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Late Pleistocene climatic change in the French Jura (Gigny) recorded in the $\delta^{18}O$ of phosphate from ungulate tooth enamel

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ABSTRACT

Oxygen isotope compositions of phosphate in tooth enamel from large mammals (i.e. horse and red deer) were measured to quantify past mean annual air temperatures and seasonal variations between 145 ka and 33 ka in eastern France. The method is based on interdependent relationships between the $\delta^{18}O$ of apatite phosphate, environmental waters and air temperatures. Horse (*Equus caballus germanicus*) and red deer (*Cervus elaphus*) remains have $\delta^{18}O$ values that range from 14.2‰ to 17.2‰, indicating mean air temperatures between 7°C and 13°C. Oxygen isotope time series obtained from two of the six horse teeth show a sinusoidal-like signal that could have been forced by temperature variations of seasonal origin. Intra-tooth oxygen isotope variations reveal that at 145 ka, winters were colder (-7 ± 2°C) than at present (3 ± 1°C) while summer temperatures were similar. Winter temperatures mark a well-developed West–East thermal gradient in France of about −9°C, much stronger than the −4°C difference recorded presently. Negative winter temperatures were likely responsible for the extent and duration of the snow cover, thus limiting the food resources available for large ungulates with repercussions for Neanderthal predators.

Introduction

The Late Pleistocene is characterized by marked and regular climatic cycles. Five Heinrich events (H6, H5, H4, H3 and H2) have been identified during marine oxygen isotope stages OIS4 and OIS3 (Heinrich, 1988). These abrupt cooling phenomena are thought to have resulted from the melting of ice in the Atlantic Ocean, thus reducing water density. As a result, thermohaline circulation changed to lower latitudes, leading to cooling in more northern latitudes. On the other hand, interstades have also been recognized such as the Moershoofd, Hengelo or Denekamp warmer periods. This succession from cold to warmer climate periods played an important role on species evolution and distribution. As a special case, it is largely debated whether climate and environment could have exerted a significant control on the replacement of Neanderthal by *Homo sapiens* in Europe during the Late Pleistocene (Gamble, 1995, 1999; D'Errico and Sanchez-Goni, 2003; Finlayson, 2004). Indeed, human behavior is closely related to food resources, which are themselves dependent on the climate mode (D'Errico and Sanchez-Goni, 2003; Finlayson, 2004). Methods for palaeoclimate reconstructions generally depend on proxies such as pollen spectra (De Beaulieu and Reille, 1984; Guiot et al., 1989) or mammal associations (Chaline, 1972; Andrews et al., 1979; Delpech et al., 1983; Legendre, 1986). The geochemical methods of air temperature determination most commonly used in continental environments involve the stable isotope analysis of speleothems, tree rings and mammals bones and teeth (e.g. Ayliffe et al., 1992; Bar-Matthews et al., 1997; Feng et al., 1999). The $\delta^{18}O$ value of tooth enamel phosphate from mammal is a function of the $\delta^{18}O$ value of the animal's body water as well as of its body temperature (Kolodny et al., 1983; Longinelli, 1984; Luz et al., 1984). The $\delta^{18}O$ value of body water is related to the $\delta^{18}O$ value of ingested water and to the animals' ecology and physiology. The main source of ingested oxygen is drinking or plant water, which is meteoric water or derived from it (D'Angela and Longinelli, 1990; Kohn et al., 1996). As the $\delta^{18}O$ value of meteoric water depends on climatic parameters such as air temperature, hygrometry and amount of precipitation (Dansgaard, 1964; Grafenstein et al., 1996), mammals thus indirectly record in their phosphatic tissues the climatic conditions of their living environment. Several paleoclimate studies have been successful in analyzing the oxygen isotope composition of large mammals such as mammoths, horses, deer and bison (Bryant et al., 1994; Sanchez Chillon et al., 1994; Delgado Huertas et al., 1997; Genoni et al., 1998; Koch et al., 1998; Sponheimer and Lee-Thorp, 2001; Higgings and MacFadden, 2004; Sharma et al., 2004; Bernard et al., 2009). Paleoclimatic interpretations of oxygen isotope data obtained from rodents teeth have been proposed even though they remain the subjects of debate and controversy (Longinelli et al., 2003; Navarro et al., 2004; Héran et al., 2010). Rodent

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remains are abundant and provide a high temporal resolution. However, the use of oxygen isotope compositions as a proxy of the composition of ingested water is limited by 1) a deposit location that can be different from the living area because of the large hunting domain of their predatory birds, 2) a short mineralization time at the seasonal scale, 3) a systematic use of the M1 tooth as the only diagnosis of species determination, and 4) the existence of two oxygen isotope fractionation equations that lead to significant differences in the quantification of the isotopic compositions of waters (Longinelli et al., 2003; Navarro et al., 2004). Large ungulate grazers such as horses present sizable advantages for reconstructing the δ^{18}O of past waters which are their regular presence throughout the Pleistocene, a source of drinking waters that is mainly meteoric waters reflecting mean air temperatures at mid-latitudes (Sanchez Chillon et al., 1994; Sharp and Cerling, 1998; Higgings and MacFadden, 2004), a high-crown tooth (i.e. hypsodonty) characterized by a multi-annual mineralization time (Bryant et al., 1996; Higgings and MacFadden, 2004), and a tight prey–predator relationship providing the climatic context of human occupations (Stiner, 1994; Gamble, 1999).

Meaning and validity of the oxygen isotope composition of rodent teeth in terms of climatic records (paleotemperatures, paleohydrology) can be assessed by comparing their isotopic compositions to those of large mammals co-occurring in the same sedimentary level. Therefore, we propose to study herbivore species from La Baume de Gigny Cave (BGC), French Jura, where sediments have been deposited from −145 ka to −33 ka (Campy et al., 1989). Age of the lower level of the cave is contemporaneous to level 4 of the Coudoulous I deposit in the southwestern part of France (Lot) where mean air temperatures and seasonal variations have been already inferred from the δ^{18}O of tooth enamel phosphate from *Bison priscus* (Bernard et al., 2009). At BGC, Navarro et al. (2004) have calculated air temperatures by using the δ^{18}O values of rodent teeth, however the large isotopic variations observed within sedimentary levels have not received satisfactory explanations so far. In this study, we performed oxygen isotope measurements of phosphate from 20 horse tooth enamels and four red deer tooth enamels to establish:

– a mean air temperature curve over about 100 ka within the middle Palaeolithic based on large mammals, which is then compared to temperatures inferred from the δ^{18}O values of rodent teeth. The validity of both isotopic records is discussed in terms of the most appropriate use of available oxygen isotope fractionation equations.

– an east–west climatic gradient in France at ca. 145 ka by comparing the calculated mean air temperatures and seasonality between the Coudoulous I (Lot) and BGC (Jura) sites.

Geological setting

The BGC, located in the French Jura, is a karstic cave (Fig. 1) with a 12 m thick stratigraphic sequence (Campy et al., 1989). The sediments are subdivided into 31 layers organized in three complexes according to Campy et al. (1989). Horse and red deer teeth come from the Middle Complex with the top (level VIII) dated by radiocarbon isotopes providing ages of 33.4 ± 1.4 cal ka BP and 32.2 ± 1.4 cal ka BP (Evin, 1989). Migration of the steppe lemming *Lagurus lagurus* was also used to estimate an age of about 60 ka (Campy and Chaline, 1993) for the bottom sequence (level XX). A speleothem located at the limit between the Middle Complex and the Lower Complex was dated at 145 ± 15 ka using the ^{234}U/^{230}Th method and at 145^{+66}_{-45} ka using the Electron Spin Resonance (ESR) method (Evin, 1989). Levels thickness range from 0.15 m to 0.50 m, which most likely correspond to a maximum time span of 3.5 ka per level. Flint tools and bone remains

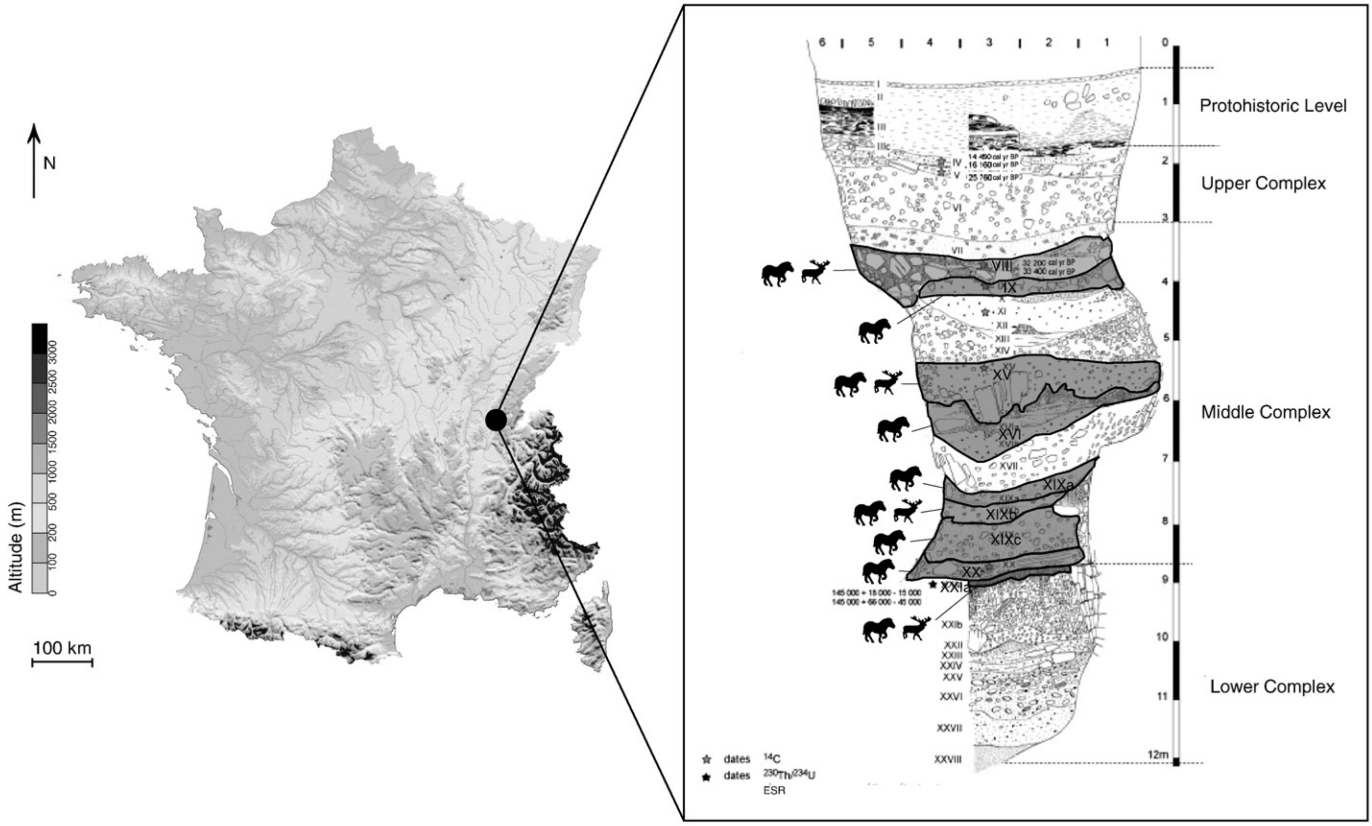

Fig. 1. Geographic location of the Late Pleistocene cave of "La Baume de Gigny" and the stratigraphic sequence of its sedimentary deposits with sampled levels (from Campy et al., 1989). Roman number: level number; Grey star: radiocarbon date; Black star: Electron Spin Resonance date or U^{234}/Th^{230} date. Map from Geoatlas France vectorielle 2, 1997.