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Immigration and the Ancient City of Teotihuacan in Mexico: a Study Using Strontium Isotope Ratios in Human Bone and Teeth

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Teotihuacan, in highland Mexico, is the earliest and largest prehispanic city in the New World, occupied primarily between AD 1 and AD 650. There are many distinctive areas within the city limits, including major ceremonial precincts, large pyramids and temples, residential areas, exchange sectors, thousands of residential compounds, and tunnels under the northern half of the city. Some of these residential compounds contain non-local architecture, artefacts, and burial arrangements known from areas on the Gulf Coast and in Oaxaca. The identity of the residents of these "foreign" compounds is uncertain. Were these local individuals adopting foreign customs, recent immigrants to the city, or a mix of locals and outsiders? After the fall of Teotihuacan, people with Coyotlatelco culture came to the city and contributed to its extensive looting. Some scholars have proposed a northern or western origin for these groups.

We have measured the strontium isotope ratios ($^{87}Sr/^{86}Sr$) in human bone and tooth enamel from individuals buried in various areas of the city for information on their original place of birth. Strontium isotope ratios are signatures for local geologies. Strontium in human bone and tooth enamel comes from the food growing in local geologies. Strontium isotope ratios in human bone reflect the source of a diet around the time of death; ratios in tooth enamel reflect the source of the diet around the time of birth. Differences between enamel and bone ratios in the same individual indicate differences in local geologies and thus a change in residence. Our study indicates that a number of the individuals were born outside the city. Comparison with other isotopic methods for assessing residential change is also made.

Keywords: TEOTIHUACAN, OAXACA, STRONTIUM ISOTOPES, MIGRATION, ARCHAEOMETRY, CLASSIC, MEXICO.

Introduction

The ancient city of Teotihuacan, located in the Basin of Mexico about 50 km northeast of the centre of modern Mexico City (Figure 1), was one of the most complex, urban developments in the prehispanic New World. During the Classic horizon (AD 1–650), a major population centre developed here with numbers estimated at more than 100,000 people (Cowgill, 1992; Storey, 1992). The city grew very quickly in the centuries following the birth of Christ and this rapid increase must have involved immigration into the city (Millon, 1973, 1981; Sanders *et al.*, 1979; Blanton, 1981).

There are a number of distinctive areas in the city, including ceremonial precincts, administrative areas, "palaces", exchange areas, avenues, tunnels, and residential compounds (Figure 2). These compounds are essentially apartment complexes, groups of residential structures placed together inside an outer wall.

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Figure 1. The location of Teotihuacan and Oaxaca in Mexico.

At least two distinctive ethnic compounds are known from Teotihuacan (Altschul, 1987; Rattray, 1993). Houses in these residential enclaves are constructed with a "foreign" architecture and contain artefacts such as pottery and other items, along with burials, distinctive to distant areas. These compounds are known as the *Barrio de los Comerciantes*, or the Merchants' Barrio (Rattray, 1987), and *Tlailotlacan*, or the Oaxaca Barrio (Spence, 1976, 1992), and likely represent foreign wards in the ancient city. The *Barrio de los Comerciantes* contains round adobe architecture, approximately 10% foreign pottery, and other artefacts characteristic of the Gulf Coast region of Mexico (Rattray, 1988). Burials and food preparation techniques are also typical of the Gulf Coast region, although the specific source of these materials is unknown. This barrio was apparently established initially in the later phases of the Classic city, after AD 300 (Rattray, 1987).

The Oaxaca Barrio, in the southwestern part of the city, encloses distinctive materials from the Zapotec region to the south (Figure 1). These materials include tombs with an antechamber, Zapotec funerary urns, Oaxaca Gray Ware pottery, Oaxaca-style figurines, and, in general, a fairly complete set of the Monte Albán ceramic complex (Rattray, 1993: 4). Burials from this area date to the Late Tlamimilolpa and Xolalpan phases (AD 300–650).

Teotihuacan was largely abandoned after AD 650, but parts of the city continued to be used. Recent investigations in the tunnels and quarries behind the Pyramid of the Sun, known as Cueva de las Varillas and Cueva del Pirul, have uncovered many human burials (Figure 3), dating from the sixth to tenth centuries AD, along with palaeoenvironmental data regarding faunal and floral resources and diet (Barba & Manzanilla, 1987; Manzanilla, 1993; Manzanilla *et al.*, 1996). Individuals buried in these caves were later inhabitants of Teotihuacan, and may have come into the city from outside areas or had remained there as residents.

The primary concerns of our research deal with questions about the original homes of some of the inhabitants of Teotihuacan: (1) were the people buried in the Zapotec and Merchants' Barrios migrants to Teotihuacan? (2) If these people were migrants, how long had they been in the city? (3) Were the people buried in the tunnels during the later periods of occupation, when the city was collapsing, also migrants into the Teotihuacan Valley? Strontium isotope analysis of human bone and tooth enamel was used to investigate these questions.

Strontium Isotope Analysis

The use of stable strontium isotopes in environmental and human ecology studies was proposed some years ago (Ericson, 1985). Strontium isotopes have since

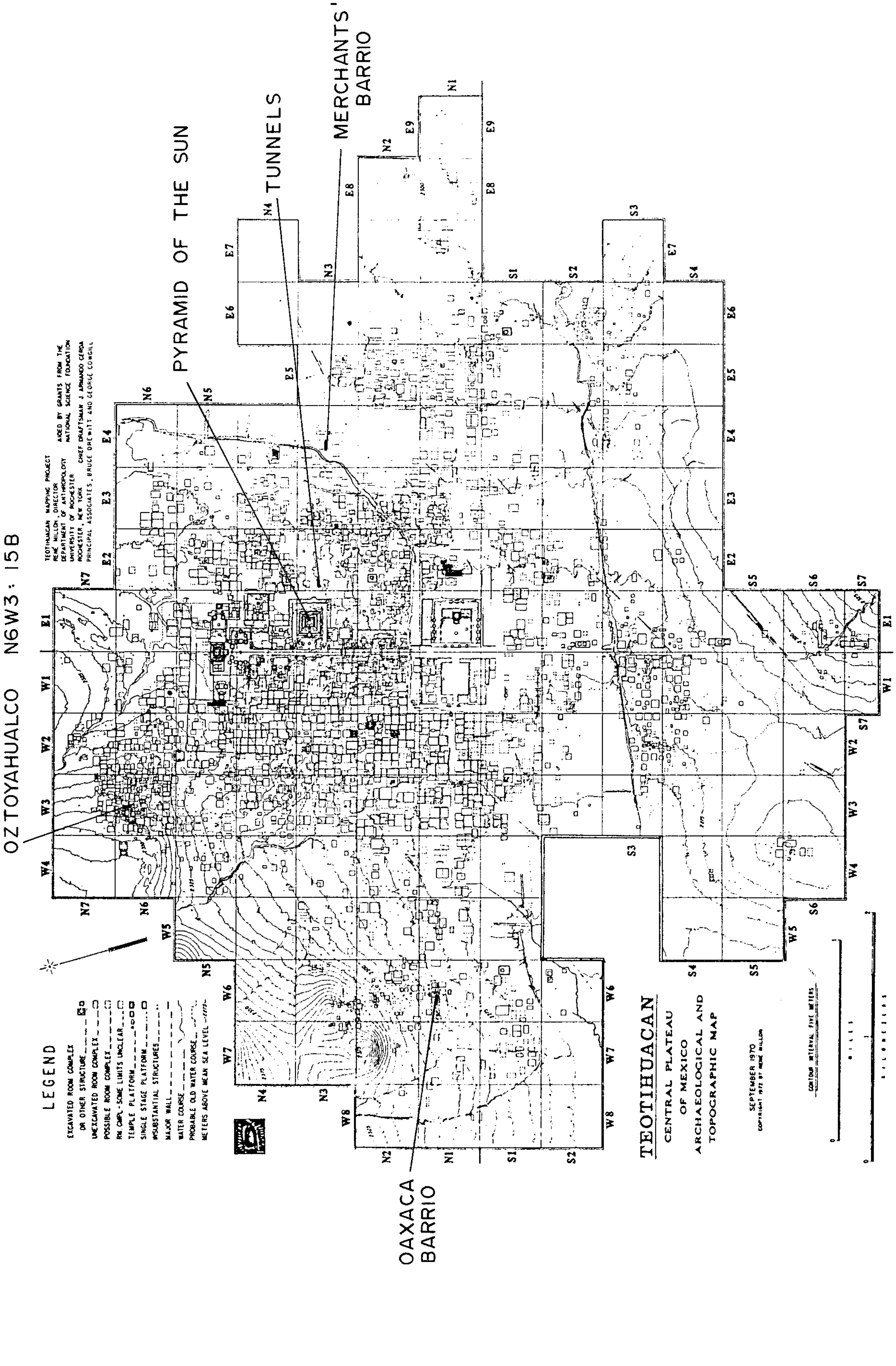

Figure 2. The plan of the city of Teotihuacan in the Basin of Mexico. The location of areas mentioned in the text are shown on the map.

Figure 3. Burial 2 from the Varillas tunnel.

been used as tracers in a variety of environmental studies (Åberg, 1995). Sr isotope ratios in animal hard tissue have been used, for example, to identify the origin of illegally exported elephant ivory (van der Merwe *et al.*, 1990; Vogel *et al.*, 1990). Studies of humans have been reported for prehistoric American Indian groups in the southwest United States (Price *et al.*, 1994*b*; Ezzo *et al.*, 1997), late prehistoric groups in Central Europe (Price *et al.*, 1994*a*, 1998; Grupe *et al.*, 1997; Latkoczy *et al.*, 1998), and in South Africa (Sealy *et al.*, 1991; Sillen *et al.*, 1998).

A major concern in the analysis of bone is the recovery of the original biological signal, rather than post-depositional contaminants (e.g. Koch *et al.*, 1990; Price *et al.*, 1992; Stuart-Williams *et al.*, 1996). However, diagenesis is generally not a significant problem in stronium isotope analysis. Acid cleaning of bone samples is normally effective in removing most contaminants (Price *et al.*, 1992). Diagenetic study of bone from Teotihuacan and Oaxaca (Stuart-Williams *et al.*, 1996) has demonstrated that there was little evidence of post-mortem isotopic oxygen in the samples. In addition, measurement of elemental uranium as a proxy for diagenesis on the whole showed little evidence of contamination. With regard to strontium, any contaminants remaining in bone or enamel samples after cleaning would exhibit the $^{87}Sr/^{86}Sr$ ratios of the local geology. Thus, values that indicate different geological source materials and residential change are not heavily contaminated.

The mineral matrix of hard human tissues (bones and teeth) consists mainly of largely insoluble calcium phosphate hydroxyapatite [$Ca_{10}(PO_4)6(OH)_2$]. Common substitution of strontium for calcium in this mineral produces strontium concentrations in the order of 10^2–10^3 ppm in hard tissue. In nature, strontium occurs in the form of four stable isotopes (Faure, 1986): most abundant is ^{88}Sr (*c.* 82·53%), followed by ^{87}Sr and ^{86}Sr (*c.* 7·04% and *c.* 9·87%, respectively), while ^{84}Sr is least abundant (*c.* 0·56%). ^{87}Sr is a decay product of radioactive ^{87}Rb, which has a half-life of approximately $4{\cdot}7 \times 10^{10}$ years. Consequently the relative abundance of ^{87}Sr in rocks is a function of both the initial concentration of ^{87}Rb and the age of the rocks. Strontium isotope ratios in nature are expressed as a ratio of ^{87}Sr with the non-radiogenic isotope, ^{86}Sr, following standard convention (Faure, 1986).

Since the relative mass differences between ^{87}Sr and ^{86}S are small, no isotopic fractionation takes place during Sr transport in any ecosystem (Graustein, 1989). For non-mobile individuals, the $^{87}Sr/^{86}Sr$ ratio in hard tissue will therefore match the Sr isotopic composition of their habitat. The earth's surface is highly variable in terms of bulk composition (affecting $^{87}Rb/\ ^{87}Sr$ ratios) and age, and in terms of $^{87}Sr/^{86}Sr$ ratios.

Rocks that are geologically young (<1–10 million years) and that have low Rb/Sr ratios, such as many of the late Cenozoic volcanic fields in the highlands of Mesoamerica, generally have $^{87}Sr/^{86}Sr$ ratios of less than 0·706. Some rocks with very low original Rb/Sr ratios, such as basalt, can have $^{87}Sr/^{86}Sr$ ratios of less than 0·704. Clay-rich rocks that contain high Rb/Sr ratios, such as shales and granites, can have Sr isotope ratios up to 0·730 (Farmer & DePaolo, 1984). These variations may seem small, but they are exceptionally large from a geological standpoint, and far in excess of analytical error. Modern mass spectrometers have a measurement error between $\pm 0{\cdot}00003$ and $\pm 0{\cdot}0001$ for strontium isotope ratios.

Because of the variability of strontium isotope ratios on the earth's surface and because these isotopes are deposited in human hard tissue, it is possible to trace changes in residence through analysis of Sr isotope ratios in tissues which formed at different ontogenetic stages (Ericson, 1985; Sealy *et al.*, 1991, 1995; Price *et al.*, 1994*a*, 1994*b*). Bone and dental enamel have been used in this study.

Due to its rather slow rate of turnover, compact bone in adults contains Sr which has been incorporated throughout the life of the individual. Turnover rates of approximately 3% per year in cortical and 26% per year in trabecular bone have been estimated (e.g. Parfitt, 1983). The half-life for turnover in bone composition is approximately 23·1 years for cortical bone and 2·9 years for trabecular bone, meaning that approximately half of the material in the bone is replaced in that period. Dental enamel, on the other hand, as a cell-free tissue, does not undergo turnover after formation. Thus, the Sr in the enamel of the first permanent molar contains Sr which has been incorporated from birth to approx. 4 years of age (Hillson, 1989).

Differences in the Sr isotope signature between enamel and bone in the same individual thus indicate a change in residence. Such differences mean that the individual was born in a place geologically and isotopically different from the place where he/she died. Because of the slow turnover rate in bone the age of the individual and the length of residence are important factors in assessing changes in location. Although there is some variation in $^{87}Sr/^{86}Sr$ ratios within local environments in both plants and geological materials (e.g. Sillen *et al.*, 1998), the long-term accumulation of elements in the growth and turnover of bone over a number of years provides an average for individual diet for the area.

Procedure

Strontium isotope analysis for information on prehistoric residential mobility requires samples of bone and dental enamel. Each bone sample was mechanically abraded with a Dremel tool fitted with a sanding bit to remove any visible dirt and/or preservative; tooth samples were drilled to remove the enamel layer from the underlying dentine. Samples were then placed in sterile plastic vials and sonicated in deionised (18 megohm) water for 15 min. After rinsing, each vial was filled with 5% ultrapure acetic acid and the sonication procedure repeated. Samples were left overnight in the acid, rinsed in deionised water, and placed in a drying oven at 80°C for approx. 24 h. Dilute acetic acid will dissolve not only the soluble carbonates, but also that portion of the bone mineral that is most likely to have been contaminated by interaction with diagenetic fluids. After drying, samples were transferred to sterile silica glass tubes that have been soaked in hot ultrapure, concentrated nitric acid and ashed in a muffle furnace at 825°C for 8 h.

Bone and tooth enamel ash samples were then transferred to sterile savilex digestion vials and hot digested in ultrapure concentrated nitric acid, dried in a sterile laminar flow drying box, and redisolved in ultrapure 2·5 N hydrochloric acid. This procedure may be repeated if there are any trace organics remaining in the sample. Strontium is then isolated using cation exchange chromatography with 2·5 N hydrochloric acid as the mobile phase.

Samples were then mounted on zone-refined tantalum filaments, and strontium was analysed using a thermal ionisation multiple collector mass spectrometer. $^{87}Sr/^{86}Sr$ ratios are corrected for mass fractionation in the instrument using the exponential mass fractionation law and $^{86}Sr/^{88}Sr=0{\cdot}1194$. Twelve samples were analysed at the Radiogenic Isotope Facility, Department of Geology and Geophysics, University of Wisconsin (UW). The remaining samples were analysed at the Isotope Geochemistry Laboratory, Department of Geological Sciences, University of North Carolina at Chapel Hill (UNC-CH). The same type of instrument was used at both labs, a MicroMass Sector 54, multicollector mass spectrometer. Both laboratories produce the same results for standard samples. At UNC-CH, $^{87}Sr/^{86}Sr$ analyses (N=40) of the NIST SRM strontium carbonate yield a value of $0{\cdot}710259 \pm 0{\cdot}0003$ (2 s.e.). All $^{87}Sr/^{86}Sr$ ratios from the UNC-CH laboratory are reported relative to an expected value of 0·710250 for this standard (typically, four standards were analysed with each turret of samples; if the $^{87}Sr/^{86}Sr$ ratio for the four standards averaged 0·710259, a value of 0·000009 was subtracted from the ratio that is reported for each sample from that turret). Internal precision (s.e.) for the samples analysed at UNC-CH is typically 0·000006 to 0·000010, based on 100 dynamic cycles of data collection. At UW, 52 analyses of NBS-987 Sr standard produced an $^{87}Sr/^{86}Sr$ of $0{\cdot}710273 \pm 0{\cdot}000011$ (2 s.e.). The samples analysed at UW have similar internal precision to those run at UNC-CH; the ratios for samples analysed at UW were not adjusted to a specific value for NBS-987 Sr standard.

The Teotihuacan and Oaxaca Samples

A total of 81 samples have been analysed for this study. These samples are listed in Table 1. There were 71 samples from Teotihuacan, including nine samples of modern and prehistoric rabbit bones found in deposits in the tunnels beneath the city. The nine rabbit samples were obtained in order to provide an independent measure of the local ratio of stable strontium isotopes. Analysis of the nine rabbit bones produced an average strontium isotope ratio of 0·7046, with a standard deviation of 0·00005. This mean should represent a base line for the local values at Teotihuacan. The remaining 62 samples from Teotihuacan are human bone and enamel and come from Oztoyahualco 15B:N6W3 (N=8), Cueva de las Varillas (N=13), Cueva del Pirul (N=13), the Barrio de los Comerciantes (N=8), and the Oaxaca Barrio (N=20).

Results of the strontium isotope analysis are presented in Figure 4. The samples in this bar graph are arranged in the same order as in Table 1 and the discussion below will follow this order. Bone and tooth bars from the same individual are connected in the graph. Values are grouped by location of burials. The horizontal line on the side of the graph and marked local average shows the mean for the nine rabbit bones.

We would expect individuals who were long-term residents of Teotihuacan to have strontium isotope ratios similar to the rabbit values. An individual born in the area of Teotihuacan should be indicated by identical or exceedingly close ratios in bone and tooth enamel. Recent immigrants should be signalled by different ratios in tooth enamel and bone. Smaller differences between the bone and enamel values indicate more recent arrival of the immigrant.

Several general patterns are apparent in the results from Teotihuacan. There is substantial variation in enamel $^{87}Sr/^{86}Sr$ ratios, but relatively little variation in the bone samples. The variability in the enamel samples indicates that a number of the individuals in this study must have been migrants to the city. This interpretation conforms with speculation that the growth of the city was so rapid as to require substantial

Table 1. Samples used in this study for strontum isotope analysis. Results show the Sr ppm and $^{87}Sr/^{86}Sr$ of 81 bone and tooth samples from Teotihuacan and Oaxaca

Site	Provenience	Species	Material	Element	Age/sex	(^{87}Sr/^{86}Sr)	% S.E.
Teotihuacan	11203 CV C2 N334 E96 1l	Rabbit	Bone	Femur	Adult	0·704595	0·00060
Teotihuacan	11145 CV C2 N331 E93 1k	Rabbit	Bone	Humerus	Adult	0·704588	0·00090
Teotihuacan	3110 CV C1 N342 E94 1a	Rabbit	Bone	Humerus	Adult	0·704689	0·00060
Teotihuacan	8186 CV T N333 E81 2d	Rabbit	Bone	Tibia and femur	Adult	0·704591	0·00070
Teotihuacan	3294 CV C1 N338 E91 1a	Rabbit	Bone	Tibia	Adult	0·70464	0·00080
Teotihuacan	7531 CV NS N334 E91 1a	Rabbit	Bone	Femur	Adult	0·704717	0·00130
Teotihuacan	22422 CP C5 N348 E116 1f/2a AA207	Rabbit	Bone	Humerus	Adult	0·704612	0·00070
Teotihuacan	790 CB N325 E16 S	Rabbit	Bone	Femur and 2 tibia	Adult	0·704709	0·00080
Teotihuacan	706 CB N332 E31 S	Rabbit	Bone	F, T and H	Adult	0·704654	0·00060
Teotihuacan	Oztoyahualco	Human	Tooth			0·7050885	0·00001
Teotihuacan	Oztoyahualco	Human	Bone			0·7047958	0·00001
Teotihuacan	Oztoyahualco N30 MEZ76 Entiero 13 E2C10 R10 AA26	Human	Tooth	Tooth		0·706504	0·00070
Teotihuacan	Oztoyahualco N30 MEZ76 Entiero 13 E2C10 R10 AA26	Human	Bone	Long bone		0·705061	0·00060
Teotihuacan	Oztoyahualco N311 E284 C21 F6 Entiero 8	Human	Bone	Long bone		0·705071	0·00060
Teotihuacan	Oztoyahualco N317 E284 C19 F11 Entiero 10	Human	Bone	Long bone		0·704672	0·00130
Teotihuacan	Oztoyahualco N310 E287 E2 C22 F29 R1 Entiero 11-a	Human	Bone	Long bone		0·704759	0·00060
Teotihuacan	Oztoyahualco N310 E287 E2 C22 F29 R1 Entiero 11-b	Human	Bone	Long bone		0·704736	0·00060
Teotihuacan	Cueva de las Varillas N334–5 E95 Entiero 2	Human	Tooth		Adult female	0·7046508	0·00001
Teotihuacan	Cueva de las Varillas N334–5 E95 Entiero 2	Human	Bone			0·7046479	0·00001
Teotihuacan	Cueva de las Varillas C2 N333 E96 1k Entiero 3	Human	Tooth			0·7054281	0·00002
Teotihuacan	Cueva de las Varillas C2 N333 E96 1k Entiero 3	Human	Bone			0·704703	0·00002
Teotihuacan	Cueva de las Varillas C2 N334–5 E96 R1–3 E2 Entiero 5	Human	Tooth		Adult	0·7069271	0·00001
Teotihuacan	Cueva de las Varillas C2 N334–5 E96 R1–3 E2 Entiero 5	Human	Bone			0·7046624	0·00001
Teotihuacan	Cueva de las Varillas CVC2 N337 E97 Entiero 7	Human	Tooth	Tooth		0·704961	0·00070
Teotihuacan	Cueva de las Varillas CVC2 N337 E97 Entiero 7	Human	Bone	Long bone		0·704678	0·00070
Teotihuacan	Cueva de las Varillas CVC2 N333 E94–95 1K Entiero 4 Ind. 1	Human	Tooth	Tooth		0·705555	0·00080
Teotihuacan	Cueva de las Varillas CVC2 N335 E97 E2 R1–R2 Entiero 9	Human	Bone	Long bone	Newborn	0·704625	0·00050
Teotihuacan	Cueva de las Varillas CVC2 N335–6 E98 E2 R1–R2 Entiero 10	Human	Bone	Long bone	Newborn	0·704624	0·00070
Teotihuacan	Cueva de las Varillas CVC2 N335 E96 E2 R1–R3 Entiero 9	Human	Bone	Long bone	Adult	0·704615	0·00050
Teotihuacan	Cueva de las Varillas CVC2 N337 E981 g Entiero 8	Human	Bone	Long bone		0·704633	0·00070
Teotihuacan	22145 Cueva del Pirul Entiero 22	Human	Bone	Rib	Adult	0·704612	0·00070
Teotihuacan	22146 Cueva del Pirul Entiero 23	Human	Bone	Rib	Adult	0·704608	0·00070
Teotihuacan	22468 Cueva del Pirul Entiero 24	Human	Bone	Rib	Adult	0·704664	0·00070
Teotihuacan	25175 Cueva del Pirul Entiero 25	Human	Bone	Rib	Adult	0·704652	0·00060
Teotihuacan	25308 Cueva del Pirul Entiero 26	Human	Bone	Rib	Adult	0·704663	0·00070
Teotihuacan	25312 Cueva del Pirul Entiero 27	Human	Bone	Rib	Adult	0·704641	0·00060
Teotihuacan	25498 Cueva del Pirul Entiero 28	Human	Bone	Rib	Adult	0·704558	0·00090
Teotihuacan	25334 Cueva del Pirul Entiero 29	Human	Bone	Rib	Adult	0·70464	0·00070
Teotihuacan	25679 Cueva del Pirul Entiero 30	Human	Bone	Rib	Adult	0·704672	0·00060
Teotihuacan	25492 Cueva del Pirul Entiero 31	Human	Bone	Rib	Adult	0·704611	0·00060
Teotihuacan	25424 Cueva del Pirul Entiero 32	Human	Bone	Rib	Adult	0·704662	0·00070
Teotihuacan	25654 Cueva del Pirul Entiero 33	Human	Bone	Rib	Adult	0·704616	0·00060
Teotihuacan	21220 Cueva del Pirul Entiero 21	Human	Bone	Rib	Adult	0·704603	0·00070
Teotihuacan	Comerciantes	Human	Tooth	Tooth		0·7053876	0·00002
Teotihuacan	Comerciantes	Human	Bone	Long bone		0·7047584	0·00001
Teotihuacan	Comerciantes	Human	Tooth	Tooth		0·7064574	0·00001
Teotihuacan	Comerciantes	Human	Bone	Long bone		0·704658	0·00002
Teotihuacan	Comerciantes 3E:N3E4 E1N5–E2N5 Entiero 4	Human	Tooth	Tooth		0·704223	0·00060
Teotihuacan	Comerciantes 3E:N3E4 E1N5–E2N5 Entiero 4	Human	Bone	Long bone		0·70466	0·00080

Table 1. (Continued)

Site	Provenience	Species	Material	Element	Age/sex	($^{87}Sr/^{86}Sr$)	% S.E.
Teotihuacan	Comerciantes 12:N3E4 W153 Entiero 22	Human	Bone	Long bone		0·704826	0·00070
Teotihuacan	Comerciantes 3E:N3E4 E1N5–E2N5 Entiero 4.12	Human	Tooth	Tooth		0·704302	0·00070
Teotihuacan	6:N1W6 Ent. 322 Oaxaca Barrio	Human	Tooth	URM1	Adult	0·704599	0·00090
Teotihuacan	6:N1W6 Ent. 322 Oaxaca Barrio	Human	Bone	LF		0·704613	0·00080
Teotihuacan	6:N1W6 Ent. F223 Oaxaca Barrio	Human	Tooth	URM1	Adult	0·704633	0·00070
Teotihuacan	6:N1W6 Ent. F223 Oaxaca Barrio	Human	Bone	LF		0·704626	0·00080
Teotihuacan	6:N1W6 Ent. F3455 Oaxaca Barrio	Human	Tooth	LRM1	Adult	0·705053	0·00100
Teotihuacan	6:N1W6 Ent. F3455 Oaxaca Barrio	Human	Bone	F		0·70469	0·0006
Teotihuacan	6:N1W6 Ent. F284A Oaxaca Barrio	Human	Tooth	LRM1	Adult	0·705189	0·00090
Teotihuacan	6:N1W6 Ent. F284A Oaxaca Barrio	Human	Bone	RF		0·704811	0·00060
Teotihuacan	6:N1W6 Ent. Tumba Sur Oaxaca Barrio	Human	Tooth	LRM1	Adult	0·705329	0·00080
Teotihuacan	6:N1W6 Ent. Tumba Sur Oaxaca Barrio	Human	Bone	RF		0·704797	0·00080
Teotihuacan	6:N1W6 Ent. 372 Oaxaca Barrio	Human	Tooth	LRM1	Adult	0·705346	0·00070
Teotihuacan	6:N1W6 Ent. 372 Oaxaca Barrio	Human	Bone	LF		0·704905	0·00070
Teotihuacan	6:N1W6 Ent. Tumba Norte Oaxaca Barrio	Human	Tooth	LRM1	Adult	0·705518	0·00080
Teotihuacan	6:N1W6 Ent. Tumba Norte Oaxaca Barrio	Human	Bone	RF		0·704855	0·00060
Teotihuacan	6:N1W6 Ent. F409 Oaxaca Barrio	Human	Tooth	DURM1	Adult	0·705803	0·0007
Teotihuacan	6:N1W6 Ent. F409 Oaxaca Barrio	Human	Bone	LF		0·705085	0·0007
Teotihuacan	6:N1W6 Ent. F261 Oaxaca Barrio	Human	Tooth	ULM1	Child	0·706885	0·0009
Teotihuacan	6:N1W6 Ent. F261 Oaxaca Barrio	Human	Bone	RF		0·704948	0·0011
Teotihuacan	6:N1W6 Ent. F381 Oaxaca Barrio	Human	Tooth	URM1	Adult	0·707023	0·0008
Teotihuacan	6:N1W6 Ent. F381 Oaxaca Barrio	Human	Bone	RF		0·704859	0·0007
Monte Albán	Monte Albán 1991–26A	Human	Tooth	Tooth	Adult	0·706642	0·00070
Monte Albán	Monte Albán 1991–26A	Human	Bone	Femur		0·706989	0·00070
Monte Albán	Monte Albán 1991–34	Human	Tooth	Tooth	Adult	0·707621	0·00070
Monte Albán	Monte Albán 1991–34	Human	Bone	Femur		0·707627	0·00130
Monte Albán	Monte Albán 1991–53	Human	Tooth	Tooth	Adult	0·707534	0·00080
Monte Albán	Monte Albán 1991–53	Human	Bone	Femur		0·707778	0·00080
Monte Albán	Monte Albán 1991–74	Human	Tooth	Tooth	Adult	0·707524	0·00080
Monte Albán	Monte Albán 1991–74	Human	Bone	Femur		0·707558	0·00080
Monte Albán	Monte Albán 1991–83	Human	Tooth	Tooth	Adult	0·707471	0·00090
Monte Albán	Monte Albán 1991–83	Human	Bone	Femur		0·707493	0·00080

immigration (e.g. Millon, 1973, 1981; Blanton, 1981). Oztoyahualco 15B:N6W3 is a residential compound at the northwestern periphery of Teotihuacan that is assumed to have housed local residents (Figure 2). Occupation of this compound dates from throughout the Tlamimilolpa and Xolalpan phases (AD 300–550), although some materials from the Metepec phase are present (Table 2). The ceramics found in this compound (San Martin Orange, Thin Orange, Copa, Matte, Polished and Burnished Wares) as well as the residential and funerary remains are typical of the distinctive styles of Teotihuacan and suggest that these individuals were local residents (Manzanilla, 1993).

Most of the individuals from Oztoyahualco exhibit bone isotope ratios at or close to the local average. Two high bone values, both from adult males (burials 13 and 14), stand out, however, suggesting recent immigration to the city. The enamel value paired with one of these bone samples clearly indicates an outside migrant. Both of the individual enamel values are higher than the Teotihuacan local signal in bone and likely represent individuals who moved into this area.

As noted earlier, the burials in Cueva del Pirul (Late Coyotlatelco phase) and Cueva de las Varillas (Late Coyotlatelco and Mazapa phase) represent later inhabitants of the city (Manzanilla *et al.*, 1996) and may be either locals or outsiders. The fact that the bone values from the tunnel burials are very similar and close to the mean value for the rabbits suggests that most of these individuals had been in the city long enough for bone isotope values to calibrate to local geology. It is important to recall that the bone samples in most cases are compact femoral bone which has a slow turnover rate, suggesting that these individuals may have been in the city for some time. No enamel samples were analysed from Cueva del Pirul, but there are at least three significantly higher enamel values from Cueva de las Varillas. These individuals are probable immigrants; the differences among the enamel values suggest they originated in several different locations.

As noted above, the Barrio de los Commerciantes contains a variety of materials from the Gulf Coast region of Mexico, and the Oaxaca Barrio is characterised by materials from the Zapotec region. The strontium isotope values from the burials at Barrio de los Commerciantes show a dual pattern (Figure 4). The bone samples clearly have equilibrated to the local Teotihuacan ratio; enamel ratios show two higher and two lower values indicating that all four individuals are

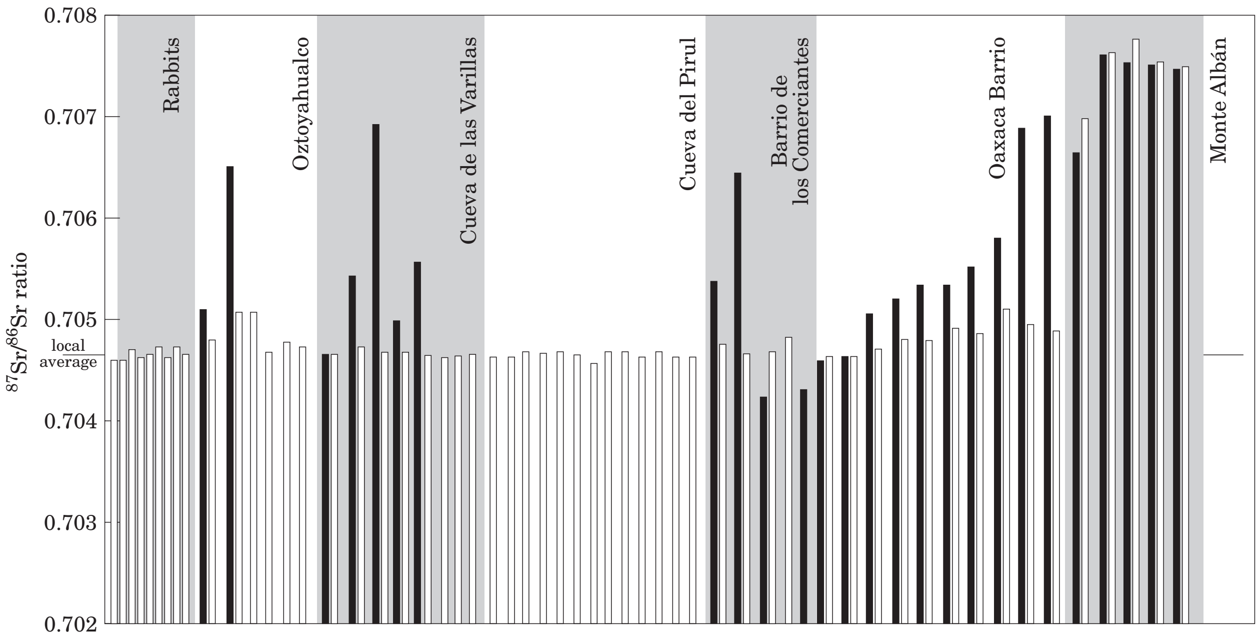

Figure 4. Bar graph of strontium isotope ratios for Teotihuacan study. ■, tooth enamel; □, bone. Paired bone and tooth bars are from the same individual. The values are grouped by location of burials. The local average shows the mean for nine rabbit bones from Teotihuacan. There are a total of 81 samples, 71 from Teotihuacan and 10 from the site of Monte Albán in Oaxaca.

immigrants from at least two different areas outside of Teotihuacan. This pattern suggests the occupants were coming from different areas of the Gulf Coast to the city of Teotihuacan.

The individuals from the Oaxaca Barrio are very interesting. There are a total of ten individuals represented by paired samples of bone and enamel. The bone values are somewhat more variable than the other groups from Teotihuacan. The enamel values are highly varied and fall into three groups: (1) the first two have values for both bone and enamel that are very similar to the local Teotihuacan ratio, suggesting that they were life-long residents; (2) the next five individuals have intermediate values that suggest a different place of origin; bone values for these five individuals are also higher than the local signal at Teotihuacan suggesting they are recent immigrants; and (3) the last two individuals in the graph have the highest enamel values; their bone values are also higher than the Teotihuacan average. It is entirely possible that these last two individuals may have migrated from Oaxaca.

Monte Albán is a major prehistoric centre in the the Valley of Oaxaca. This site is a potential place of origin of individuals living in the Oaxaca Barrio at Teotihuacan. Ten samples (five pairs of bone and enamel) from burials at the site of Monte Albán have been included in this study, specifically for comparison. With the exception of grave 83 from period IIA (the last bar pair in the graph), the samples date from Period IIIA (AD 200–550), roughly contemporary with the major occupation of Teotihuacan. Soils in both the

Table 2. Chronological phases and age at the site of Teotihuacan (Cowgill, 1996)

Age of site	Chronological phase
700	Xometla
	Oxtoticpac
600	Metepec
500	Late Xolalpan
400	Early Xolalpan
300	Late Tlamimilolpa
	Early Tlamimilolpa
200	Miccaotli
100	Tzacualli
AD/BC	
100	Patlachique (Tezoyuca?)
200	Late Cuanalan

Oaxaca and the Teotihuacan area are derived from Cenozoic lava and pyroclastic deposits (Stuart-Williams *et al.*, 1996). However, there are pronounced differences in the strontium isotope levels in human bone from these two regions (Table 1), suggesting significant geological differences in the subsistence resource zones of these populations. The average human bone value at Teotihuacan is 0·70472 (N=41), while average bone value in the Monte Albán sample is 0·70749 (N=5).

A scatterplot of the strontium isotope ratios in the individual bone-tooth enamel pairs is shown in Figure 5. The bone–tooth pairs from the site of Monte Albán are very similar, with one exception, and suggest that all these individuals were life-long local residents at

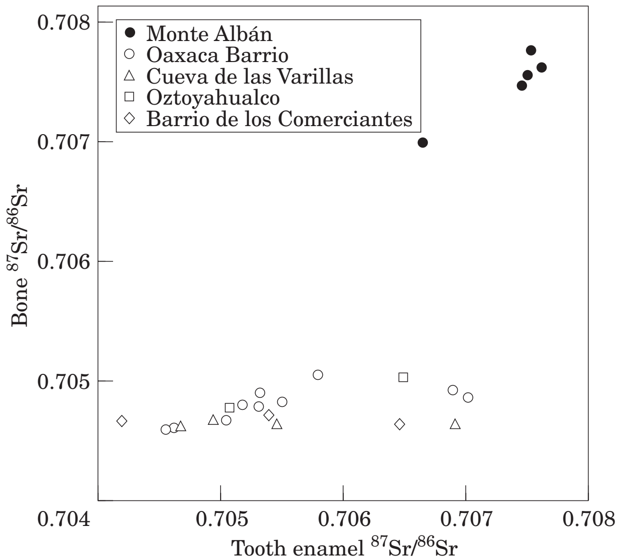

Figure 5. Scatter plot of strontium isotope ratios for bone–tooth enamel pairs for 24 individuals in the Teotihuacan study.

Monte Albán. The one individual with a slightly lower enamel ratio may have lived and died in another part of the valley of Oaxaca, or elsewhere. It is also clear from this graph that, with the exception of the Monte Albán samples, the isotope ratios in the bones of these individuals are not greatly different, ranging between 0·7046 and 0·7051. On the other hand, the majority of the tooth enamel ratios in the non-Monte Albán individuals (12/19) exhibit values greater than 0·7051. This suggests that most of these individuals had been at Teotihuacan for a number of years, sufficient for the ratio in cortical bone to shift towards the local signal. The high proportion of enamal values greater than 0·7051, however, indicates that many of these individuals originally migrated to the city from a variety of areas.

Comparison with other studies

Strontium isotopes have been successfully used to explore residential changes in human populations in several different prehistoric contexts. Sealy has examined the origins of recent and prehistoric residents of the Cape region of South Africa (Sealy *et al.*, 1991, 1995). Price *et al.* (1994*b*) investigated strontium isotopes at Grasshopper Pueblo in north-central Arizona and found very high rates of migration in this population. Price *et al.* (1994*a*) studied migration in Bell Beaker populations in southern Germany and reported rates of migration of at least 25% among these groups.

Similar investigations of residential change have been attempted with other isotopes. Carlson (1996) used lead isotopes in prehistoric bone to examine questions of prehistoric cultural affinity in Alberta, Canada. Gulson *et al.* (1997) have recommended the analysis of stable lead isotopes in teeth as an indicator of past domicile for forensic purposes. Modern diets, however, come from a wide range of geological backgrounds, making such determinations questionable.

Oxygen isotopes have also been employed to study residence changes (e.g. Schwarcz *et al.*, 1991), including the geographical origins of burials from prehistoric Mexico. White *et al.* (1998) measured oxygen isotope ratios in bone phosphate from human ribs from 11 individuals from the Teotihuacan site of Tlajinga and 16 individuals from Monte Albán in Oaxaca. These two sets of samples were compared with measurements from 11 burials from the Oaxaca Barrio of Tlailotlacan at Teotihuacan. The results showed differences in oxygen isotopes between Oaxaca (13·01‰) and the Teotihuacan valley (14·75‰). The results from the Oaxaca Barrio in general were closer to the local values in the Teotihuacan valley. Children under 5 years of age in this sample show values higher than the local signal. In another study (Stuart-Williams *et al.*, 1996), variation in oxygen isotope ratios among 48 bone samples from various parts of the Teotihuacan site had a mean of 15·08‰ and a standard deviation of 0·89. The range of variation in oxygen isotope measurements makes interpretation difficult. Part of this variation is due to problems with the identification of specific water sources (the primary source of $^{18}O/^{16}O$) for the deceased individuals, problems with turnover in bone, and the use of secondary burials which may not be associated with their assumed context.

Conclusions

In general, the use of strontium isotopes is straightforward and a robust technique for the identification of residential change. Measurement of dental enamel provides a signal of place of birth, and measurement of bone indicates the place of death. Differences in these values in the same individual are indicative of residential changes during life.

Strontium isotope analysis of a large group of burials from the ancient city of Teotihuacan directly supports a picture of substantial migration to the site, particularly in foreign neighbourhoods and for Epiclassic and Early Postclassic populations. The uniformity of $^{87}Sr/^{86}Sr$ ratios in bone suggests that most of these individuals had spent a considerable period of time at the site prior to their death. Burials from specific areas of the ancient city [the Oaxaca Barrio, Cueva de las Varillas, Oztoyhualco 15B:N6W3 (two burials), and the Barrio de los Comerciantes] show highly variable enamel values suggesting a variety of original homes for these individuals. The general picture that emerges from the analysis of the bone-enamel pairs is that the majority of individuals examined were migrants to the city from a variety of different places.

Given these intriguing results, we plan to continue our study of residence change in terms of place of birth and death at Teotihuacan. Several kinds of information are needed. We need to analyse more individuals from indigenous residential areas such as Oztoyahualco to learn more about variation in strontium isotope ratios in the local population. It will be very interesting to compare isotope ratios in cortical and trabecular bone, as well different skeletal elements, to see if we can better estimate the age of individuals at the time of migration.

We also need to analyse more individuals from the "foreign" areas at Teotihuacan such as the Barrio de los Comerciantes for improved estimates of the incidence of migration into these compounds. It will be of particular interest to examine the life history of these individuals in an attempt to determine at what age they migrated to Teotihuacan (Sealy *et al.*, 1995; Price *et al.*, 1998). Finally we need to analyse geological samples and human burials from the potential homelands of the foreign individuals at Teotihuacan in order to identify the place from which they came. At the moment we can say that the individuals from Barrio de los Comerciantes, for example, came from outside the city, but we cannot say from where. One of several exciting aspects of strontium isotope analysis is the possibility of answering these questions as well. Strontium isotope analyses of human bone and tooth clearly has a high potential for answering a number of important archaeological questions. We look forward to expanding research in this area.

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