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Stable isotopic evidence for terrestrial latitudinal climate gradients in the Late Miocene of the Iberian Peninsula

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ABSTRACT

The late Neogene of the Mediterranean region is marked by significant faunal and floral turnover in terrestrial ecosystems, paleogeographic and paleoceanographic changes associated with the Messinian Salinity Crisis (MSC), and regional climate transition associated with the onset of northern hemisphere glaciation. In this paper we report stable oxygen isotope compositions (δ^{18}O) of terrestrial mammal faunas from the Late Miocene, Pliocene and Pleistocene of Spain, and compare these data with Late Miocene mammal δ^{18}O values from northern Libya. Since tooth enamel δ^{18}O from modern horses has been demonstrated to be a reasonable proxy for the δ^{18}O of local meteoric water, which is in turn strongly dependent on mean annual temperature (MAT), we use the δ^{18}O of fossil horse tooth enamel to estimate MAT. Our paleotemperature reconstructions are consistent with global cooling during the late Cenozoic, with MAT for the Late Miocene that is warmer than today by ~1–2 °C in NE Spain and by ~4–5 °C in SE Spain. The difference of ~8–9 °C between NE and SE Spain for the Late Miocene is ~60% greater than the MAT difference between these same areas today. The δ^{18}O values from Libya are lower than those for southern Spain, and may suggest cooler and/or wetter climates in northeastern Africa during the latest Miocene and early Pliocene. We examined intrafaunal δ^{18}O patterns to make interpretations about paleoecology and to qualitatively assess paleoaridity. Comparisons of δ^{18}O values between clades are consistent with a semi-aquatic lifestyle for anthracotheres, hippopotamids, and castorids. We also compare intra-tooth samples of enamel and dentine to examine possible diagenetic alteration of these materials. Comparisons of enamel and dentine δ^{18}O suggest slight diagenetic alteration of dentine, but we demonstrate that these δ^{18}O values can be used to reconstruct reasonable values of diagenetic water δ^{18}O. Overall, our data do not support large climatic changes in the Iberian Peninsula during the MSC, but are consistent with long-term global cooling and sharper latitudinal climate gradients in Spain during the Neogene.

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1. Introduction

Some of the most important Cenozoic changes in global climate and terrestrial ecosystems occurred during the Neogene. Global cooling throughout the Neogene led to the Late Miocene expansion of Antarctic continental ice sheets (Zachos et al., 2001; Anderson and Shipp, 2001) that initially formed at the Eocene–Oligocene boundary (Liu et al., 2009), and to glaciation in the northern hemisphere during the Pliocene (Shackleton et al., 1988; Maslin et al., 1998; Zachos et al., 2001). Aridification during this period is reflected by terrestrial ecosystems that had been characterized by forested environments throughout the early Cenozoic but became dominated by more open mixed woodland and C_3 grasslands during the Miocene, and later by C_4 grasslands at mid- to low latitudes in the latest Miocene and Pliocene (Potts and Behrensmeyer, 1992; Quade and Cerling, 1995; Cerling et al., 1997; Jacobs et al., 1999; Fox and Koch, 2003; Strömberg, 2005). Associated with this change in vegetation was a global turnover in ungulate faunas, in which brachydont browsing taxa were gradually replaced by gracile, hypsodont grazing taxa throughout the Late Miocene (Janis et al., 2000, 2004). This gradual faunal turnover culminated in the widespread extinction of non-hypsodont ungulates during the latest Miocene and early Pliocene (Janis et al., 2002; Tedford et al., 2004).

The Mediterranean region experienced broadly similar patterns during the Neogene, but this area is also distinguished by several important differences from general global trends. For example, while terrestrial ecosystems in the Mediterranean region also experienced the Miocene transition to more open mixed woodland and grassland environments (Solounias et al., 1999; Agustí et al., 1999), they have remained dominated by C_3 vegetation to the present (Quade et al., 1994; Cerling et al., 1997). In addition to global changes in climate, regional changes in circum-Mediterranean paleogeography helped to drive important changes in the composition of mammal faunas. The Messinian Salinity Crisis (MSC) is the most intensively studied of

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these paleogeographic changes, and it had important ecological implications for both marine and terrestrial ecosystems. During the MSC, combined tectonic and glacio-eustatic isolation of the Mediterranean Basin from the Atlantic Ocean between 5.59 and 5.33 Ma (Krijgsman et al., 1999) led to widespread desiccation of the Mediterranean Sea, a base-level drop of up to 1500 m, deep incision of river valleys emptying into the Mediterranean Basin, and deposition of up to 2–3 km-thick evaporite sequences (Hsü et al., 1973, 1977; Krijgsman, 2002). The MSC event also affected terrestrial ecosystems through faunal interchanges between Africa and Europe (van der Made et al., 2006; Agustí et al., 2006). Paleoclimatic reconstructions for the MSC interval have largely focused on the timing and climatic causes for this event (Hodell et al., 1994; Clauzon et al., 1996; Krijgsman et al., 1999), but more recent studies have begun to explore its potential effects on regional climate (Fluteau et al., 2003; Fauquette et al., 2006; Blanc, 2006; Costeur et al., 2007).

To investigate changes in terrestrial climate during the Late Neogene of the Mediterranean region, we developed a stable oxygen isotope record from Late Miocene and Pliocene fossil mammals from Spain. For temporal and geographic comparison, we also report similar data from the Pleistocene of southern Spain and the latest Miocene of northern Libya. A primary connection between climate and oxygen isotopes in continental systems is the strong positive correlation between mean annual temperature (MAT) and the oxygen isotopic composition (δ^{18}O value) of meteoric water ($\delta^{18}O_w$) for modern temperate latitudes, which is related to preferential rainout of the heavy oxygen isotope (^{18}O) during poleward transport of air masses (Dansgaard, 1964; Rozanski et al., 1993; Fricke and O'Neil, 1999). Though the slope and intercept of the global MAT–δ^{18}O relationship can change depending on temporal changes in latitudinal temperature gradients and the δ^{18}O of precipitation source water (Boyle, 1997; Fricke and O'Neil, 1999), if the modern MAT–δ^{18}O relationship was generally similar in the past then records of the δ^{18}O of past meteoric waters can be used as proxies for paleotemperature.

Stable oxygen isotopes in fossil mammal skeletons have been widely used as a proxy for paleo-precipitation δ^{18}O (Koch, 1998; Kohn and Cerling, 2002). Mammals offer a unique advantage for isotopic studies compared to other animals because they internally regulate their body temperature, thereby eliminating variable fractionation due to temperature variation during skeletal tissue growth (Longinelli, 1984; Luz and Kolodny, 1985). The δ^{18}O of mammalian skeletal hydroxylapatite (i.e., tooth enamel and dentine, and bone) is directly controlled by the δ^{18}O of body water, which is in turn a function of several oxygen influxes (e.g., breath O_2 and H_2O, drinking water, H_2O and free or chemically bound oxygen in diet) and effluxes (e.g., breath CO_2 and H_2O, water in urine and feces, transcutaneous water loss). For large-bodied mammal species that rely on drinking water, hydroxylapatite δ^{18}O is controlled primarily by the δ^{18}O of local meteoric water and by relative humidity (Luz et al., 1984; Kohn, 1996; Kohn et al., 1996).

2. Materials and methods

2.1. Geologic setting

The majority of the data reported in this paper come from the Neogene Fortuna and Teruel Basins, and the Plio-Pleistocene Baza Basin. We also report data from the late Miocene localities of Venta del Moro (VM) and Almenara-M (AM) in eastern Spain, and from the latest Miocene Sahabi locality (SH) in northern Libya. Venta del Moro is located in the Cabriel Basin, approximately 80 km west of the city of Valencia (Fig. 1). The sedimentary infill of the Cabriel Basin is dominated by lacustrine limestones and marls, and fluvial sandstones, conglomerates and mudstones. An age of approximately 5.9 Ma for Venta del Moro has been proposed based on biostratigraphic and magnetostratigraphic studies (Opdyke et al., 1990, 1997; Agustí et al., 2006; Montoya et al., 2006). The Almenara-M locality is an isolated karst fissure-fill located in a carbonate massif near the Mediterranean coast between Castellón and Valencia (Fig. 1). The rodent fauna at Almenara-M suggests an age between approximately 6.1 and 5.3 Ma, and the karst development there has traditionally been associated with base-level drawdown and erosion during the MSC (Krijgsman et al., 1999; Köhler et al., 2000; Agustí et al., 2006). The Qasr as-Sahabi locality is located in northern Libya, approximately 120 km southeast of the Gulf of Sirt between Ajdabiyah and the Jalu oasis. The fossils used in this study come from the Sahabi Formation (members T, U, and V of de Heinzelin et al., 1987), which is composed of interbedded transgressive marine sands, lenticular sand and gravel channel deposits, incipient paleosols, and dolomite beds. The Sahabi fauna includes both terrestrial (e.g., mammals, crocodiles, birds, and turtles) and marine (e.g., sharks, sirenians, and cetaceans) taxa, and unconformably overlies highly gypsified middle and Late Miocene marine facies (Boaz et al., 1987). This locality has been interpreted to represent fluvial incision and subsequent estuarine deposition associated with the onset and recovery phases of the MSC near the Miocene–Pliocene boundary (de Heinzelin et al., 1987). Biostratigraphic correlations suggest an age of approximately 5.2 or slightly older for the Sahabi fauna (de Heinzelin et al., 1987; Bernor and Scott, 2003; Beyer, 2008).

The fossil localities Librilla (LB), Molina de Segura (MS), and La Alberca (LA) are located in the Fortuna Basin in southeastern Spain, approximately 20 km west of the city of Murcia (Fig. 1). The basin lies at the contact between the Internal and External Zones of the Betic Cordillera, and is bounded in the north by the ENE–WSW-trending Crevillente Fault and in the south by the NE–SW-trending Alhama de Murcia Fault. Basin subsidence associated with transtension along these sinistral faults is recorded by a late Tortonian transgressive marine sequence consisting of turbidites, pelagic marls, deltaic deposits and reef complexes (Garcés et al., 2001). These sediments are overlain by a late Tortonian regressive marine unit consisting of marls, diatomites, and gypsum representing a period of localized basin restriction (Garcés et al., 1998; Krijgsman, et al., 2000; Garcés et al., 2001). The fossils used in this study come from interbedded Messinian lacustrine carbonates and alluvial conglomerates and sandstones that conformably overlie the evaporite sequence and were derived from massifs of Meso-Cenozoic carbonates (External Zone) and Paleozoic–Cenozoic metamorphic complexes (Internal Zone) that were uplifted during a period of latest Miocene transpression. Biochronologic (Mein et al., 1973; Steininger et al., 1996; Agustí et al., 2006), radiometric (Kuiper et al., 2006), magnetostratigraphic (Garcés et al., 1998, 2001), and astrochronologic (Kruvier, et al., 2002) studies of these terrestrial sediments suggest ages of approximately 5.9–6.3 Ma for Librilla, 6.6–6.0 Ma for Molina de Segura, and 5.6 Ma for La Alberca.

The fossil localities Venta Micena (VA), Puerto Lobo (PL), Barranco del Paso (BP), and Barranco León (BL) are located in the Baza Basin in southeastern Spain, approximately 100 km east of the city of Granada (Fig. 1). The Baza Basin forms the eastern part of the largest of the intramontane basins of the Betic Cordillera, and like the Fortuna Basin, it is located at the boundary between the Internal and External Betic Zones. Subsidence during the Late Miocene isolated the Baza Basin from the Mediterranean Sea and from surrounding basins, and led to the deposition of 2000–3000 m (Alfaro et al., 2008) of lacustrine and palustrine carbonates and mudstones and alluvial sandstones under endorheic conditions from the Late Miocene until the Middle Pleistocene (Garcés et al., 1997a; Gibert et al., 2006; Scott et al., 2007). After this time, neotectonic uplift combined with stream piracy from a tributary of the Guadalquivir River to the north led to external drainage and the incision of Neogene strata that characterizes this area today (Scott et al., 2007). Detailed basin analysis combined with biostratigraphic and magnetostratigraphic studies (Scott et al., 2007; Gibert et al., 2007) suggest ages of approximately 1.3 Ma for Venta

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