LAPITA MIGRANTS IN THE PACIFIC'S OLDEST CEMETERY: ISOTOPIC ANALYSIS AT TEOUMA, VANUATU

R. Alexander Bentley, Hallie R. Buckley, Matthew Spriggs, Stuart Bedford, Chris J. Ottley,
Geoff M. Nowell, Colin G. Macpherson, and D. Graham Pearson

Teouma, an archaeological site on Efate Island, Vanuatu, features the earliest cemetery yet discovered of the colonizers of Remote Oceania, from the late second millennium B.C. In order to investigate potential migration of seventeen human individuals, we measured isotopes of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$), oxygen ($\delta^{18}\text{O}$), and carbon ($\delta^{13}\text{C}$), as well as barium (Ba) and strontium (Sr) concentrations, in tooth enamel from skeletons excavated in the first two field seasons. The majority of individuals cluster with similar isotope and Ba/Sr ratios, consistent with a diet of marine resources supplemented with plants grown on the local basaltic soils. Four outliers, with distinctive $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$, are probably immigrants, three of which were buried in a distinctive position (supine, with the head to the south) with higher Ba/Sr and $\delta^{13}\text{C}$, consistent with a terrestrial, nonlocal diet. Among the probable immigrants was a male buried with the crania of three of the locally raised individuals on his chest.

Teouma, sur l'île d'Efate, Vanuatu, est le site du cimetière le plus tôt pourtant découvert des colonisiers d'Océanie à distance, tard deuxième millénaire avant J.-C. Nous avons mesuré des isotopes de strontium, de carbone, et d'oxygène aussi bien que des oligoéléments (Ba, Sr) dans l'émail des dents des squelettes excavés dans la première et deuxième saisons de champ, pour étudier la migration potentielle de ces individus. Le faisceau de majorité avec l'isotope semblable et les rapports d'oligoélément, conformés à un régime des ressources marines complétées avec des plantes cultivées sur les sols basaltiques locaux. Quatre adultes, avec $^{87}\text{Sr}/^{86}\text{Sr}$ et $\delta^{18}\text{O}$ distinctifs, sont probablement les immigrants, dont trois ont été enterrés dans une position distinctive (en supination, avec la tête aux sud) avec un plus hauts Ba/Sr et $\delta^{13}\text{C}$, conformés à un régime plus terrestre que la majorité. Parmi ces derniers était un mâle enterré avec le crania de trois des individus local-soulevés sur son coffre.

The colonization of the Pacific has occupied the attention of archaeologists, linguists, and human geneticists for decades, and more particularly its debated origins in Southern China, Taiwan, Island Southeast Asia, or some combination (e.g., Bellwood 2005; Cox 2005; Cox and Lahr 2006; Gray and Jordan 2000; Kirch 2000; Matisoo-Smith and Robins 2004; Oppenheimer and Richards 2001; Trejaut et al. 2005). At its ultimate extent in the Eastern Pacific, Polynesian contact with the Americas brought the sweet potato into

Eastern Polynesia (Hather 1992; Yen 1974) and may have introduced new canoe and fishhook technology to the California Chumash (Jones and Klar 2005; cf. Anderson 2006).

Over fifty years of archaeological research has yielded a broad chronology of Pacific colonization (e.g., Kirch 2000; Spriggs 1997). Beginning at least 40,000 years ago in Near Oceania (New Guinea to the end of the Solomons chain), movement eastward followed a route of mostly inter-visible islands, until reaching the point where

R. Alexander Bentley ■ Evolutionary Anthropology Research Group, Department of Anthropology, Durham University, Durham DH1 3HN, United Kingdom (r.a.bentley@durham.ac.uk)

Hallie R. Buckley ■ Department of Anatomy and Structural Biology, School of Medical Sciences, University of Otago, PO Box 913, Dunedin, New Zealand

Matthew Spriggs ■ School of Archaeology and Anthropology, College of Arts and Social Sciences, AD Hope Building, The Australian National University, Canberra, ACT 0200, Australia

Stuart Bedford ■ Department of Archaeology & Natural History, Research School of Pacific and Asian Studies, The Australian National University, Canberra ACT 0200 Australia

Chris J. Ottley, Geoff Nowell, Colin G. Macpherson, and D. Graham Pearson ■ Department of Earth Sciences, Durham University, South Road, Durham, DH1 3LE, United Kingdom

substantially larger water gaps separate smaller islands. About 36,000 years later, at the end of the 2nd millennium B.C., a very rapid colonization then reached as far as Tonga and Samoa in just a few centuries. These bearers of the Lapita culture—ancestral to the later colonization of the rest of Polynesia—brought horticultural plants, domestic animals, and distinctive material culture within a purported ranked social organisation (Green 2003; Kirch and Green 2001). Inter-island connections at short- and long-distance scales are evidenced through distinctive dentate stamped Lapita pottery (e.g., Cochrane 2007; Dickinson 2006; Dickinson and Shutler 2000; Summerhayes 2000) and obsidian sourced from a limited number of geographical locations (Summerhayes 2003). Presumably, this contact between small, scattered colonizing settlements was essential for their demographic viability (Pawley 1981).

Despite more than 200 Lapita sites having been identified, skeletal remains of the “Lapita people” from Near or Remote Oceania had, until recently, consisted of only 15–20 individuals from several different sites (Pietrusewsky 1996). This changed dramatically in late 2003, with the discovery of the Lapita cemetery site of Teouma, on the south coast of Efate Island, Central Vanuatu (Bedford et al. 2004). By the end of the second excavation season, the cemetery had yielded 26 inhumations comprising 36 individuals, which more than doubled the previously existing sample of Lapita burials. As the oldest cemetery yet found in the Pacific, ca. 3200–3000 B.P., Teouma is associated with the initial human settlers of the Vanuatu archipelago. It provides unprecedented opportunities for research into the origins, colonization strategies, social dynamics, health, ritual behaviour, and diet of a Lapita group (Bedford et al. 2006), and, more generally, an early colonizing group in a previously uninhabited environment.

Teouma also provides the opportunity to use isotope analyses to characterize human migration during this early stage of colonization in remote Oceania. Strontium and oxygen isotopes are arguably the most effective isotopes for characterizing prehistoric human and animal mobility (e.g., Bentley 2006; Budd et al. 2004; Müller et al. 2003). Here we report our analyses of isotopes of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$), oxygen ($\delta^{18}\text{O}$), and carbon ($\delta^{13}\text{C}$), along with concentrations of Ba and Sr, in the tooth

enamel of individuals excavated in the first two field seasons.

Materials

Although there is considerable variation in burial positions at Teouma, one consistent feature was that the skulls of each burial had been removed sometime after decomposition of the periodontal ligaments, as indicated by the presence of teeth around the neck and thorax regions of most of the burials. All individuals with teeth present were included in the study. This broad sampling includes a range of different burial treatments, sex, and age at death. One exceptional burial, Burial 10 (Figure 1), contained five individuals, including an adult male (10E) lying supine with three skulls (10A, B and C) and the mandible (10D) of a separate individual on his chest (Figure 1). Only the mandible held no teeth for sampling from Burial 10.

Age and sex of individuals were estimated based on the standards of Buikstra and Ubelaker (1994) and seriation of dental attrition within the sample. The age groups assigned to the adults may be roughly correlated with chronological age as; Young (20.0–29.9), Mid (30.0–39.9) and Old (40+).

Isotopes and Ba/Sr Ratios in Archaeological Tooth Enamel

Oxygen isotope compositions ($\delta^{18}\text{O}$, relative to Standard Mean Ocean Water [SMOW]) in the environment depend upon the fractionation of ^{18}O vs. ^{16}O during evaporation, condensation, and precipitation in the hydrologic cycle, with ^{18}O preferentially retained in the liquid phase. In groundwater, oxygen isotope ratios reflect the mean $\delta^{18}\text{O}$ in precipitation over the catchment area, with negligible effect from interaction with local bedrock at low temperatures. Determined largely by atmospheric temperature, and hence grossly dependent on latitude and altitude, the mean annual $\delta^{18}\text{O}$ in precipitation is relatively homogeneous in the Pacific Trade Wind belt, with averaged variations of less than 2‰ across the entire Western Pacific (Bowen and Wilkinson 2002). Within a Pacific island with moderate topographic relief such as Efate (with elevations over 600 m), $\delta^{18}\text{O}$ in precipitation will deplete pro-

Figure 1. Burial 10E in situ with the three skulls placed over the chest. The skull of the female is in the middle. Burial 10E is the only inhumation treated in this distinctive manner.

gressively with altitude (Poage and Chamberlain 2001), and possibly be slightly higher on the windward side than the leeward side. On the islands of Hawai'i and Maui, for example, volume-weighted $\delta^{18}\text{O}$ in rain decreases by 1.2‰–1.6‰ per 1000 m altitude, with $\delta^{18}\text{O}$ on the windward side about 1.8‰ higher than for the same altitude on the leeward side (Scholl et al. 1996, 2002). Fed from higher altitudes, stream or spring water near sea level on Maui can have $\delta^{18}\text{O}$ on the order of 2–3‰ less than in the rain (Scholl et al. 2002). However, estimates of the global mean lapse rate of -0.24‰ km^{-1} for rain (Gonfiantini et al. 2001; Poage and Chamberlain 2001) suggest that the maximum altitude effect on Efate will be less than 1.6‰. Any rainshadow effect will also be smaller on Efate because the southwestern, windward side of Efate receives only twice the annual precipitation of the leeward northeast, whereas these differences on Hawai'i and Maui are a factor of five or more. Efate's two-fold decrease from windward to lee is more similar to that observed at Mt. Etna, where

there is little isotopic contrast between precipitation supplying the different flanks of that 3350 m peak (D'Alessandro et al. 2004). Details can be tested by future sampling on Efate, where spring waters must be sampled at all seasons of the year to record a volume-weighted mean annual $\delta^{18}\text{O}$ value.

Geographic origins are reflected in enamel $\delta^{18}\text{O}$ of species—including humans—primarily via $\delta^{18}\text{O}$ in ingested water (e.g., Balasse et al. 2002; Budd et al. 2004; D'Angela and Longinelli 1990; Kohn 1996). Due to biological averaging, seasonal $\delta^{18}\text{O}$ variations within the tooth enamel of mammals (those with continuous dental growth) are less than in the precipitation, on the order of about 5‰ or less in cows from South Africa, for example (Balasse et al. 2002). In humans with a consistent water supply, the variations in tooth enamel $\delta^{18}\text{O}$ are smaller, often varying by about 1‰ among prehistoric people from settled communities (Budd et al. 2004). Because the regression slope between drinking water and enamel values is close to one

(D'Angela and Longinelli 1990), the magnitude of variation in human enamel reflects the magnitude of geographic variation.

Strontium isotopes in human tooth enamel can serve as a geologic, and hence geographic, signature from childhood, when the enamel was forming (e.g., Balasse et al. 2002; Ericson 1985). Through rock weathering and environmental transport, strontium isotopes are conveyed, without measurably fractionating, into soils and into the food chain where strontium substitutes for calcium in the hydroxyapatite of tooth enamel (e.g., Bentley 2006). In most continental landscapes, there can be great local variability in soils and plants weathered from different rock types (e.g., Sillen et al. 1998). In Vanuatu, however, there are mainly two rocks for us to be concerned with, as discussed below: basalts, of volcanic origin, with Sr isotope ratios reflecting an origin in the Earth's mantle; and carbonates, with Sr isotope ratios reflecting an origin as precipitates from seawater. At the same time, sea-spray or precipitation can supply significant Sr of marine derivation ($^{87}\text{Sr}/^{86}\text{Sr} = .7092$) to the bio-available pool on Pacific islands such as Hawaii (e.g., Chadwick et al. 1999), and so there is a challenge in untangling the various contributions of seawater strontium—including coral reefs, sea-spray, and seafood in the diet—which mix with Sr from the regional island arc basalts of values between .7030 and .7045 (Raos and Crawford 2004).

Once the "local" biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ range is estimated for a particular site, the most parsimonious interpretation is that humans with values within that range lived locally, and those with isotopic ratios outside of the prescribed range were immigrants. In the case of Vanuatu, however, where seafood and terrestrial food have distinct $^{87}\text{Sr}/^{86}\text{Sr}$ values, a "nonlocal" could just be someone who ate a distinctly different ratio of seafood/terrestrial food in his/her diet. Also, people with strongly marine-based diets will typically have nearly the same $^{87}\text{Sr}/^{86}\text{Sr}$ value (close to .7092) no matter how far away they may have come from.

To help resolve the ambiguity, we also measured trace element concentrations of barium and strontium, as each provides additional information of diet, which can help to disentangle the dietary components of the strontium isotope signatures from their geographic components. These trace ele-

Table 1. Ranges of Ba/Sr Values (Mean $\pm$ 1 s.d.) in Marine and Terrestrial Materials, as Compiled from Published Studies by Burton and Price (1990:Table 1).

Material	Ba/Sr range
Soil	2.5–8.4
Land plants	.35–.79
Land mammals	.3–2.07
Freshwater fish	.63
Freshwater shell	.45–.71
Freshwater	.19–.56
Salmon (anadromous)	.019
Cod (marine)	.0045
Marine shell	.003–.005
Seawater	.0003–.004
Human bone (marine diet)	.011–.064
Human bone (terrestrial diet)	.301–1.729

ments substitute for calcium in the hydroxyapatite of tooth enamel, and through a phenomenon known as biopurification in moving up the trophic levels (Elias et al. 1982), Ba/Ca ratios reduce by a factor of 10, and Sr/Ca by a factor of about 5. For example, a carnivore retains 20 percent of Sr from a herbivore that it eats, and a herbivore retains 20 percent of the Sr from the plants of its diet (Burton et al. 1999, 2003). Since meat is low in Ca, Sr, and Ba, usually it is primarily plants in the diet that deliver Sr and Ba to human skeletal and dental tissues, even if the plants are only 30–40 percent of the diet (Burton et al. 2003). Plants have so much more Sr on average that they can dominate the meat signature, such that low Sr/Ca implies both the consumption of meat and an insignificant level of high-mineral plant foods in the diet.

In the case of Vanuatu, the proportion of marine foods in the diet will determine the Ba/Sr in human enamel. Because seawater has lower Ba/Sr ratios than typical terrestrial environments by almost three orders of magnitude (Burton and Price 1990: Appendix 1), marine organisms consequently have much lower Ba/Sr ratios than terrestrial foods (Table 1). The Ba/Sr ratio can thus reflect the amount of marine resources in the diet (Burton and Price 1990), such that low Ba/Sr in tooth enamel should be diagnostic of a marine diet. While a high Ba/Sr implies terrestrial foods, it does not necessarily mean absence of seafood, as the Ba comes from other sources, such as nonstarchy plants, that supplement the overall diet.

In addition to Ba/Sr ratios, carbon isotopes provide an independent measure of marine vs. terres-

Figure 2. Simplified basalt geology of the islands of Vanuatu. Gray, Late Miocene to Early Pliocene; Cross-hatched, Late Oligocene to Middle Miocene; No fill, Late Miocene to Holocene. After Raos and Crawford (2004:Figure 1).

trial food consumption. Apatite carbonate is enriched in humans by about 9.4‰ relative to the whole diet (e.g., Ambrose et al. 1997). For the Western Pacific, a comprehensive study by Ambrose et al. (1997) determined that a diet of pure C_3 plants would yield a $\delta^{13}C$ of -16.1‰ in carbonate, whereas a pure marine diet would yield -4.6‰. Each 1‰ difference in $\delta^{13}C$ thus equated to about 9 percent change toward the opposite end-member.

Vanuatu Geology

The Vanuatu island arc (Figure 2) exists at the margin of the Australia-India Plate and the Pacific Plate,

with a complicated subduction history since the Oligocene (Raos and Crawford 2004). Through processes of ocean floor uplift and subduction-related magmatism, Vanuatu consists of multiple belts of islands of different basaltic rock types (gabbros, tholeiitic lavas, calc-alkaline basalts) of varying age (35 – < 1 Ma) and trace element composition (Raos and Crawford 2004). Despite this geological variety, the volcanic rocks are characterized by a relatively restricted range of Sr isotope values ($^{87}Sr/^{86}Sr \sim .703-.7045$). The Efate Island Group itself (Figure 3) is geologically young, with the oldest deposits being the Efate Pumice For-

Figure 3. Geology of the Efate Island Group. After Raos and Crawford (2004:Figure 2).

mation of about 1 Ma, which consist of volcanic breccias from an explosive eruption (Raos and Crawford 2004). This formation is overlain by lavas of the Basalt Volcanic Formation (BVF), which erupted approximately .7 Ma and now remain in the higher elevations of the centre of the main island as well as three smaller islands to the north (Figure 3). The BVF basalts are high in barium (200–550 ppm) and Sr (800–1200 ppm), and have a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$, from .7040–.7042 (Raos and Crawford 2004). These Sr and Ba concentrations are high in comparison with a typical arc tholeiite suite such as the Kermadec lavas (Sr ~ 200 ppm, Ba ~ 100 ppm).

Driven by the convergence of the Australian and Pacific plates, some of the islands of Vanuatu have been uplifted by at least 600 m in the last 300,000 years—averaging 3 mm per year the last 20,000 years on Espiritu Santo, for example (Cabioch et al. 2003)—leaving raised reef limestone around many of the coasts (Figure 3). The Sr isotope composition of these recently formed reef limestones will mirror that of seawater, ~ .7092, and hence be quite distinct from that of the basalts. The Sr con-

centrations in a reef limestone should be quite high, as Sr substitutes for Ca in the aragonite phase, but even though Ba also makes this substitution, Ba concentrations are low in reef limestone because of the low Ba concentrations in seawater. A coral reef off Ambitle Island, Papua New Guinea, contains about 7,500 ppm Sr (with $^{87}\text{Sr}/^{86}\text{Sr}$ ~ .7092), but only a trace of Ba (Pichler et al. 2000). Hence, plants grown on calcareous soils derived from reef limestone should have low Ba/Sr and a seawater Sr isotope signature.

Procedure

We sampled tooth enamel rather than bone for isotope analysis because enamel, which contains larger mineral crystals and is much less porous than bone, is highly resistant to biochemical alteration (e.g., Hoppe et al. 2003; Sharp et al. 2000; Trickett et al. 2003). Because this is a destructive sampling technique, we only analyzed one tooth per individual in this study. But if warranted, there is the future opportunity to analyze additional teeth, potentially yielding information on the timing of a person's mobility by analyzing different molars,

Table 2. Age, Sex and Burial Position of Teouma Individuals, with Isotope and Trace Element Values in Human Tooth Enamel Samples. Typical Analytical Errors for (± 1 S.E.) Measured Values Are $\pm .0004$ for Ba/Sr, $\pm .00001$ for $^{87}\text{Sr}/^{86}\text{Sr}$, $\pm .1$ for $\delta^{18}\text{O}$, and $\pm .1$ for $\delta^{13}\text{C}$.

Burial	Age	Head	Position	Sex	Tooth	Ba/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$\delta^{18}\text{O}_{\text{SMOW}}$	$\delta^{13}\text{C}_{\text{PDB}}$
1	Old	S	Prone	M	L mand. P1	.011	.70757	24.0	-13.3
2A	Old	E	Prone	M	L max. P	.011	.70775	24.7	-13.2
3	Mid	S	Supine	F	L max. M3	.030	.70885	26.4	-10.4
4	Old	W	Supine	M	R max. M1	.007	.70716	25.0	-12.8
5A	Mid	NNE	Prone	F	L mand. P1	.011	.70740	23.1	-12.2
6	Mid	E	Supine	M	R max. M3	.012	.70763	24.3	-13.1
8	Old	S	Supine	M	R max. M1	.023	.70764	24.3	-13.3
10A	Old	—	*†	M	L Max. M1	.014	.70717	24.5	-14.2
10B	Old	—	*†	F	L max. M2	.011	.70696	24.5	-12.2
10C	Old	—	*†	M	R max. M1	.008	.70773	24.6	-12.4
10E	Mid	S	Supine	M	R max. CI	.022	.70866	26.8	-12.2
12	Old	N	Supine	F	R max. M3	.005	.70754	23.6	-12.5
14	Old	W	Supine	M	L max. M2	.013	.70686	24.1	-13.0
15	Young	S	Supine	F	L Max. CI	.037	.70893	25.9	-10.9
16	Old	S	Supine	F	R max. P2	.012	.70765	23.4	-12.5
17	Old	—	*§	F	R max. M1	.017	.70730	24.3	-13.1
18	Young	NNW	Supine	M	R max. M1	.013	.70897	26.0	-9.8

'Head' = Direction the Head Pointed in the Burial. Sampled Tooth Abbreviations: Left, Right, Maxillary, Mandibular, Molar (1st, 2nd, 3rd), Premolar (1st, 2nd), Central Incisor.

* Secondary burial of skull.

† placed on chest of TEO 10E (see Figure 1)

§ deposited in a pottery vessel with another pot as a lid.

which develop at sequential ages during childhood.

Using an established procedure (e.g., Bentley et al. 2005), about 5–20 mg of tooth enamel from each individual was mechanically cleaned and dentine removed with a surgical steel scalpel, and soaked for 8 hours in weak (5 percent) acetic acid. After the strontium was purified through columns of Sr-specific resin, the $^{87}\text{Sr}/^{86}\text{Sr}$ was analyzed using a VG-MicroMass Sector 54 thermal ionization mass spectrometer (TIMS) at the National Oceanography Centre, Southampton (NOC). During the time period of the NOC analyses, 4 measurements of the NBS SRM-987 standard yielded an average $^{87}\text{Sr}/^{86}\text{Sr}$ value of $.710245 \pm .000010$ (1 s.d.), in good agreement with estimates of the "accepted" value that range from .710230 to .710260.

Having prepared and cleaned additional portions of tooth enamel in the same manner as above, the enamel samples were weighed and then dissolved in 3 HNO₃, and in an aliquot of this solution, Ba and Sr concentrations were measured using a Thermo Element2 ICP-MS. The high sensitivity and low sample uptake ($\sim 100\mu\text{l min}^{-1}$) achievable with the Element2 were required for the low concentrations and sample volumes. Prior to analysis

the ICP-MS was optimized to produce minimal polyatomic oxide interference while maintaining a high overall sensitivity (typically Ce/CeO < 2.5 percent, with 1 ppb Indium in solution yielding 1×10^6 cps). External calibration lines for Ba and Sr were achieved using Romil(tm) calibration solutions.

We then measured $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the carbonate (CO₃) component of the tooth enamel, following another established procedure (e.g., Balasse et al. 2002; Bentley et al. 2005; Koch et al. 1997) under which the enamel samples were coarsely ground with an agate mortar and pestle before soaking for four hours in 5 percent acetic acid to remove postburial carbonate contamination. The samples were then analyzed via a Thermo Electron MAT253 mass spectrometer with "Gas Bench" extraction unit in the Durham University Department of Earth Sciences. Repeated analyses of the NBS 19 standard ($n = 16$) and also an internal standard (DCS01, $n = 7$) yielded a precision of .12‰ (1 s.d.) for $\delta^{18}\text{O}$.

Results

Overall, the Ba/Sr and $\delta^{13}\text{C}$ in all Teouma samples (Table 2) were within the range of generally marine-

based diets (cf. Table 1). In terms of $^{87}\text{Sr}/^{86}\text{Sr}$, a majority group of 13 individuals yielded intermediate ratios between basement basalt values of Efate (.704) and seawater/coral reef limestone (.709), which is consistent with Sr derived from a mixture of these sources. Alluvial deposits of the Teouma valley are primarily volcanically derived sediments, whereas the terrace of the site is constructed on old limestone that is covered by volcanic airfall tephra. Soils evolved from the terrace should reflect a mixture of Sr derived from marine limestone and relatively unradiogenic Sr from the ash component. Hence, the Sr isotopic composition of the majority of individuals is probably a manifestation of agricultural subsistence, as suggested by microfossil analysis in Lapita contexts elsewhere in Vanuatu (Horrocks and Bedford 2005). The $\delta^{18}\text{O}_{\text{SMOW}}$ values from these 13 individuals cluster between 23.1‰ and 25.0‰ (Figure 4a), which, given their apparently local Sr signatures, we take to represent the local $\delta^{18}\text{O}$ range, quite possibly reflective of drinking water from the local spring-fed stream.

Four Immigrants

Four individuals (TEO 3, 10E, 15, and 18), including the man (TEO 10E) with three skulls on his chest, yielded a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (.7087–.7090) that is entirely distinct ($p < .0001$) from the remaining 13 ($.7074 \pm .0003$). It is highly unlikely that any postburial contamination would be responsible for the isotopic distinctiveness of these four because (a) tooth enamel is highly resistant to postburial contamination, (b) the recovered teeth were exceptionally well-preserved, (c) the burials were in separate locations, and (d) the $^{87}\text{Sr}/^{86}\text{Sr}$ value in TEO 10E is significantly ($p < .05$) different from the three skulls placed on him in the same burial ($.7073 \pm .0004$).

Without any other data, the near-seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among the four could be interpreted as reflecting seafood diets. However, since their mean Ba/Sr ratio is significantly ($p < .001$) higher, seafood was relatively *less* important in their diet than for the local majority. Their mean $\delta^{18}\text{C}$ values are also higher ($p < .03$, excluding outlier TEO 18), i.e., more terrestrial, such that they stand out on a plot of Ba/Sr vs. $\delta^{18}\text{C}$ (Figure 4b). In considering possible coastal terrestrial diets, these individuals' higher Ba/Sr ratios tend to rule out plants grown on reef limestones, including those on Efate itself,

because reef corals, derived from seawater, are very high in Sr but have almost no Ba. The basaltic lavas of Vanuatu are relatively rich in barium (Ba/Sr ~ .5) by comparison, but the near-seawater $^{87}\text{Sr}/^{86}\text{Sr}$ in these four individuals could come from any plants enriched in seawater Sr sources, such as seaweed, or plants nourished by seaspray and/or ocean-derived precipitation. Seawater-derived rain can be a significant source of Sr on highly weathered basaltic islands (Chadwick et al. 1999; Toulkeridis et al. 1998), and the near marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could, in principal, have come from an island area where rain is a principal source of Sr in the soils.

Further indicating that these four individuals migrated from elsewhere is their $\delta^{18}\text{O}$ values (26–27‰), which are a full 2‰ heavier than the majority (23–25‰). This significant ($p < .00001$) difference can be seen in Figure 4a, where the group stand out clearly. The simplest explanation is that these four came from a place where the drinking water was derived from rainfall near sea level, which should be isotopically heavier than the local spring-fed stream at Teouma. As discussed above, it is unlikely that altitude or rain-shadow effects on Efate itself can account for a difference as large as 2‰, suggesting the heavier $\delta^{18}\text{O}$ derives from another island. Averaged variations in mean annual $\delta^{18}\text{O}$ are less than 2‰ in precipitation across the Western Pacific (Bowen and Wilkinson 2002), and we can expect this basic pattern of the Pacific Trade Wind belt also applies 3,000 years ago. Hence, like the $^{87}\text{Sr}/^{86}\text{Sr}$ values, the $\delta^{18}\text{O}$ results indicate that the four outlier individuals drank their water from a different, presumably coastal location during childhood, with potentially very distant origins not ruled out.

Incorporating burial treatment adds a social dimension to these patterns. The five burials in a supine position, with the head to the south (TEO 10E, 3, 8, 15, and 16) have significantly higher mean Ba/Sr than the rest of the sample ($p < .04$, two-tailed t-test, assuming unequal variances), and generally higher $\delta^{13}\text{C}$ values as well. All except TEO 16 stand out clearly in Figure 4b. This has revealing social implications, because three of these south-pointing, supine burials were among the probable immigrants. The fourth probable immigrant (TEO 18), with neither south-oriented burial nor high Ba/Sr, had the highest $\delta^{13}\text{C}$ of the study

Figure 4. (a) Ba/Sr vs. $\delta^{13}\text{C}_{\text{PDB}}$ and (b) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}_{\text{SMOW}}$ in Teouma human enamel samples, showing burial numbers. Circles: females; triangles: males; filled symbols: burial in supine position with head to south. Typical analytical uncertainties: $\pm .0004$ for Ba/Sr, $\pm .00001$ for $^{87}\text{Sr}/^{86}\text{Sr}$, $\pm .1$ for $\delta^{18}\text{O}$, and $\pm .1$ for $\delta^{13}\text{C}$.

(Figure 4b), suggesting some variation in social identity and diet among these immigrants, whose similar $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values (Figure 4a) nonetheless appear to reflect a single origin.

Determining where the outlier individuals came from is our new objective. While isotope sampling on Efate and other islands will enhance the comparative context, this alone is unlikely to resolve the issue because we are searching for a coastal ori-

gin, and many low-latitude coastal locations will have very similar $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ signatures. Most instructive at this point will be new kinds of independent evidence, including the basic archaeology, isotopic analyses of associated artifacts and faunal remains, and genetic assessments from skeletal biology. While nearby origins are possible, we can also consider very distant ones, since the people of the Lapita culture were clearly tech-

nologically capable of long-distance voyaging for material exchange (Bellwood and Koon 1989; Dickinson 2006; Dickinson and Shutler 2000).

Conclusions

Our results show significant variability and correlated patterns in Lapita mobility, social identity, and diet. Among 17 individuals, four outliers formed a distinct cluster of $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values, consistent with a nonlocal, potentially distant, coastal location.

Although difficult to narrow down where they were from, these probable immigrants were socially different. One man was buried with three skulls on his chest. Their diets were more terrestrial on average. Three were buried in a supine burial position, with head to the south—a treatment that correlated strongly with higher Ba/Sr and $\delta^{13}\text{C}$. This contrasts with the majority of locally raised individuals, with more marine diets and wider variety of burial orientations.

One possible interpretation is that the four immigrants of both sexes were among the first generation of settlers to Vanuatu, as suggested by their more terrestrial diets and three of them being in distinctive, south-oriented burials. Two of the locally raised individuals were buried in the same position—could they be the first descendants of the colonizing group?

If they were not the very first colonists, then these migrants may instead reflect voyaging between communities for marriage, economic or political purposes that sustained these demographically small, potentially unstable communities (Pawley 1981:294–295; Summerhayes 2003:143). With evidence for obsidian from the Bismarck Archipelago found in Lapita sites in the Southeast Solomon Islands, Vanuatu, New Caledonia and even Fiji (Best 1987; Galipaud and Swete-Kelly 2007; Sand and Sheppard 2000), the accompanying social networks may have linked the islands back to an ancestral “homeland” some 2000 km away (e.g., Green 1987; Kirch 2000). This is also suggested by rare finds of long-distance movement of decorated Lapita pots (Dickinson 2006). Perhaps the fourth probable immigrant (TEO 18)—apparently from the same general location but with a different diet and burial treatment—arrived later from the “homeland” of the other three?

As regards the majority of *local* residents, all with similar dietary signatures but a variety of burial orientations, their isotope signatures, midway between that of the local island arc basalt and seawater, could reflect horticulture on the local soils of mixed basaltic and reef limestone sediments. Although the enamel data reflect only childhood, it does not appear that the lifestyle for most members of this particular community was one “in which people moved regularly throughout their lives” as Gosden (1992:25) hypothesized for Lapita. In any case, the majority spent their childhood near Teouma and were ultimately buried at Teouma, their apparent home within the expanding and changeable Lapita universe.

Acknowledgments. The Teouma Archaeological Project is a joint initiative of the Vanuatu National Museum and The Australian National University (ANU), directed by Matthew Spriggs and Stuart Bedford of ANU and Ralph Regenvanu, Chair of the Vanuatu National Cultural Council. Funding of the project in 2004 and 2005 was provided by the Pacific Biological Foundation, The Royal Society of New Zealand (Marsden Fast-start) and the Department of Archaeology and Natural History and School of Archaeology and Anthropology at the ANU. The laboratory research for this study was funded by the Royal Society of New Zealand (Marsden Fast-start) and a University of Otago Research Grant. The support of the leaseholder Robert Monvoisin and family is acknowledged, as is the support and assistance of the traditional landowners of Eratap Village. For providing access to a clean lab and TIMS for the strontium isotope analyses, we thank Rex Taylor, Matthew Cooper, and especially Tina Hayes of National Oceanography Centre, Southampton.

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Received May 25, 2006; Accepted March 26, 2007.