SPECIAL REPORT

Oxygen isotope composition of human tooth enamel from medieval Greenland: Linking climate and society

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ABSTRACT

Because the oxygen isotope composition of mammalian tooth enamel ($\delta^{18}O_p$) can be used as a proxy for local surface temperature, teeth from archaeological sites can serve as records of climate change on the time scale of decades to thousands of years. Such records can be interpreted in terms of the response of human societies to climate change. In the first such study, the analyses of Norse and Inuit teeth from North Atlantic sites validate the relation between $\delta^{18}O_p$ and temperature. A 3‰ decrease in $\delta^{18}O_p$ from sites in Greenland about A.D. 1400 to 1700 implies rapid cooling during the Little Ice Age.

INTRODUCTION

One of the most promising methods of continental climate reconstruction is the use of $\delta^{18}O$ and δD values of local meteoric water ($\delta^{18}O_w$ and δD_w) as a proxy for mean annual surface temperature. The correlation between $\delta^{18}O_w$ and temperature first observed by Dansgaard (1964) has been substantiated by numerous measurements made over the years of modern meteoric waters from a network of International Atomic Energy Agency (IAEA) stations and other sources, although the relation can be complicated because of local effects of relative humidity, seasonality, storm rainout, proportion of winter precipitation, and the source of air masses (e.g., Yurtsever and Gat, 1981; Rozanski et al., 1993). Therefore, unless the effects of all of the climate variables are known at one locality, $\delta^{18}O_w$ should be considered a reflection of a given "climate state" dominated by average surface temperature, and change in $\delta^{18}O_w$ should be viewed as a change in these states.

It has been well established that $\delta^{18}O_w$ is related to the oxygen isotope composition of biogenic phosphates ($\delta^{18}O_p$; Longinelli, 1984; Luz et al., 1984); therefore, a useful proxy for $\delta^{18}O_w$ is the oxygen isotope composition of mammalian tooth enamel (99% $Ca_5[PO_4,CO_3]_3[OH]$). Mammals precipitate tooth enamel in equilibrium with their body water at a constant temperature (~37 °C). The oxygen isotope composition of the body water ($\delta^{18}O_{bw}$) is in turn a reflection of the oxygen isotope composition of the water ingested by the mammal. The extent to which body water is isotopically fractionated relative to ingested water depends on the size and metabolic rates of the mammal, and such relations have been determined empirically for several mammalian species common to archaeological sites, including pigs, cattle, sheep, deer, horses, and humans (Luz and Kolodny, 1985; Ayliffe and Chivas, 1990; D'Angela and Longinelli, 1990; Luz et al., 1990; Yoshida and Miyazaki, 1991; Ayliffe et al., 1992; Bryant et al., 1994). Assuming that the water ingested by mammals is locally derived meteoric precipitation, $\delta^{18}O_{bw}$ and, hence, $\delta^{18}O_p$ should be an accurate reflection of $\delta^{18}O_w$, and any change in $\delta^{18}O_p$ values over time should reflect only a change in the value of $\delta^{18}O_w$.

The oxygen isotope composition of mammalian tooth enamel also provides a time-averaged value for $\delta^{18}O_w$. Tooth enamel is formed gradually over the early part of a mammal's life and, because it does not continuously dissolve and reprecipitate like bone, $\delta^{18}O_p$ is a reflection of the average value of $\delta^{18}O_w$ for that period of growth (on the order of years and species specific). As a result, a climate change that results in a change in $\delta^{18}O_w$ must last long enough so that it can subsequently be recorded in the enamel of mammals living in the area. Thus, oxygen isotope analysis of tooth enamel is not applicable to investigations of seasonality, annual averages, or even some of the very short time period climate changes observed in the Greenland ice cap (Johnsen et al., 1992; Meese et al., 1994), but to persistent variations that occur for years, decades, or longer.

Archaeological sites are an ideal source of mammalian tooth enamel from a variety of species. They are widespread in time over the past several thousand years, thereby filling a critical gap between geological and historical records, and their strata are generally resolvable on the decade to millennia scale. In addition, they cover most areas of current human habitation and are well described in terms of stratigraphy, generalized paleoenvironment, and temporal correlation to other locations. Therefore, material from archaeological sites is well suited not only for quantitative time-series reconstructions of temperature (climate) change, but also for the spatial reconstruction of temperature variation. Such reconstructions have the potential to relate climate change in the historical past to present-day climate in a more locally relevant manner than is possible at present.

Finally, archaeological material is by definition related to human activities and thus provides a unique opportunity to link records of climate change to civilizations and societal change. In combination with related archaeological data, quantitative records of local climate change are critical to the understanding of the response of human groups to climate change in the past (McGovern, 1991). Thus, there is great potential for coordinating detailed natural and social scientific investigations of climate change and the rate of climate change and its effect on human groups of different sizes and complexity and in different physical environments.

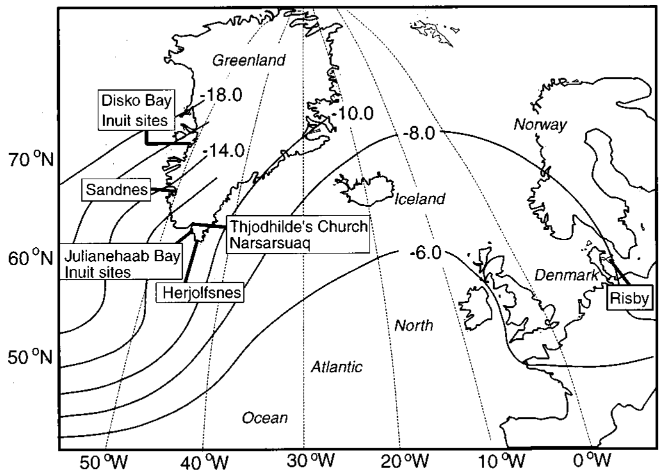

Figure 1. Location of sampled archaeological sites from Greenland and Denmark and contours of mean $\delta^{18}O_w$ of modern precipitation (Yurtsever and Gat, 1981). Latitudinal scale is accurate for Greenland only. There is a modern difference of ~8‰ in $\delta^{18}O_w$ between Risby and Disko Bay, which is the result of differences in average surface-air temperatures.

HUMAN TEETH FROM MEDIEVAL GREENLAND AND DENMARK: A TEST CASE

A pilot study of the oxygen isotope composition of mammalian tooth enamel from archaeological sites known to have undergone temperature change established the viability of the oxygen isotope results. The technique was applied to an investigation of temperature change in medieval Greenland during and after Norse colonization, at the onset of the Little Ice Age in the North Atlantic. The significance of climate change to the Norse colonies has been discussed at length (e.g., Lamb, 1977; McGovern, 1980; McGovern et al., 1988) and is beyond the scope of this paper. We studied the oxygen isotope systematics of human tooth enamel from three areas in Greenland which were intermittently occupied by Inuits and European settlers (the Norse) since ca. A.D. 1000, and another site in Denmark. The sites in Greenland are located along its west and southwest coasts near Disko Bay, Sandnes, and Julianehaab Bay; the site in Denmark is located near Risby (Fig. 1). The Disko Bay sites were occupied solely by Inuits, half of the individuals having lived 300 to 400 yr ago and half thought to be fairly recent (18th to 19th century), although the ages are poorly constrained (Gad, 1970). All the Greenland Norse material was excavated from former Norse churchyards. Recent accelerator mass spectrometer (AMS) radiocarbon ages determined for samples from the Sandnes site (Fig. 1) are ca. A.D. 1300 to 1400 (Lynnerup, 1995). In the Julianehaab Bay area, samples have been obtained from three radiocarbon-dated Norse sites (Thojhilde's Church, A.D. 1000 to 1250; Herjolfsnes, A.D. 1400 to 1450; and Narsarsuaq, A.D. 1300 to 1450). Samples have also been obtained from two younger, but poorly dated, Inuit sites in the Julianehaab Bay area (Fig. 1). Finally, samples were obtained from a Danish medieval churchyard at Risby (ca. A.D. 1100 to 1600).

Oxygen isotope analyses were made of enamel phosphate using the technique of O'Neil et al. (1994) and are reproducible to better than ±0.3‰. Because there is a change of 0.4‰–0.7‰ in $\delta^{18}O_w$ per degree Celsius (depending on latitude) for modern-day meteoric water (Rozanski et al., 1993), it should be possible to resolve temperature changes of less than 1 °C with our measurements. The results of the oxygen isotope analyses of the tooth enamel are presented in Table 1. Ranges of $\delta^{18}O_p$ values measured were 11.8‰ to 13.6‰ (n = 6) for all the Disko Bay samples, 14.3‰ to 15.9‰ (n = 3) for Sandnes samples, and 16.9‰ to 18.9‰ (n = 5) for Risby samples. Analyses of the late Norse samples from Julianehaab Bay range from 16.4‰ to 16.7‰ (n = 4; Herjolfsnes and Narsarsuaq) and from 15.9‰ to 18.4‰ (n = 10; Thjodhilde's church), whereas the $\delta^{18}O_p$ values of Inuit samples from the same area are distinctly lower, ranging from 13.0‰ to 15.0‰ (n = 6). Although only a limited number of samples were available to us for analysis, there is a significant difference in the intrapopulational variation in $\delta^{18}O_p$ from site to site (Fig. 2). Analyses of the late Norse samples from Julianehaab Bay have a standard deviation less than analytical error, as seen in data for modern mammal groups from one locality (Luz et al., 1984; Luz and Kolodny, 1985; Yoshida and Miyazaki, 1991). The standard deviations observed for all the other groups are closer to ~1.0‰, similar to what is found in temporally heterogeneous collections of fossil samples from rock layers (Bryant et al., 1994) and caves (Reinhard et al., 1995).

TABLE 1. OXYGEN ISOTOPE COMPOSITION OF TOOTH ENAMEL FROM NORSE AND INUIT SITES

Sample	$\delta^{18}O_p$	Mean, s.d.*
Risby,		18.1 ± 0.86
ca. A.D. 1100-1600, lat 55°N		
5	18.8	
10	18.9	
38	17.5	
D1	16.9	
D2	18.3	
Thjodhilde's Church,		17.2 ±0.90
A.D. 1000 - 1250, lat 61°N		
1032	17.2	
1084	17.5	
1654	18.4	
1655	15.9	
1659	16.2	
91	16.5	
97	17.8	
MI	17.5	
MII	16.2	
MIII	18.3	
Narsarsuaq,		16.5 ± 0.07
A.D. 1300-1450, lat 61°N		
0996	16.4	
0999	16.5	
Herjolfsnes,		16.7 ± 0.00
A.D. 1400-1450, lat 61°N		
0903	16.7	
0907	16.7	
Julianehaab Bay Inuit,		13.9 ± 0.75
ca. A.D. 1500 - 1700, lat 61°N		
0838	14.0	
0847	13.3	
1460	13.0	
1464	15.0	
1465	13.5	
1471	14.4	
Sandnes,		15.0 ± 0.82
A.D. 1300-1400, lat 64°N		
0928	14.3	
0936	14.8	
0947	15.9	
Disko Bay Inuit,		11.6 ± 0.60
ca. A.D. 1500 - 1850, lat 72°N		
0161	13.6	
0633	13.2	
0445	13.5	
1548	12.6	
1550	11.8	
1551	11.9	

*Standard deviation.

DISCUSSION

Despite relatively large standard deviations, it appears that $\delta^{18}O_p$ does record past values of $\delta^{18}O_w$ and can be used to record latitudinal temperature differences and climate change in the past. The spread in $\delta^{18}O_p$ values between the northernmost Disko Bay and southernmost Risby sites is on the order of 7‰, almost identical to that found for modern-day meteoric precipitation, and supports the assumption that temperature differences are accurately reflected

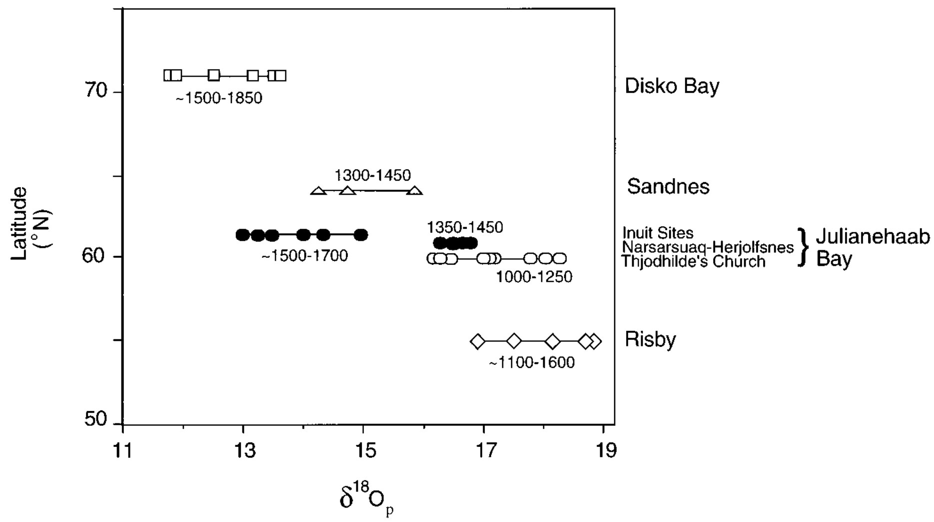

Figure 2. Human tooth enamel $\delta^{18}O_p$ values from each archaeological site vs. latitude of that site. Note differences in intrapopulational variation of values from different sites. Large variations could be result of human behavioral patterns or poor dating of samples. Thjodhilde's Church data appear to cluster into three distinct groups, probably the result of individual migration (see text). Range in $\delta^{18}O_p$ values between Risby and Disko Bay is ~7‰, similar to that for modern precipitation. Number labels are years A.D.

by the oxygen isotope composition of human tooth enamel (Fig. 2). Even more exciting is the lowering of the average $\delta^{18}O_p$ value by about 3‰ for the Julianehaab Bay sample groups during the Middle Ages (Fig. 3). The timing of this cooling period corresponds to historical records of cooler temperatures in the North Atlantic during the Middle Ages, a period that is commonly called the Little Ice Age. Climate during this period is characterized as fluctuating between colder and more mild periods, the colder periods being more common and pronounced relative to those prior to and following the Middle Ages (Meese et al., 1994; Grove, 1988). An estimate for present-day $\delta^{18}O_p$ can be made by using the values of precipitation collected from IAEA stations (Rozanski et al., 1993) in Groennedal and Prins Christians Sund (located on either side of Julianehaab Bay) and the relation between $\delta^{18}O_p$ and $\delta^{18}O_w$ for humans (Longinelli, 1984). This value, 15.3‰, is 1.4‰ higher than the Little Ice Age values, and it clearly reflects the known return to a more mild climate regime (Fig. 3).

Because the intrapopulational variation in $\delta^{18}O_p$ values affects the interpretation of these data in terms of absolute temperature and temperature change, it is necessary to evaluate two of the more probable causes for the scatter in $\delta^{18}O_p$ values in some of the sites: (1) limited chronological resolution between samples and (2) variable patterns of behavior of the human populations. In the former case, the unstratified nature of human burials in Greenland makes it very difficult to determine absolute or even relative ages between graves unless each individual is directly dated. Therefore it is possible that in the case of the poorly dated Risby and Inuit sites, individuals who did not live at the same time, and were even separated in time by hundreds of years, are being grouped together by us as roughly contemporaneous. If this is the case, and if individuals from different time periods ingested waters with different $\delta^{18}O$ values (assuming a change in local surface temperature over time), the result would be large intrapopulational variations in $\delta^{18}O_p$. Individuals from the Julianehaab Bay Norse sites of Herjolfsnes, Narsarsuaq, Sandnes, and Thjodhilde's Church, however, have been directly dated by means of AMS radiocarbon dating (Lynnerup, 1995). The contemporaneous samples from Herjolfsnes and Narsarsuaq have an intrapopulational variation, within analytical error, similar to that of modern human populations (Longinelli, 1984) and demonstrate the possible increase in the resolution of $\delta^{18}O_p$ changes, given more precise chronological control. The resolution made possible by AMS ^{14}C dating, however, is still limited by the associated analytical error of ±40 yr, and efforts are now being made to increase temporal control by analyzing animal remains from well-stratified middens associated with some of the Norse settlements and cemeteries.

In contrast to Herjolfsnes and Narsarsuaq, the larger standard deviation of samples from Sandnes and Thjodhilde's Church indicate that other factors most likely related to human behavior may also play a role in the intrapopulational variation of $\delta^{18}O_p$ at a given site. For example, people living in Greenland had a selection of water sources, including several streams and springs, melted snow, and glacial runoff, and their choices may have varied through time, as a result of environmental or other stresses, or between different social groups of Norse and Inuits. Also humans commonly migrate and are often not buried where they were raised. Because the $\delta^{18}O_p$ values of enamel are "locked in" during adolescence, individual migration to and burial in an area with a different $\delta^{18}O_w$ invalidates the assumption that $\delta^{18}O_p$ is a proxy of *local* meteoric precipitation. Although both of these aspects of human behavior are difficult to quantify archaeologically, evidence from Thjodhilde's Church suggests that the apparent spread in $\delta^{18}O_p$ values may be an artifact of human migration. It is very likely that the church is one of the earliest built in Greenland, and its cemetery could have the remains of the first European settlers as well as the first Green-

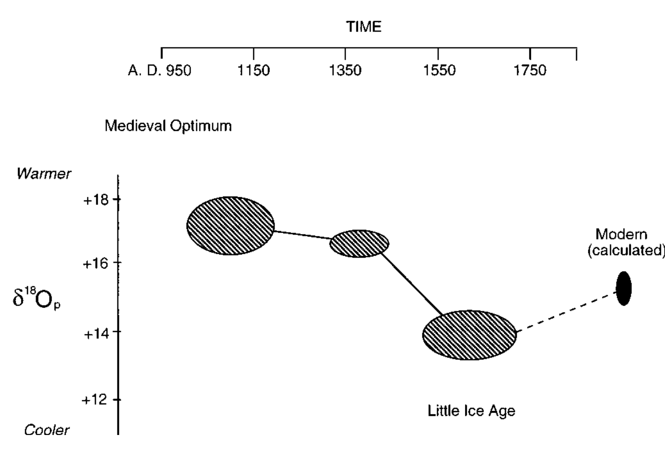

Figure 3. Change in $\delta^{18}O_p$ over time in Julianehaab Bay area. Data from Thjodhilde's Church, Herjolfsnes-Narsarsuaq, and Inuit sites are plotted as ovals, heights being ±1 standard deviation from the mean, and widths being estimated range in age of samples. Lowering in values at ca. A.D. 1400 is related to greater frequency of cooler temperatures in Middle Ages. Calculated modern $\delta^{18}O_p$ values reflect return to more mild climatic conditions following Little Ice Age.

land-born Norsemen. Adult émigrés from Iceland and possibly northern Norway would have markedly different values of $\delta^{18}O_p$, and this fact could explain the clustering of $\delta^{18}O_p$ values into distinct groups (Fig. 2). Therefore, in some cases, resolution of $\delta^{18}O_p$ change may be limited despite known temporal relations, owing to behavioral factors that cannot be accounted for in quantitative terms.

Rough estimates of local temperature change and rates of change can be made by applying to the Greenland localities the global modern-day relation between $\delta^{18}O_w$ and temperature at high latitudes of ~0.7‰/°C (Dansgaard, 1964; Rozanski et al., 1993). The lowering of ~3‰ in $\delta^{18}O_p$ values corresponds to a rapid decrease of ~4.2‰ in $\delta^{18}O_w$ (Longinelli, 1984), which is equivalent to a (rapid) drop of ~6 °C in the mean annual local air temperature over ~300 yr (or ~1 °C per 50 yr). Similarly, the 1.4‰ increase in $\delta^{18}O_p$ following the Little Ice Age corresponds to an increase of 2.2‰ in $\delta^{18}O_w$, or about 3 °C over ~250 yr (~1 °C per 80 yr). It must be noted, however, that recent work employing general circulation models suggests that sources of Greenland precipitation vary with different climate regimes, and Pacific sources with lower $\delta^{18}O_w$ values become more important during glacial episodes (Charles et al., 1994). Thus, the lowering in $\delta^{18}O_p$ observed in this study may also be influenced by air masses with lower $\delta^{18}O_w$ values, or perhaps climate parameters other than local surface temperature, and the estimates of temperature change presented here should be interpreted as maximum limits only. Regardless of the complex local relation between $\delta^{18}O_w$ and temperature, the future dating of the individuals from Risby and the Inuit graves and the analysis of well-stratified midden remains (in progress) will allow better estimates of latitudinal temperature differences, of change in climate variables, and—most important—the rate of that change.

CONCLUSIONS

In light of myriad possible complications, real or imagined, the regularities observed in the oxygen isotope systematics of these analyses lend credence to the approach and bode well for future applications to archaeological material, particularly mammalian tooth enamel from well-stratified middens. Given good dating and sufficient knowledge of the timing of enamel formation and of mammalian behavior, oxygen isotope analysis of mammalian tooth enamel from archaeological sites can provide an accurate record of climate change and the rate of climate change on a time scale of decades to centuries. These records can then be used to provide important constraints on the response of human groups to climate variations. The integration of climate change with human societal change in the past lends the described technique a relevance not usually found in climate records that are purely geologic and will, we hope, foster more interdisciplinary research in the North Atlantic and elsewhere.

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