

# Spatial and temporal variations in the $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ ratios of mammoth hairs: Palaeodiet and palaeoclimatic implications

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## Abstract

Four sets of C and N stable isotope analyses carried out on mammoth hairs of different radiocarbon age from four different sites in northern Siberia are reported here. Another set of analyses from the same region, published elsewhere, is reported for comparison. The analyses were performed on small increments along the length of the hairs providing information about short- (seasonal) and long-term (before and after the Last Glacial maximum) diet variation and, hence, about the environment in which the mammoths lived. The mean  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values for the four sites range between  $-24.1\%$  and  $-20.9\%$  and between  $5.8\%$  and  $9.6\%$ , respectively. Both the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  signals increment towards east when samples from the same age are considered. Hair  $\delta^{15}\text{N}$  correlates well with the current amount of precipitation independently of the radiocarbon age of the sample. This could mean that during the periods considered this environmental parameter did not change significantly in the studied sites. Hair  $\delta^{13}\text{C}$  appears to be affected by a different environmental factor that, in this case, varies in function of the radiocarbon age of the samples. This factor could be the  $\text{CO}_2$  atmospheric content that, as is well known, varies across a glacial cycle depending on temperature. The isotope patterns obtained from each set of samples exhibit roughly sinusoidal oscillations of the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values. These oscillations have been attributed to seasonal changes in the isotope values of the mammoth's diet due to plant adaptation to the different seasonal environmental conditions or to the different seasonal plant type availability. A direct physiological effect on the hair  $\delta^{15}\text{N}$  values can also be considered. This study strongly supports the possibility of using hair  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  signals as indicators of geographical and temporal variation in plant isotope composition and, ultimately, as indicators of palaeoclimate changes.

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## 1. Introduction

The measurement of the carbon and nitrogen stable isotope composition of animal hair is becoming an important tool for obtaining information on past dietary

habits of mammals and on past environmental conditions. In fact, carbon and nitrogen ratios of hair have been shown to depend on diet and, ultimately, on plants at the base of the food web as is also the case with bone collagen (e.g., Jones et al., 1981; Minson et al., 1975; O'Connell and Hedges, 1999; O'Connell et al., 2001; Schwertl et al., 2003; Sponheimer et al., 2003; Webb et al., 1980; White, 1993; Yoshinaga et al., 1996). When C and N are transferred from the producers through food

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webs, the consumers are enriched in  $^{13}\text{C}$  and  $^{15}\text{N}$ . Hairs mainly consist of keratin and are very resistant to diagenesis (Lubec et al., 1987). Keratin  $\delta^{13}\text{C}$  values appear to be enriched from about 1‰ to about 3.4‰ with respect to dietary values and the time period before keratin registers changes due to a variation in diet is at least 74 days (White, 1993; Jones et al., 1981; Katzenberg and Krouse, 1989; Nakamura et al., 1982; Tieszen et al., 1983). The relationship between keratin and diet  $\delta^{15}\text{N}$  values has not been yet defined: O'Connell and Hedges (1999) report a mean isotope difference between collagen and hair keratin measured on human fossil remains, in the range of 0–2‰ but with a high degree of variability.

Hairs have the advantage over bone collagen of being obtained non-invasively from fossil or living specimens and every growth increment contains information on a well-defined time period, being metabolically inactive after its formation. Therefore, hairs along their length can record dietary changes that may result from seasonal variations of food resources and/or from animal migration.

Thus, well preserved hairs, e.g., of Siberian mammoth, can be used for diet reconstruction. The length of mammoth hairs varies from a few cm to over 90 cm, and therefore can represent a long and continuous temporal isotope archive.

In a previous paper on mammoth hair (Iacumin et al., 2005) only one specimen from Bol'shoy Lyakhovskiy Island was investigated and seasonal changes in the isotope composition of the consumed plant food were recognized. The aim of this study is to expand on these findings by investigating several mammoth hairs from different specimens of different ages coming from different north Siberian sites, to check the geographical and long-term isotope variations in the food consumed and, ultimately, the environmental variations throughout the past.

## 2. Sample and site information

Nine hairs belonging to four different woolly mammoth specimens (*Mammuthus primigenius*) coming from four different localities of northern Siberia above the Arctic circle (Fig. 1) were analysed for their carbon and nitrogen isotope compositions. Along the Yuribey River in the Gydanskiy Peninsula (site 1), in 1979, a small adult female mammoth (10–14 years old) was discovered, dating to  $10,000 \pm 70$  and  $9730 \pm 100$  years BP ( $^{14}\text{C}$  age) (Vereshchagin and Kuzmina, 2001). Its gastrointestinal tract was packed with a grassy mass, and the other internal organs were entirely preserved. Botanical analysis of the samples taken from the stomach showed vegetation mass mainly composed of

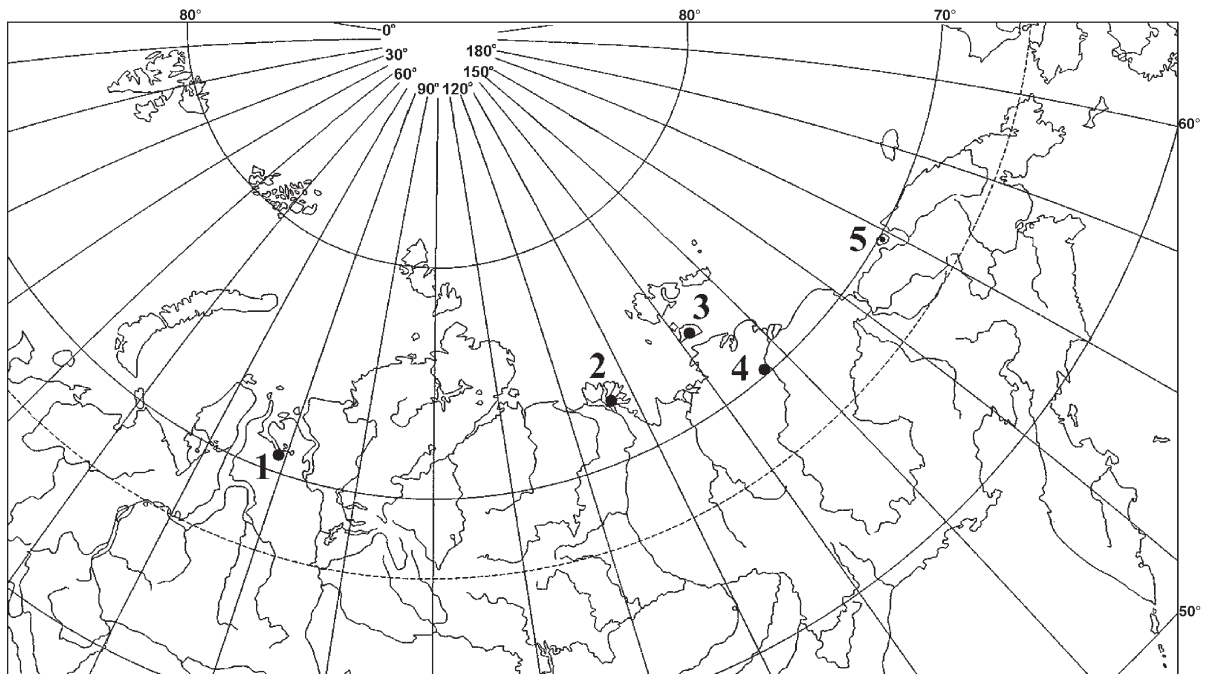


Fig. 1. Locations where mammoth remains were found. 1=Gydanskiy Peninsula; 2=Mouth of Lena River; 3=Bol'shoy Lyakhovskiy Island; 4=Bereliekh River; 5=Ion Island.

the remains of herbaceous plants (95%) with scarce remains of trees (1%) and mosses (0.5%). Palynological spectra of the stomach and colon contents are still dominated by pollen of herbs followed by moss spores (Gorlova, 1982). The Adams mammoth's frozen carcass was discovered in 1799, at the mouth of the Lena River (site 2). It was a male, which died at the age of 45 years. The hair samples were collected from its head. It was radiocarbon dated to  $35,800 \pm 1200$  and  $34,450 \pm 2500$  years BP (Heintz and Garutt, 1964). In 1806 it was removed to St. Petersburg Museum. The site 4, on the Bereliekh River banks, is known for its "cemetery" of thousands of naturally accumulated mammoth bones. The  $^{14}\text{C}$  age of these remains varies from 12,250 to 10,000 years BP: the studied samples date to  $10,000 \pm 100$  years BP ( $^{14}\text{C}$  age) (Lozhkin, 1998). No information is available for site 5 (Ion Island). In Fig. 1 the site of Bol'shoy Lyakhovskiy Island (site 3) is also reported for comparison.

Most of the well preserved Siberian carcasses are dated to two periods: before 30,000 and between 13,000 and 10,000 years ago. These two periods represent, respectively, an interstadial and climatic amelioration after the last glacial maximum, before the extinction of mammoths. The climate was slightly milder than that of the last glaciation, with more water available to create mudflows; it is therefore possible that carcasses were quickly covered by sediments and, hence, more effectively preserved.

At the beginning of the middle Valdai period (50/55,000–24,000 BP) the climate was slightly warmer and more humid than at present (Klimanov, 1976) but the overall trend was towards a decreasing temperature, increasing aridity and continentality, with few climatic oscillations (e.g., Velichko, 1984). Palynological data and studies on stomach content indicate that during this period plant communities that spread over Northern Siberia were close to modern plant communities with a predominance of arid grasslands with low sward profiles such as steppe and subordinate tundra, shrubs, boreal coniferous forest and/or deciduous forest along floodplains (Guthrie, 1984; Solonevich et al., 1977; Kind and Leonov, 1982).

Around 10,000 years BP the warm conditions after the last glacial maximum probably favoured the development of arboreal species over open vegetation. Previous isotope studies suggest that during the Upper Pleistocene moisture regimen and global circulation patterns in Northern Siberia were similar to those at present (Genoni et al., 1998; Iacumin et al., 2000).

The modern climate of these locations is continental, with extremely low temperatures, scarce precipitation

distributed mainly during the warm season, dry winds and a short growing season (only three months). However, some climatic differences exist among the sites and are summarized in Table 1: the mean annual amount of rain decreases from 330 to 180 mm from east to west and the Bereliekh river area (site 4) presents the lowest mean annual temperature. The real warm season (with temperatures above 0 °C) lasts for only three months from June to August (only for site 1 from June to September). Arctic tundra is the dominant landscape of modern arctic regions and vegetation includes grasses, low growing shrubs, mosses and lichens (Atlas of the USSR, 1969). One unique characteristic of arctic tundra is permafrost, ground that is permanently frozen. The surface layer above the permafrost thaws each summer. When the water saturates the upper surface, bogs and ponds may form, providing moisture for plants.

### 3. Methods

Hair samples were first gently cleaned with a chloroform:ethanol (2:1) solution and, successively with acetone to eliminate endogenous lipids (Yoshinaga et al., 1996). After cleaning, the hair strands were cut in sequence into segments of about 0.2–0.6 cm in length and about 0.13–0.16 mg in weight. Three hairs from the same individual were measured in the case of sites 1 and 5 and two hairs in the case of site 4 to be sure of the accuracy and reliability of the sampling procedure (Schwertl et al., 2003). One hair was measured in the case of site 2. The number of segments for each hair varies between 34 and 171 depending on hair length and diameter, for a total of 763 samples. Each segment was weighed into tin capsules and then rolled into balls. Carbon and nitrogen elemental analysis and their isotope ratios were determined together using a

Table 1  
Landscape, mean annual temperature and rainfall at the studied sites

Site	Mean annual $t$ (°C)	Min/max $t$ (°C)	Annual precipitation (mm)	Landscape
Site 1 (Gydanskiy Peninsula)	-10.8	-26.7/+7.6	330	Arctic tundra
Site 2 (mouth of Lena River)	-13.4	-33.3/+7.5	240	Arctic tundra
Site 4 (Bereliekh River)	-14.1	-33.1/+9.4	220	Arctic tundra
Site 5 (Ion Island)	-13.0	-30.0/+4.3	180	Arctic tundra
Site 3 (Bolshoy Lyakhovskiy Island)	-14.4	-31.0/+2.5	160	Arctic desert

continuous flow mass spectrometer (ThermoFinnigan delta plus XP) on line with a Carlo Erba AE1110 elemental analyser. Stable isotope ratios are reported versus PDB-1 for carbon and versus atmospheric N<sub>2</sub> for nitrogen. The standard deviation was  $\pm 0.1\%$  ( $1\sigma$ ) for  $\delta^{13}\text{C}$  and  $\pm 0.2\%$  ( $1\sigma$ ) for  $\delta^{15}\text{N}$  measurements.

#### 4. Results and discussion

All the isotope data determined on the nine hair samples can be considered valid, their C/N ratios (between 3.2 and 3.5) being within the range 2.9–3.8 measured in modern hairs (O'Connell and Hedges, 1999). This ratio can be used only as a general indicator of sample preservation. However, it is probable that keratin retained its pristine C and N isotope composition also because of the low temperature related to the presence of ice layers in the sediment around the body. Ice desiccated the soil and dehydrated the carcasses allowing a good preservation of the soft tissues.

The results are reported in Table 2 and Figs. 2–5. The results of mammoth hair from the Bol'shoy Lyakhovskiy Island samples (site 3) (Iacumin et al., 2005) are also reported for comparison in Figs. 2 and 3. These hairs were from 18 to 52.5 cm long. The standard deviations of the analyses of the separate segments along each hair were lower than  $\pm 0.4\%$  in  $\delta^{13}\text{C}$  and variable from  $\pm 0.3\%$  to  $\pm 1.2\%$  in  $\delta^{15}\text{N}$ .

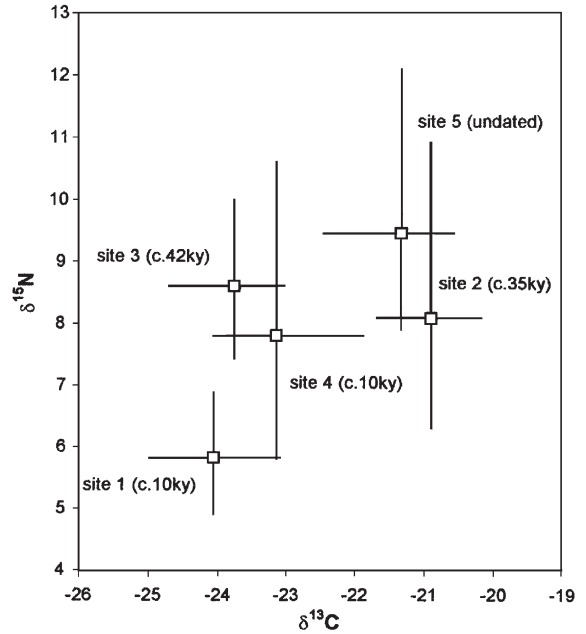


Fig. 2. Mean isotope values and range of variation of hair samples at each site.

##### 4.1. Nitrogen

The mean  $\delta^{15}\text{N}$  (present work samples and Iacumin et al., 2005 samples) varies between groups from 5.8‰ to 9.6‰ (Table 2, Fig. 2). The difference between

Table 2  
Age and isotope analyses of hairs grouped by different sites

Sample	<sup>14</sup> Cage (ka)	Hair length (cm)	Number of segments	Mean $\delta^{13}\text{C} \pm \text{std}$	Min/max	Mean $\delta^{15}\text{N} \pm \text{std}$	Min/max
<i>Site 1 (Gydansky Peninsula — 71.0°N/78.0°E)</i>							
1.1	10±0.07/9.7±0.1	35.0	92	-24.0±0.4	-25.0/-23.3	5.8±0.4	4.9/6.7
1.2	10±0.07/9.7±0.1	29.5	55	-24.2±0.3	-25.0/-23.4	5.9±0.4	5.1/6.9
1.3	10±0.07/9.7±0.1	33.0	70	-24.0±0.4	-24.9/-23.1	5.7±0.3	5.0/6.7
<i>Site 2 (mouth of Lena River — 72.5°N/127.5°E)</i>							
2.1	35.8±1.2/34.4±2.5	24.0	111	-20.9±0.3	-21.7/-20.2	8.1±1.0	6.3/10.4
<i>Site 4 (Bereliekh River — 70.7°N/147.0°E)</i>							
4.1	10±0.1	52.5	171	-23.2±0.4	-24.0/-21.9	7.7±1.2	5.8/10.0
4.2	10±0.1	44.7	124	-23.2±0.4	-24.1/-21.9	7.9±1.2	5.9/10.6
<i>Site 5 (Ion Island — 69.8°N/169.0°E)</i>							
5.1	Not dated	18.0	34	-21.4±0.4	-22.4/-20.8	9.4±0.8	7.9/11.1
5.2	Not dated	27.6	76	-21.4±0.4	-22.4/-20.7	9.6±0.9	8.0/12.1
5.3	Not dated	18.5	30	-21.3±0.4	-22.5/-20.6	9.4±0.8	7.9/11.4
<i>Site 3 (Bolshoy Lyakhovsky Island — 73.2°N/141.2°E)</i>							
3 <sup>a</sup>	42.7±1.3			-23.8±0.4 <sup>a</sup>	-24.8/-23.0	8.6±0.4 <sup>a</sup>	7.4/10.0

<sup>a</sup> Refers to four hairs. For more detail see Iacumin et al., 2005.

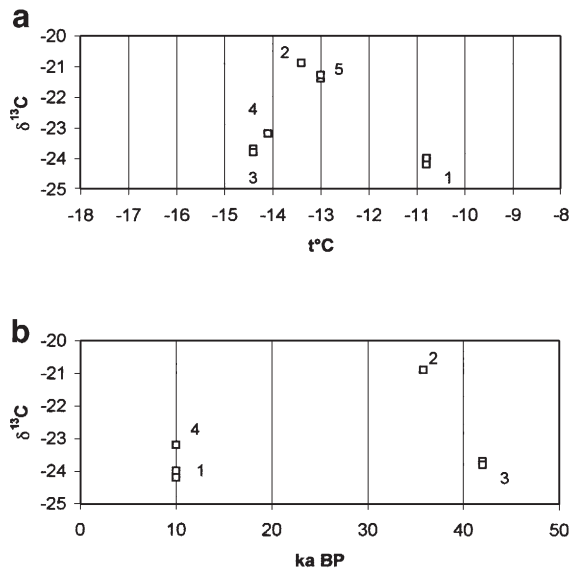


Fig. 3. (a) Mean carbon isotope analyses of each hair as a function of modern mean annual temperature at different sites. Numbers refer to the sites as in Fig. 1. (b) Mean carbon isotope analyses of each hair as a function of the radiocarbon age of the sample. Numbers refer to the sites as in Fig. 1.

groups was statistically analysed comparing the data set belonging to one or more complete oscillation to avoid possible seasonal influence on the results. The test showed that all the groups are statistically different ( $T$ -test,  $P < 0.0001$ ). All the samples show a very good correlation with longitude (Fig. 3a) and with the amount of precipitation (Fig. 3b), the correlation coefficient being 0.96 and  $-0.92$ , respectively. In this respect Handley et al. (1999) showed that a strong negative correlation exists between foliar  $\delta^{15}\text{N}$  and the amount of rain for modern plants from different habitats all around the world. In general, plant  $\delta^{15}\text{N}$  is related to soil  $\delta^{15}\text{N}$  and to environmental conditions. For example acidic soils show very low  $\delta^{15}\text{N}$  values and plants growing on it show negative  $\delta^{15}\text{N}$  on the order of  $-5\%$  (Mariotti, 1984). Plants growing on cold and humid soils present still lower  $\delta^{15}\text{N}$  values. On the contrary, plants from arid and warm soils show more enriched  $\delta^{15}\text{N}$  values (e.g., Delawiche et al., 1979; Stevenson, 1986).

From the present data it is possible to compare hairs from sites 1 and 4 having the same radiocarbon age: they show a significant difference of  $2\%$  suggesting that a spatial difference in the  $\delta^{15}\text{N}$  of diet did exist with higher values eastward.

A long-term climatic effect on the plant  $\delta^{15}\text{N}$  cannot be considered, the samples coming from different regions even if they have different radiocarbon ages.

A temporal variation from higher to lower values of the collagen  $\delta^{15}\text{N}$  was observed from 23–24 to 12–13 ka for European and Siberian herbivores from the same area (Iacumin et al., 2000; Richards and Hedges, 2003). However, mammoths from Yakutia (Siberia) dated around 10, 30 and 40 ka BP (before and after the above-mentioned period, as is the case with the present work samples) did not show significant temporal variations in their collagen  $\delta^{15}\text{N}$  values suggesting that, the differences found in the hair  $\delta^{15}\text{N}$  signal in the different sites were affected mainly by the local environmental conditions and not by long-term variations.

#### 4.2. Carbon

The mean  $\delta^{13}\text{C}$  values (present work samples and Iacumin et al., 2005 samples) varies between groups from  $-24.1\%$  to  $-20.9\%$ . Each group of hair (considering only complete oscillation as for N) shows a statistically significant difference ( $P < 0.0001$ ): hair samples from the Gydanskiy Peninsula area (site 1) show the lowest  $\delta^{13}\text{C}$  and hair samples from the mouth of Lena river (site 2) show the highest  $\delta^{13}\text{C}$  values (Table 2, Fig. 2). The hair  $\delta^{13}\text{C}$  differences are related to differences in the isotope composition of the plant food at the base of mammoth diet. In general, a spatial variation of the plant  $\delta^{13}\text{C}$  exists depending on local climatic and environmental conditions such as

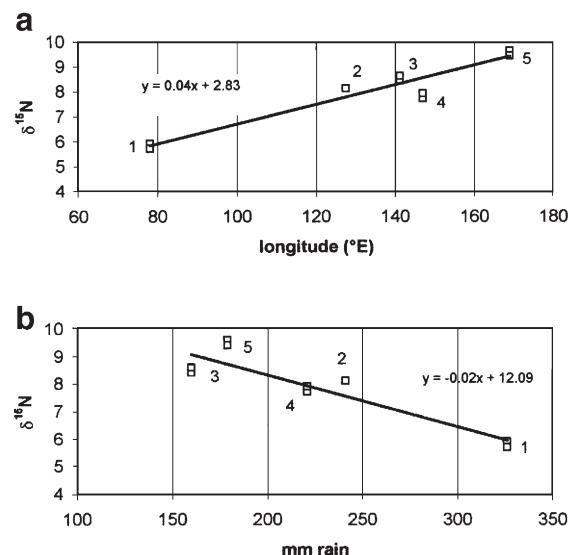


Fig. 4. (a) Mean nitrogen isotope analyses of each hair as a function of longitude of different sites. Numbers refer to the sites as in Fig. 1. (b) Mean nitrogen isotope analyses of each hair as a function of modern annual rainfall at different sites. Numbers refer to the sites as in Fig. 1.



temperature and aridity. For example, an increase in temperature or in water stress produces a  $^{13}\text{C}$  enrichment (Stuiver and Braziunas, 1987; Leavitt and Danzer, 1992; Heaton, 1999).

Tundra is the main landscape for all the sites with approximately the same kind of vegetation.  $\delta^{13}\text{C}$  measurements carried out on 136 modern woody and herbaceous plants from Yakutia and the surrounding area exhibit a statistically fairly significant correlation ( $r = -0.60$  to  $-0.79$ ) with the mean annual temperature or with the ratio temperature/amount of precipitation, depending on the species. However, surprisingly enough, in this case the correlation was found to be negative (Nikolaev et al., 2004). Weak or no correlation was found between plant  $\delta^{13}\text{C}$  and the amount of precipitation or relative humidity. It seems that, in the Polar Regions considered, temperature is the main factor affecting plant  $\delta^{13}\text{C}$ .

The main difference between mean annual temperatures at the studied sites is between site 1 and the others (Table 1, Fig. 4a). Site 1 (the warmest site) currently shows the lowest mean hair  $\delta^{13}\text{C}$  value but no correlation can be found between hair  $\delta^{13}\text{C}$  and the modern mean temperature. Therefore, temperature is not the main or the only factors that have affected the hair  $\delta^{13}\text{C}$  values at the different sites.

Another consideration that can be made to try to explain the carbon isotope differences found between sites is about the different age of the samples. Samples show different radiocarbon ages with the exception of those from sites 1 and 4, both dated around 10 ka BP. Samples from sites 2 and 3 are dated before the Last Glacial Maximum (LGM). This is important since Richards and Hedges (2003) found that the  $\delta^{13}\text{C}$  signal of collagen from herbivore bones from Northwest Europe varied over the last 40 ka BP: in particular, after 14 ka BP there is a depletion of this value becoming apparent at 10 ka BP and reaching its minimum value at about 8.5–9 ka BP. The overall depletion is of about 1.6‰ and the pattern seems to agree with the change in atmospheric  $\text{CO}_2$  concentration obtained from ice cores at the end of LGM. As the collagen  $\delta^{13}\text{C}$  is a function of the  $\delta^{13}\text{C}$  of diet, the authors related this depletion to the effect of higher  $\text{CO}_2$  atmospheric content on plant physiology and, ultimately, to the global climatic change. On the other hand, a positive correlation between the  $\text{CO}_2$  atmospheric content and the mean annual temperature has been observed in the past: higher concentrations during warm periods (interstadials) and lower ones during cold periods (glaciation) (Barnola et al., 1987).

Leavitt and Danzer (1992) found a similar pattern of the  $\delta^{13}\text{C}$  values of different plant categories over the last 50 ka: plant  $\delta^{13}\text{C}$  gradually rises from 40 up to 22 ka BP and declines after about 12 ka BP with a number of oscillations. The authors take into consideration only the mean plant  $\delta^{13}\text{C}$  values after and before 10 ka BP which are different by about 1‰. Mammal remains dated before 12–14 ka BP should then be enriched in  $^{13}\text{C}$  by about 1–1.6‰ when compared to more recent samples from the same area. Taking into consideration this effect, the different radiocarbon age of the samples could explain the higher hair  $\delta^{13}\text{C}$  values obtained from site 2 (about 35 ka BP) than those from sites 1 and 4 (about 10 ka BP) but not the low values from site 3 (Fig. 4b). On the other hand, if the plant  $\delta^{13}\text{C}$  patterns reported by Leavitt and Danzer (1992) are considered in more detail (low  $\delta^{13}\text{C}$  values around 40 ka BP slowly increasing up to 22 ka BP) the values from site 3 agree with the long-term  $\delta^{13}\text{C}$  plant variability. Colder climatic conditions would then characterize the period around 36 ka BP when compared to those existing around 10 and 42 ka ago. This is in agreement with what found by Klimanov (1976).

In the case of samples from site 1 and 4 they show different mean hair  $\delta^{13}\text{C}$  values (samples 4 are more positive) despite the same value of their radiocarbon age. Taking into consideration the behaviour of local modern plants, this could be really an effect of the local environmental factors such as temperature on the  $\delta^{13}\text{C}$  values of vegetation. However, it is also possible that the plant community in the two sites were different with different plant  $\delta^{13}\text{C}$  values. The modern plants measured in the area are various species of grass, shrubs, leaves, mosses and club-mosses. The ranges of  $\delta^{13}\text{C}$  values are quite similar among the groups and vary between  $-25$ ‰ and  $-31$ ‰, the mean values differ of about 1‰ (Nikolaev et al., 2004). The difference between site 1 and 4 is of the same order and it could be ascribed to the presence of different plant association at 10 ka years BP in the two areas.

It appears that hair keratin is enriched in  $^{13}\text{C}$  from about 1‰ to about 3.5‰ with respect to diet (Minson et al., 1975; Jones et al., 1981; Nakamura et al., 1982; Tieszen et al., 1983; Katzenberg and Krouse, 1989; White, 1993; Sponheimer et al., 2003). From the carbon values measured on our samples it is therefore possible to calculate a probable  $\delta^{13}\text{C}$  range for the vegetation at the base of mammoth diet in the different sites and in the different periods considered. The calculated plant  $\delta^{13}\text{C}$  values from the samples dated around 10 ka BP vary from a maximum of  $-24.2 \pm 0.4$  (considering 1‰ of fractionation) to a minimum of

$-27.5 \pm 0.4$  (considering 3.5‰ of fractionation). The mean  $\delta^{13}\text{C}$  value measured on modern plants from Yakutia and surrounding areas is  $-28.9 \pm 1.6$ ‰ (Nikolaev et al., 2004). This value is probably depleted by no less than 1.5‰ when compared with the values calculated from fossils due to the progressive depletion in  $^{13}\text{C}$  of atmospheric  $\text{CO}_2$  as a result of human activity over the past 200 years. Considering this effect and the variability of modern plant  $\delta^{13}\text{C}$  values, the calculated plant  $\delta^{13}\text{C}$  values are equal or more positive of the values of modern plants suggesting that climatic conditions around 10 ka ago were not too different from the present ones.

### 4.3. Temporal patterns

We combined the temporal curves obtained from hairs of the same individual according to their isotope patterns, minima, maxima and peak widths. To minimize error as much as possible when reporting the isotope data for each hair in a temporal curve, the length of each single segment was calculated from its weight, knowing the total weight and the total length of the hair according to the equation:

$$\begin{aligned} &\text{total length (cm)} / \text{total weight (mg)} \\ &\times \text{segment weight (mg)} = \text{segment length (cm)}. \end{aligned}$$

In this way we avoided the problem of using segments of different lengths.

In some cases the isotope patterns were displaced relative to each other probably due to the fact that hairs were in different growing phase. According to Valkovich (1977) a single hair can be in the telogen phase (quiescent phase) and consequently it does not contain the most recently formed tissue and the last isotope information. The shortest hairs were shifted in respect of the longest one so that the same value on the x-axis corresponds to the same growth instant for the different hairs regardless of their length. In all cases the peak shape and the distance among peaks matched nearly perfectly. This means that the growth rate was the same for hairs from the same individual and that, as already pointed out by Schwertl et al. (2003), a single hair is a representative sample. In Figs 5a and b the temporal isotope patterns, obtained from the different mammoths, were reported together for comparison. To avoid to hide some variations and for a easier reading of the graphs in the case of two or three hairs from the same individual a single line was drawn representing the sum of all the isotope values obtained. This was possible thanks to the good overlapping of the hairs from the same mammoth.

The total range of variation of the  $\delta^{15}\text{N}$  within each group goes from 3.6‰ to 4.8‰ with the exception of hairs from site 1 that shows a narrow range of only 1.8‰ (Fig. 5a); a roughly sinusoidal pattern of lighter and heavier values is shown by the nitrogen isotope values again with the exception of samples from site 1. Hairs from site 4 also show a depression in the centre of the positive peaks and sites 2 and 5 exhibit a trend from the tip towards lighter values. A difference of about 1‰ can be calculated between the first and the second complete oscillation of hairs from sites 2 and 5.

In the case of carbon the total range of variation is  $\leq 1.9$ ‰ with the exception of hairs from group 4 which show a rather positive peak that increases the overall variability to 2.2‰ (Fig. 5b). All the samples show two or more main oscillations (and many secondary ones) which differ from one site to the other for their width and shape. The sample from site 1 shows a trend towards lighter values from the tip up to 17 cm and the mean  $\delta^{13}\text{C}$  value of this first part is of 0.5‰ more positive than the second one.

Schwertl et al. (2003) found similar ranges of variation between maxima and minima for cattle hairs in the order of 1–4‰ for  $\delta^{15}\text{N}$  and 0.5–3‰ for  $\delta^{13}\text{C}$ .

Moreover, the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  patterns from the same site never correlate with each other.

The existence of the isotope oscillations implies a seasonal variation of the isotope values of diet throughout the time of hair growth.

The observed isotopic temporal patterns could arise from a number of different causes some of which may be concurrent:

- seasonal and annual changes in the  $\delta^{13}\text{C}$  values of plants. Heaton (1999) summarizing the  $\delta^{13}\text{C}$  variability of plants states that this seasonal/annual variability is in the order of  $\pm 1$ ‰;
- seasonal changes in the type of vegetation: mainly herbs in summer and more mosses, lichens and low-growing shrubs in winter (Gorlova, 1982). Nikolaev et al. (2004) report a mean difference of 1‰ between the two groups;
- seasonal and annual changes in the  $\delta^{15}\text{N}$  values of plants. Handley et al. (1999) showed the existence of a negative correlation between site-averaged foliar  $\delta^{15}\text{N}$  and soil moisture during a single growing season. However, even though no plants from arctic areas were used in the above-mentioned study, the large variability found at a single site (apart samples from site 1) may be explained with the  $\delta^{15}\text{N}$  variations of plants at the base of mammoth diet related to dry

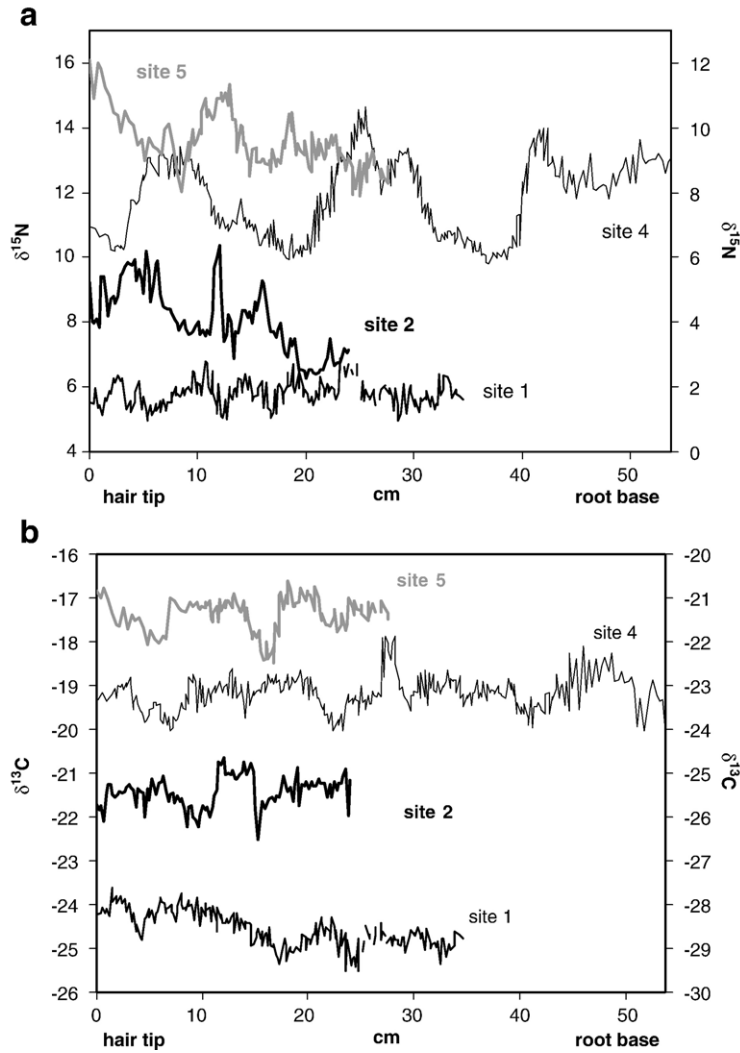


Fig. 5. (a) Carbon isotope values of hairs from each site versus distance from hair tips. For each site (apart site 2) the 2 or 3 hairs measured are plotted together after position correction for growth cycle error (see text for explanation). (b) Nitrogen isotope values of hairs from each site versus distance from hair tips. For each site (apart site 2) the 2 or 3 hairs measured are plotted together after position correction for growth cycle error (see text for explanation). Hairs from sites 1 and 2 are reported on the left axis and hairs from sites 4 and 5 on the right axis.

winters and to the large availability of water during summer.

- the physiological effect on mammoths directly related to water availability under extreme environmental conditions (e.g., very arid conditions): mammoths were probably subject to water and dietary stress during winter. In these conditions it has been found that mammal collagen  $\delta^{15}\text{N}$  correlates positively with the amount of precipitation in the different areas (Heaton et al., 1986; Cormie and Schwarcz, 1996).

As the plant  $\delta^{15}\text{N}$  is negatively correlated to water availability the positive peaks should record winter

conditions while the negative ones should be related to summer conditions.

Hair accretion took place throughout the whole year and on the base of a complete oscillation it is possible to calculate the growth rate for the different mammoth hairs. For example, in the case of hairs from site 4 the longest isotope record should represent the last 33 months of mammoth’s life. This means that hairs grew at a rate of about 19 cm/year. The growth rate for the Adams mammoth (site 2) is about 12 cm/year while that for mammoth from site 5 was about 9 cm/year. The calculated growth rates are very different from one another. It is possible that hairs were collected from different parts of mammoth bodies



and that the growth rates vary according to different body sections. Unfortunately we only know that the hairs of Adams mammoth (site 2) were collected from its head.

On the base of the segment length of hairs each isotope measurement is representative of the food intake over a period of 6–7 days in the case of hairs from sites 2 and 4 and of 15–25 days in the case of hair 5. This is true only provided that the growth rate is the same throughout the year.

It is possible that, in the case of site 1 where no seasonal variations are apparent, mammoths were forced during winter to move southwards (less severe winters) minimizing, in this way, the seasonal effect on the isotope patterns.

## 5. Conclusion

The reported results corroborate the possibility of using hair  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values as indicators of geographical and temporal variation in plant isotope composition and, ultimately, as indicators of climate changes in the past.

When samples of the same age are considered, it is apparent that both the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  mean values of mammoth's hairs, increase towards the east. In the case of nitrogen this is true also independently of the radiocarbon age of the samples. This suggests the existence of a geographical variation of the isotope signal related to different environmental conditions. In the case of nitrogen the amount of rain seems to be the main factor indirectly affecting the hair  $\delta^{15}\text{N}$  via its effect on the  $\delta^{15}\text{N}$  of plants. One should conclude that the rate of atmospheric precipitation at the studied sites did not change significantly in the different periods considered.

In the case of carbon the changes in the atmospheric  $\text{CO}_2$  content related to temperature changes seems to be the main factor indirectly influencing the hair  $\delta^{13}\text{C}$ , again through its effect on vegetation.

The isotope analyses carried out on single hairs revealed quasi-sinusoidal patterns of lighter and heavier carbon and nitrogen isotope values with the only exception of samples from site 1. The two isotope patterns do not correlate with each other perhaps because they are influenced by different environmental factors. These patterns can be considered as an expression of the seasonal  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  change in the mammoth diet (change in the isotope composition of plant or in the type of plant) or, only in the case of nitrogen, as a physiological effect related to arid winter conditions.

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