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Late Oligocene ambient temperatures reconstructed by stable isotope analysis of terrestrial and aquatic vertebrate fossils of Enspel, Germany

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Abstract During the Oligocene, waxing and waning ice sheets on Antarctica caused global sea level fluctuations, as well as climatic and palaeoenvironmental changes that affected faunal evolution in Europe. The ~24.7 Ma upper Oligocene lacustrine sediments of Enspel in western Germany have yielded a fossil vertebrate fauna of the Mammal Palaeogene (MP) reference level 28. Here, we present carbon and oxygen isotope analyses of these terrestrial and aquatic vertebrate fossils, enabling us to reconstruct the isotopic composition of the ingested food and water sources and to gain insights into the palaeoclimate and palaeoenvironment. The crocodile *Diplocynodon* has enamel $\delta^{13}C$ values above the range expected for a carnivore feeding on terrestrial animals from a C_3 plant ecosystem, probably reflecting a diet composed mainly of ^{13}C-enriched aquatic vertebrates from the Enspel Lake. Enamel $\delta^{13}C$ values as low as −14 ‰ indicate that the large ungulate mammal *Anthracotherium* fed in a forested environment around the Enspel maar. *Anthracotherium* did not predominantly ingest its drinking water from the ^{18}O-enriched lake; *Diplocynodon* enamel $\delta^{18}O_{PO4}$ values represent a $\delta^{18}O_{H2O}$ value of −2‰, whereas *Anthracotherium* enamel gives a $\delta^{18}O_{H2O}$ value of −6.9±0.3 ‰. This is inconsistent with a semi-aquatic mode of life for *Anthracotherium*, but rather suggests that it drank meteoric water, presumably reflecting the late Oligocene precipitation, thus giving a mean annual air temperature (MAT) estimate of 15.0± 1.3 °C. This MAT is in good agreement with previous MAT reconstructions based on plant fossils from Enspel and *Anthracotherium* teeth from slightly younger MP29 fossil sites in Switzerland. We suggest that a MAT of around 15±2 °C prevailed in central Europe during the late Oligocene during MP28 and 29.

Keywords *Anthracotherium* · Palaeoclimate · Oxygen isotopes · Enamel · Semi-aquatic · Diagenesis

Introduction

The Oligocene was a period of major global climatic, environmental and faunal change. At the beginning of the Oligocene, a polar ice cap formed during the Oi-1 glaciation of Antarctica leading to sea level changes (e.g. Miller et al. 1987; Katz et al. 2008), reorganisation of major ocean currents (e.g. Goldner et al. 2014) and global cooling (e.g. Zachos et al. 2001; Liu et al. 2009). In Europe the climatic changes led to an overall cooler (e.g. Hren et al. 2013) and drier climate with tropical and subtropical forests being replaced by temperate woodlands in the early Oligocene (Janis 1993). These climatic and environmental changes caused a major faunal turnover known as "Grande Coupure" at the Eocene/Oligocene transition (Stehlin 1909; Hooker et al. 2004). Multiple vertebrate taxa became extinct and many new immigrant species from Asia appeared in Europe during this time interval. Among ungulate mammals, lophiodontids and some endemic cetartiodactyls were replaced by rhinoceroses, traguloids, and pecoran ruminants (Janis 1993). Anthracotheres such as *Anthracotherium* were among the immigrants from Asia and became highly diversified during the Oligocene in Europe (e.g. Scherler 2011). Faunal migration from Asia to Europe occurred following the closure of the

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