Quaternary International xxx (2017) 1–15

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Mountain adaptation of caprine herding in the eastern Pyrenees during the Bronze Age: A stable oxygen and carbon isotope analysis of teeth

Juliette Knockaert [a,*], Marie Balasse [a], Christine Rendu [b], Albane Burens [c], Pierre Campmajo [d], Laurent Carozza [c], Delphine Bousquet [d], Denis Fiorillo [a], Jean-Denis Vigne [a]

[a] *Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environnements, UMR 7209 CNRS, Muséum national d'Histoire naturelle, Sorbonne Universités, France*
[b] *France Méridionale et Espagne: Histoire des Sociétés du Moyen-Âge à l'Epoque contemporaine, UMR 5136 CNRS, Université Toulouse Jean Jaurès, France*
[c] *Géographie de l'Environnement, UMR 5602 CNRS, Laboratoire Géode, Université Toulouse Jean Jaurès, France*
[d] *Travaux et Recherches Archéologiques sur les Cultures, les Espaces et les Sociétés, UMR 5608 CNRS, Université Toulouse Jean Jaurès, France*

A R T I C L E I N F O

Article history:
Received 24 May 2016
Received in revised form
20 February 2017
Accepted 17 May 2017
Available online xxx

Keywords:
Sequential isotope analysis
Altitudinal mobility
Mountain
Sheep and goats
Bronze age
Herding strategies

A B S T R A C T :

Pastoral activities in the northeastern Pyrenees increased substantially during the Bronze Age, raising the question of the modalities of occupations in zones where the snow cover limited access to grasslands for a significant part of the year. The present study explores how stable isotope analysis may characterize the adaptation of husbandry to mountain environments through herding strategies, including the vertical mobility of livestock. It also addresses the broader issue of the occupation of territories by Bronze Age communities in the Western Mediterranean area, focusing on possible links between coastal plains and mountainous areas. For this purpose, sequential stable carbon and oxygen isotope analyses were conducted on caprines' teeth from the mountain site of Llo (Pyrénées-Orientales, 1630 m asl, Middle Bronze Age) and the permanent coastal site of Portal-Vielh (Hérault, 0 m asl, Late Bronze Age). An exploratory analysis was also conducted on modern sedentary and transhumant ewes to investigate the effect of altitudinal mobility on enamel oxygen isotope values. The range of $\delta^{18}O$ values measured in modern and archaeological caprines raised in mountain zones was lower than the one measured in the lowland caprines, while no significant difference could be observed in the range of $\delta^{13}C$ values. Co-variations between $\delta^{13}C$ and $\delta^{18}O$ sequences reveal the most information. The positive correlation observed in all instances at low elevation sites was not the leading pattern at Llo, where a variety of schemes could be observed, including opposite $\delta^{13}C$ and $\delta^{18}O$ sequences. This opposition could not be explained by a reversal of the $\delta^{18}O$ cycle due to vertical mobility. Other causes could involve changes in the pattern of variation of $\delta^{13}C$ values, potentially linked to human responses to the local constraints, including vertical mobility and/or foddering. Portal-Vielh delivered a fully lowland signal. At Llo, although a full adaptation to a mountain environment seems clear, the question of the vertical mobility of the livestock cannot be resolved at the moment. Most importantly, Llo was characterized by a high inter-individual variability in the co-variation of $\delta^{13}C$ and $\delta^{18}O$ profiles, reflecting great plasticity of the husbandry practices on the inter-annual scale. This could have been a key to the adaptation to these marginal environments. The apparent disjunction between the coastal and mountain settlements, as far as herd trajectory is concerned, must be reaffirmed by further investigations in a larger number of sites.

1. Introduction

As observed by Carozza et al. (2005, 2007), mountain zones have long been viewed as too harsh and inhospitable to be settled by Bronze Age societies. Recent research in the Pyrenees Mountains

* Corresponding author.
E-mail address: juliette.knockaert@mnhn.fr (J. Knockaert).

http://dx.doi.org/10.1016/j.quaint.2017.05.029

revealed a different reality. In the French northeastern Pyrenees, the earliest evidence of pastoral activities above 1500 m asl appears during the second half of the early Neolithic (around 4700 and 4500 cal BC) (Reille, 1990; Rendu, 2003; Guiter et al., 2005). Those intensified during the Middle Neolithic (around 4200 cal BC) at a time when pollen and archaeological data reflect an opening in forest cover, the emergence of plants associated with agropastoral activities and the presence of habitat structures in the sub-alpine and alpine zones (Rendu et al., 1996; Davasse et al., 1997; Galop, 1998, 2000; Vannière et al.,2001; Rendu, 2003; Miras et al., 2007; Palet Martinez and Orengo Romeu, 2009; Ejarque et al., 2010).

The agropastoral pressure in the mountain to alpine zones increased substantially during the Bronze Age (Galop, 1998; Rendu, 2003; Carozza and Galop, 2008; Orengo Romeu, 2010; Rius et al., 2012). This phenomenon is well-documented in Cerdanya, where it is reflected by pollen indicators of pastoralism in the Enveitg Mountain subalpine zone (*Plantago lanceolata, Rumex* and *Artemisia,* Cichorioideae, Chenopodiaceae) (Galop, 1998; Galop et al., 2003) and by increasing fire frequency in the medium altitude forests (Vannière et al., 2001). Landscape anthropization also included the building of cultivation terraces between 1600 and 2000 m in the Enveitg slope, as highlighted by pedo-anthracological and archaeological analysis (Rendu, 2003; Bal, 2006; Bal et al., 2010; Harfouche and Poupet, 2013). Furthermore, a large stone building ('site 88'), discovered at 2100 m on the Enveitg slope, was unusually large for a pastoral site. It could have been a type of *summer farm*, unless its use was perennial (Rendu et al., 2012).

The rhythmicity and period of occupation of the mountain slopes (mountain to alpine zones) is therefore a central focus of on-going research on the management of mountain environments (Bal et al., 2010; Rendu et al., 2012). In particular, uncertainty remains about the modalities of exploitation of middle altitude landscapes for the dominantly caprine husbandry. Bearing in mind that the snow cover might have limited access to grasslands for a significant part of the year, a perennial occupation in middle altitude zones could have created the necessity of foddering during the shortage season. An alternative solution could have included herd mobility towards lower plain grasslands in the winter and/or higher elevation grasslands in the summer to find available grazing resources. Moreover, on a regional scale, another question is to determine whether agropastoral activities in this mountain area were connected to the occupation in the coastal plains as part of a unique cultural landscape in the Bronze Age. Explaining the pattern and rhythms of the seasonal livestock mobility along the altitudinal gradients would contribute to an improved understanding of the mountain territories' structuration and the modalities of their use.

To address these questions, we analysed intra-tooth variations in stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic ratios in Bronze Age caprines' tooth remains. These biogeochemical signatures are governed by environmental factors, some of which vary with altitude. They are integrated in vertebrates' skeletons through diet and drinking. In particular, isotopic signals are recorded in enamel bioapatite during tooth mineralization with no remodelling. Sequential analysis in tooth enamel gives access to the animal's isotopic history with an infra-annual resolution (Bryant et al., 1996a, b; Fricke and O'Neil, 1996), potentially revealing seasonal altitudinal mobility. This approach has been successfully applied to detect the vertical movements of wild and domestic small stock in East Africa (Balasse and Ambrose, 2005), North America (Fisher and Valentine, 2013), the Peruvian Andes (Goepfert et al., 2013) and Armenia (Tornero et al., 2016). These works demonstrated that the isotopic 'mountain signature' varies from one place to another depending on the environmental and climatic contexts: in mixed C_3-C_4 plants areas, a key parameter may be the decreasing relative proportion of C_4 plants with altitude, whereas in places where C_3 plants dominate, the focus is on the altitudinal effect inducing increasing $\delta^{13}C$ values in plants and decreasing $\delta^{18}O$ values in precipitations. These parameters are exacerbated when the considered altitudinal gradient is very high. In the present study, we aim to characterize the mountain signature for the French Pyrenees. For this purpose, a combined analysis of stable carbon and oxygen isotope ratios could be more efficient than strontium isotope analyses, which are well-adapted for detecting mobility (e.g., Bentley and Knipper, 2005; Viner et al., 2010; Valenzuela-Lamas et al., 2015) but not adapted to a patchy and complicated geological substratum such as the one of the Pyrenean mountains and, generally speaking, complex orogenic areas.

First, we explored the signature of the mountain environment and vertical mobility on the oxygen isotopic ratios of modern transhumant and sedentary ewes raised in the Western Pyrenees, filling the absence of such modern dataset for European mountains context to date. Then, the approach combining the $\delta^{13}C$ and $\delta^{18}O$ sequential analysis was applied to animal remains from the Bronze Age mountain settlement of Llo (1630 m asl) (Campmajo, 1983), on the one hand, to address the adaptation of husbandry to mountainous environments and to the Late Bronze Age site of Portal-Vielh (coastal plain of the Languedoc) (Carozza and Burens, 2000) on the other hand, to consider whether herding strategies may have created a link between coastal plains and mountainous areas. Additionally, we refer to the unique set of previously published sequential stable isotope analyses in caprines' teeth available to date for the Mediterranean margin of France at the late Neolithic sites of Collet-Redon and La Citadelle, respectively, coastal and hinterland settlements (Blaise et al., 2006; 2010; Blaise and Balasse, 2011) (Fig. 1 A).

2. Stable oxygen and carbon isotopes, altitudinal mobility and diet

2.1. Stable oxygen isotopes

In large mammals from temperate Europe, a direct relationship was established between $\delta^{18}O$ values in skeleton bioapatite and that of local surface water though the ingested water (Land et al., 1980; Luz and Kolodny, 1989; D'Angela and Longinelli, 1991). The $\delta^{18}O$ values in precipitation change spatially and temporally, according to climatic and geographical factors. Under intermediate and high latitudes, the rainfall $\delta^{18}O$ values are mainly controlled by the water vapour source and transport patterns, and ambient temperature is a key parameter to seasonal variations: ^{18}O-enriched rains occur in summer and ^{18}O-depleted rains in winter (Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993). In the study area, seasonal variations in monthly isotopic data in modern rainfall support this global pattern (Avignon, Dax and Montpellier, Fig. 1A; IAEA/WMO, 2016; data reported in Supplementary Material 1). Presently, the study area is principally under Atlantic climatic influence. Paleoclimate proxies do not indicate any change in the atmospheric circulation and weather pattern within the mid-latitudes during the Holocene period (Magny et al., 2009b). The Bronze Age was marked by climatic instability. Two climatic deteriorations are observed across Europe. The first one, dated to 1650-1350 cal. BC, induced a temperature cooling (mean annual temperature decreased by c. 0.7 °C) and increasing humidity (annual precipitation increased by c. 70–100 mm, more particularly during summer) (Magny et al., 2009a, 2009b). The second pejoration occurred around 850 cal. BC (van Geel et al., 1996; Magny et al., 2007). On a global scale, a possible consequence when comparing modern and Bronze Age $\delta^{18}O$ values would be lower ratios for the latter.

Please cite this article in press as: Knockaert, J., et al., Mountain adaptation of caprine herding in the eastern Pyrenees during the Bronze Age: A stable oxygen and carbon isotope analysis of teeth, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.05.029