Identifying immigrants to Tikal, Guatemala: Defining local variability in strontium isotope ratios of human tooth enamel

Lori E. Wright*

Department of Anthropology, Texas A&M University, College Station, TX 77843-4352, USA

Received 29 July 2004; received in revised form 14 November 2004

Abstract

Stable strontium isotopes have been used to identify the skeletons of migrants in several recent archaeological studies, in which local $^{87}\text{Sr}/^{86}\text{Sr}$ values have been inferred through statistical parameters of human $^{87}\text{Sr}/^{86}\text{Sr}$ data, or by reference to local fauna or other environmental samples. This paper compares these approaches using data from the ancient Maya city of Tikal, Guatemala. The skeletons of eight migrants from distant geological zones are readily apparent among the 83 Tikal skeletons sampled. Three additional non-local skeletons can be eliminated to obtain a normally distributed “local” Tikal sample. The mean of this sample is higher than the available data for local fauna and for lime that may have been used to treat maize at Tikal. It is possible that imported sea salt with a high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio could account for this elevated mean for Tikal humans. Modeling demonstrates that dietary $^{87}\text{Sr}/^{86}\text{Sr}$ may be raised to the level found at Tikal by a daily intake of only 6 g of sea salt.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Strontium isotopes; Migration; Tooth enamel; Local signature; Salt

1. Introduction

Stable strontium isotope ratios of human skeletons are emerging as extremely useful tools for assessing migration in prehistory. They have been used to address archaeological questions of migration in human populations in Europe [3,49], South Africa [50], Mesoamerica [42], the American southwest [16,41], and the Andes [24,25], as well as in australopithecines [53]. This paper addresses approaches to identifying the strontium isotope signature of an archaeological site, and how human behavior may modify an expected local value. I compare a statistical assessment of the “local” value for human skeletons from Tikal, Guatemala, to comparative data from the environment of this ancient Maya city.

* Tel.: +1 979 862 7665; fax: +1 979 845 4070.
E-mail address: lwright@tamu.edu

The ratio between the two stable isotopes of strontium, $^{87}\text{Sr}/^{86}\text{Sr}$, in human tissues is determined by the ratio of all Sr ingested by a person during the ages at which skeletal tissues are formed. Plant and water $^{87}\text{Sr}/^{86}\text{Sr}$ values reflect the geology of the habitat where they originate, and these values are passed on to animals and humans that consume them. The stable isotopes of Sr are not measurably fractionated through the food web because of the relatively small mass differences between the isotopes. $^{87}\text{Sr}$ is a radiogenic isotope, derived from the decay of rubidium (Rb). Relative to the non-radiogenic $^{86}\text{Sr}$, its abundance in rocks is determined by the age of the parent material, and its original Rb content. Rb is much more abundant in crustal materials than in the Earth’s mantle, thus, old metamorphic rocks of crustal origin have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, near 0.715, while recent volcanic rocks have low $^{87}\text{Sr}/^{86}\text{Sr}$, near 0.704. Marine sedimentary rocks show variable ratios between 0.707 and 0.710, which are determined by the $^{87}\text{Sr}/^{86}\text{Sr}$ of seawater at the time they
were formed [12,17,39]. Soils, plants and animals feeding on them in a given locality have values that generally mirror underlying bedrock composition, or average the variability seen in local geological substrates.

The enamel of permanent human teeth is formed during the first 12 years of life, and does not change appreciably during later life. Although exogenous minerals may be taken up into the surface of the tooth during life, and diagenetically, this material seldom penetrates deep into the enamel of recent archaeological materials. By sampling permanent teeth that mineralize in childhood, \(^{87}\text{Sr}/^{86}\text{Sr}\) can be used to characterize the geologic signature of the location where an individual had lived at the specific ages when the sampled teeth mineralized. By contrast, bone mineral is turned over during life, and bone \(^{87}\text{Sr}/^{86}\text{Sr}\) will equilibrate to the location where an individual lived during the last several years of life.

A key issue for the application of strontium isotope ratios to study ancient migration is the need to define local signatures and variability for the site in question, so that the skeletons of migrants may be identified from their divergent signatures. Initially, Price et al. [41] suggested that migrants could be identified as those skeletons with \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios that are removed from the mean of human \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios from the site by more than two standard deviations. The success of this approach depends on the variability of ratios in the local environment, and the proportion of the skeletal sample that might indeed have been migrants. Both of these parameters may vary dramatically in different archaeological contexts; more variability can be expected in transhumant populations, and in any population located close to boundaries between geological provinces with distinct \(^{87}\text{Sr}/^{86}\text{Sr}\) signatures.

Therefore, characterization of the habitat seems a logical approach to defining local signals. The geological context of a site provides some indication of the values that might be expected in humans who lived and consumed foods there. However, an isomorphic relationship between bedrock and human values cannot be assumed, especially where the geology is quite heterogeneous. With a view to studying australopithecine mobility, Sillen et al. [54] studied spatial variability in \(^{87}\text{Sr}/^{86}\text{Sr}\) in soils and plants in the Sterkfontein Valley of South Africa. Because they found somewhat different isotope ratios in plants than in whole soil samples, Sillen et al. argued that bedrock and soil values should not be used to define local site values; only biologically available Sr should be considered. In a complementary approach, Price, Bentley and colleagues [3,40] recommend sampling modern fauna, especially rodents, that share the same habitat as the ancient inhabitants. Because they generally have small ranges, rodents can effectively measure local biologically available values, and will generally average the variability that might be found in soil or plant values within a fairly small territory. Modern wild animals that range over a larger area may not be good indicators for the localized signatures of archaeological sites if the animals range beyond the catchment area of the archaeological site or into isotopically distinct regions. Although larger domestic animals—such as pigs—may provide a better proxy for human diets especially if they are fed human table refuse, modern domesticates are often given mineral supplements that may bias Sr isotope ratios, or fodder that is imported from distant areas. However, archaeological fauna can also provide an important source of information regarding the \(^{87}\text{Sr}/^{86}\text{Sr}\) of ancient human diets [3].

Strontium substitutes for calcium in skeletal mineral. When considering the sources of Sr in the diet and their effects on \(^{87}\text{Sr}/^{86}\text{Sr}\), it is helpful to keep in mind the varied sources of alkaline earths (Ca, Sr, Ba, etc.) ingested. To date, studies have focused on water and food as the vehicles by which Sr makes its way into the body. Humans often eat materials that are not strictly food, but which may have substantial implications for their alkaline earth intake. The most common mineral additive worldwide is salt. Sea salt is high in both Sr and Ca, and could theoretically affect \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios. Moreover, salt is scarce in some environments, therefore it may be traded over long distances.

In the New World, most cultures that rely heavily on maize as a staple food have traditionally processed maize in an alkaline solution to dissolve the pericarp from the kernels [23]. In Mesoamerica, maize is commonly treated with a lime solution that raises the Ca (and Sr) content of the resulting nixtamal by 10–20-fold. Experimental studies demonstrate that the Ca from the lime treatment is highly bioavailable [51,52], so there is little reason to suspect that Sr is not also absorbed from the lime. Modeling shows that the Sr/Ca ratio of the lime used to treat maize dominates the Sr/Ca ratio of the total diet, even when maize constitutes less than 20% of the diet [6]. Thus, for a maize-based diet, Sr obtained from alkaline processing is also likely to dominate the \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio of all ingested material. Indeed, Reid et al. [47] have shown that alkaline processing explains the \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio of the teeth of modern and archaeological children from the Solis Valley, which do not mirror the local volcanic signature. For maize agriculturalists, therefore, the lime used to process maize should perhaps be considered the primary determinant of the \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of human skeletons.

1.1. Immigration to Tikal, Guatemala

Since the early 20th century, migration has been a recurring theme in the archaeology of Mesoamerica. Material culture evidence of interaction between ancient Mesoamerican states has spawned competing theories of
conquest and exchange [4,34], as well as models that see Mesoamerican cities as multiethnic products of both rural–urban and long-distance migration [9,13,44,45,48]. For the ancient Maya, the city of Tikal has been the focus of ongoing debate regarding the role of Central Mexican powers in its Early Classic rise to political prominence [8,30,31,55].

First settled by 900 B.C., Tikal saw exponential population growth during the 6th and 7th centuries A.D., and reached 62,000 persons at A.D. 700 [11]. Migration from both rural areas and distant cities may have contributed to this growth. Together with other lowland Maya cities, Tikal was largely abandoned by A.D. 950. Excavated by the University of Pennsylvania in the 1950s and 1960s, and by the Guatemalan Proyecto Nacional in the 1980s, the site is now the center of a large national park, and is the country’s most visited tourist site.

In this paper, I report strontium isotope work in progress at Tikal, which is part of a larger bioarchaeological investigation of this important Maya city [60,64,65,68]. Strontium isotope study of the Tikal skeletons was initiated partly to test a recent hypothesis based on epigraphic decipherments which proposes that Tikal’s Early Classic period king, Yax Nuun Ayiin, may have come from Teotihuacan [31,55,67]. The implications of immigration to the city for demography, and for social patterning in diet and health are also of interest. To date, studies of migration at Maya sites have focused on oxygen isotope ratios in tooth enamel, which vary with climate and rainfall patterns [58,62]. Strontium isotopes provide a complementary avenue, and are well suited to study of prehistoric mobility in Mesoamerica due to the varied geology of key regions in this culture area [21,42,65].

1.2. Considerations for the local Tikal \( ^{87}\text{Sr}/^{86}\text{Sr} \)

Situated on Paleocene limestone, Tikal lies near the center of the ancient Maya world, in the northern part of the Guatemalan Department of Petén (Fig. 1). Strontium isotope studies on archaeological human skeletons from western Mesoamerica [42,65] and the Maya area [5,65], as well as rock, soil, plant and water samples analyzed by Hodell and colleagues [21] provide a useful baseline for interpreting Sr isotope ratios at Tikal. Both data sets illustrate that the sedimentary Maya lowlands have higher values than the volcanic Maya highlands. The limestone bedrock in the southern Maya lowlands has \( ^{87}\text{Sr}/^{86}\text{Sr} \) ranging from 0.7071 to 0.7099. There appears to be a slight gradient toward higher ratios as one moves from the Cretaceous and Paleocene southern lowlands (0.7071–0.7082) northward into the Eocene-Oligocene-Miocene-Pliocene carbonates of the Yucatan peninsula (0.7083–0.7099). However, there is considerable overlap in values from these two regions, and Campeche, Quintana Roo and northern Belize are poorly studied as yet. By contrast, the Mexican and Guatemalan highlands are characterized by low \( ^{87}\text{Sr}/^{86}\text{Sr} \) in the range 0.7038–0.7053. A metamorphic province spanning from the Bay of Honduras up the Motagua Valley to the western Guatemalan highlands has very variable \( ^{87}\text{Sr}/^{86}\text{Sr} \) (0.704–0.720), however, within this zone, the Motagua Valley area near Copan shows a narrow range of intermediate values, 0.7055–0.7071. To the southeast of Tikal, the granitic Maya Mountains show very high \( ^{87}\text{Sr}/^{86}\text{Sr} \), reaching 0.720 [21].

Hodell and colleagues’ data includes numerous samples from the central Petén, including several from Tikal. Two limestone samples they collected at Tikal show values of 0.70779 and 0.70813. While these analyses measured whole rocks, soluble carbonate \( ^{87}\text{Sr}/^{86}\text{Sr} \) is not likely to differ appreciably due to the very low silicate content of this bedrock. Moreover, both water and a plant that they sampled from the Tikal
Reservoir were 0.70802 and 0.70784 [21]. Because the surface waters in Peten (such as the lakes, or the Maya-constructed reservoirs at Tikal) are perched high above the water table, surface water values closely match the bedrock values in this region [21]. Hodell et al. also measured $^{87}\text{Sr}/^{86}\text{Sr}$ of samples from Uaxactun, Yaxha, and several of the central Peten lakes. Samples from Uaxactun, located 22 km N of Tikal, were measured at 0.70779, 0.70794, and 0.70799. All of the samples collected within 50 km of Tikal lie in the range 0.7074–0.7081. Samples at the lower end of this range are primarily water samples from lakes Peten Itza, Sacpuy, Salpeten, and Yaxha. The lakes lie along the fault which separates the Paleocene rock that underlies Tikal from the late Cretaceous deposits to the south. Of those samples collected north of the escarpment that runs between El Remate and Yaxha, the lowest has a $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70778. These data would thus lead us to expect that the local $^{87}\text{Sr}/^{86}\text{Sr}$ value for Tikal humans should lie in the range 0.7078–0.7081, assuming that they consumed only locally grown foods and were not highly mobile.

As in other Mesoamerican civilizations, maize was the key staple of ancient Maya diets. Stable carbon isotopes in Tikal collagen average $-10.1\%_\text{oo}$ (PDB) [64], indicating that maize contributed more than half of the dietary intake. Thus alkaline processing must have been the primary source of Sr in Tikal diets, and should be considered the primary determinant of the $^{87}\text{Sr}/^{86}\text{Sr}$ of Tikal skeletons. In Guatemala today, most maize is treated with commercially prepared lime, but traditionally it has been made with slaked limestone. Indeed, burned lowland limestone is still sold today in village markets in highland Guatemala that lie in volcanic areas. Given the abundance of limestone at Tikal, it is unlikely that lime was imported to the site from a distant region, thus Hodell et al.’s rock data provide a useful proxy for lime that may have been produced at Tikal.

The modern Lacandon Maya, who live in the lowland forests of Chiapas, Mexico, burn and slake freshwater snail shells to produce lime for nixtamal preparation. The Lacandon report that shells of the river snail *Pachychilus* produce lime that is superior to that made from limestone [38,57]. Although *Pachychilus* is occasionally found in archaeozoological deposits at Tikal, the apple snail *Pomacea flagellata* is more abundant. *Pomacea* thrives in the seasonal swamps that surround Tikal. Thus, Nations [38] suggested that the Tikal Maya may have used *Pomacea* to make lime for processing maize. Accordingly, I sampled modern *Pomacea*, collected near Tikal.

This paper compares two different approaches to identifying the local value for Tikal. I consider comparative data regarding biologically available Sr and the non-dietary sources of Sr at Tikal, such as lime for processing maize. In addition, I evaluate the statistical coherence of the human data. By eliminating outlying values from the data set, I demonstrate that the Tikal data are normally distributed. Therefore, I suggest that migrant skeletons can be identified as those outliers that contribute to a non-normal distribution of the data.

### 2. Methods

I sampled tooth enamel from 83 Tikal burials that span the chronological occupation of the site, and that derive from a broad range of architectural contexts that represent a wide spectrum of Tikal’s Early and Late Classic period society. I have analyzed tooth enamel because I am interested in where individuals spent their childhood before coming to live at Tikal. Moreover, bone preservation at Tikal is very poor, so it is possible that even migrants from very distinct geological provinces might show local, diagenetic values, regardless of their time in residence at Tikal. The enamel samples are primarily from permanent mandibular canines (N = 45 skeletons) and third molars (N = 27) targeted primarily for ongoing childhood paleodietary reconstruction. The canine enamel forms between birth and 3 years of age, while third molar enamel forms between 9 and 12 years of age. A few samples were selected from other teeth, including four first molars, three deciduous canines, one third premolar, one central incisor, one lateral incisor, and one second molar. Samples of enamel 30–50 mg in mass were selected that span at least half of the crown height. Enamel was mechanically cleaned of any adhering dentine, and of discolored surface enamel.

Sample $^{87}\text{Sr}/^{86}\text{Sr}$ was measured at the University of North Carolina in Dr Paul Fullagar’s lab. Samples were sonicated in sterile plastic vials with deionized water. The enamel was then soaked with 5% ultrapure acetic acid at 80 °C for 24 h to dissolve soluble and possibly diagenetic carbonates. The dried samples were ashed at 825 °C in sterile silica glass tubes for 8 h using a muffle furnace. The ashed samples were hot-digested with ultrapure concentrated HNO$_3$ in sterile savilex digestion vials, dried in a sterile laminar flow drying box, and then re-dissolved in ultrapure 2.5 N HCl. Sr was isolated with cation exchange chromatography using 2.5 N HCl as the mobile phase.

At the University of North Carolina-Chapel Hill, a Micromass Sector 54 thermal ionization multiple collector mass spectrometer (TIMS) was used to measure the $^{87}\text{Sr}/^{86}\text{Sr}$ of the samples, which were mounted on zone-refined tantalum filaments. Mass fractionation in the instrument was corrected using the exponential mass fractionation law, with $^{86}\text{Sr}/^{88}\text{Sr}$ equal to 0.1194. At UNC-CH, the long term average for $^{87}\text{Sr}/^{86}\text{Sr}$ analyses of the NIST SRM strontium carbonate standard is 0.710242 [24], and the standard error of analyses at UNC-CH is typically 0.000006–0.000010, over 100 dynamic cycles of data collection.
In addition to the human samples, a few rodents and *Pomacea* shells collected near Tikal were analyzed. Fauna cannot easily be sampled from within Tikal National Park. However, I did obtain data for bone samples from two agoutis and two mice collected about 30 km southwest of Tikal, near the Reserva Bio-Itza, north of San José. Agoutis commonly inhabit burrows located in maize fields, where they are easily trapped. They were exploited prehistorically as a source of meat, and remain a favorite food in El Petén today. Archaeological work indicates that this area was within Tikal’s sphere of influence during the Classic period, and the underlying limestone is Paleocene in age, like that at Tikal. I sampled *Pomacea* from a pond, 10 km north of Tikal, just outside the park, but within the city’s catchment area. The rodent bones and shell samples were prepared using the same methodology described above for the tooth enamel samples. SPSS 11.0 was used for all statistical analyses.

### 3. Results

Table 1 contains descriptive statistics for the 83 human enamel samples from Tikal. Raw data will be presented in separate publications [66,67], where the culture-historical implications of specific burials will be addressed. There is no difference in the $^{87}\text{Sr}/^{86}\text{Sr}$ by tooth position, for the data set as a whole (ANOVA, $F=0.223$, $n=83$, $p=0.98$), or between the mean values of canines and third molars ($t=-0.278$, $df=70$, $p=0.78$). The complete data set has a mean of 0.70804, and shows a substantial degree of variability, as evidenced by the large standard deviation, range, and variance. The distribution is skewed toward values higher than the mean, resulting in a median and mode that are higher than the mean. Moreover, it is extremely leptokurtic.

Fig. 2 illustrates the $^{87}\text{Sr}/^{86}\text{Sr}$ of the 83 archaeological human enamel samples from Tikal, compared to the regional clusters obtained by Hodell et al. [21]. The vast majority of the Tikal data cluster together at the interface between Hodell et al.’s clusters 1 and 2, which represent the Northern and Southern Maya lowlands, respectively. It is important to note that these cluster boundaries are partly artifacts of the locations sampled by Hodell et al. [21]. They did not collect samples in the northern part of the Guatemalan Petén or in southern Campeche, Mexico, presumably due to the scarcity of passable roads in this area. Thus, the boundary between clusters 1 and 2 is less well defined than it appears in the figure. Moreover, the ranges indicated in Fig. 2 represent the cluster boundaries given in Hodell et al.’s Table 1 [21], not the maximal ranges measured within each region. Rocks and soils within a region are likely to be more variable than human values, which average values within catchment areas. $^{87}\text{Sr}/^{86}\text{Sr}$ measured in the Metamorphic Province spans the entire range seen in Mesoamerica, and provides a reminder that skeletal $^{87}\text{Sr}/^{86}\text{Sr}$ values help to constrain possible homelands of migrants, but do not conclusively identify them. Within the Metamorphic Province, however, there is notable consistency among values from the Motagua River valley and around Copan, hence the range of this cluster is indicated in Fig. 2.

Among the Tikal data, migrants with $^{87}\text{Sr}/^{86}\text{Sr}$ that is consistent with an origin in the volcanic highlands, the
Maya Mountains, the Motagua valley, and the Northern Lowlands are evident from their divergent $^{87}\text{Sr}/^{86}\text{Sr}$ signatures. Eight skeletons can be easily identified as migrants because they show widely divergent signatures that fall into Hodell et al.’s clusters 1, 3, 4, or 5; these individuals represent 10% of the total data set. Six of these skeletons date from the Early Classic period (A.D. 250–600). Several of them were excavated from ritual contexts that I sampled because they contained foreign artifacts, which raised the possibility that the human remains might not be local. Therefore, the percentage of immigrants to Tikal from distant regions is undoubtedly less than 10%. Although most of the migrants from distant regions are Early Classic in date, there is no chronological difference in $^{87}\text{Sr}/^{86}\text{Sr}$ among samples from all periods ($F = 1.04$, $N = 83$, $p = 0.38$), or between Early and Late Classic period samples ($t = 0.70$, $df = 70$, $p = 0.48$).

The local value for Tikal can be better defined by excluding these eight clearly foreign migrants from consideration. Table 1 also contains descriptive statistics for this “trimmed” data set, which spans from 0.7075 to 0.7085. Having eliminated the extreme values of these migrants, the dispersion of the trimmed data set is substantially reduced, the mean and median coincide, and the distribution resembles a normal one, with a slight negative skew. Nonetheless, the skewness of the trimmed data set is 2.6 times its standard error, indicating a non-normal distribution. As in the complete data, there is no chronological variation in $^{87}\text{Sr}/^{86}\text{Sr}$ among skeletons from all time periods ($F = 0.89$, $N = 75$, $p = 0.45$) or between Early and Late Classic period skeletons ($t = 0.13$, $df = 63$, $p = 0.90$).

Fig. 3 contains a histogram of the trimmed data set ($N = 75$). At either end of the distribution, several samples stand out as possible outliers; were any of these also not local to Tikal? Only the lowest three samples fall more than two standard deviations from the mean of this trimmed data set. Chauvenet’s criterion can be used to evaluate whether or not a given data point is a “ridiculously improbable” member of a distribution [56]. Strictly speaking, it does not permit us to reject any of these data, although the lowest point coincides with Chauvenet’s cut-off, at 2.7 standard deviations. However, fewer than one sample would be expected to lie more than 2.6 standard deviations from the population mean in a sample this size; three have a $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7075. By comparison with a normal distribution, it is clear that the lower tail of the Tikal sample is suspect.

The Shapiro–Wilk test for normality rejects the hypothesis that this trimmed sample is a normal distribution ($W = 0.958$, $df = 75$, $p = 0.015$). This test is especially sensitive to deviation in the tails of a distribution, and confirms that the tails of the distribution may be non-local skeletons. Fig. 4 shows the normal probability plot (Q–Q plot, generated by SPSS), which compares the data by quantiles to the expected normal curve. The plot highlights the group of outliers at 0.7075, as well as both extremes of the trimmed data set.

Archaeological data can help to confirm this suspicion. Epigraphic data demonstrate that elite marriage partners often came from distant cities [37]. Likewise, disarticulated remains may be those of captives of war from distant sites, although other explanations are also possible for these problematic deposits. If the tails of the distribution were local Tikal children, and all local inhabitants consumed diets with equivalent $^{87}\text{Sr}/^{86}\text{Sr}$, those burials ought to have been randomly drawn from Tikal’s burial population. At the lower end of the trimmed distribution, the 0.7075 outlier group includes two domestic burials and a probable royal tomb. The next lowest group of four, and the four burials found in the upper tail of the distribution are not everyday citizens of Tikal. One of them is from a tomb in the east-central structure of the Preclassic astronomical...
commemoration complex [28], and two are decapitated crania recovered from chultunes (storage features carved into the bedrock). Two of the burials at the upper extreme, and one from the lower extreme are from Group 7F-1, an hypothesized royal palace [19]. It is significant to note that the most elaborately furnished interment from this palace group, Burial PTP-160, is among the foreign skeletons excluded from the trimmed sample. While many Tikal graves lack artifacts, all of the domestic burials at the extremes of the distribution were well furnished with grave goods. Thus, the extremes of the distribution do not appear to be representative of the burial series at large, which supports their identification as migrants. Alternately, social inequality in diet may have contributed to distinct 87Sr/86Sr among social groups, a possibility evaluated below.

This circumstantial evidence suggests that the limits of the “local” Tikal strontium isotope signature should be drawn slightly closer to the center of the distribution than two standard deviations, although exactly where to draw the boundary for the local signature is uncertain. Eliminating only the outliers at 0.7075 reduces the Shapiro–Wilk statistic to non-significance (W = 0.983, df = 72, p = 0.418), and removes the skew, making the distribution indistinguishable from a normal one. Although it is possible that the samples near the tails of the distribution that are highlighted in Fig. 4 are not local, or that they moved to Tikal at a very young age when the sampled enamel was only partly formed, I conservatively exclude only the 0.7075 samples from a “local” data set. Table 1 contains descriptive statistics for this reduced “local” Tikal data set. Migrants who spent their childhood at nearby sites with 87Sr/86Sr equivalent to Tikal cannot be distinguished from locally born individuals, hence the use of quotations around the term “local.” This “local” sample spans from 0.7076 to 0.7085. As with the larger data sets, 87Sr/86Sr does not vary chronologically within this sample (F = 1.24, n = 72, p = 0.30). At Tikal, burials can be classified to broad social status groups by the complexity of the architectural contexts in which they were interred [20,36]. Considering all periods together, there is no difference between the mean 87Sr/86Sr of articulated skeletons buried in civic/ceremonial architecture, range structures, intermediate domestic groups, and small domestic groups (F = 1.36, n = 72, p = 0.26), indicating little systematic social variability in 87Sr/86Sr within this “local” data set.

Table 2 contains the 87Sr/86Sr measured on modern faunal samples collected near Tikal. From the rodent data, one might expect Tikal humans to have 87Sr/86Sr near 0.7079, if human 87Sr/86Sr were determined solely by diet and water. Similarly, the Pomacea samples average 0.70779, comparable to both the San José fauna and Hodell et al.’s [21] samples. Thus, the values for rodents, and Pomacea, as well as Tikal rock, plant and water [21] all suggest a local Tikal signature in the range 0.7078–0.7081. By comparison, the human samples span a broader range, and the human mean coincides with the upper limit of this comparative data. Half of the human samples show higher 87Sr/86Sr ratios than were measured in this comparative data. Note that the three skeletons removed from the trimmed sample to define a “local” data set show lower 87Sr/86Sr (<0.7076) than any of the comparative data; the lower limit of the “local” sample coincides with the comparative data.

4. Discussion

For Tikal, eliminating outlying 87Sr/86Sr values resulted in a normally distributed data set. This result suggests a new approach to defining local Sr values. One might expect skeletal 87Sr/86Sr to be normally distributed at an archaeological site where there is good reason to believe that the majority of the population were born locally, that all individuals consumed foods grown on the same soils, and, for maize dependent populations, that all made use of lime from the same source. At Tikal, no systematic social variability is evident that would indicate differential access to agricultural products from distant areas, and the geological context of the site, its catchment area, and possible lime sources are fairly homogeneous. Together, these factors probably explain the normal distribution of the Tikal data. However, a normal distribution of 87Sr/86Sr might not be expected in archaeological contexts with marked local geological variability, substantial transport of food, or highly mobile populations.

Those samples at the lower tail of the trimmed Tikal human data set that deviate from the expectations of a normal distribution are almost certainly those of immigrants to the city. Several additional skeletons in both the upper and lower tails are from distinctive contexts that may be consistent with a foreign identity, however, there is no statistical justification to eliminate them from the “local” sample. The lowest four skeletons in this sample are consistent with the non-human comparative data from Tikal. A detailed discussion of the culture-historical implications of the identification of

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tissue</th>
<th>Species</th>
<th>Location</th>
<th>87Sr/86Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>F765</td>
<td>Bone</td>
<td>Dasyprocta punctata</td>
<td>N of San Jose</td>
<td>0.70790</td>
</tr>
<tr>
<td>F766</td>
<td>Bone</td>
<td>Dasyprocta punctata</td>
<td>N of San Jose</td>
<td>0.70787</td>
</tr>
<tr>
<td>F767</td>
<td>Bone</td>
<td>Mouse, sp. indet.</td>
<td>N of San Jose</td>
<td>0.70794</td>
</tr>
<tr>
<td>F768</td>
<td>Bone</td>
<td>Mouse, sp. indet.</td>
<td>N of San Jose</td>
<td>0.70791</td>
</tr>
<tr>
<td>F2071</td>
<td>Shell</td>
<td>Pomacea flagellata</td>
<td>Bajo de Santa Fe</td>
<td>0.70779</td>
</tr>
<tr>
<td>F2072</td>
<td>Shell</td>
<td>Pomacea flagellata</td>
<td>Bajo de Santa Fe</td>
<td>0.70779</td>
</tr>
<tr>
<td>F2073</td>
<td>Shell</td>
<td>Pomacea flagellata</td>
<td>Bajo de Santa Fe</td>
<td>0.70780</td>
</tr>
</tbody>
</table>
specific burials as immigrants is beyond the scope of this paper, and will be addressed elsewhere [66,67]. Nonetheless, this approach does not resolve uncertainty about the origin of burials with values that lie in the tails of a trimmed distribution that cannot be statistically identified as outliers.

One might expect that comparative data on the $^{87}\text{Sr}/^{86}\text{Sr}$ of lime used to treat maize and biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ would help to constrain the human mean. In the case of Tikal, however, these data raise additional questions. If human $^{87}\text{Sr}/^{86}\text{Sr}$ were determined by either the $^{87}\text{Sr}/^{86}\text{Sr}$ of the lime or the $^{87}\text{Sr}/^{86}\text{Sr}$ of the food and water, then the mean of human data should coincide with this value. For Tikal, the $^{87}\text{Sr}/^{86}\text{Sr}$ of the lime sources coincides well with the faunal data, but the human mean is substantially higher. It is possible that the limited data has not adequately defined the variability in lime sources available at Tikal. However, the broad homogeneity of values obtained throughout the central Peten [21] argues against a distinctive, higher value for Tikal. The low geological variability of the central Peten is radically different from the disparate geological formations found in close proximity within the Sterkfontein Valley, South Africa, where Sillen et al. [54] documented dramatic differences between biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ and substrate values, and between riparian and upland habitats. By contrast with the Sterkfontein Valley, where rainwater percolates through rocks of distinct origins and varied $^{87}\text{Sr}/^{86}\text{Sr}$ in a single small watershed (15 km radius), the geology of central Petén is much more homogeneous. Moreover, the perched surface waters of this region are not mixed with groundwaters that have interacted with older geological strata [21].

It is unlikely that the Sr absorbed from lime-treated maize has a different $^{87}\text{Sr}/^{86}\text{Sr}$ than the lime used to treat it. It is also unlikely that lime would have been imported to Tikal from a distant area, since Pomacea are abundant at Tikal, small streams with Pachychilus are found within a days hike, and limestone is ubiquitous at the site. Moreover, Sr intake from drinking water would have the same value as lime, since Sr in drinking water at Tikal was derived from carbonate dissolution in artificial reservoirs that were excavated into, and plastered with local limestone.

One possible explanation for the higher human ratios is the ingestion of sea salt. Ancient trade of salt has been a recurring interest in Maya archaeology. Could salt have provided enough Sr to change $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in skeletons? Given the $^{87}\text{Sr}/^{86}\text{Sr}$ of modern seawater, this salt would have a $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7092 [39], considerably higher than the local Tikal value. Because the Sr/Ca ratio of commercial sea salt is 38 times higher than that of Pachychilus and Pomacea from the Peten [63], the possibility that imported salt might measurably elevate bone $^{87}\text{Sr}/^{86}\text{Sr}$ deserves consideration.

Ethnographic data on salt consumption by the Yucatec Maya in the 1920s indicates an intake of 8 g of salt per person per day [1,46]. This is 50% higher than the level recommended by the National Academy of Medicine, but comparable to mean adult consumption in the US today [18]. Fig. 5 shows the effect of varying levels of salt consumption on a maize dependent diet, for which the majority of Sr and Ca is derived from lime. For illustrative purposes, I assume that lime was made from Pomacea shells with $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70779, as measured at Tikal, and that Pomacea lime contains 0.559 mg of Sr for every gram of Ca [63]. I assume sea salt that is 0.05% Ca, and has a Sr/Ca ratio of 0.0214, values found in commercial sea salt today. Fig. 5 shows differing levels of calcium and salt intake; the intermediate line represents a realistic diet of 600 g of dry maize daily, a value measured ethnographically in the 1930s [2]. Using INCAP data on the calcium content of alkaline treated maize [22], this would provide 2.26 g of calcium daily. For comparison, the upper and lower lines indicate an intake of 1 g and 5 g of calcium from limed maize, respectively. For a diet including 600 g of maize, an intake of only 6 g of sea salt would raise dietary $^{87}\text{Sr}/^{86}\text{Sr}$ to the observed mean for Tikal. Evidently, a little salt goes a long way.

Mayanists have been interested in salt trade for many years, because there are no local sources for salt in the central Petén, where the largest Maya cities are located. Coastal Yucatec salt was traded into the Petén...
in ethnohistoric times, and in times of shortage, palms were burned to obtain potassium chloride as a substitute for salt [1]. The only terrestrial source for sodium chloride is at Salinas de los Nueve Cerros, some 160 km south of Tikal. At that site, salty stream water was boiled to evaporate salt in enormous ceramic vessels during the Classic period [14]. Sea salt has been produced on the north coast of the Yucatán since prehispanic times and this area produced enormous quantities of salt (sal solar) by solar evaporation at the time of the conquest, well before it was industrialized [1,43]. Excavations on the coast of Belize show that salt was boiled in highly standardized ceramic vessels during the Classic period [29,33]. Mackinnon and Kepecs [29] suggested that this sal cocida (boiled salt) was exported inland for commoner consumption, while Peten elites may have consumed more exotic Yucatec sal solar, which is of higher quality. McKillop [33] has argued that salt production in coastal Belize was of a scale sufficient to supply the needs of large interior cities, like Tikal. The saltworks at Punta Ycacos Lagoon and at Placencia in coastal Belize are only slightly farther from Tikal than is Nueve Cerros, but would have been more accessible by canoe travel along the coast and Belize river.

Although Fig. 5 demonstrates that sea salt import can explain the high mean $^{87}\text{Sr}/^{86}\text{Sr}$ of Tikal enamel, other explanations deserve comment. Imported food from regions with higher $^{87}\text{Sr}/^{86}\text{Sr}$ could also raise the mean $^{87}\text{Sr}/^{86}\text{Sr}$. Although the import of food to Tikal has been suggested [10], the recent discovery of channelized fields in the nearby Bajo de La Justa [15,26] suggests a higher local carrying capacity than once assumed. While environmental heterogeneity within the Southern Maya lowlands may have constrained agricultural productivity and fostered the development of regionally specific agrotechnologies, most all Maya cultigens were grown across the lowlands, so there is little reason to suspect long distance trade of specific foodstuffs. One exception is cacao (Theobroma cacao), which has fairly narrow requirements for soil fertility and humidity, and may not grow well at Tikal. Cacao grown in the Sibun valley of Belize may have been traded inland [32]. Hodell et al. [21] report extremely high $^{87}\text{Sr}/^{86}\text{Sr}$ for water from the Sibun River (0.71192), due to its drainage from the granitic Maya Mountains. Given this high $^{87}\text{Sr}/^{86}\text{Sr}$ and the moderately high Ca content of cacao, it is possible that imported cacao could raise human $^{87}\text{Sr}/^{86}\text{Sr}$ at Tikal. Unlike salt, however, social inequality is likely for the consumption of imported cacao, which is thought to have been a luxury good [7,32].

Unlike the Andean city of Tiwanaku, where camelid caravans both brought cultigens from distant geological regions and provided meat with non-local values [24], the Maya at Tikal had no beasts of burden and consumed few animals that ranged over very large territories. Migratory birds are the most likely source of meat with a non-local $^{87}\text{Sr}/^{86}\text{Sr}$, but probably formed a very minor part of the diet, and would not contribute much Sr to the total intake. Although marine fish may travel up estuaries and can be caught at some inland sites, such as Lamanai [61]. Tikal is not located on a river system, nor are the central Peten lakes, the closest source from which freshwater fish might have been obtained, some 30 km away.

Like cacao, marine foods that might have been traded inland [27,35] would have high $^{87}\text{Sr}/^{86}\text{Sr}$, equivalent to sea salt, and are likely to have been elite foods. Indeed, Valdez and Mock [59] argue that Belizean sal cocida production was geared to the salting and preservation of fish for transport to inland consumers. Although dietary inequality is evident in carbon isotope ratios ($\delta^{13}\text{C}$) of bone collagen from Tikal [64], $^{87}\text{Sr}/^{86}\text{Sr}$ does not vary with social status. Thus, imported elite foods (salted or not) are less likely to account for the high $^{87}\text{Sr}/^{86}\text{Sr}$ than is the consumption of imported sea salt, which may have been consumed by all status levels. While no systematic social pattern is evident, individual variation in salt intake undoubtedly contributed to the variability seen among Tikal skeletons in dental $^{87}\text{Sr}/^{86}\text{Sr}$.

5. Conclusions

Using the $^{87}\text{Sr}/^{86}\text{Sr}$ of tooth enamel from Tikal skeletons, it was possible to identify skeletons who had spent their childhood elsewhere, by reference to human and non-human data from other parts of Mesoamerica. Approximately 10% of the sampled Tikal skeletons had migrated from regions with clearly distinct $^{87}\text{Sr}/^{86}\text{Sr}$. It is likely that another 4–13% were also migrants from sites located within the same broad geochemical province as Tikal, but which show slightly different values than Tikal does. Although samples were not selected at random, this does suggest that migration was significant to both the structure and growth of Tikal’s population. Ongoing work with oxygen isotopes and dental morphological traits may help us to better refine the identity of some of these questionable migrants.

Although sampling of comparative data from Tikal’s environment was not extensive, it appears that the human values are slightly higher than local biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ and than the sources of lime that would have been used to process maize at Tikal. While a more diverse comparative data set would be ideal, the disparity between the human and comparative data sets suggests that local resources alone may not explain the human values. I hypothesize that the $^{87}\text{Sr}/^{86}\text{Sr}$ of human remains provide circumstantial evidence for the trade of sea salt from the Belize or Yucatan coasts to Tikal.
Both biologically available Sr and statistical analyses of the human data provide meaningful information regarding the local strontium isotope value. For Tikal, a determination of local \(^{87}\text{Sr}/^{86}\text{Sr}\) based solely on faunal data could lead one to identify an enormous proportion of the human samples as migrants. Given that the Tikal data are normally distributed when outliers are eliminated, local values for a human population are perhaps best determined by reference to both biologically available Sr and statistical analyses of human data. Possible sources of culinary mineral resources such as salt and lime should also be considered, because these additives may be a significant source of ingested Sr that cannot be assessed using dietary faunal or floral data.

Acknowledgements

The Ahau Foundation, Inc., funded TIMS analyses of the Tikal enamel. This work was partially supported by NSF grants SBR-9870351 and SBR-0075231. I sampled teeth with the permission of the Instituto de Antropología e Historia de Guatemala (IDAEH) and the University Museum of the University of Pennsylvania. I thank the staff of both institutions, as well as of the Museo Nacional de Arqueología y Etnología and the Parque Nacional Tikal for their assistance. My thanks go to Paul Fullagar for TIMS analyses, to Pat Culbert who provided the Pomacea samples, to Bill Middleton who collected the San José rodents, and to Peter Harrison and Chris Jones for their enthusiasm. I also thank Mariana Valdizón, Juan Pedro Laporte, Oswaldo Gómez, Doug Price, Jim Burton, Sheela Athreya and Jennifer McCaskill for their invaluable contributions. Two anonymous reviewers provided especially helpful comments on the manuscript.

References


[22] Instituto de Nutrición de Centro América y Panama (INCAP), Food composition table for use in Latin America, National Institutes of Health, Bethesda, Maryland, 1961.


[67] L.E. Wright, In search of Yax Nuun Ajiin I: revisiting the Tikal Project’s burial 10, Ancient Mesoamerica 16 (in press).