TRACING HUMAN MIGRATION WITH STABLE ISOTOPES

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Abstract

The diet of ancient humans can be partly inferred from analyses of the stable isotopes of carbon and nitrogen in the collagen of their bones. As well, the ratios of the isotopes of oxygen ($^{18}O/^{16}O$) in bone mineral are determined by the isotopic composition of local meteoric water (rain, snow). These ratios vary with climate and distance from the ocean. Isotopic data can thus be used to identify the locale in which a person had lived. Teeth preserve an isotopic record of their natal habitat, whereas bones record the environment over the last 10 y of life. We can use these data to track the migration of humans and to recognize "outsiders" in an otherwise homogeneous population. Examples of the application of these methods are presented from Mesoamerica, Canada, Italy, and Africa.

Introduction

In studying the skeletal characteristics of ancient and historic human populations it would be useful to be able to determine if individuals were natives of the site at which they were found. In general we can conceive of a number of possible scenarios for the life history of a given member of a population, for example:

a) they were conceived, born, lived, and died at the site
b) they lived elsewhere until shortly before their death
c) they spent part of their life (e.g., infancy) elsewhere, and later moved to the site

Each of these scenarios has potentially different consequences with respect to the stable isotopic composition of the skeleton. Therefore we can use isotopic analyses of skeletal materials to learn about residential and migratory history of these individuals. This is based on the well-known principle that "we are what we eat" and, as well, "what we drink and breathe," since the isotopic compositions of bones and teeth are controlled by all fluxes of relevant isotopic atoms into and out of the living human. We are abetted in these studies by the accretionary nature of the skeleton which allows us to track changes in these inputs through the life of the person. It is essential to this research that the atoms of which the body is principally composed (carbon, oxygen, hydrogen, nitrogen) have stable isotopes whose relative abundances vary depending on the location where they are obtained. For example, the $^{18}O/^{16}O$ ratios of water and locally-grown foods from northern Europe are significantly lower than those of water and foods of central and southern Italy. In this way we can use the stable isotopic composition of skeletons not only to tell that a person did not always live where we find them but, in some cases, to suggest whence they came.

Chemical and Isotopic Composition of Bones and Teeth

Bones and teeth consist of crystals of mineral set in a matrix of protein. The mineral, hydrous calcium phosphate or apatite, contains isotopes whose relative abundances vary in nature: oxygen (O), hydrogen (H), and carbon (C, as carbonate). Isotopes are atoms of an element which differ in atomic mass, but which have essentially the same chemical properties. As a result of slight differences in their chemical properties, isotopes of the lighter elements C, H, O, and N tend to be chemically separated from one another (fractionated). Thus we can detect differences in the relative abundances of these stable isotopes in samples of different chemical or biological origin, and can use these variations in isotope ratios to learn about the source of these atoms in a biological material. Some heavy elements in bone (e.g., strontium) have isotopes whose ratios vary depending on the sources of foods.

The protein component of bone is collagen. It is composed of carbon, hydrogen, and nitrogen, which also carry isotopic signals indicative of the source of these atoms in food and drink ingested. Variations in the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios in bone collagen have been widely used to determine the diet of people in the past. Distinctive differences in dietary patterns can identify outsiders in an otherwise homogeneous population (Schwarcz & Schoeninger 1992; Katzenberg 1992). Culturally and individually determined food choices within a population can also have a large effect on collagen's isotopic composition. For example, a single high status individual who was treated differently (fed a different diet) than the remainder of the population might appear to be an outsider. Nevertheless, paleodietary data, if used with appropriate caution, may provide us with an additional indicator of membership (or lack of it) in the community.

Oxygen isotope ratios of bones and teeth are particularly useful as tracers of geographic origin because most of the oxygen atoms in skeletal mineral were acquired from water locally available to the individual, either as drinking water, or as a component of the foods consumed (plant tissues, meat, milk, eggs). The water is ultimately derived from local meteoric precipitation or from wells or aqueducts delivering water from sources that are generally not more than a few tens of kilometers distant from the site. We can use the $^{18}O/^{16}O$ ratio of precipitation as a geographic tracer because it varies across the earth's surface in a regular fashion (Figure 1). The data on this figure and elsewhere in this paper are presented as $\delta^{18}O$ values, which give the fractional difference between the $^{18}O/^{16}O$ ratio in the sample (rain, bone, etc.) and that of standard, SMOW (Standard Mean Ocean Water):

$\delta^{18}O(\text{sample}) = [\{(^{18}O/^{16}O)\text{sample} / (^{18}O/^{16}O)\text{standard}\}- 1] *1000$ (in per mil, ‰)

Negative values of $\delta^{18}O$ indicate that the $^{18}O/^{16}O$ of the sample is less than of SMOW. By definition, $\delta^{18}O$ (SMOW) = 0 ‰.

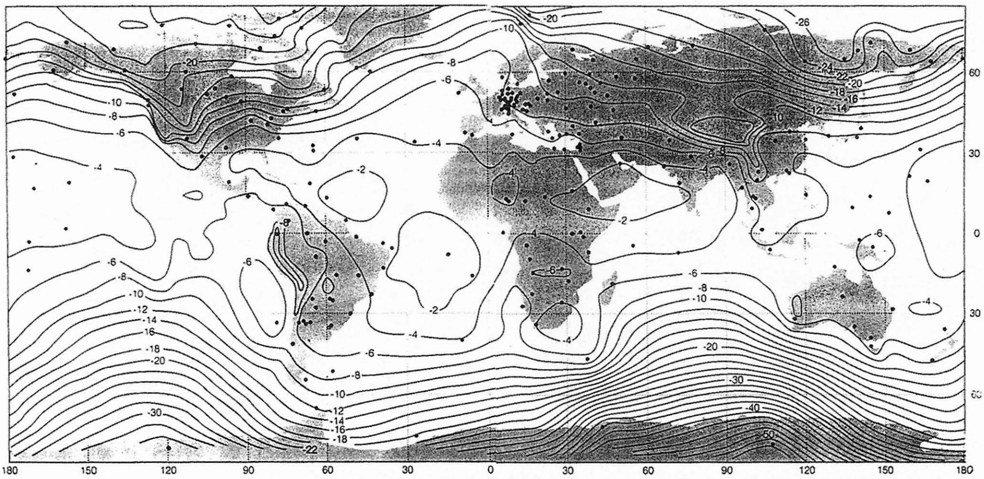

Figure 1. Map of isopleths of $\delta^{18}O$ in precipitation. Adapted from Clark & Fritz (1997).

In general, $\delta^{18}O$ of precipitation decreases as we move further inland, further away from the equator, and to higher elevations (Yurtsever & Gat 1981). The pattern of changing $\delta^{18}O$ shown on Figure 1 is poorly known in many regions, especially Africa, Asia, and Central America. Consequently the use of isotope ratios as geographic tracers is somewhat limited by the scarcity of data at potential source regions. The isotopic composition of precipitation varies on various time scales. Seasonally, $\delta^{18}O$ increases in proportion to the temperature of precipitation; $\delta^{18}O$ of winter rain and snow is lower than that of summer rain. On a longer time scale, $\delta^{18}O$ increased with the transition from the last Ice Age to the Holocene, c. 10,000 y ago, in response to increasing continental temperatures (Bradley 1999). Within the Holocene, however, there has been relatively little long-term change in $\delta^{18}O$ of rainfall, and intersite differences should have remained virtually constant.

Oxygen Isotope Systematics of Bone and Teeth

We can use $^{18}O/^{16}O$ ratios in skeletal mineral as a tracer of $\delta^{18}O$ of local water sources. This has been principally studied in mammals where it was shown that $\delta^{18}O$ of bone mineral is proportional to that of the water in blood-plasma ("body water"). This is determined by the inputs of water to the body as food, drink, and respired oxygen, and also by the outputs in the form of respired carbon dioxide, urine, sweat, etc (Luz et al. 1984). Thus $\delta^{18}O$ of human bones is linearly correlated with $\delta^{18}O$ of local "environmental" water (Figure 2). The same isotopic relationship to body water is true of the minor carbonate (CO_3) component of apatite, although δ^{18}O of carbonate is systematically higher than that of phosphate (Iacumin et al. 1996). Both phosphate and carbonate in well-preserved fossil bone can serve as tracers of the isotopic composition of local water sources. In a study of δ^{18}O of phosphate in bones of white-tailed deer (Odocoileus virginianus), Luz et al. (1990) found the continent-wide variation in δ^{18}O values of deer bones tracked regional variation in δ^{18}O, with some effects due to relative humidity (Figure 3). We could thus use δ^{18}O of deer-bones to partially constrain the place of origin of a deer. However, δ^{18}O does not give a unique source location because precipitation with the same δ^{18}O value occurs over a wide region (Figure 1). Nevertheless δ^{18}O of bone mineral (either phosphate or carbonate) could be used to determine whether two or more individuals were from the same location and could, within limits, be used to tell where else on the continent an individual may have come.

In applying such methods to ancient human bones another problem arises: the bones may have been chemically altered because they were buried in the earth since the time of death.

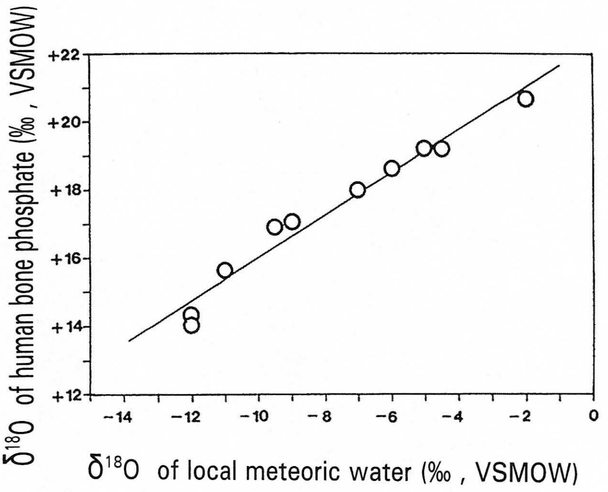

Figure 2. Relation between δ^{18}O of bones and environmental water, from Longinelli 1984.

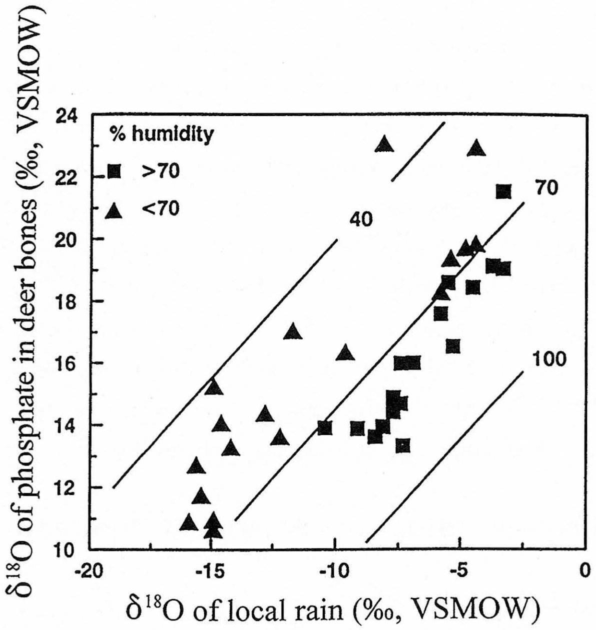

Figure 3. Correlation between δ^{18}O of white-tailed deer bones and δ^{18}O of local precipitation for North America; δ^{18}O(bone) also increases slightly with decreasing relative humidity as a result of enrichment of ^{18}O in leaves of plants which are the deers= entire source of water. From Luz et al. 1990.

Iacumin et al.(1996), Bocherens and Mariotti (1992), Koch et al.(1997), and others have shown that $\delta^{18}O$ of carbonate in tooth enamel is highly resistant to post mortem alteration, and accurately preserves even seasonal changes in $\delta^{18}O$ of the water consumed by an animal. The isotopic signal is less well-preserved in cortical bone, although where bone was buried in a dry environment, $\delta^{18}O$ of carbonate can also be used as an indicator of provenance. Luz and Kolodny (1989) showed that the phosphate component of bones and teeth also resists alteration during burial.

The isotopic composition of bones and teeth at the time of death has been acquired over some period prior to death of the individual. The duration of this period is controlled by the fact that bone is constantly being remodelled through the action of osteoclasts and osteoblasts which gradually consume and then replace the mineral and collagen (Parfitt 1994; Martin & Burr 1989). The time needed for complete turnover of cortical bone in a particular skeletal element varies widely, but is on average about ten years (Manolagas 2000). Therefore the isotopic signal which we obtain from the analysis of either the mineral or collagen of a bone represents a dietary and environmental record of the individual averaged over approximately the last decade of their life. This limits our ability to probe the total migrational history of individuals, since many skeletons which we study are of individuals who died long after migrating to their ultimate home. Teeth, on the other hand record the diet and environment during the first part of the individual's life, including the prenatal period (and thus record the living conditions of the mother). Neither enamel nor dentine are subsequently remodelled. The last teeth to be mineralized, the third molars, continue to acquire both enamel and dentine until early adolescence. Therefore, analyses of human teeth give us a privileged view of the early history (pre-migratory, in some cases) of humans. Unfortunately, teeth are also used for study of the health and life-habits of humans and are not generally available for destructive isotopic analyses.

Isotopic Analysis

Methods for the measurement of $\delta^{18}O$ in bones and teeth have been developed by isotope geochemists (Longinelli & Nuti 1973; Stuart-Williams & Schwarcz 1995; Koch et al. 1997; O'Neil et al. 1994). Analysis of phosphate is difficult and error-prone. It requires extraction of the phosphate from the bone in a highly purified state, conversion to silver phosphate, and reaction at high temperature with a powerful reagent such as bromine. By contrast, analysis of carbonate is simpler. About 2 milligrams of powdered bone or tooth enamel is pre-treated with dilute acetic acid to remove contaminant carbonate, and then reacted with phosphoric acid to liberate carbon dioxide gas (CO_2). This gas is then analyzed on a mass spectrometer, to determine the abundance ratio of isotopes $^{18}O/^{16}O$ and $^{13}C/^{12}C$.

Analysis of collagen begins with extraction of this protein from acid-demineralized bone. The collagen is purified, dried, and reacted in vacuum with copper oxide, producing nitrogen gas, CO_2, and water. The nitrogen gas can be directly analyzed for $\delta^{15}N$.

Tracing Human Migration with Oxygen Isotopes

From the above description it is clear that we should be able, in principle, to use analyses of $\delta^{18}O$ of either phosphate or carbonate in teeth, and phosphate of bones as indicators of provenience. In this discussion we shall assume that we are considering the analysis of a collection of skeletal remains from a single site representing the burials of individuals who lived over a relatively limited period (e.g., < 200 y) at the site. We can assume that there existed a resident community of people with a wide range of ages at death and a balance of sexes, who represent the "normal" residents at the site. We could then hope to be able to use isotopic analysis methods to identify burials at this site of individuals who were not native to this community. I shall refer to such individuals as outsiders.

In order to increase the resolution of the analysis, it is generally useful to consider plots of two isotope ratios measured on the same individual. Where bone carbonate has been used to provide $^{18}O/^{16}O$ ratios, we automatically also obtain values for $^{13}C/^{12}C$ (as $\delta^{13}C$ values). Like $\delta^{13}C$ of bone collagen, this is an index of dietary choices of the individuals (Ambrose & Norr 1993). It is thus also an indicator of community membership, since the factors which control $\delta^{13}C$ of diet (principally proportions of C4 plants and marine foods) may differ between populations. The second isotopic parameter may be either $\delta^{13}C$ or $\delta^{15}N$ of collagen, where it is available for analysis. When we analyze two isotopic ratios for individuals from a site, we may expect the following patterns (Figure 4):

Homogeneity: All individuals display the same ratios in all preserved skeletal materials.

Intra-population dispersion: All individuals lie on continuous gradients over a range of a few per mil.

Outliers: Population displays either homogeneous or dispersed distribution, but with a few individuals as discrete outliers, possibly isotopically resembling people from another population.

The first two cases represent populations indigenous to a single site with little variation in the local sources of food and water. The gradient in isotopic composition represented in the second case can occur even in such a closed (non-migratory) population depending on the nature of the samples analyzed and the life histories of the individuals. This is shown, for example, by Wright and Schwarcz (1998) who analyzed $\delta^{18}O$ and $\delta^{13}C$ of teeth from adults at a site in Guatemala. By sampling teeth which had been mineralized at successive stages in the individual's life history, they could show the effect of weaning on

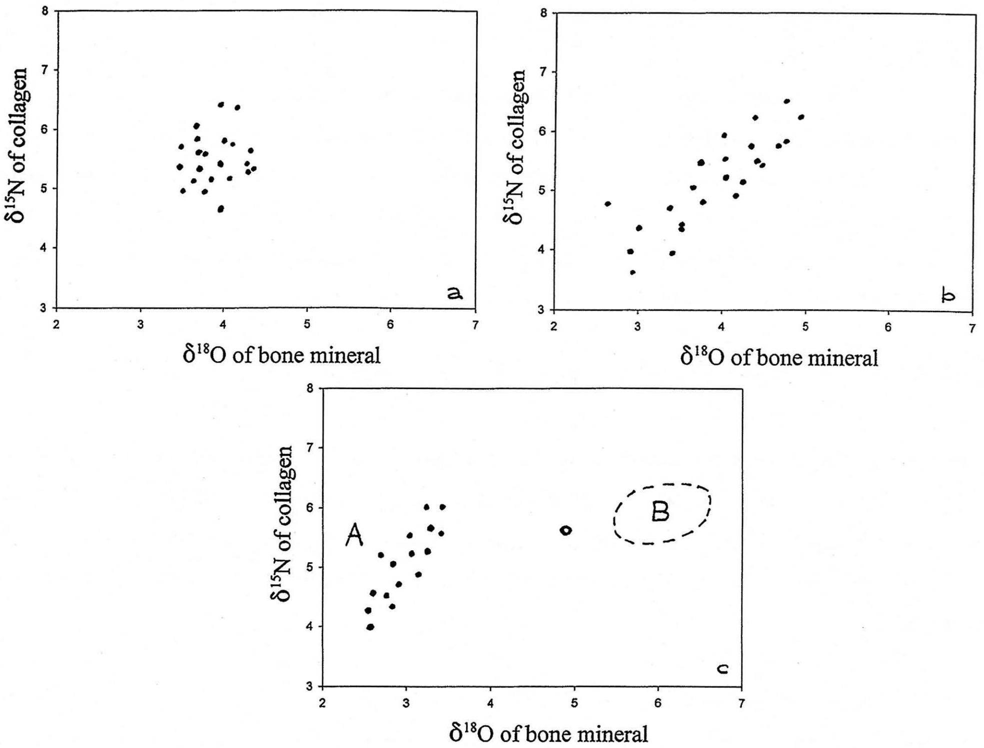

Figure 4. Idealized representation of isotopic variation as seen in isotopic analyses of human bone mineral (δ^{18}O) and collagen (δ^{15}N): a) homogeneous population with little inter-individual variation in diet; b) single population with internal variability in sources of food and/or water; c) single homogeneous population A containing one outlier (open symbol); a suggested source population B with more enriched diet and water source is shown (dashed region). Outlier may have been living with population A long enough for bones to have partially turned over.

both isotopic signals. This is because breast milk is enriched in ^{18}O and depleted in ^{13}C with respect to the overall intake of the adult. Therefore, we observe a sequence of progressive changes in these two isotope ratios in teeth which were mineralized early (M1) compared to teeth which acquired their mineral content later in life (M3). Analysis of skeletal bone phosphate or carbonate of adults would be less likely to show such a dispersion due to later remodelling.

In the third case (Figure 4 C) we observe some individuals who had arrived in the community from a region in which the supply of food or environmental water was isotopically different from that prevalent at the "home" site, the place of residence of the majority of buried individuals. From the direction of isotopic offset, and from a knowledge of gradients in isotopic composition of environmental water in the region, we may be able to infer in what direction the outsiders may have migrated to arrive at the site. For example, in a region where there is a northward gradient of decreasing δ^{18}O values in regional precipitation, we might infer that outsiders with generally lower skeletal $\delta^{18}O$ values had arrived from the north.

Another possible scenario which we have considered is that of a burial site (e.g., an ossuary in a cave or a battlefield cemetery) at which the interments were of individuals none of whom were "native" to the site. We can assume in this case that the individuals came from a few specific localities, rather than scattered at random over the continent. Therefore, we would expect to find a number of clusters of data in our isotopic analyses, corresponding to the number of different localities at which individuals had lived.

Paleodiet Studies as Indicators of Provenance

Some paleodiet studies of carbon and nitrogen isotopes in human skeletal remains have been undertaken specifically for the purpose of tracking the migration of people (e.g., Sealy & van der Merwe 1986). In other studies, specific individuals were recognized to have eaten strikingly different diets than the remainder of the population. The following are a few examples:

Lamanai, Belize: White and Schwarcz (1989) studied a Maya population at Lamanai, Belize, and noted that $\delta^{15}N$ did not vary significantly throughout the long occupation history of this site, from Preclassic to Postclassic periods (average = 9.9 ± 0.9 ‰). One male individual buried in an Early Classic tomb displayed a distinctly higher $\delta^{15}N$ value (13.2 ‰), similar to that observed in coastal consumers of reef fish (Keegan & Deniro 1988). It is possible that this individual arrived from outside the site within the time needed for turnover of bone collagen (c. 10 years) although it is also possible that this high-status person was fed a distinctive diet while living at Lamanai. His $\delta^{13}C$ value suggests that he consumed much less maize than others buried at the site.

Surma, Ontario: In studies of the isotopic composition of bone collagen of aboriginal peoples from southern Ontario, we observe an increase in $\delta^{13}C$ beginning around AD 700, as the newly arrived cultigen maize, a C4 plant, replaces the native C3 plants which are much less enriched in ^{13}C (Katzenberg et al. 1995). The Surma site near Fort Erie dates from AD 700 or slightly later. We analyzed the remains of four adult individuals, three of whom (two males and one of indeterminate sex) gave $\delta^{13}C = -18.4 \pm 0.1$ ‰. This is characteristic of individuals consuming a diet consisting almost entirely of C3 plants or the flesh of C3-consuming herbivores. One female individual, aged between eighteen and twenty-one, gave a $\delta^{13}C$ of -15.6 ‰. This indicates a much higher level of maize consumption than is observed in any contemporaneous specimens from Ontario. Katzenberg et al. comment that "postmarital residence patterns may explain different stable isotope signatures...if marriage is between groups with different diets." Comparable or higher enrichment in ^{13}C at this date is

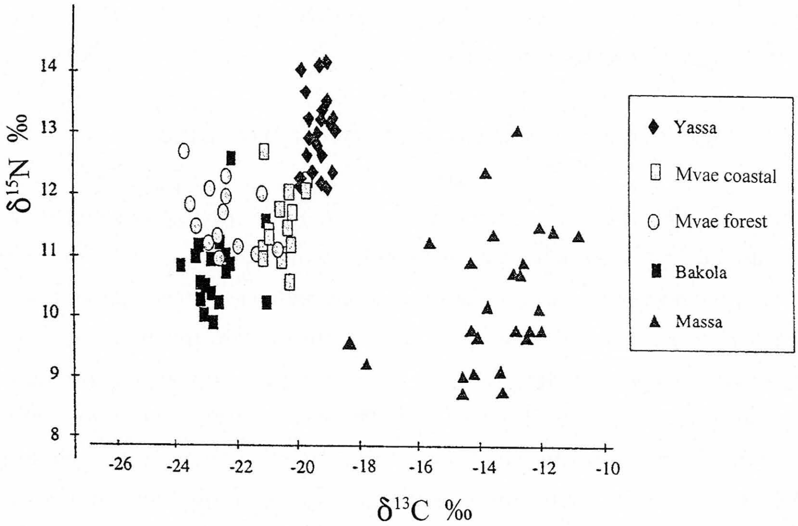

Figure 5. Isotopic composition of hair samples from five tribal groups in the Cameroons, each of which exploits discretely different resources: Yassa: coastal fishers; Mvae: forest and open field agriculturalists; Bakola: forest hunters (higher δ ^{15}N values of Mvae is attributed to fish consumption); Massa: pastoralists in savannah rich in C4 grasses. From Froment & Ambrose 1995.

seen in peoples from the U.S. For example, one individual with δ ^{13}C = -14.0 ‰ was analyzed from the Gard Island 2 site, Michigan by Schurr and Redmond (1991). If we assume that this female had been brought to the Surma site at age fourteen (typical of the marriage age in aboriginal populations), and, assuming a ten year turnover time for bone collagen, then her initial δ ^{13}C value would have been close to -14 ‰. This strongly suggests that this female was brought to Surma from a region in which maize was already a major nutrient.

Cameroon, Africa: Froment and Ambrose (1995) studied δ ^{13}C and δ ^{15}N in the hair of living populations from Cameroon, to determine if these data were correlated with known differences in diet. They found (Figure 5) that δ ^{13}C alone discriminated between individuals with different consumption habits. The Yassa group, a coastal fishing population, besides being slightly enriched in ^{13}C with respect to hunters and farmers, were also enriched in ^{15}N. Fish consumption by Mvae may explain ^{15}N-enrichment relative to Bakola. It is clear that ancient populations with these dietary differences could be resolved isotopically through analysis of bone collagen, and migrants from one environment to another could be easily detected.

Other studies could be cited in which either carbon or nitrogen isotope differences revealed individuals who lay outside an otherwise homogeneous population, such as at the late prehistoric Antelope Creek populations of Texas (Habicht-Mauche et al. 1994) or sites in the interior of British Columbia (Lovell et al. 1986) at which consumption of decreasing proportions of anadromous salmon led to progressively smaller skeletal ^{13}C enrichment at sites at increasing distances from the coast.

Oxygen Isotope Ratios as Indicators of Provenance

Some isotopic studies have been specifically directed at identifying outsiders or determining the provenance of individuals within an heterogeneous ancient population. These studies have mainly used oxygen isotope variations as the indicator of geographic origin, largely because of the spatial variability in the ^{18}O/^{16}O ratio of environmental water. Variations in the abundance of hydrogen isotopes have also been used in tracking migration of non-human species including butterflies and birds (Hobson 1999). Applications of such methods to humans depends on the presence of a significant gradient in oxygen and hydrogen isotopic composition over the region separating the home of migrants and their final resting place. Typically, these gradients are steepest at boundaries between geographically diverse regions, for example, away from a marine coastline, or going from a mountainous region to a plain or steppe. The season of occupation of a site can influence the isotopic composition of the bones and teeth of temporary inhabitants, because in most regions there is a strong seasonal gradient in δ^{18}O of precipitation.

Both carbonate and phosphate of bone are in oxygen isotopic equilibrium with body water. The ^{18}O/^{16}O ratio of body water is correlated with that of environmental water, according to a relationship that varies slightly between mammalian species. For humans, Luz et al. (1984) showed that

$$\delta^{18}\mathrm{O(PO4)} = 0.78\ \delta^{18}\mathrm{O(env.\ water)} + 22.7\ (‰,\ \mathrm{SMOW}).$$

[see also Bryant & Froelich (1995)]. A similar relationship can be constructed for δ^{18}O of carbonate. The indirect effect of humidity on δ^{18}O of body water (and thus on bone) is less for humans than for herbivorous mammals, since humans consume so much of their water intake by drinking or as other forms of ingested liquid. In some cases, low humidity may lead to increase in δ^{18}O of body water as a result of sweat evaporating from the skin. The following are some examples of the application of these methods to past populations.

Snake Hill Cemetery, Ontario: One of the first applications of oxygen isotopic analyses of bone to track human migration was to help resolve the origin of soldiers presumed to be members of the U.S. Army, buried in a military cemetery near Fort Erie, Ontario, Canada. These men were victims of a battle of the War of 1812, and were buried near the battleground. For unknown reasons their remains had not been repatriated at the end of the war and the location, and even the very existence of the cemetery, was forgotten. An extensive forensic study of the remains was carried out in Canada prior to returning them for burial in the U.S. (Pfeiffer & Williamson 1993). As a part of this study we analyzed the $^{18}O/^{16}O$ ratios of bone samples from six of these burials: they gave a uniform average value of 12.6 ± 0.3 ‰. For comparison, two natives of southwestern Ontario, analysed by the same procedure, gave $\delta^{18}O(PO4) = 12.15 \pm 0.02$ ‰, whereas a sample from Antietam, Maryland, U.S. gave 13.2 ‰. The latter values are consistent with the known gradient in $\delta^{18}O$ of precipitation between southwestern Ontario and western Maryland of about +1 to 1.5 ‰. The uniform values of the soldiers suggested that they were all recruited from the same region, which could have lain in eastern Pennsylvania, New York, or New England. These possible sites of origin are consistent with the historical evidence for recruitment patterns during the War of 1812.

Teotihuacan, Mexico: This was a vast urban center in the Central Valley of Mexico, occupied sometime after 100 BC. The city experienced rapid growth between AD 1 and 150, which is believed to have been largely due to immigration from both the immediate region (Basin of Mexico) and farther afield in Mexico. Storey (1983) has suggested that continued immigration was necessary in order for the city to maintain its vast size. One of the cultural enclaves (barrios) recognized in the city, called Tlailotlacan, was populated by people whose artifacts and lifestyle suggested an association with coeval populations in the region of Oaxaca, 550 km SE of Teotihuacan. It was proposed that some of the residents of the Oaxacan barrio were in fact natives of Oaxaca who had emigrated to Teotihuacan. In order to test this hypothesis, we analyzed $\delta^{18}O$ of phosphate bones of the residents of this barrio, as well as comparative samples from a locally resident population at the Tlajinga site, and from the Oaxacan site of Monte Alban (White et al. 1998). Although these samples had been partially altered as a result of burial, we showed that their isotopic composition was not correlated with the degree of alteration (Stuart-Williams et al. 1996). The reference samples from Tlajinga were isotopic homogeneous, with $\delta^{18}O = 14.8 \pm 0.3$ ‰ (N = 11). Likewise, the Oaxacan samples (N = 11) gave $\delta^{18}O = 13.1 \pm 0.6$ ‰. The slightly lower value for Monte Alban was somewhat surprising since the site is further to the south and closer to the sea, but local topographic effects and meteoric circulation patterns may have resulted in more isotopically depleted rain falling in this region. Isotope ratios of remains from Tlailotlacan, on the other hand, ranged from 14.1 to 16.5 ‰, higher than those from Oaxaca, and including some values higher even than from the control site of Tlajinga. We surmised that this "Oaxacan" site might indeed contain remains of immigrants, but from other as yet unidentified site where the water supply was enriched in ^{18}O relative to Teotihuacan. Notably, reburied skeletons gave the highest values, possibly indicating transport of remains of relatives from a distant home site.

Isola Sacra, Italy: The port city of Portus was constructed near the mouth of Tiber during the reign of the emperor Trajan, in order to facilitate the shipment of grain and other foods to the burgeoning population of Rome. A cemetery was constructed on an island in the Tiber to serve the needs of the Portus community. Sometime after the closure of the port, this cemetery was covered with alluvial and wind-blown sediment, and lost from view. It was accidentally rediscovered in the 1930s and excavated to reveal a beautiful series of mausolea containing burial goods, and many well-preserved skeletons; further burials were subsequently found in the spaces between these tombs. About two thousand burials have been recovered so far.

As a part of the Isola Sacra Project of the Pigorini Museum (Bondioli & Macchiarelli 1997), we have studied the isotopic composition of bones and teeth of selected individuals from this site (Prowse et al. 1999). While this study was principally focussed on the identification of the diet of these people, we also investigated the $^{18}O/^{16}O$ ratios of teeth to determine provenance. Given the fact that some the members of this population were engaged in maritime trade, we expected to find some individuals whose isotopic composition indicated that they had immigrated to this site from someplace else in the empire. Historical documents indicated that a significant part of the grain being shipped to Rome was arriving from North Africa (Stambaugh 1988). We therefore might expect that individuals with isotopic signatures characteristic of an African origin might be encountered.

We analyzed the carbonate in enamel of first molars (M1) of adults. This would mainly give us information about the locations of the mothers of these individuals at the time of their pregnancy. As a reference collection, we analyzed teeth from the late Iron Age site of Pontecagnano, about 240 km SE of Rome near Salerno. The population at this site would have consumed drinking water similar in isotopic composition from that in Rome, but it is unlikely that immigrants from distant locations were living at this site.

Figure 6 shows $\delta^{18}O$ of the teeth from Isola Sacra plotted against $\delta^{13}C$. The latter ratio is principally indicative of the diet of the people, but is also useful to estimate the homogeneity of the population, since there is some regional variation in the average $\delta^{13}C$ of diet. We see that the reference population at Pontecagnano displays a fairly narrow range of $\delta^{18}O$ which overlaps part but not all of the population from Isola Sacra. About one quarter of the latter population lies outside the $\delta^{18}O$ range observed at Pontecagnano, and presumably includes people who were not native to Portus. These outsiders have $\delta^{18}O$ values which are up to 2 ‰ lower than those of the reference population. We would therefore infer that they were born to mothers who had been living (at least during their pregnancy) at locations where $\delta^{18}O$ of the local water supply was lower than in Rome. The reported range in average $\delta^{18}O$ of precipitation in Italy today is small, although it is likely that lower values would be encountered in the mountainous terrain along the axis of the Italian peninsula. Alternatively, these outsiders could have arrived in Rome from more distant parts of the empire lying to the north (e.g., Gaul, Britain) where $\delta^{18}O$ of average precipitation is up to 3 ‰ lower than that in Rome.

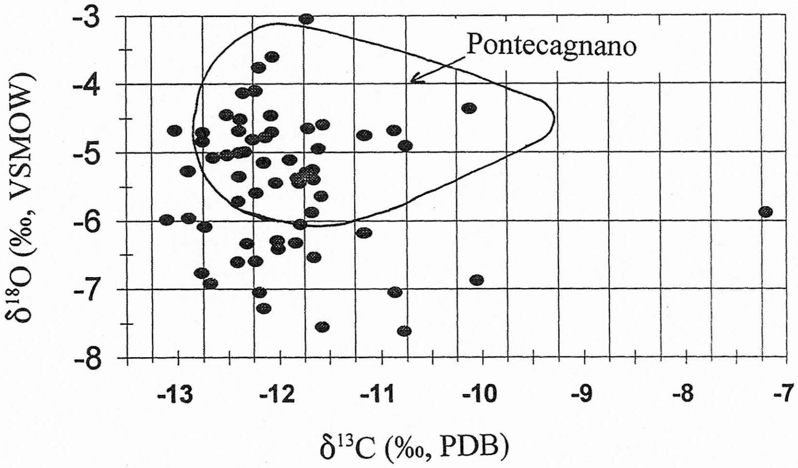

Figure 6. Carbon and oxygen isotope data for first molar teeth from the cemetery of Isola Sacra, Rome, Italy; also shown is the envelope of data from the site of Pontecagnano, near Salerno. Samples with lower $\delta^{18}O$ values appear not to be indigenous to Isola Sacra region.

Dakhleh Oasis, Egypt: This oasis in the Western Desert of Egypt (Figure 7) was occupied towards the beginning of the Christian era by a dwindling Egyptian population mixed with other cultural elements including a garrison of Roman soldiers guarding one of the farthest outposts of the empire. The oasis was nutritionally essentially self-sufficient, with adequate food and water for a population of several thousand people. However, written records found at the oasis indicate that dates and other agricultural products were traded with communities along the Nile. Isotopic paleodiet studies of remains from cemeteries at this site are being carried out by T. Dupras and others (2001). Excellent preservation at this hyperarid site allowed us to carry out carbonate analysis of cortical bone. Iacumin et al. (1996) showed that $\delta^{18}O$ of acid-liberated carbonate from bones from sites in the Nile Valley were offset from analyses of bone phosphate by 8.5 ‰ as is found in living bone; this indicates that the carbonate isotopic signal has not been significantly disturbed.

Figure 8 shows $\delta^{18}O$ of bone carbonate plotted against $\delta^{15}N$ of collagen of the same bone for one of the cemeteries (Kellis 2). We find that the majority of individuals have highly enriched $\delta^{15}N$ values, which is an expected consequence of living at a hyperarid site (Schwarcz et al. 1999). $\delta^{18}O$ values of bone carbonate are consistent with the low $\delta^{18}O$ of local drinking water (c. -11 ‰) which is "fossil" water of Pleistocene age, derived from the underlying Nubian aquifer. At least two individuals, however, display significantly lower $\delta^{15}N$ and higher $\delta^{18}O$ values, approaching those observed for individuals from dynastic sites along the Nile (Iacumin et al. 1998; White & Schwarcz 1994). The individual who most closely approached the isotopic range of the Nile population, a young male, was one of several burials at Dakhleh displaying signs of lepromatous leprosy (Dupras & Schwarcz 2001). We suggest that victims of this disease may have been sent to the oasis from settlements

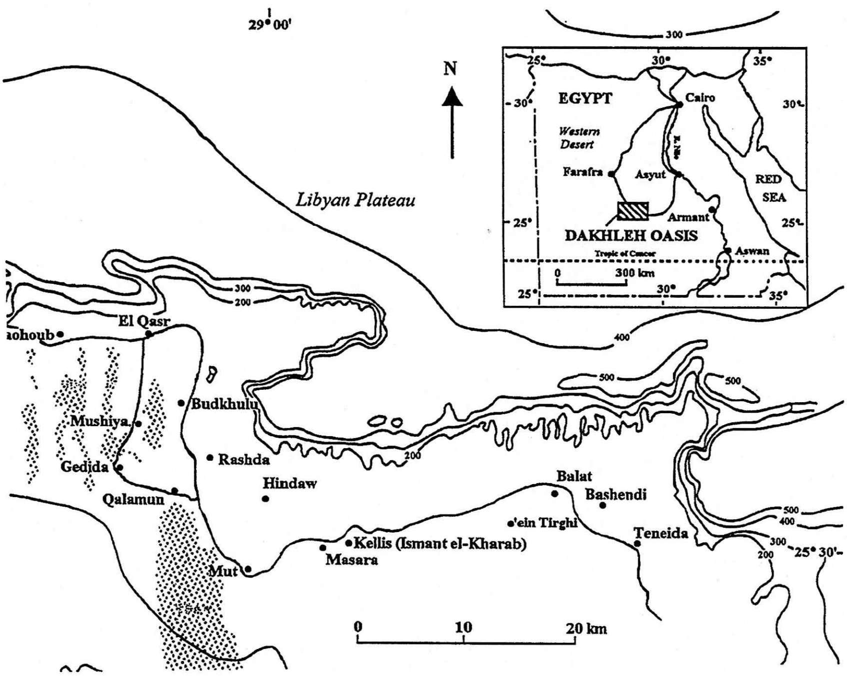

Figure 7. Dakhleh Oasis: a) map showing location.

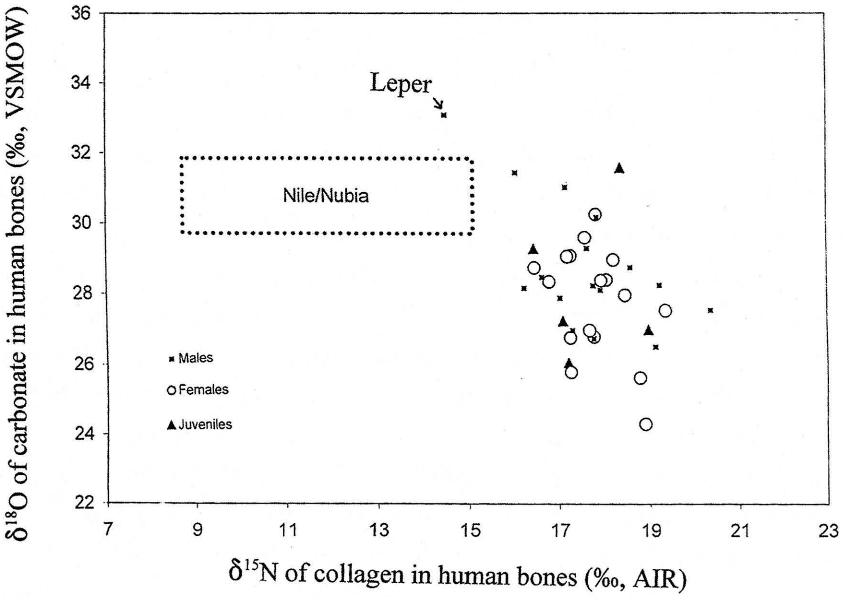

Figure 8. isotopic analyses, showing outsiders. From Dupras & Schwarcz (2001). Two outsiders exhibit lepromatous features.

along the Nile.

Interestingly, in their study of dynastic people from the Nile Valley, Iacumin et al. (1998) also identified one outlier, a mummy (No. 8, "probably of Dynastic period") whose $\delta^{18}O$ values were much lower than those of the remainder of their data set. They conclude that this individual had consumed water with a $\delta^{18}O$ value of -8‰ which was completely unrealistic for Egypt. In fact, this is a value that is quite consistent with the values obtained for burials at Dakhleh. We presume that the mummified body was that of an immigrant from an oasis in the Western Desert (since all of these oases obtain water from the Nubian aquifer). As discussed earlier, our estimate of the time that may have elapsed since immigration depends on the turnover rate of O isotopes in bone mineral, estimated to be about 10y. If we suppose that Mummy No. 8 had been initially drinking water with $\delta^{18}O$ = -11 ‰, then the bone mineral of this person may have partially readjusted to the much higher $\delta^{18}O$ values of the Nile (estimated to be about + 2 ‰) in the years following migration to the Nile Valley.

Conclusions

Human bones are labelled with a wide variety of stable and radiogenic isotopes which can be used to trace the provenance of the person. Variations in the $^{18}O/^{16}O$ ratio of bone mineral (both phosphate and carbonate) can be used to identify outliers from otherwise coherent populations, and in some cases to give some idea of the region whence these outliers have come. The limitations of this method lie in the difficulty in obtaining unaltered bone material for analysis, and in the broad distribution of meteoric water with a given isotopic composition. The first problem can be largely eliminated by analyzing carbonate in tooth enamel, which is also experimentally simpler. Where there are multiple loci at which a person could have acquired a particular $\delta^{18}O$ value, it may be possible to use several isotopic tracers at the same time, e.g., isotopes of O, N, C, and also radiogenic isotope ratios such as $^{87}Sr/^{86}Sr$.

In most populations, isotope ratios are quite homogeneous, confirming the archaeological and anthropological indications of idigenousness. Against this homogeneous background we should be easily able to identify outliers. These would be people who lived in some other environment long enough, and soon enough before death to have acquired and preserved the isotopic label of that other place. In this context, "long enough" depends on the skeletal component being analyzed. For cortical bone, the turnover rate is on average about ten years, but the value varies between skeletal elements. Bones of immigrants will display an isotopic signal that is transitional between the place they came from and the site where they are buried. The extent of the transformation to the new home-site isotope values will depend on the rate of remodelling of the bone tissue. Tooth enamel, on the other hand, records either the place of residence of the mother or, for later mineralized teeth, the place of residence during adolescence.

Acknowledgments

I am grateful to Tracy Prowse and Tosha Dupras for allowing me to use their unpublished data. I also acknowledge the continuing assistance of various archaeologists in collaborating on the isotopic study of human bones and teeth, including Christine White, Lori Wright, Michael Spence, Anthony Mills, Susan Pfeiffer, Roberto Macchiarelli, and Luca Bondioli. I am grateful to the Social Sciences and Humanities Research Council and Natural Sciences and Engineering Research Council of Canada for continued support of this research. I acknowledge the assistance of Martin Knyf in carrying out many of the analyses reported here.

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