies.

Keywords: Sheep/goat, transhumance, strontium, oxygen, carbon, isotopes, Iron Age, Spain

1. Introduction

Transhumance – understood here as the seasonal movement of livestock between complementary pastures (Geddes, 1983; Khazanov, 1984) – is a highly specialised economic system, the adoption of which has important implications for a community's socio-political structure, practices and cultural ideology (Walker 1983, Mc Donnell 1988). For years, the subject has generated an intense academic debate concerning the presence/absence of transhumance in different areas of prehistoric Europe, as well as its temporal origin (e.g: Higgs 1976, Cunliffe 1978, Chapman 1979, Davidson 1980, Halstead 1987, 1996, Cherry 1988, Greenfield 1999, Hill 1995, Kienlin and Valde-Nowak 2002-2004, Arnold and Greenfield 2006, Tullet 2011). The Iberian Peninsula also featured in this debate (e.g: Molina and Arteaga 1976, Molina 1978, Walker 1983, Cara and Rodríguez 1987, Galán and Martín 1991-1992, Delibes and Romero 1992, Harrison 1993, 1995, Cura 1995, Sánchez-Moreno 1998, Cebrià et al. 2003, Riera et al. 2007).

Up to now, most studies have used indirect evidence to address this issue. This includes typological similarities in artefacts between distant territories (e.g: Molina and Arteaga 1976, Molina 1978, Delibes and Romero 1992, Kienlin and Valde-Nowak 2002-2004), settlement patterns (e.g: Higgs 1976, Cara and Rodríguez 1987, Galán and Martín 1991-1992, Cebrià et al. 2003), as well as the absence of cereal storage structures – silos – in some areas (e.g: Cura 1995, Hill 1995).

This paper aims to provide direct evidence to inform the debate on seasonal movement of livestock in Iron Age Catalonia (north-eastern Spain), based on data from stable isotopes of strontium ($^{87}Sr/^{86}Sr$), oxygen ($^{18}O/^{16}O$) and carbon ($^{13}C/^{14}C$) obtained from archaeological sheep teeth. It represents the first isotopic study applied to Iron Age sheep remains in this region.

The Iberian culture (6^{th}-2^{nd} century BC) developed in the eastern area of the Iberian Peninsula as the result of the evolution of the small-scale societies of the Late Bronze Age into more complex ones in the Iron Age, organised in political entities (e.g. Sanmartí 2001a; 2004; 2009a; Sanmartí et al. 2006). Each Iberian territory contained settlements of different sizes and functions (towns of different scales, villages, fortified sites, rural settlements), which were organized following a hierarchical pattern and according to a proto-state structure probably in place from the 6^{th} to the 5^{th} century BC (Asensio et al. 1998, Sanmartí 2002, Sanmartí et al. 2006). On the basis of landscape studies (Grau 2003, Sanmartí 2001b; 2002; 2004; Sanmartí and Santacana 2005), the proposed boundaries between the different proto-states were found to correspond approximately to different ethnic groups, as indicated by ancient sources (Ptolemy – *Geographia*, II, 6, and Pliny the Elder – *Naturalis Historia*, III, 4, 20), and already suggested by Bosch Gimpera (1932).

The archaeological record of the Iberians inhabiting present-day Catalonia indicates close trade links with other Mediterranean populations – Phoenicians and Greeks (Sanmartí and Asensio 2005, Rouillard 2009, Sanmartí 2009b) - as well as an economy based on intensive cereal farming and animal husbandry (Sanmartí 2001a; Iborra 2004; Pérez-Jordà et al. 2007; López et al., 2011). According to zooarchaeological analysis, caprines were the most abundant taxon, followed by pigs and cattle (Albizuri and Nadal 1999; Franquesa et al. 2000; Valenzuela-Lamas 2008; Albizuri et al. 2010; López et al., 2011). Hunting is represented by the remains of red deer and rabbit in low proportions (usually less than 5% NISP), whereas equids and dogs were not part of the usual meat diet, though were occasionally consumed (Albizuri et al. 2010; López et al. 2011).

The presence of a number of stone enclosures dating from the early Iron Age (7^{th} c. BC) in the central coast of Catalonia (Miret and Miret 1981, Mestres et al. 1994-1996, Cebrià et al. 2003) led to the hypothesis that an intensive pastoralism, perhaps in relation to colonial markets, could have existed in this geographic zone (Cebrià et al. 2003). Progressive deforestation was attested by palynological evidence, which led to the hypothesis that movement of livestock between the coast and the interior in this area may have occurred (Riera et al. 2007).

The Iron Age site of Turó de la Font de la Canya was selected for a variety of reasons. Firstly, the site provides good bone preservation and a reliable chronology. Secondly, it is a central storage site for cereals, and it could be a gathering point also for livestock. Thirdly, it is located in the area where palynological evidence suggests movement of livestock in the Iron Age (Riera et al. 2007), and a number of stone enclosures were interpreted as livestock enclosures built in this period (Miret and Miret 1981, Mestres et al. 1994-1996, Cebrià et al. 2003). Finally, the site is located at the junction of two historical transhumant routes (Rovira and Miralles, 1999), on distinctive geological bedrock (figure 1).

2. Materials and Methods

Turó de la Font de la Canya (Avinyonet del Penedès, Catalonia) is an Iron Age site located 40 km south of Barcelona. It represents a 'silos champ' – a site specialized in cereal storage. These sites are characterized by a small habitation area compared to the extension devoted to cereal storage (Asensio et al. 1998, Sanmartí 2002, Sanmartí et al. 2006; figure 2). Cereals are stored in holes excavated in the ground – 'silos' – where anaerobic conditions favour preservation. According to archaeobotanical evidence, the most common cultivated species was barley (*Hordeum vulgare*), followed by common wheat (*Triticum aestivum*) and durum wheat (*Triticum durum*), among others (López 2004). After several years of use, these structures were back-filled with all kinds of domestic waste, and therefore they provide precious evidence of human activity (López 2004).

The site was built in the 7th century BC on a small promontory (230 m a.s.l.), about 15 km from the present-day coastline, and it was abandoned in the first half of the 2nd century BC, during the Roman period. Excavations conducted in the last fifteen years indicate that this settlement was a central point of cereal storage, and it provided the first evidence of wine production in this region, as well as numerous Phoenician imports (López 2004, López et al. 2011, López et al. 2013). The site has very good visual connection with other sites in the surrounding area, and it is located on the natural way that connects the pre-littoral valley with the coast. The underlying geology is composed of Early Miocene chalk, which is highly recognizable from the surrounding Cretaceous, Triassic and Pleistocene sediments (figure 1).

Seasonal changes in the strontium, carbon and oxygen isotopic ratios of diet are preserved in the mineral fraction of the enamel (hereafter referred to as bioapatite) during tooth growth, and they can be detected by sequential sampling of enamel along the tooth crown (Sharp and Cerling, 1998; Gadbury et al., 2000; Bocherens et al., 2001, Balasse et al. 2002, Bogaard et al. 2013).

Seven archaeological third lower sheep molars were chosen for isotopic analysis. Despite the higher inter-individual variation in the enamel mineralization of the third molar in comparison to the second (Blaise and Balasse 2011, Tornero et al. 2013), and the possible averaging of isotope ratios (Montgomery et al. 2010), this tooth was selected because it was easily identifiable even when isolated, and it provided higher tooth crowns than the available second molars. Sufficient crown height was necessary to analyze mobility in the longest possible time span.

The isotopic analyses were performed on seven lower sheep third molars recovered from three silos dating to the 4th-3rd c. BC. This chronological phase was selected because it corresponds to the period when the Iberian state structure was already well established, and a market economy probably existed (Sanmartí 2004). Therefore, it is the period when transhumance could have existed with more probability. The species was determined based on the criteria described in Halstead et al. (2002). In order to test the existence of seasonal movements during the period of tooth formation three transversal slices from the protoconid of each tooth were cut for strontium isotopic analysis using a diamond cutter disc coupled to a dentist drill (figure 3). In four teeth, the first sample was located just above the enamel root junction (ERJ), the second one at 6-8mm, and the third one at 12-14mm from ERJ. In three cases, where the animals were younger and the tooth crowns were higher, between six and eleven transversal slices of c.2 mm of width were sequentially taken for oxygen isotopic analysis, and the three strontium samples were more spaced: 0 mm, 6 mm and 15mm from ERJ in one case; 0 mm, 12 mm and 24 mm from ERJ in another case; and 0 mm, 15 mm and 30 mm in the third case (figure 3). In all cases, only fully formed teeth (i.e. with closed roots and in wear) were chosen for analysis. In addition, three dentine samples and two present-day leaves from downy oak (*Quercus humilis*) and evergreen oak (*Quercus ilex*) were analyzed to obtain the local strontium signature of the site. For the regional comparison, we relied on the predicted strontium isotopic values based on the ones obtained on local mineral waters (Voerkelius et al. 2010).

In total, we got 26 strontium isotope ratios coming from seven archaeological third lower sheep molars and two present-day leaves, together with 26 carbon and oxygen ratios from the three archaeological teeth having the highest tooth crowns.

2.1. Strontium isotope analysis

Strontium isotopes ($^{87}Sr/^{86}Sr$) provide direct evidence of geographical origins and patterns of livestock mobility (e.g: Balasse et al., 2002; Bentley, 2006; Evans et al., 2007; Pellegrini et al., 2008; Sykes et al., 2006; Viner et al., 2010, Bogaard et al., 2013, Minniti et al., 2014). The Sr isotopic ratio ($^{87}Sr/^{86}Sr$) varies in different geological formations according to the age and original rubidium (Rb) content of the bedrock (Bentley, 2006). As ^{87}Rb decays into ^{87}Sr over time, the older a rock formation, the higher the proportion of ^{87}Sr compared to ^{86}Sr (Faure and Mensing, 2005).

The $^{87}Sr/^{86}Sr$ isotope composition of skeletal material derives from the food and drink ingested by the animal, as strontium substitutes for calcium in the minerals of the skeletal tissue (Comar et al., 1957; Toots and Voorhies, 1965). In the case of teeth, the isotopic signature of the enamel bioapatite reflects the period of tooth formation with little subsequent change. Dentine is more susceptible to diagenetic alteration (Budd et al., 2000; Evans et al., 2007; Price et al., 1992), and therefore its strontium isotopic values usually reflect the burial environment rather than the original lifetime composition (Viner et al., 2010, Minniti et al. 2014).

The enamel samples were prepared following standard practices used at NERC Isotope Geosciences Laboratory at Keyworth (UK) in previous studies of herbivores (Viner et al. 2010, Towers et al. 2010). The samples were first mechanically abraded to remove all dentine and cementum. The enamel surface of the tooth was abraded to a depth of >100 microns using a tungsten carbide dental burr and the removed material was discarded. Thin enamel slices (c. 2mm wide) were then cut from the tooth using a flexible diamond edged rotary dental saw. The resulting samples were transferred to a clean (class 100, laminar flow hood) working area for further preparation. This involved ultrasonic cleaning to remove adhered material and immersion in 60°C water for an hour for further clean. After each cleaning phase the sample was rinsed three times on MilliQ high purity de-ionized water. Once cleaned and dried in a laminar flow hood, the samples were weighed into pre-cleaned Teflon beakers. The samples were mixed with ^{84}Sr tracer solution and dissolved in Teflon distilled nitric acid (8 M HNO_3). Strontium was collected using standard resin columns and then loaded onto single tungsten filaments.

Samples of modern leaves were crushed using a pestle and mortar, and then weighed into pre-cleaned pressure vessels in a clean laboratory environment. They were dissolved in Teflon distilled nitric acid (8M HNO_3) overnight at room temperature. Further acid and a trace of H_2O_2 were added next, before the samples were processed in a microwave oven at 175°C for 20 min. The samples obtained were then dried down overnight on a hotplate prior to a secondary oxidation step comprising the whole process again. The samples were converted to chloride by taking them up in 6M HCl, then dried and taken up again in 2.5M HCl prior to strontium separation using standard resin columns.

The strontium isotope composition and concentrations were determined by Thermal Ionisation Mass Spectroscopy (TIMS). The international standard NBS 987 for $^{87}Sr/^{86}Sr$ gave a value of 0.710253±0.00006 for static analysis (1s, n=350; data for last 2 years).

2.2. Oxygen and Carbon

The ratio between ^{18}O and ^{16}O (hereafter $\delta^{18}O$) changes with temperature in meteoric water and, in a similar process to that of strontium, oxygen isotopes are incorporated into enamel bioapatite through food and drink during tooth formation (Fricke and O'Neil, 1996; Sharp and Cerling, 1998). In general, the highest $\delta^{18}O$ ratios occur in warm waters and the lowest in cold waters, although other factors, such as the amount and the timing of precipitation can influence them (McCrea, 1950; Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993; Gat, 1996; Kohn and Welker, 2005). In latitudes where seasonal variations in temperature occur, the $\delta^{18}O$ ratios provide a time frame related to the annual cycle that, in combination with strontium signatures, can be used to detect seasonal movements between different geological areas during the time of tooth formation (Balasse 2002, Bentley and Knipper 2005, Bogaard et al. 2013).

Oxygen isotopes were obtained from enamel carbonate previously cleaned, as explained above for strontium analysis. Once cleaned and dried in a laminar flow hood, the samples were weighed into pre-cleaned Teflon beakers and then crushed using an agate mortar and pestle. Approximately 3 milligrams of prepared enamel was loaded into a glass vial and sealed with septa. The vials were transferred to a hot block at 90°C on the GV Multiprep system, then evacuated, and 4 drops of anhydrous phosphoric acid were added. The resultant CO_2 was collected cryogenically for 14 minutes and transferred to a GV IsoPrime dual inlet mass spectrometer. The resultant isotope values were treated as a carbonate. $\delta^{18}O$ is reported as per mil (‰)($^{18}O/^{16}O$) normalized to the PDB scale using a within-run calcite laboratory standard (KCM) calibrated against SRM19, NIST reference material. For comparison with other studies, the values were also converted to the SMOW scale using the published conversion equation of (Coplen 1988): SMOW=(1.03091 x $\delta^{18}O$ VPDB) +30.91. Both carbon and oxygen VPDB values, together with carbonate oxygen results ($\delta^{18}O$ SMOW) are presented in Table 3.

Analytical reproducibility for this run of laboratory standard calcite (KCM) was 0.09‰ (1 σ, n=6) for $\delta^{18}O$ SMOW, and ± 0.04‰ (1s, n=6) for $\delta^{13}C$ PDB.

Analysis of oxygen obtained from carbonate, as opposed to phosphate, is a well-established technique (Balasse et al. 2013, and references within), and the carbonate has been shown to be robust in archaeological burial conditions (Chenery and Evans 2012, and references within). An advantage of obtaining oxygen ratios from carbonate is the additional availability of $\delta^{13}C$ compositions, which provide information on diet and vegetation (e.g. Sullivan and Krueger 1981, Krueger and Sullivan 1984, Lee-Thorp et al. 1989, Ambrose and Norr 1993, Tieszen and Fagre 1993, Quade and Cerling, 1995; Cerling et al., 1997; Koch, 1998; Tipple and Pagani, 2007). $\delta^{13}C$ in herbivore teeth mainly reflects the proportion of C_4 (typically tropical grasses) and C_3 plants (mostly temperate zone plants) in the diet. C_4 plants have relatively higher $\delta^{13}C$ values than C_3 because of an extremely efficient CO_2 fixation (Monson et al. 1984). Indeed, the average of $\delta^{13}C$ values in C_4 plants is −12‰, compared to a mean of −26‰ in C_3 plants (Smith and Epstein, 1971; Koch, 1998). The formation of enamel bioapatite in herbivores is accompanied by a carbon isotopic fractionation of ~ 13‰ (Koch, 1998), so that average values of −13‰ and +1‰ characterize the apatite of pure C_3 and C_4 consumers, respectively (van Dam and Reichard, 2009). A seasonal increase in $\delta^{13}C$ values of C_3 plants naturally occurs in summer (Smedley et al., 1991). Also, a large range in bioapatite (from −20‰ to −7‰) may reflect gradients from closed forest to open, more water-stressed environments (Farquhar et al., 1989; Van der Merwe and Medina, 1991; Ehleringer and Monson, 1993; Passey et al., 2002). As well as for strontium, we used the time frame provided by oxygen isotopic ratios to investigate dietary changes from $\delta^{13}C$ values at a seasonal scale.

3. Results

3.1. Strontium isotope ratios from dentine samples

The $^{87}Sr/^{86}Sr$ isotope ratio obtained from the three archaeological dentine samples and the two present-day leave samples range from 0.7094 to 0.7096 (Table 1). The two present-day leaves give the strontium signature of the site, which is consistent with the expected isotopic ratios for the local Miocene sediments of the area (Voerkelius et al. 2010, see also figure 1). As expected, diagenetically altered dentine samples are consistent with the local signature provided by leaves, and display higher concentrations than enamel samples (see table 2).

3.2. Strontium isotope ratios from enamel

Table 2 presents the isotopic ratio and strontium concentration for each enamel sample. All teeth – except SU1087A – display ratios between 0.7092 and 0.7096, which are consistent with the range observed in Miocene sediments (Evans et al. 2010; Voerkelius et al. 2010, see also table 1). Figure 4 shows the variation of strontium values across the crown height, each line representing one tooth. From the figure it is clear that SU1087A, with values from 0.7088 to 0.7090, plots separately from the other archaeological teeth. According to the strontium radiogenic ratios published in Evans et al. 2010 for Britain and Voerkelius et al. 2010 for Europe, these ratios are compatible with the signal obtained from Cretaceous sediments. This kind of sediments can be found in the proximity of the site, in the Garraf massif, distant only c.3 km from the site (figure 1).

From figure 4 it is also apparent that most teeth have very low isotopic variation across the crown height, with SU1030 and SU1090A and being the most stable (variation 0.000041 and 0.000048 respectively). Two teeth, SU1090B and SU1087A, however, display higher variation (0.000201 and 0.000202).

3.3. Oxygen and Carbon ratios from enamel

Table 3 presents the oxygen $\delta^{18}O$ PDB and carbon ratios for the three selected teeth. As explained above, these teeth were chosen because they were those with higher crown heights and, therefore, they were suited to provide a whole seasonal cycle. The $\delta^{18}O$ values measured vary from -3.0 to 0.8‰, and the amplitude of intra-tooth variation of $\delta^{18}O$ values is 2.1‰.

Two teeth (SU1090A and SU1087B) display a similar pattern of $\delta^{18}O$ variation through the crown height (figure 5). In both cases, the oxygen ratios first increase and then decrease from the apex (the youngest part preserved) to the ERJ. In tooth SU1081, where the crown height is significantly higher, the $\delta^{18}O$ value first decreases from apex to ERJ, then increases and decreases. In this case, the value located at 15 mm does not follow the values of the other two teeth, but the trend is common from the sample located at 9 mm onwards (figure 5).

Some variations may also be observed in the $\delta^{13}C$ values (figure 6). The measures obtained range from -12.2 to -10.0‰, with amplitudes of intra-tooth variation around 1.3 (0.8 to 1.6). In teeth SU1081, some correlation between higher $\delta^{13}C$ values and higher $\delta^{18}O$ values seems to exist. This correlation is not clear in teeth SU1090A and SU1087B.

3.4. Strontium and Oxygen isotopes

Figure 7 plots the oxygen curves and the strontium ratios obtained on the selected third lower molars. As expected from the results in figure 4, it is clear that similar strontium ratios were incorporated into enamel bioapatite in different periods of the year during the period of tooth formation.

4. Discussion

4.1 Strontium and oxygen isotope ratios and animal mobility

The local signature of the site was obtained on the basis of two present-day leaf samples and, more tentatively, three archaeological dentine samples (table 1). The results obtained are consistent with the studies stating that dentine re-equilibrates with the Sr isotopic signal of the burial environment (Budd et al. 2000, Evans et al. 2007, Viner et al. 2009, Madgwick et al. 2012, Minniti et al. 2014).

Concerning enamel results (table 2), all strontium isotopic ratios except the ones from tooth SU1087A are consistent with the local Miocene geology (figure 1; Evans et al. 2010, Voerkelius et al. 2010). This implies that, during the period of enamel mineralization of the third molar – (between 18 and 30-36 months; Balasse et al. 2013)–, these animals were grazing on pasture that had the same radiogenic signature as the archaeological site. This suggests that the animals were kept in the site area, were imported from elsewhere on the same plain (Penedès), or came from areas further afield, with similar geology (e.g: els Pallaresos area, near Tarragona; see figure 1).

The lower strontium isotope ratios obtained for SU1087A (from 0.7088 to 0.7090) are consistent with Cretaceous signatures observed in other parts of Europe (Evans et al. 2010, Voerkelius et al. 2010). In the area, this kind of geological substrate is located in the Garraf massif, only c.3 km from the site. This means that the animal could originate from an area with a different Sr isotopic ratio range (e.g. the Garraf massif) but still be relatively local. The fairly variable strontium isotopic ratio that characterizes this tooth could also indicate movement between the two geological areas – the Penedès plain and the Garraf massif – during the period of tooth formation but, on the basis of the current evidence, this can only be a tentative suggestion.

According to the data obtained on the three sheep lower molars where both strontium and oxygen data were available (figure 7), no seasonal movement of livestock could be demonstrated at Turó de la Font de la Canya.

4.2 Carbon isotope ratios and sheep diet

The $\partial^{13}C$ values obtained are compatible with a diet mainly composed of C_3 plants, which constitute the vast majority of plant species in the Penedès and Garraf regions today (Bolòs and Vigo 1990, 1995). The observed correlation between higher $\delta^{18}O$ and $\delta^{13}C$ values in tooth SU1081 (figure 6) could correspond to the natural seasonal variation occurring in C_3 plants (Smedley et al., 1991). The presence of stable carbon isotope values around −10‰ in the three teeth analysed (table 3) could correspond to a small contribution of C_4 plants to the diet (Balasse et al. 2013). The occurrence of C_4 plants in the wild is minimal in the Penedès plain, with just two taxa, poorly represented in the landscape: saltwort (*Salsola genistoides*) and saltbush (*Atriplex glauca*) (Bolòs and Vigo 1990, Pla de Ports de Catalunya). However, broomcorn millet (*Panicum milliaceum*), a domestic C_4 plant, has been attested from charred seeds in the site from the earliest levels of occupation (López 2004). In the case of teeth SU1987B and SU1090A, some high $\delta^{13}C$ values occur when $\delta^{18}O$ are lower and vice-versa, therefore not fitting with the seasonal pattern of variation of $\delta^{18}O$ ratios in C_3 plants. More data are needed about the patterns of seasonal variation of $\delta^{13}C$ values in the area of study, but the $\delta^{13}C$ ratios suggest that broomcorn millet could have been occasionally used as complementary fodder in sheep diet. Alternatively, it may also correspond to C_3 plants collected in summer and then given to the animals later on in the year.

5. Conclusion

Seven lower third sheep molars from Turó de la Font de la Canya (Catalonia, north-eastern Spain) dating from the 4th-3rd c. BC were analysed for strontium, oxygen and carbon stable isotopes. The aim of the study was to test the current hypothesis that – in the middle Iron Age (4th-3rd c. BC) - seasonal movement of livestock occurred between the Garraf massif and the interior (Penedès plain), as suggested on the basis of landscape (Cebrià et al. 2003) and palynological studies (Riera et al. 2007). Oxygen data were used to estimate the season in which these movements could occur, as well as to detect seasonal changes in diet through the period of enamel mineralization.

The results obtained from strontium isotopes indicate that six of the seven sheep were raised on sediments with a radiogenic signal compatible with the local Miocene geology of the site. Consequently, they probably are of local origin, either from the site itself or from neighbour sites in the Penedès plain. One sheep displays strontium ratios identified in Cretaceous sediments, which can be found in the Garraf massif, c. 3 km away from the site. This tooth displays some variation in $^{87}Sr/^{86}Sr$ ratios along the tooth crown (figure 4), and the values could reflect the existence of a movement between the Penedès plain and the Garraf massif during the period of enamel mineralization, and back again to the Penedès plain later on, where it was slaughtered. Although this hypothesis tantalisingly suggests seasonal movement for this animal, the results are not fully conclusive as the two geological areas converge at the ratio of 0.7090 (the higher value documented in the tooth). Consequently, we cannot exclude the possibility that the animal was bred at the Garraf massif all the year round, and then imported to the site at a later stage.

The combined study of both strontium and oxygen showed that, at different times of the year, these animals were grazing on Miocene sediments. In Catalonia, these sediments are present in the Vallès-Penedès valley, and in fairly distant areas like the Cerdanya (Pyrenees, 156 km towards the north), and the Empordà valley (178 Km to the north east; ICC geological map). A seasonal change of pastures for the sheep from Turó de la Font de la Canya cannot be definitively be excluded, but the restricted area of distribution of the Miocene sediments makes it unlikely.

As regards to sheep diet, the $\delta^{13}C$ values obtained are compatible with a diet mainly composed of C_3 plants all the year round. This is unsurprising, as these plants are typical of temperate Europe and largely dominate the landscape today. However, the presence of stable carbon isotope values around −10‰ in the three teeth analysed, not always coinciding with higher $\delta^{18}O$ values – which could reflect the natural seasonal variation occurring in C_3 plants – could indicate a small contribution of C_4 plants to diet (Balasse et al. 2013). Because C_4 plants are only found in saltmarshes near the sea in this area, it is probable that millet (*Panicum miliaceum*) – a domestic C_4 cereal documented at the site from the earliest levels of occupation – was occasionally used as complementary fodder. Another possibility is that C_3 plants were collected in summer and then given to the animals later on in the year.

Overall, isotopic analyses from animal bioapatite provide the most direct evidence to support the existence (or absence) of seasonal movements of livestock. The results of this pilot study indicate that the sheep analysed did not move across geological areas during the time of enamel mineralization, and that C_3 plants predominated in their diet. C_4 plants –such as broomcorn millet– may have been used as fodder in a limited way. Although more evidence is needed, this study provides a baseline to address the question of transhumance in Iron Age Spain based on direct evidence obtained from animal remains, and it provides valuable isotopic ratios for the region that can be used in further studies. We are currently working on extending the mapping of the bioavailable strontium in the region, as well as to increase the number and chronological range of the archaeological samples.

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