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Vertical sheep mobility along the altitudinal gradient through stable isotope analyses in tooth molar bioapatite, meteoric water and pastures: A reference from the Ebro valley to the Central Pyrenees

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ABSTRACT

Although the frequency of pastoral activities involving vertical sheep mobility has decreased over the last century, this is a herding strategy still used in the Ebro basin, where animals move from overwintering valley locations up to the Pyrenees from late spring to early autumn. Such practice allows herders to avoid the worst climatic conditions, seasonally balancing the great contrast between ecological zones in this region, from dry lowland Mediterranean steppe to wet mountain subalpine grasslands. As recent regional archaeological works have suggested, the altitudinal movement of flocks may have begun with the first early Neolithic groups settled in this territory. Here we investigate through stable isotope analyses one of the last flocks that still performs this activity. Sheep specimens were analyzed by sequential analyses ($\delta^{13}C$ and $\delta^{18}O$) in bioapatite of tooth enamel, allowing detection of seasonal changes. Tooth series are interpreted according to rainfall distribution, seasonal patterns in $\delta\ ^{18}O$ of meteoric water, vegetation changes and $\delta^{13}C$ values in pastures along the altitudinal gradient in the area. Vertical movements in sheep sequential series are recognized by an inverse relationship between $\delta^{13}C$ and $\delta^{18}O$ values. Monthly $\delta^{18}O$ values in meteoric water obtained in valley and mountain locations describe the same type of seasonal oscillation, with high values during the warm months and low values during the cold months. Pastures analyzed along the altitudinal gradient showed a decrease in $\delta^{13}C$ values with altitude, linked to the seasonal availability of precipitation and vegetation differences among locations. These results define a new analytical and conceptual framework for the interpretation of archaeological samples in this region.

1. Introduction and research objectives

In the Iberian Peninsula mobile herding systems have always been of major importance in livestock management. Large-scale transhumance, especially related to sheep husbandry and fine wool production, is historically the best documented strategy, in particular for the Middle Ages (Blanks, 1995; Braudel, 1972; Carter, 1964; Delano Smith, 1979; Klein, 1920; Wickham, 1983). Historical and ethnographic evidence suggests that herders of domestic livestock exploit differentiated pastures seasonally and altitudinally in order to maximize herd production and survivorship (Fillat, 1981; Moreno-García, 1999; Ott, 1981), and because the best feeding resources are found in two different ecological zones. Differences in temperature and rainfall between lowlands and uplands mean a displacement of annual pasture productivity peaks within both ecosystems (Bunce et al., 2006; Cabo Alonso, 1998; Manzano-

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Baena and Casas, 2010; Ruiz and Ruiz, 1986). Hence grazing areas located in the plains are best exploited during the winter and early spring, whereas mountain pastures offer livestock an escape from the hot dry summers on the plains as well as an opportunity for human communities to benefit from areas marginal to cultivation. Although this strategy has played a key role in shaping landscapes in mountain ecosystems and rural areas, nowadays it is used at a much smaller scale than in the past. Its decline is leading to what ecologists have recently described as the loss of "traditional ecological knowledge (TEK)" (Fernández-Giménez and Fillat Estaque, 2012; González et al., 2012; Oteros-Rozas et al., 2012, 2013).

Recognition of past mobile pastoral economies as part of prehistoric subsistence systems has also been a significant issue in archaeological studies. From the 1980s a large corpus of data has been generated by research carried out among traditional mountain rural economies in the Mediterranean (Barker and Grant, 1991; Bartosiewicz and Greenfield, 1999; Chang, 1992; Halstead, 1987, 1990; Koster and Koster, 1976; Lewthwaite, 1981, 1983; Moreno-García, 2001). The aim of most of these works has been to identify and characterize potential patterns of seasonal livestock movements in order to gain an insight into the cultural, socio-economic and environmental variables that define each of them. Indeed, these studies have demonstrated that there is far greater diversity in the patterns and practices connected with seasonal movements of livestock than previously thought (i.e. short-range movements within local territories, large-scale herding, small- and medium-sized flocks kept as part of a mixed farming economy and so on) (Halstead and Jones, 1989; Halstead and O'Shea, 1989; Halstead, 1990). These data were eventually used not as direct analogies, but as guides to the questions that should be asked of the archaeological record when analyzing past mobile pastoral strategies (Halstead, 1987). Therefore, this led some archaeological studies to integrate artefact and prehistoric site catchment area data, whereas others combined vegetation and sedimentary evidence with the analysis of faunal remains. As a result, the main contributions made derived from the geoarchaeological study of *fumiers* deposits in caves and rock-shelters, the estimation of caprine culling profiles based on tooth wear analyses or by looking at the relative frequency of perinatal and juvenile individuals. These methodological approaches evidenced the use of caves as breeding enclosures and allowed seasonal pastoral activities related to the mobility of livestock to summer altitude sites among early Neolithic human communities to be inferred (Angelucci et al., 2009; Helmer et al., 2005; Martín et al., 2016; Polo Díaz et al., 2013). These studies, however, lack accuracy when it comes to exploring environmental signals, such as seasonal variations in diet composition, which are closely related to the movement of animals between altitudes that differ climatically.

Over the last decade new analytical procedures such as stable isotope analyses have emerged as useful tools to study in more detail the living conditions of past animal populations, including their mobility patterns (Balasse et al., 2002; Pellegrini et al., 2008; Tornero et al., 2016). Isotopic signatures incorporated into animal tissues from the food and drink they consumed can be used to reconstruct the environmental conditions under which the animals lived and how these changed throughout their lives. Sequences analyses performed in some tissues following their ontogenetic pattern have allowed the tracing of individual life histories in fine temporal detail, i.e. seasonally.

However, despite the great attractive potential of this technique, considerable knowledge of its principles is required for precise and meaningful interpretations to be made when using it. Understanding seasonal isotopic signatures recovered from animal tissues requires detailed knowledge of their sources and their potential variations throughout the seasonal cycle. Furthermore, these background data should be understood at the local level, paying careful attention to the particular environmental conditions of the study site.

With all of the above in mind, the present study focuses on the stable isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) of modern Iberian sheep specimens that during their lives were involved in altitudinal movements between the Ebro valley and the Central Pyrenees. These sheep belong to one of the last remaining flocks still performing this transhumance activity in the area. Sequential analyses in bioapatite of tooth enamel were carried out on the specimens in order to detect seasonal changes. To better understand these results, we compared the tooth values with seasonal patterns of $\delta^{18}O$ in meteoric water in high mountain and valley locations, and the composition and $\delta^{13}C$ values of pastures along an altitudinal gradient. Differences in annual and seasonal rainfall in the area of study were also noted. All these data were compared against the temporal and spatial resolution of the sheep sequential analyses.

As different archaeological studies have shown, husbandry activities in locations high in the Pyrenees mountains have been taking place at least since the Neolithic (Rojo-Guerra et al., 2012, 2013; 2014, 2015; Clemente et al., 2014; Gassiot-Ballbè et al., 2012; Gassiot-Ballbè et al., 2014), suggesting the potential existence of vertical mobility strategies with flocks since this period (Rojo-Guerra et al., 2014). Our results will contribute to help build the analytical framework needed to interpret the stable isotope analyses of archaeological samples currently under study.

1.1. The environmental setting of the modern sheep specimens under study

The Ebro basin possesses some of the greatest contrasting ecological zones of the whole of the Iberian Peninsula ranging from low and extremely dry areas to elevated and wet ones. The basin is a wide depression between two mountainous systems, the Pyrenees and the Iberian System. The Pyrenees are located in the northern part with elevations in excess of 3000 m. The Iberian System is located to the western and southern parts of the basin and its elevations are more moderate, under the 2500-m range. Since the humid winds of the sea do not reach as far as the basin, its thermal amplitude is therefore great and rainfall is scarce during the year. Nevertheless, its 40,000-squared kilometre surface is not homogeneous leading to steppe zones coexisting with perpetually snow-covered areas.

The annual average temperature in the lowland areas is about 15 °C whereas in the high zones it is around 7 °C. Rainfall is scanty in general, and irregular.

Rainfall in the highland areas of the Pyrenees can reach 2000 mm/year, whereas in the lowland areas they do not tend to reach 350 mm/year, although it can vary anywhere between 800 and 300 mm/year. Summer droughts are common for the whole of the territory, with little to no rainfall between three and four months each year, and episodic summer storms. Summer aridity is amplified by the habitual presence of a cold and dry northern wind locally known as 'cierzo', which can reach speeds of up to 100 km/h (Creus and Ferraz, 2000).

Given this setting, throughout history sheep herding has had to adapt to such seasonal and extreme environmental conditions through mobility strategies. As such, herders move their flocks during specific times of year. The success of this strategy is based on the possibilities offered by the altitudinal gradient. Although today vertical mobility strategies are no longer widespread in the Pyrenees, these were pivotal over the last few centuries (Violant i Simorra, 2001; Miralles and Rovira, 2007; Rovira et al., 2010), and probably of much importance in the distant past.

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