Shifting Gender Relations at Khok Phanom Di, Thailand

Isotopic Evidence from the Skeletons

R. Alexander Bentley, **Nancy Tayles**, **Charles Higham**, **Colin Macpherson**, and **Tim C. Atkinson**

Department of Anthropology, Durham University, 43 Old Elvet, Durham DH1 3HN, UK (r.a.bentley@durham.ac.uk)/ Department of Anatomy and Structural Biology, University of Otago, P.O. Box 913, Dunedin, New Zealand (nancy .tayles@anatomy.otago.ac.nz/Anthropology Department, University of Otago, P.O. Box 56, Dunedin, New Zealand (charles.higham@stonebow.otago.ac.nz)/Department of Earth Sciences, Durham University, Science Labs, Durham DH1, UK 3LE (colin.macpherson@durham.ac.uk)/Department of Earth Sciences, University College London, Gower Street, London WCIE 6BT, UK (t.atkinson@ucl.ac.uk). 31 X 06

The values for isotopes of strontium, carbon, and oxygen in human tooth enamel from the prehistoric site of Khok Phanom Di (ca. 2100–1500 BC) in Thailand shed light on human mobility and marital residence during a crucial period of subsistence change. Khok Phanom Di was a sedentary coastal community that apparently relied on hunting, gathering, and fishing in the midst of a transition to rice agriculture in the interior. The results of the isotope analyses indicate female immigration and then a marked shift to local strontium isotope signatures among females accompanied by a clear increase in the prestige of female burials. A possible explanation is a shift in the pattern of exogamy with a concomitant change in gender relations. Observation of a very similar transition at Ban Chiang, in northeastern Thailand, suggests the possibility of a regionwide social transition. In the case of Khok Phanom Di, the increasing role of females in producing high-quality ceramic vessels may have contributed to the change.

In contrast to the rapid and complete spread of agriculture into central Europe about 7,500 years ago in only a century or two, hunting and gathering persisted in parts of prehistoric Southeast Asia for many centuries after agriculture arrived about 4,000 years ago (Bellwood 2005). In fact, hunter-gatherer populations have persisted in parts of Southeast Asia until the present, including the "People of the Yellow Leaves" or Phi Tong Luang in northern Thailand (Pookajorn and Staff 1992). There is every reason to believe that farmers would have continued to hunt and gather alongside their cultivation (Morrison 2006). Rural people in Thailand still hunt and gather as much as they can where the wildlife (small animals, snakes, insects, plants) has survived predation, and foraging continues to contribute to the diet.

 0011-3204/2007/4802-0006$10.00

In the case of Southeast Asia, there is still much to be learned about the nature of the prehistoric intensification of farming during and after the third millennium BC. A major question concerns *who* was involved—that is, to what degree agriculture spread with the migration of farmers from southern China as opposed to being gradually adopted by indigenous hunter-gatherers. Another question is, given some degree of farmer colonization, how much intermarriage there was between migrant farmers and native hunter-gatherers. The answers undoubtedly varied from one region to another.

Other questions center around *how* it happened and what the consequences were—for example, whether individual specializations such as cultivators, livestock herders, fisher folk, and/or hunter-gatherers emerged. These questions are about social changes as much as they are about environmental adaptations. In small-scale societies, individual decisions about subsistence activity are never far from the bonds of kinship, and in almost all prehistoric settings we can expect strong relationships between prehistoric subsistence, specialized occupations, and kinship systems. For example, the spread of pastoralism into sub-Saharan Africa has been shown to have caused a regionwide shift from matriliny to patriliny, probably because male control of livestock made matriliny unsustainable (Holden and Mace 2003). In Island Southeast Asia and Melanesia, matrilineal kinship and matrilocality have been more common in the past, especially among coastal groups and hunter-gatherers, possibly because the absence of men on fishing or hunting expeditions leaves the women to manage the interests of the kin group (Hage and Marck 2003). In fact, since gene distributions suggest a prehistory of matrilocality in parts of Thailand (Oota et al. 2001), as opposed to prehistoric patrilocality in Europe (Bentley et al. 2002; Seielstad, Minch, and Cavalli-Sforza 1998), the comparatively long persistence of hunting-gathering in Thailand leads to an interesting question: Did matrilocal residence correspond to the prehistoric intensification of agriculture? Isotopic evidence from Ban Chiang, in northeastern Thailand, suggests a possible transition to matrilocality during the second millennium BC (Bentley et al. 2005). Perhaps the prolonged transition to agriculture in Thailand is associated with a matrilocal marriage custom that existed during the same time period. With anthropological reasons to suggest that forager societies are less virilocal (Fox 1983; Hage and Marck 2003; Marlowe 2004) and that the reckoning of descent can shift in response to changes in subsistence (Holden and Mace 2003, 2005), we propose to characterize human mobility and residence at Khok Phanom Di during this crucial prehistoric period.

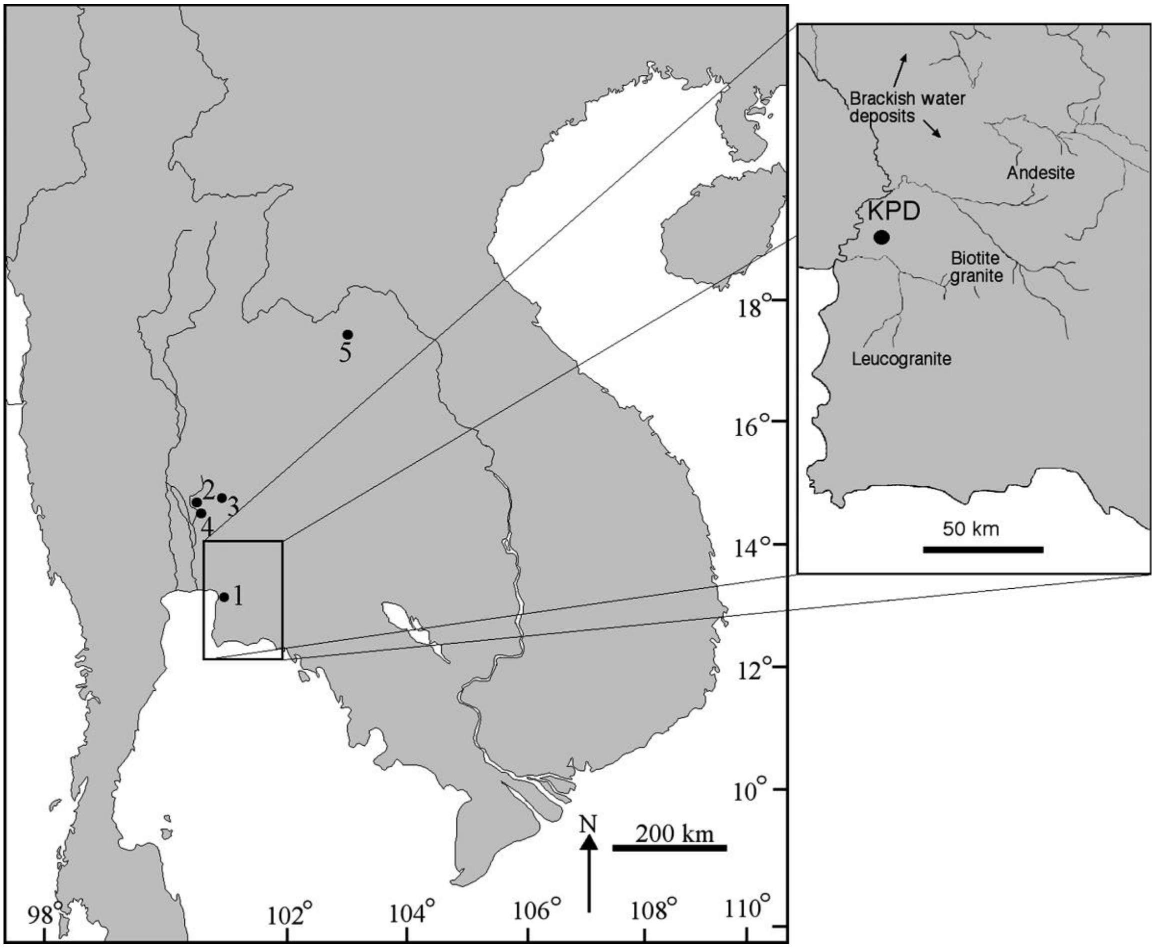

Figure 1. Geographic setting, showing sites mentioned in text: *1*, Khok Phanom Di; *2*, Non Pa Wai; *3*, Khok Charoen; *4*, Ban Tha Kae; *5*, Ban Chiang. *Inset*, area of Khok Phanom Di, showing probable sources of stone artifacts.

Khok Phanom Di

In this study, our objective was to acquire direct evidence regarding human mobility during the period when agriculture was being adopted from the prehistoric individuals involved by measuring isotopes of strontium, carbon, and oxygen in the tooth enamel of human skeletons from the archaeological community of Khok Phanom Di (ca. 2100–1500 BC). The site (Higham and Thosarat 1994, 2004), which lies on a mound in the lower valley of the Bang Pakong, was located adjacent to a mangrove-fringed shore of a major estuary (fig. 1). Over the period of occupation, which lasted for at least half a millennium, the environment underwent a series of changes. One of these, pinpointed to a brief period during the third and fourth of seven mortuary phases, witnessed a fall in sea level and the establishment of freshwater conditions in the vicinity of the settlement. A reversion to saline conditions deleterious to rice cultivation ensued during the final three mortuary phases.

Although domesticated rice is present from the earliest levels at Khok Phanom Di, it is never found in great quantities, and it is still uncertain whether rice was cultivated locally or imported from surrounding agricultural communities (Thompson 1996). The few rice-tempered potsherds from the earliest contexts were all exotic to the site (Vincent 2004). In fact, the diet of the occupants of the site during mortuary phases 1, 2, and 3A centred on gathered marine and estuarine resources, particularly fish, shellfish, and crabs (table 1). The biological remains from these three phases are dominated by the marine bivalve *Anadara granosa*, the marine and estuarine fish *Lates calcarifer* and *Plotosus canius*, and the mangrove crab *Scylla serrata* (Cassaidy 1991; Kijngam 1991).

With mortuary phases 3B and 4, however, there is un-

Table 1. The Mortuary Sequence at Khok Phanom Di

Mortuary Phase	Date (cal BC)	Number of Burials	Diet	Environmental Conditions
1	1900–1850	6	Marine fish, shellfish, crabs	Estuarine-coastal mangrove
2	1850–1800	55	Marine fish, shellfish, crabs	Estuarine-coastal mangrove
3A	1800–1750	23	Marine fish, shellfish, crabs	Estuarine-coastal mangrove
3B	1750–1700	20	Increasing freshwater fish, rice	Freshwater ponds, lakes
4	1700–1650	29	Increasing freshwater fish, rice	Freshwater ponds, lakes
5	1650–1600	4	Marine	Estuarine-coastal mangrove
6	1600–1500	12	Marine	Estuarine-coastal mangrove
7	ca.1500	5	Marine	Estuarine-coastal mangrove

doubted evidence for the consumption of cultivated rice in the form of rice husk remains in human faeces and stomach contents. At this juncture, the relative frequency of freshwater indicators increases at the expense of mangrove and marine species. There is no evidence for the domestication of any animal other than the dog during the course of the seven mortuary phases. Dog remains are also so few that even if consumed they would have contributed a minute part of the human diet. Other mammals found during the currency of the mortuary phases include three species of deer, bovids, monkeys, and pigs, but they too were always rare throughout the mortuary sequence. This contrasts with inland sites, such as Ban Chiang in northeastern Thailand (Pietrusewsky and Douglas 2002), where initial settlement witnessed rice cultivation and the presence of domestic cattle, pigs, and dogs. As in all sites from the Neolithic period to the present, however, hunting, gathering, and fishing continued unabated (Higham 2002).

The 154 graves found at the site fall into seven successive mortuary phases, each distinguished not only stratigraphically but also by changes in ritual and the type and quantity of offerings (Higham and Thosarat 2004). Six burials represent the first phase (MP 1). They were scattered across the site and interred at a time when marine shell middens were accumulating. Numerous hearths were encountered, while bone awls and clay net weights were added to the artefact assemblage. Changes in ceramics compared with those found in the initial occupation layers at the base of the site have been noted by Vincent (2004), changes that might reflect settlement by a new group of people.

There is an increase in fishhooks and net weights in MP 2, stressing the importance of fishing to this community. It was during this period that the first one or two dog bones were found. There is no discernible difference in grave goods placed with men and women in the MP 2 burials, which included red ochre, intricately decorated pottery vessels, shell beads, stone adzes, cowrie shells, and animal teeth.

An increase in freshwater shellfish species and a corresponding decrease in intertidal species indicates a transition to a non-estuarine environment during late MP 3 (3B) and MP 4. During MP 3B there is evidence suggestive of an influx of immigrants—new ceramic decorations and different sources of clay and temper, possibly introduced by immigrant women with new potting traditions (Vincent 2004).

A series of changes in mortuary behaviour took place with MP 4. Burials were now more evenly spaced, and men and women were distinguished by different sets of grave offerings. Men were interred with large turtle-carapace ornaments, while women were associated with the anvils used in the forming of ceramic vessels. Rice was cultivated locally during MP 3B–MP 4, seen not only in the presence of shell reaping knives and granite hoes but also in the remains of rice in stomach contents and human faeces. Compared with previous phases, infant mortality was lower, and men had weaker musculature (Tayles 1999). As conditions reverted back to a coastal mangrove swamp during MP 5, status differences became more pronounced, particularly in the most prominent burial from Khok Phanom Di (B15), dubbed the "Princess," who was interred with over 120,000 beads, an anvil, burnishing stones, clay preforms, and pottery with exotic trace-element composition (Vincent 2004). An infant interred adjacent to this rich woman was accorded precisely the same ritual in death, including a miniature clay anvil and clay preforms over the body. Social conditions appear to have become more complex with the return to marine fishing and gathering during this phase, as exotic ivory and shale appeared and females were buried with specialist potting equipment. Mortuary practices were further elaborated during MP 6, with substantial mortuary structures, one of which contained three distinctively rich burials: a woman in her mid-twenties with bracelets and 1,600 thin shell beads (B19), a woman over 40 with almost 10,000 shell disc beads (B18), and, on top of her, a child with over 17,000 beads (B6).

Methods

In order to characterize the variation in human geographic origins and diets, we analyzed isotopes of strontium, carbon, and oxygen in archaeological tooth enamel sampled from the Khok Phanom Di individuals.

Strontium Isotopes

Strontium isotope signatures ($^{87}Sr/^{86}Sr$) are conveyed, without measurably fractionating, from eroded rocks through soils into the food chain and thus serve as geologic/geographic signatures in the mineral of mammalian tooth enamel (e.g., Ericson 1985; Bentley 2006). The strontium isotope signature in tooth enamel derives from the biologically available strontium of the region, which at least partly reflects the geologic material where the diet was obtained during childhood (when the enamel was forming). For settled communities, a parsimonious interpretation of a "non-local" $^{87}Sr/^{86}Sr$ ratio in tooth enamel is that the person was an immigrant, but often another possibility is that the person spent substantial childhood time elsewhere. Also, isotopic "locals" may actually have migrated between geochemical provinces with similar $^{87}Sr/^{86}Sr$ ratios, such as coastal areas.

Geology provides a general basis for what we expect the biologically available $^{87}Sr/^{86}Sr$ to be in different areas. Khok Phanom Di is located on the lower Chao Phraya Plain, which is a fault-bounded basin that formed during the Plio-Pleistocene and has since filled with almost 2,000 m of Quaternary sediments (Sinsakul 2000). These sediments reflect both the deposits of the Chao Phraya River and its tributaries and 15 m of tide-dominated delta deposits of soft marine clay in the area of modern Bangkok (Aitken 2004; Sinsakul 2000). Given also its coastal position, we expect the local strontium isotope signature at the site to be dominated by marine sources, since sea spray or precipitation can be major strontium sources in environments that are more extremely weathered and coastal (e.g., Chadwick et al. 1999; Whipkey et al. 2000). Because of the long residence time of strontium in the oceans, $^{87}Sr/^{86}Sr$ in sea water is essentially a worldwide constant of 0.7092, which applies throughout the Holocene (McArthur, Howarth, and Bailey 2001), with very slight deviations ($<$ 0.0001) associated with local inputs of discharging rivers (Lavelle and Armstrong 1993). Therefore we expect the biologically available $^{87}Sr/^{86}Sr$ at the site to be within about $\pm$ 0.0001 of the sea-water value of 0.7092 for residents eating seafood and possibly even for those eating foods raised on local land. Although this means that immigrants from other maritime communities may be indistinguishable from locals by $^{87}Sr/^{86}Sr$ alone, we gain added resolution by measuring carbon and oxygen isotopes in the same samples. Certainly also, values significantly different from 0.7092 can be easily identified as non-local. In particular, we expect much higher $^{87}Sr/^{86}Sr$ ratios from the granitoid belts distributed throughout Thailand (Charusiri et al. 1993), including areas within 60–100 km southeast of Khok Phanom Di (fig. 1), with typical strontium concentrations in these granites on the order of 50–200 ppm (Wu and Ishihara 1994). These north–south-trending granite belts generally originated during the Late Triassic to early Jurassic (220—180 million years ago) from partial melting of crustal rocks, and the isotopic data available indicate that they would be a source of much higher $^{87}Sr/^{86}Sr$ ratios (Charusiri et al. 1993; Beckinsale et al. 1979). The Khao Daen granites, for example, which outcrop near the western coast of Thailand, have whole rock $^{87}Sr/^{86}Sr$ ratios ranging between 0.749 and 0.820, while the Hub Kapong Triassic granite complex, southwest of Khok Phanom Di in the northern Thai Peninsula, has whole-rock $^{87}Sr/^{86}Sr$ ratios of 0.775–0.789 (Beckinsale et al. 1979). Furthermore, these uplands were the likely sources for stone tools such as adzes and burnishing stones at Khok Phanom Di and may have been traded in by communities occupying these areas (Higham and Thosarat 1994, 96–99).

Given the local variability in soils, rocks, and plants (e.g., Sillen et al. 1998; Capo, Stewart, and Chadwick 1998), the best way to "map" the prehistoric, biologically available $^{87}Sr/^{86}Sr$ ratios is to sample it directly in the tooth enamel of local animals from archaeological sites around the study area (Bentley, Price, and Stephan 2004). Local animals do a wonderful job of averaging the $^{87}Sr/^{86}Sr$ in their feeding area (Burton, Price, and Middleton 1999). As in southern Germany (Bentley and Knipper 2005), regional analysis is a long-term endeavour the expense of which is warranted by its value in explaining the ongoing isotopic results from human and domestic animal skeletons. For this region of Thailand, mapping of the biologically available $^{87}Sr/^{86}Sr$ signatures is a work in progress (cf. Bentley et al. 2005).

Carbon Isotopes

Carbon isotopes ^{12}C and ^{13}C fractionate during primary production of organic matter in such a way that C_3 plants (e.g., rice) have $\delta^{13}C$ (relative to the Pee Dee Belemnite [PDB] carbonate standard) values between -23 and $-34‰$ (O'Leary 1988). Fortuitously, King (2006, table 6.2) recently measured a significant number ($n = 34$) of samples of modern rice (both wild and domestic) from northeastern Thailand whose average $\delta^{13}C$ we calculate to be -24.8 ± 0.6 (including King's correction of 1.5‰ for the fossil-fuel effect). For marine foods at Khok Phanom Di, we can offer an approximate estimate of $-14.0‰$ based on analyses from the Marianas Islands by Ambrose et al. (1997).

For reasons of sample availability, we measured $\delta^{13}C$ in tooth enamel (rather than bone collagen), which is enriched in humans (non-ruminant species) by about 9.4‰ relative to the whole diet (Ambrose and Norr 1993; Koch, Fogel, and Tuross 1994; Tieszen and Fagre 1993; Ambrose et al. 1997). We thus expect that $\delta^{13}C$ in tooth-enamel carbonate should be about $-15.4‰$ ($-24.8‰ + 9.4‰$) for a pure C_3 diet (rice) and about $-4.6‰$ ($-14‰ + 9.4‰$) for a pure marine diet (Ambrose et al. 1997).

Using these end-members for a linear mixing model, we can use $\delta^{13}C$ to estimate percentages of marine foods in the diet, but, considering the uncertainties regarding $\delta^{13}C$ in coastal food webs (Schoeninger and DeNiro 1984) and in apatite (e.g., Prowse et al. 2004), we treat these estimates only as approximations. Given similar levels of temperature, humidity, and insolation, all of which have secondary effects on $\delta^{13}C$ in plants (Van Klinken, van der Plicht, and Hedges 1994; Heaton 1999), the important possible causes of $\delta^{13}C$ variations include (*a*) consumption of marine resources, which are generally several per mil richer in ^{13}C than terrestrial C_3 plant foods, (*b*) altitude, with high-altitude plants (above 1,000 m, adapted to lower partial pressure of CO_2) being enriched in ^{13}C by a few per mil (Körner, Farquhar, and Wong 1991), (*c*) forest density, with plants growing beneath a dense forest canopy having $\delta^{13}C$ values several per mil more negative than similar plants in cleared areas (Heaton 1999), and (*d*) meat consumption, with $\delta^{13}C$ increasing by about one per mil per trophic level (DeNiro and Epstein 1978; Post 2002).

Oxygen Isotopes

Oxygen isotope compositions ($\delta^{18}O$, relative to standard mean ocean water [SMOW]) in the environment depend upon the fractionation of ^{18}O versus ^{16}O during evaporation, condensation, and precipitation in the hydrologic cycle, with ^{18}O preferentially retained in the liquid phase. Geographic origins are reflected in enamel $\delta^{18}O$ values measured in species, including humans, that take in much of their oxygen through ingested water (e.g., Balasse et al. 2002; Budd et al. 2004; D'Angela and Longinelli 1990; Kohn 1996). Determined largely by temperature, the mean annual $\delta^{18}O$ in precipitation depends on latitude and altitude (Bowen and Wilkinson 2002) but also on topographic relief, distance from large bodies of water, and relative humidity. Because of the time-averaging effect of enamel formation, $\delta^{18}O$ variations in mammal tooth enamel are less than the seasonal $\delta^{18}O$ variations in precipitation (e.g., Balasse et al. 2002; Passey et al. 2005). In humans from settled communities, whose water supply is more consistent, the variations are smaller, with tooth enamel $\delta^{18}O$ potentially varying as little as 1‰ among prehistoric people from one place (Budd et al. 2004). Unfortunately, in this tropical region of the world, there does not appear to be much systematic geographic variation of $\delta^{18}O$ in prehistoric human enamel (cf. Krigbaum 2003; Bentley et al. 2005). Nevertheless, in theory we expect that ^{18}O may be depleted in enamel from people who lived inland; $\delta^{18}O$ tends to decrease with distance from the sea, as ^{18}O is preferentially condensed in clouds carrying rain from the sea.

Procedures

In order to characterize patterns of human mobility at Khok Phanom Di, we measured strontium, carbon, and oxygen isotopes in tooth enamel from selected human skeletons, with sampling preference for the premolar (crown complete between ages 3 and 6 years [Hillson 1997, 123]) second molar (ages 7–8), or third molar (ages 12–16) wherever possible. Many studies indicate that buried prehistoric bone tends to be contaminated by groundwater strontium (Bentley, Price and Stephan 2004; Horn and Müller-Sohnius 1999), so while human bone may help identify the local $^{87}Sr/^{86}Sr$ ratio at the site, we focus our analyses on the tooth enamel, which robustly resists isotopic contamination (e.g., Chiaradia, Gallay, and Todt 2003; Hoppe, Koch, and Furutani 2003; Horn, Hölzl, and Storzer 1994; Koch, Tuross, and Fogel 1997; Trickett et al. 2003; Bentley 2006). The Khok Phanom Di sample includes a tooth fragment each from 30 adult females, 23 adult males, and 19 children.

Using our regular procedure (e.g., Bentley et al. 2004, 2005; Bentley and Knipper 2005), we mechanically cleaned about 5–20 mg of tooth enamel from each individual and removed its dentine with a surgical steel scalpel and then soaked it for eight hours in weak (5%) acetic acid. After the strontium was purified through columns of Sr-spec resin, the $^{87}Sr/^{86}Sr$ was analyzed using a VG-MicroMass Sector 54 thermal ionization mass spectrometer at the Southampton Oceanography Centre. During the time period of the analyses, four measurements of the NBS SRM-987 standard yielded an average $^{87}Sr/^{86}Sr$ ratio of 0.710245 $\pm$ 0.000010 (1 s.d.).

We also measured $\delta^{18}O$ and $\delta^{13}C$ in the carbonate (CO_3) component of the tooth enamel, following a tested procedure (Balasse et al. 2002; Koch, Tuross, and Fogel 1997) that we have used successfully at the Ban Chiang site in Thailand (Bentley et al. 2005). About 5 mg of tooth enamel (sampled from the cervix end whenever possible) was mechanically cleaned of all dentine, powdered and soaked overnight in 5% acetic acid to remove post-burial carbonate contamination, and then analysed via a Kiel III automated cryogenic distillation system interfaced with a ThermoFinnigan Mat 253 gas-source mass spectrometer at the Bloomsbury Environmental Isotope Facility, University College London. Repeated analyses of the NBS 19 standard yielded a precision better than 0.1‰ (1 s.d.) for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$.

Results

The results of strontium, carbon, and oxygen isotope analyses of human tooth enamel samples are shown in table 2. An estimate of the local $^{87}Sr/^{86}Sr$ comes from tooth samples from 17 of the children,[1] which yielded an average $^{87}Sr/^{86}Sr$ of 0.70933 $\pm$ 0.00005 over the seven mortuary phases. The remarkably low variance in these values and their closeness to the expected sea-water value (0.7092) indicates that these children were raised locally. To double-check the local range (see Bentley, Price, and Stephan 2004; Bentley and Knipper 2005), we analysed enamel samples from seven pigs from Khok Phanom Di and found that they yielded a mean $^{87}Sr/^{86}Sr$ of 0.70924 $\pm$ 0.00005 (table 3), whereas a single rat tooth had a value of 0.70926. The mean pig $^{87}Sr/^{86}Sr$ ratio was within 0.0001 of the average in the human children's teeth, rein-

1. Two outliers were not included. A deciduous tooth from Burial 96, a four-year old child, yielded a vastly lower $^{87}Sr/^{86}Sr$ value (0.70753) than any other sample and $\delta^{13}C$ unlike any other (-6.1). We view this cautiously, as Burial 96 was heavily disturbed in prehistory. The second outlier is an anomalously low $^{87}Sr/^{86}Sr$ value (0.70914) from Burial 2, a nine-month-old infant from MP 6 that was found crushed and fragmented.

Table 2. Isotope Analyses of Human Tooth Enamel Samples from Khok Phanom Di

Burial #	Lab #	Sex	Phase	Age	Tooth	$\delta^{18}O$ SMOW	$\delta^{13}C$	$^{87}Sr/^{86}Sr$
1	KPD 59	child	7	9	P1	n.d.	n.d.	0.70927 (1)
2	KPD 69	child	6	1	C?	25.5 (1)	−12.7 (1)	0.70914 (1)
4	KPD 06	F	6	25	P2	25.9 (1)	−11.6 (1)	0.70939 (1)
6	KPD 60	child	6	1	P1 d	n.d.	n.d.	0.70929 (1)
8	KPD 29	M	6	Immat.	P1	25.9 (1)	−12.2 (1)	0.70935 (1)
9	KPD 07	M	6	30	P1	25.5 (1)	−11.1 (1)	0.70933 (1)
11	KPD 64	child	6	12	P2	25.3 (1)	−11.8 (1)	0.70931 (1)
12.1	KPD 65	child	7	12	P2	n.d.	n.d.	0.70931 (1)
13	KPD 30	F	6	35	P2	25.6 (1)	−12.0 (1)	0.70925 (1)
14	KPD 70	child	5	1	P1 d	27 (1)	−10.7 (1)	0.70926 (1)
15	KPD 08	F	5	35	P2	26.4 (1)	−12.1 (1)	0.70939 (1)
17	KPD 66	child	4	12	Frags	25.4 (1)	−11.7 (1)	0.70927 (1)
18	KPD 09	F	6	42	P1(?)	24.2 (1)†	−12.5 (1)†	0.70936 (1)
19	KPD 10	F	6	25	M1	25.8 (1)†	−12.1 (1)†	0.70945 (1)
20	KPD 67	child	4	12	P1	26.1 (1)	−12 (1)	0.70937 (1)
21	KPD 61	child	4	8	M2	n.d.	n.d.	0.70941 (1)
23	KPD 31	M	4	30	P1	26.0 (1)	−11.7 (1)	0.70926 (1)
24	KPD 32	M	4	25	P1	25.6 (1)	−11 (1)	0.70948 (1)
25	KPD 33	F	4	19	M3	25.3 (1)	−12.3 (1)	0.70946 (1)
26	KPD 34	F	4	35	P1	26.3 (1)	−11.9 (1)	0.70939 (1)
27	KPD 35	F	4	40	M1	26.1 (1)	−12.7 (1)	0.70932 (1)
29	KPD 36	M	4	27	Frags	26 (1)	−12 (1)	0.70924 (1)
30	KPD 37	M	4	34	Frags	26 (1)	−11.8 (1)	0.70937 (1)
32	KPD 62	child	4	x	P2 d	n.d.	n.d.	0.70928 (1)
33	KPD 71	child	4	3	LI d	26.6 (1)	−11.2 (1)	0.70934 (1)
35	KPD 38	F	4	21	M1	26 (1)	−12.2 (1)	0.70943 (1)
37	KPD 68	child	4	9	LI	26.2 (1)	−11.7 (1)	0.70932 (1)
38	KPD 39	M	4	32	Frags	26.3 (1)	−11.9 (1)	0.70935 (1)
39	KPD 40	F	4	25	P2	n.d.	n.d.	0.70952 (1)§
40	KPD 41	F	4	38	P2	25.7 (1)	−13.8 (1)	0.70938 (1)
42	KPD 42	M	4	32	M1	26 (1)	−13.3 (1)	0.70938 (1)
43	KPD 04	M	5	30	P2	25.2 (1)	−12.1 (1)	0.70942 (1)
44	KPD 12	M	4	18	M2	25.2 (1)	−13.1 (1)	0.70938 (1)
45	KPD 13	F	4	45	P?	25.2 (2)	−13.5 (1)	0.70932 (1)
47	KPD 14	F	4	22	P1	25.3 (1)†	−13.8 (1)†	0.70928 (1)
56	KPD 15	F	3.5	45	P2	25.0 (1)†	−13.7 (1)†	0.70947 (1)
57	KPD 16	M	3	26	P2	25.1 (1)†	−12.8 (1)†	0.70931 (1)
58	KPD 17	F	3.5	35	P1	24.8 (1)†	−11.35 (1)†	0.70917 (1)
60	KPD 43	F	3	19	P1	25.3 (1)	−13.2 (1)	0.70947 (1)
61	KPD 18	F	3	48	M3	25.6 (1)	−13.3 (1)	0.70955 (1)
63	KPD 72	child	3	2	LI d	26.6 (1)	−12.8 (1)	0.70934 (1)
64	KPD 19	F	3.5	21	P2	24.8 (2)	−13.8 (1)	0.70990 (1)
67	KPD 20	M	3	35	M3	24.5 (1)†	−12.4 (1)†	0.70943 (1)
73	KPD 44	F	3	25	M2	25.2 (1)	−11.6 (1)	0.70940 (1)
74	KPD 45	M	3	40	P1	25.2 (1)	−12.2 (1)	0.70948 (1)
76	KPD 46	M	3	34	M2	25.1 (1)	−13.2 (1)	0.70921 (1)
77	KPD 47	F	3	25	M1	25 (1)	−12.2 (1)	0.70934 (1)
79	KPD 48	F	3	47	Frags	25.2 (1)	−12.1 (1)	0.70941 (1)
83	KPD 21	F	3	30	P2	24.3 (1)†	−13.0 (1)†	0.70933 (1)
90	KPD 22	M	3	27	M1	24.5 (1)†	−12.4 (1)†	0.70933 (1)
91	KPD 49	M	2	45	M2	26.2 (1)	−12.5 (1)	0.70926 (1)
92	KPD 23	M	3	18	P2	26.4 (1)	−13 (1)	0.70923 (1)
96	KPD 73	child	2	4	LI d	25.8 (1)	−6.1 (1)	0.70758 (1)
101	KPD 74	child	2	2	LI d	26.3 (1)	−12.6 (1)	0.70937 (1)
102	KPD 50	F	2	35	P2	25.3 (1)	−12.4 (1)	0.70941 (1)§
103	KPD 24	M	3	26	P2	25.2 (1)	−12.9 (1)	0.70939 (1)
107	KPD 51	F	2	40	Frags	26.2 (1)	−12.1 (1)	0.70941 (1)
109	KPD 25	F	2	31	M	25.4 (1)	−11.2 (1)	0.70983 (1)
110	KPD 52	F	2	36	Frags	25.7 (1)	−11.7 (1)	0.70969 (1)
112	KPD 53	F	2	40	P1	25.3 (1)	−12.5 (1)	0.70937 (1)§
113	KPD 54	F	2	46	P2	26 (1)	−12.7 (1)	0.70943 (1)
115	KPD 26	M	2	38	P?	25.5 (1)	−11.9 (1)	0.70945 (1)

Table 2. (*Continued*)

Burial #	Lab #	Sex	Phase	Age	Tooth	δ^{18}O SMOW	δ^{13}C	^{87}Sr/^{86}Sr
120	KPD 55	M	2	21	P1	24.9 (1)	−12 (1)	0.70946 (1)
121	KPD 75	child	2	1	C d	25.7 (1)	−13.2 (1)	0.70939 (1)
122	KPD 56	F	2	52	C	26.5 (1)	−12.1 (1)	0.70962 (1)
123	KPD 76	child	2	2	C d	24.9 (1)	−13.6 (1)	0.70938 (1)
132	KPD 57	M	2	34	M1	26.5 (1)	−13 (1)	0.70923 (1)
145	KPD 63	child	2	8	CI	26.2 (1)	−12 (1)	0.70940 (1)§
147	KPD 27	M	1	19	C	24.8 (1)	−12.9 (1)	0.70921 (1)
150	KPD 77	child	1	3	C d	25.1 (1)	−14.1 (1)	0.70935 (1)
152	KPD 58	M	1	37	P2	25.9 (1)	−13 (1)	0.70921 (1)
154	KPD 28	F	1	25	P2	25.3 (1)	−10.9 (1)	0.70998 (1)

Note: All carbon and oxygen isotope measurements were made at the Bloomsbury Environmental Isotope Facility except nine samples marked (†) that were analysed at Durham University using a Thermo Electron MAT253 mass spectrometer and "Gas Bench" extraction unit. Similarly, all the strontium isotope measurements were done at Southampton Oceanography Centre by thermal ionization mass spectrometer except four samples marked (§), which were analysed on a Thermo Electron Neptune mass spectrometer (9 Faraday detectors; standard reproducibility of 10–30 ppm) at Durham University, courtesy of Geoff Nowell and Graham Pearson. Measurement errors (2σ) corresponding to the last digits of the value are shown in parentheses. Some samples are missing δ^{18}O and δ^{13}C measurements because not enough sample remained after measuring ^{87}Sr/^{86}Sr. The abbreviations for the teeth are CI, central incisor; LI, lateral incisor; C, canine; P1, first premolar; P2, second premolar; M1, first molar; M2, second molar; M3, third molar; Frags, unidentified crown fragments; d, deciduous tooth.

forcing our local range estimate.[2] Using the range within two standard deviations of the mean for children's teeth yields an estimate of a local ^{87}Sr/^{86}Sr range from 0.70924 to 0.70943. We use this as a guide rather than a strict definition. Interestingly, the pigs ranged in δ^{13}C from about −15‰ to −13‰ (table 3), indicating that while two pigs had very little marine food in their diet, as we might have expected, some pigs apparently ate a significant amount ($< 25\%$) of marine-based foods, presumably as scraps from people or perhaps feeding themselves on the shore.

Partially digested domesticated rice remains associated with an adult female (B56) and an adult male (B67) in MP 3 burials provided a special opportunity to test the result from rice eaters. These individuals yielded ^{87}Sr/^{86}Sr ratios (0.70947 and 0.70943) above the sea-water value, suggesting that this terrestrial input may be the reason the mean ^{87}Sr/^{86}Sr for all Khok Phanom Di adults is slightly above the sea-water value: 0.70946 ± 0.00018 for all adult females ($n = 30$) and 0.70934 ± 0.00009 for all adult males ($n = 23$). The δ^{18}O values of the female (25.0‰) and the male (24.5‰) are on the low end of the range, and the comparatively negative δ^{13}C value (−13.7‰) for the female suggests that seafood was only a minor (< 20 %) component of the diet.

Figures 2–4 show the detailed results by chronological mortuary phase. The two adult males from MP 1 (B147, B152) have virtually the same ^{87}Sr/^{86}Sr (0.70921) and δ^{13}C (−13‰) values, so if they were immigrants they probably came from the same place. One of these men (B147) was the tallest person in the sample (Tayles 1999, 338). The MP 1 female (B154) had the highest ^{87}Sr/^{86}Sr ratio (0.70998) in the study, clearly non-local and also quite different from the males. This 25-year-old woman was also one of the tallest females in the group.

For MP 2, we find that the ^{87}Sr/^{86}Sr in three females (B109, B110, B122) is distinctly higher than in the males or the six other MP 2 females (figure 5,*a*). Looking at MP 1 and MP 2 combined, the individuals form a diagonal array in which ^{87}Sr/^{86}Sr and δ^{13}C are positively correlated along what appears to be a continuum with males at one end and females at the other. Since the ^{87}Sr/^{86}Sr ratio in seafood is 0.7092, the source of the higher ^{87}Sr/^{86}Sr ratios must be inland. Curiously, however, the sea-water ^{87}Sr/^{86}Sr ratios correspond to *more negative* δ^{13}C values, which is the opposite of what we would expect with a seafood diet. Seafood should push the δ^{13}C values towards −4.6‰ (pure-seafood end-member) in enamel carbonate. Thus the *positive* correlation in figure 5, *a*, between ^{87}Sr/^{86}Sr and δ^{13}C suggests other possibilities for the ^{13}C enrichment, including altitude, forest clearance, and C_4 plants in the diet. Altitude seems unlikely, since there no areas over 1,000 m in this region, but forest clearance and a small portion of C_4 plants are entirely possible with inland agricultural settlements. Although C_4 millets are not commonly discussed for this period, it is possible that they were consumed in limited quantities (Mudar 1995). An alternative explanation is that, as we move towards the upper right in the diagonal array of figure 5, *a*, the marine portion of the diet includes more higher-trophic-level marine foods, which have less strontium than lower-level marine organisms such as shellfish (Burton and Price 1999). In this setting, a mixing profile could reflect relative dependence on shellfish (marine ^{87}Sr/^{86}Sr, lower δ^{13}C) versus higher-trophic-level marine fauna (less marine-looking ^{87}Sr/^{86}Sr, higher δ^{13}C). However, this explanation still requires an end-member with a ^{87}Sr/^{86}Sr of at least 0.710 or greater, which all the data available indicate must be inland

2. Interestingly, the mean ^{87}Sr/^{86}Sr for the pigs is actually significantly lower than for the children ($p < 0.002$), probably because of the lack of any seafood in the pig diet, as the pigs have a comparatively negative mean δ^{13}C (-13.7 ± 0.8).

Table 3. Strontium Isotopes in Pig Tooth Samples from Khok Phanom Di

Find #	Lab #	Tooth	$\delta^{18}O$ SMOW	$\delta^{13}C$	$^{87}Sr/^{86}Sr$
L8:7	KPDF 01	M2	23.6 (1)	−14.8 (1)	0.70934 (1)
L6:5	KPDF 02	M2	29.1 (1)	−14.3 (1)	0.70923 (1)
L4:3	KPDF 03	M3	24.3 (1)	−13.5 (1)	0.70926 (1)
L4:4	KPDF 04	M1	27.2 (1)	−12.9 (1)	0.70921 (1)
L10:4	KPDF 05	M3	25.4 (1)	−12.8 (1)	0.70921 (1)
L7:SP2	KPDF 06	M2	26.6 (1)	−14.6 (1)	0.70924 (1)
L10:SP17	KPDF 07	M3	25.7 (1)	−13.1 (1)	0.70919 (1)

from Khok Phanom Di. In any case, given the indications of imported rice in MP 1-2, it seems likely that these women (B109, B110, B122, B154) ate inland foods as children and, given their taller statures (Tayles 1999), were probably immigrants to the Khok Phanom Di community.

By early MP 3, the mean $^{87}Sr/^{86}Sr$ for females (0.70942 ± 0.00008) is still higher than for males (0.70935 ± 0.00010) but not significantly so ($p < 0.16$), and there is less variation in $\delta^{13}C$ or $\delta^{18}O$ than in the previous phases. In fact, with the exception of an 18-year-old male (B92) and a child, the early MP 3 individuals cluster on a plot of $\delta^{18}O$ versus $^{87}Sr/^{86}Sr$, suggestive of a localized group (fig. 6, *b*), while the $\delta^{13}C$ values (fig. 5, *b*) between −14‰ and −12‰ would indicate diets of perhaps 10%–30% marine foods.

The three females from MP 3B (the latter half of MP 3) show a wider spread of $^{87}Sr/^{86}Sr$ ratios than females from MP 3A ($p < 0.005$, *F*-test). One of these females (B58) has a near-sea-water value (0.70917), whereas another (B64), in her early twenties, has the second-highest $^{87}Sr/^{86}Sr$ value (0.70990) of our sample. The $\delta^{13}C$ values further suggest that B58 (∼ 40% marine diet) came from a coastal location, whereas B64 (∼ 15% marine diet) came from inland (fig. 5, *b*). Immigration of females would be consistent with the archaeology in that Vincent's (2004) identification of new sources of clay and temper from MP 3B "might mean that people with potting skills, almost certainly women, were entering the community from other settlements which shared the same basic ceramic tradition" (Higham 2002, 65). Identifying the possible origin of these putative immigrants will require considerably more research in the hinterland of Khok Phanom Di. Fieldwork in the Khao Wong Prachan Valley north of Lopburi has led to the recognition of a Neolithic settlement at Non Pa Wai, which is a possible source (Mudar and Vincent 2003), while Ban Tha Kae has yielded Neolithic burials and ceramic vessels resembling those from Khok Phanom Di (Siripanith 1985). Khok Charoen in the Pa Sak Valley (fig. 1) is a Neolithic cemetery that has yielded shell ornaments very similar to those from Khok Phanom Di, indicating a probable trade link (Ho 1984). These sites must rank as the most likely sources for women moving south to coastal centers such as Khok Phanom Di.

A change occurs in MP 4 (fig. 2), where the mean $^{87}Sr/^{86}Sr$ (0.70939 ± 0.00008, $n = 8$) for females is significantly ($p < 0.005$) less variable than for MP 1–MP 3 and statistically indistinguishable from the mean among MP 4 males (0.70936 ± 0.00008, $n = 8$). This abrupt reduction in the variance of $^{87}Sr/^{86}Sr$ among females is accompanied by a reduction in the range of $\delta^{18}O$ for both sexes (fig. 4). At the same time, the $\delta^{13}C$ values from both sexes in MP 4 show a broader range of $\delta^{13}C$ (from −14‰ to −11‰) than in any of the preceding periods (fig. 3). MP 4 carries the first isotopic sign of a possible dietary difference between sexes in that the mean $\delta^{13}C$ may be higher among males ($p < 0.10$, two-tailed *t* test); the lowest three $\delta^{13}C$ values are from females and the highest three $\delta^{13}C$ values are from males. This should be viewed cautiously, however, as the similarity of tooth wear among males and females and the stratigraphic association of hoes and harvesting knives suggest that rice was being cultivated locally by this time (Higham 2002, 72–80). The difference between males and females in $^{87}Sr/^{86}Sr$ and possibly $\delta^{13}C$ again accords with the independent archaeological evidence, particularly new mortuary treatments, in which men were buried with large turtle-carapace ornaments and women were often associated with the clay anvils used to make pottery (Higham 2002, 73).

During MP 5, the $^{87}Sr/^{86}Sr$ ratios for both sexes appear mostly within the local range (fig. 2). Burial 15 (the "Princess") yielded a thoroughly average $^{87}Sr/^{86}Sr$ ratio of 0.70939, which was repeated (0.70942) by a remeasurement of a separate piece of enamel from the same tooth (upper right P_1). Her $\delta^{13}C$ value (−12.1‰) is in the range expected for marine foods, and so while our null hypothesis of local residence remains valid, migration from another coastal community (similar marine $^{87}Sr/^{86}Sr$) cannot be ruled out for her (or, indeed, for any of the burials in MP 5). In any case, the rich burial of a woman, potentially local, suggests a new level of

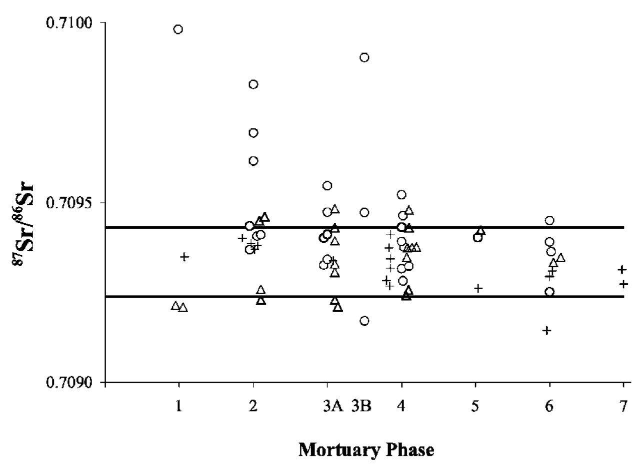

Figure 2. $^{87}Sr/^{86}Sr$ in human enamel from Khok Phanom Di by chronological phase for (*a*) adult females and (*b*) adult males. Horizontal lines indicate the local $^{87}Sr/^{86}Sr$ range, defined as within two standard deviations of the mean value in the children's teeth (0.70924–0.70943). ○, female; △, male; +, child.

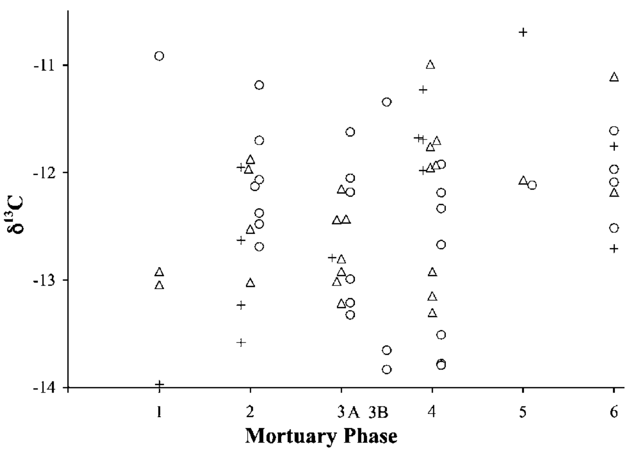

Figure 3. δ^{13}C in human enamel from Khok Phanom Di by chronological phase. ○, female; △, male; +, child.

veneration for at least certain females. Burial 43, a 30-year-old male with over 56,000 beads and a turtle carapace, among other items, also yielded the same $^{87}Sr/^{86}Sr$ (0.70942) and δ^{13}C (−12.1‰) as Burial 15. It appears probable that these rich individuals had the same childhood origins and diets.

As in MP 5, the elaborate burials in MP 6 yielded similar, local $^{87}Sr/^{86}Sr$ ratios (fig. 2). For MP 5–MP 6, the δ^{13}C and δ^{18}O cluster fairly closely, suggestive of local origins (figs. 5, *d*, and 6, *d*). The single δ^{18}O outlier in figure 6,*d*, is from one of the two exceptionally rich burials from MP 6, a 42-year-old woman (B18). The other rich burial, a 25-year-old woman (B19), had isotopic values within the local ranges.

Conclusion

Three significant patterns emerge from the isotope data at Khok Phanom Di:

1. Over all chronological phases, the $^{87}Sr/^{86}Sr$ for males falls within a narrow range (0.70934 ± 0.00009, $n = 23$) that is consistent with artefact evidence for fishing supplemented by some terrestrial foods. Whereas these near-seawater $^{87}Sr/^{86}Sr$ ratios cannot distinguish local men from fishermen from other coastal communities, the spread of δ^{18}O values would allow for a variety of coastal origins or travel during these men's childhoods.

2. During the early phases (MP 1 and MP 2), several adult females appear at the high end of a diagonal array of $^{87}Sr/^{86}Sr$ versus δ^{13}C that, together with their greater stature, strongly suggests that these women migrated from inland to the Khok Phanom Di community.

3. Of the three individuals from MP 3B, two females appear to be immigrants from different locations (one coastal, one inland). It was previously surmised from the presence of exotic pottery decoration and the use of a different clay source that female potters may have immigrated during this phase (Vincent 2004). While we can identify further design motifs with inland parallels in MP 5–7 vessels, these were not associated with a different clay source and hence more likely adopted through exchange and social contact rather than representing a further influx of women potters.

4. In MP 4, the variance in female $^{87}Sr/^{86}Sr$ ratios is significantly reduced, such that the female $^{87}Sr/^{86}Sr$ ratios are restricted within the narrow range that characterizes males. The mean δ^{13}C values suggest that diets might have been subtly different between the sexes ($p = 0.10$), which would not be surprising given the differentiation in burial treatments for males and females that began during this phase (Higham 2002, 72–81).

5. During and after MP 4, the rich female burials (B15, B18, B19) show local $^{87}Sr/^{86}Sr$ ratios. One rich male burial (B43) yielded the same strontium and carbon isotope values as the "Princess" (B15).

In this sequence, the most significant pattern is that certain females from MP 1 to MP 3 exhibit the only substantially non-local strontium isotope signatures, with an abrupt transition to local signatures in MP 4. Since Khok Phanom Di is a 5-ha site and the burials are from a 10 m by 10 m excavation square, one might argue that this is simply a sampling issue—that during MP 4 a certain segment of the Khok Phanom Di community was buried here. However, coincidences of sampling are all but ruled out by (*a*) the spatial contiguity of the burial clusters, enough even to suggest kin relatedness (Higham and Thosarat 1994, 39–49), (*b*) the logical agreement between the isotopic and the archaeological evidence for the change at MP 4, and (*c*) the similar transition observed at Ban Chiang (Bentley et al. 2005). This was a change in society, and we offer three hypotheses for interpreting it:

One hypothesis is that the kinship system in the Khok Phanom Di community was initially patrilocal, as suggested by the female immigration in MP 1-2, but then became matrilocal as MP 4 began, when all female strontium isotope signatures fell tightly into the local range. Unfortunately, the

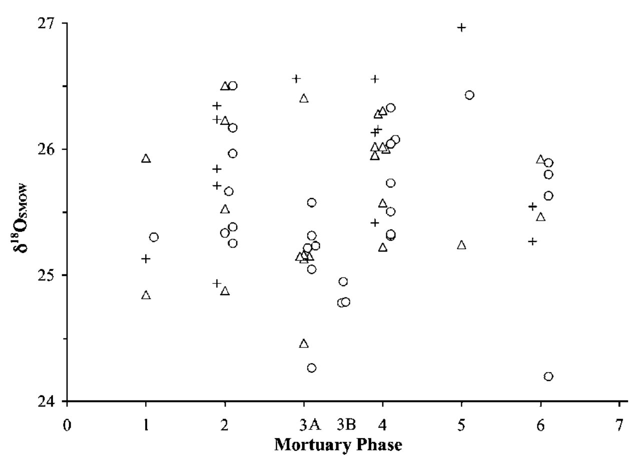

Figure 4. δ^{18}O in human enamel from Khok Phanom Di by chronological phase. ○, female; △, male; +, child.

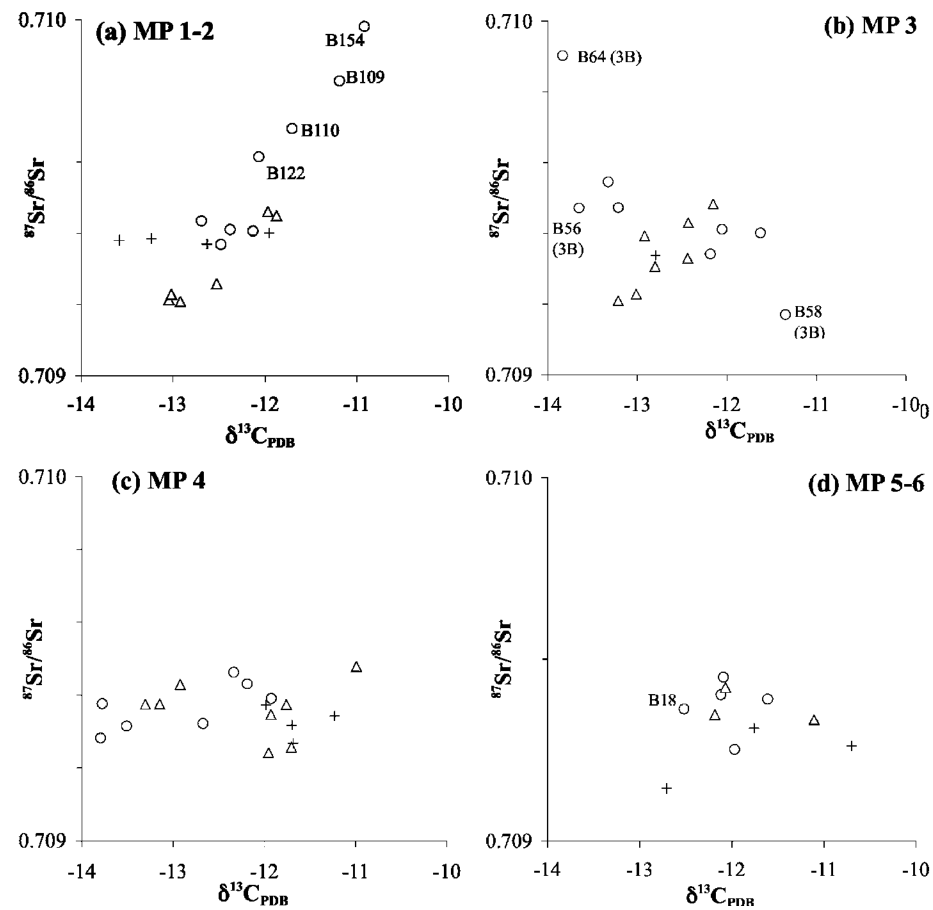

Figure 5. $^{87}Sr/^{86}Sr$ versus $\delta^{13}C_{PDB}$ in human enamel from Khok Phanom Di by chronological phase. ○, female; △, male; +, child.

strontium isotope evidence from males, consistently marine throughout the sequence, cannot confirm or reject this hypothesis, since seafaring males would have had similar strontium values isotope whether local or immigrant. What is compelling, however, is that Higham and Thorsarat (1994, 103–10) have independently made a case for an "increasing matrilocal aspect to the later people at Khok Phanom Di" based on the mortuary evidence for female craft specialists and venerated women in the community.

A second hypothesis is that women were immigrating—possibly for marriage—all along but from inland communities in MP 1–3 and from coastal groups during and after MP 4. This would accord with the interpretation of Higham and Thosarat (1994, 103–13) of increasing economic value of specialist female potters, including the increasing association of clay anvils with women (and some with girls) indicative of the transmission of potting skills from one generation of women to the next. Given increasing indications for maritime trade during and after MP 4, new marriage links may have developed along with new maritime contacts.

The third hypothesis involves the archaeological evidence for an increase in locally grown rice during MP 4, which would imply less mobility for both sexes. This, however, does not easily explain why only females show the transition at MP 4, unless in MP 1–3 females had been eating a lot of foods gathered from inland and males a lot of fish and other marine foods. Although possible, this would require that certain (but not all) MP 1–3 girls were given a special diet as their enamel formed, which would seem contrary to the increased gender differentiation in burial goods from MP 4 onwards.

In considering these hypotheses it should be recognized that the isotopic changes have been observed in human tooth enamel, which forms during childhood. In any case, the fact that the dramatic change in female mobility at MP 4 at Khok Phanom Di is not observed among males suggests an abrupt change in marriage patterns and/or the status and roles of women. During MP 5 and MP 6, the women who were clearly venerated through rich burial also exhibit coastal isotope signatures. Whether these are truly local as opposed to distantly

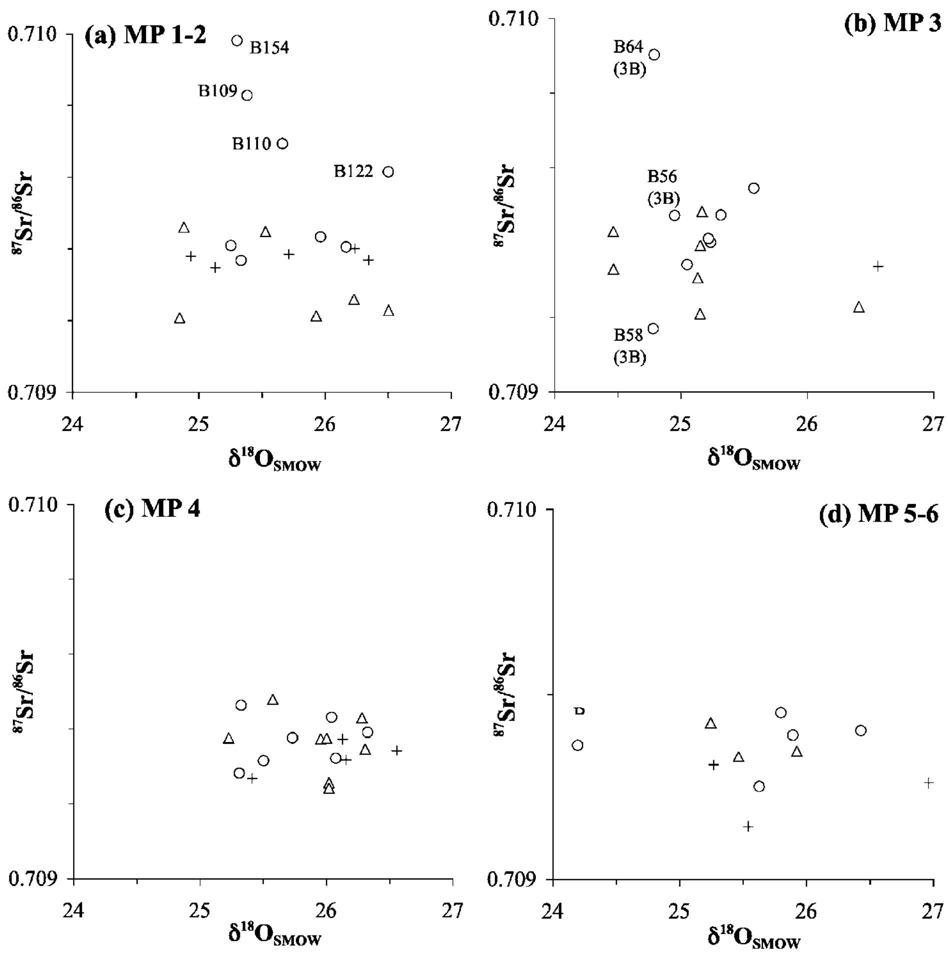

Figure 6. $^{87}Sr/^{86}Sr$ versus $\delta^{18}O_{SMOW}$ in human enamel from Khok Phanom Di by chronological phase. ○, female; △, male; +, child.

coastal signatures remains the subject of further investigation—the increased value of women in this society may have led to more female migration rather than less (*matrilineal* but not *matrilocal*). If Khok Phanom Di was a coastal trading community, women producing exchangeable pottery could have become increasingly wealthy and prestigious, which tends to reinforce the matriline, especially in Melanesian exchange systems (Lepowsky 1983). Ethnographic and linguistic evidence indicates that Proto-Oceanic societies were predominantly matrilineal (Hage and Marck 2003), and many societies, such as the famous Trobrianders, remain matrilineal today (Allen 1984).

In regional context, the change in MP 4 at Khok Phanom Di is strikingly similar to that at Ban Chiang (ca. 2100 BC–AD 200) in northeastern Thailand, where during and after EP V the range of $^{87}Sr/^{86}Sr$ among females is considerably reduced (fig. 7). Bentley et al (2005) have suggested that this change at Ban Chiang reflects a transition to matrilocality, while considering an alternative hypothesis of a sexual division of labour such that males ranged over a wide area while hunting and gathering and females remained closer to the settlement. In any case, it is remarkable to observe, at two distant sites, an abrupt reduction in the variance of strontium isotope signatures among women, whereas the male signatures do not change, remaining within a narrow range at Khok Phanom Di and continuing to be variable at Ban Chiang. The change at Khok Phanom Di is dated to about 1600–1700 BC and that at Ban Chiang to about a millennium later. The reasons in each case must be sought in the context of site-specific evidence. At Khok Phanom Di, the importance of women who manufactured ceramic vessels in a site that was clearly a major pottery-making center is cited as one possible contributory factor.

Regarding the emergence of agriculture in Neolithic Southeast Asia, the dramatic nature of the change in female mobility at Khok Phanom Di could reflect the influence of another culture. The change at MP 4 coincides with increasing evidence for local rice cultivation, and if the two are causally

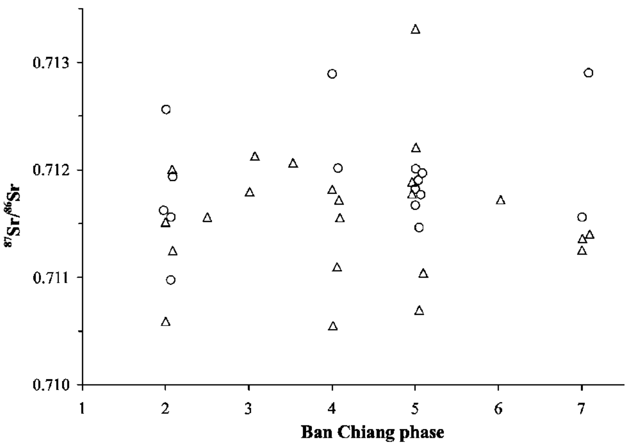

Figure 7. $^{87}Sr/^{86}Sr$ in human enamel from Ban Chiang by chronological phase. ○, female; △, male. Adapted from Bentley et al. (2005, fig. 2).

linked we still have the age-old question of whether the change was prompted by the movement of people or the spread of ideas. On one hand, the phase immediately preceding—MP 3B—yields hints of an influx of immigrant women, who may have introduced new agricultural (and potting) skills. On the other hand, the community of Khok Phanom Di, with its complex hunter-gatherer heritage, may have distinguished itself with respect to the demographic changes that were occurring in the region, with its women specializing in pottery exchange with new neighbours and new kinship and gender relations following suit. In any case, the fact that a significant social transition took place at Khok Phanom Di and perhaps regionally over time (cf. Bentley et al. 2005) leads to new hypotheses to be investigated in the prehistory of the transition to agriculture in this exciting and unique region.

Acknowledgments

For providing access to a clean lab and a thermal ionization mass spectrometer for the strontium isotope analyses, we thank Rex Taylor, Matthew Cooper, and especially Tina Hayes of Southampton Oceanography Centre. We also thank Morag McBride, who meticulously prepared the majority of the samples for carbon and oxygen isotope analysis at University College London. Geoff Nowell and Graham Pearson facilitated four strontium isotope analyses by inductively coupled plasma mass spectrometry in the Arthur Holmes Isotope Geology Laboratory of Durham University.

References Cited

Atken, J. 1992. Archaeological sediments as artifacts. Ph.D. diss., University of Otago.

Allen, M. 1984. Elders, chiefs, and Big Men: Authority legitimation and political evolution in Melanesia. *American Ethnologist* 11:20–41.

Ambrose, S. H., B. M. Butler, D. B. Hanson, R. L. Hunter-Anderson, and H. W. Krueger. 1997. Stable isotopic analysis of human diet in the Marianas archipelago, western Pacific. *American Journal of Physical Anthropology* 104:343–61.

Ambrose, S. H., and L. Norr. 1993. Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In *Prehistoric human bone: Archaeology at the molecular level*, ed. J. B. Lambert and G. Grupe, 1–37. Berlin: Springer-Verlag.

Balasse, M., S. H. Ambrose, A. B. Smith, and T. D. Price. 2002. The seasonal mobility model for prehistoric herders in the south-western cape of South Africa assessed by isotopic analysis of sheep tooth enamel. *Journal of Archaeological Science* 29:917–32.

Beckinsale, R. D., S. Suensilpong, S. Nakhapadungrat, and J. N. Walsh. 1979. Radiometric age determinations of granites in northern Thailand. *Journal of the Geological Society of London* 136:529–40.

Bellwood, P. 2005. *First farmers: The origins of agricultural societies.* London: Blackwell.

Bentley, R. A. 2006. Strontium isotopes from the Earth to the archaeological skeleton: A review. *Journal of Archaeological Method and Theory* 13:35–87.

Bentley, R. A., and C. Knipper. 2005. Geographic patterns in biologically-available strontium, carbon, and oxygen isotopes signatures in prehistoric SW Germany. *Archaeometry* 47:629–44.

Bentley, R. A., M. Pietrusewsky, M. T. Douglas, and T. C. Atkinson. 2005. Matrilocality during the prehistoric transition to agriculture in Thailand? *Antiquity* 79:865–81.

Bentley, R. A., T. D. Price, J. Lüning, D. Gronenborn, J. Wahi, and P. D. Fullagar. 2002. Human migration in early Neolithic Europe. *Current Anthropology* 43:799–804.

Bentley, R. A., T. D. Price, and E. Stephan. 2004. Determining the "local" $^{87}Sr/^{86}Sr$ range for archaeological skeletons: A case study from Neolithic Europe. *Journal of Archaeological Science* 31:365–75.

Bowen, G. J., and B. Wilkinson. 2002. Spatial distribution of $\delta^{18}O$ in meteoric precipitation. *Geology* 30:315–8.

Budd, P., A. Millard, C. Chenery, S. Lucy, and C. Roberts. 2004. Investigating population movement by stable isotope analysis: A report from Britain. *Antiquity* 78:127–40.

Burton, J. H., and T. D. Price. 1999. Evaluation of bone strontium as a measure of seafood consumption. *International Journal of Osteoarchaeology* 9:233–36.

Burton, J. H., T. D. Price, and W. D. Middleton. 1999. Correlation of bone Ba/Ca and Sr/Ca due to biological purification of calcium. *Journal of Archaeological Science* 26: 609–16.

Capo, R. C., B. W. Stewart, and O. A. Chadwick. 1998. Strontium isotopes as tracers of ecosystem processes: Theory and methods. *Geoderma* 83:197–225.

Cassaidy, D. 1991. The size frequency distribution of *Scylla serrata* crabs. In *The excavation of Khok Phanom Di, a prehistoric site in Central Thailand*, vol. 2, *The biological remains (Part 1),* ed. C. F. W. Higham and R. Bannanurag, 231–36. Society of Antiquaries Research Report 48.

Chadwick, O. A., L. A. Derry, P. M. Vitousek, B. J. Huebert, and L. O. Hedin. 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature* 397:491–97.

Charusiri, P., A. H. Clark, E. Farar, D. Archibald, and B. Charusiri. 1993. Granite belts in Thailand: Evidence from the $^{40}Ar/^{39}Ar$ geochronological and geological syntheses. *Journal of Southeast Asian Earth Sciences* 8:127–36.

Chiaradia, M., A. Gallay, and W. Todt. 2003. Differential lead and strontium contamination styles of prehistoric human teeth at a Swiss necropolis (Sion, Valais). *Applied Geochemistry* 18:353–70.

D'Angela, D., and A. Longinelli. 1990. Oxygen isotopes in living mammal's bone phosphate: Further results. *Chemical Geology* 86:75–82.

DeNiro, M. J., and S. Epstein. 1978. Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* 42:495–506.

Ericson, J. E. 1985. Strontium isotope characterization in the study of prehistoric human ecology. *Journal of Human Evolution* 14:503–14.

Fox, R. 1983. *Kinship and marriage: An anthropological perspective.* Cambridge: Cambridge University Press.

Hage, P., and J. Marck. 2003. Matrilineality and the Melanesian origin of Polynesian Y chromosomes. *Current Anthropology* 44:S121–27.

Heaton, T. H. E. 1999. Spatial, species, and temporal variations in the $^{13}C/^{12}C$ ratios of C_3 plants: Implications for paleodiet studies. *Journal of Archaeological Science* 26: 637–49.

Higham, C. F. W. 2002. *Early cultures of mainland Southeast Asia.* Bangkok: River Books.

Higham, C. F. W., and R. Thosarat. 1994. *Khok Phanom Di: Prehistoric adaptation to the world's richest habitat.* New York: Harcourt Brace.

———. 2004. *The excavation of Khok Phanom Di.* Vol 7. *Summary and conclusions.* Society of Antiquaries Research Report 72.

Hilson, S. 1997. *Dental anthropology*. Cambridge: Cambridge University Press.

Ho, C.-M. 1984. The pottery of Kok Charoen and its farther context. Ph.D. diss., University of London.

Holden, C. J., and R. Mace. 2003. Spread of cattle led to the loss of matrilineal descent in Africa: A coevolutionary analysis. *Proceedings of the Royal Society* B 270:425–33.

———. 2005. "The cow is the enemy of matriliny": Using phylogenetic analysis to test a co-evolutionary hypothesis. In *The evolution of cultural diversity: A phylogenetic approach*, ed. R. Mace, C. J. Holden, and S. J. Shennan, 217–34. London: UCL Press.

Hoppe, K. A., P. L. Koch, and T. T. Furutani. 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. *International Journal of Osteoarchaeology* 13: 20–28.

Horn, Peter, St. Hölzi, and D. Storzer. 1994. Habitat determination on a fossil stag's mandible from the site of *Homo heidelbergensis* at Mauer by use of $^{87}Sr/^{86}Sr$. *Naturwissenschaften* 81:360–62.

Horn, P., and D. Müller-Sohnius. 1999. Comment on "Mobility of Bell Beaker people revealed by Sr isotope ratios of tooth and bone: A study of southern Bell Beaker skeletal remains" by Gisela Grupe, T. Douglas Price, Peter Schrörter, Frank Söllner, Clark M. Johnson, and Brian L. Beard. *Applied Geochemistry* 14:263–69.

Kijngam, A. 1991. The remains of fish, crabs, and turtles. In *The excavation of Khok Phanom Di, a prehistoric site in central Thailand*, vol. 2, *The biological remains (Part 1),* ed. C. F. W. Higham and R. Bannanurag, 223–30. Society of Antiquaries Research Report 48.

King, C. A. 2006. Stable isotopic analysis of carbon and nitrogen as an indicator of paleodietary change among prestate Metal Age societies in Northeast Thailand. Ph.D. diss., University of Hawaii.

Koch, Paul L., M. L. Fogel, and Nancy Tuross. 1994. Tracing the diets of fossil animals using stable isotopes. In *Stable isotopes in ecology and environmental science*, ed. K. Lajtha and R. H. Michener. 63–92. Oxford: Blackwell Scientific.

Koch, P. L., Nancy Tuross, and M. L. Fogel. 1997. The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite. *Journal of Archaeological Science* 24:417–29.

Kohn, M. J. 1996. A predictive model for animal $\delta^{18}O$: Accounting for diet and physiological adaptation. *Geochimica et Cosmochimica Acta* 60:4811–29.

Körner, C., G. D. Farquhar, and S. C. Wong. 1991. Carbon isotope discrimination by plants follows latitudinal and altitudinal trends. *Oecologia* 74:623–32.

Krigbaum, J. 2003. Neolithic subsistence patterns in northern Borneo reconstructed with stable carbon isotopes of enamel. *Journal of Anthropological Archaeology* 22:292–304.

Lavelle, M., and R. A. Armstrong. 1993. Strontium isotope ratios in modern biogenic and chemical marine precipitates from southern Africa. *South African Journal of Science* 89: 533–36.

Lepowsky, M. 1983. Sudest Island and the Louside archipelago in Massim exchange. In *The kula: New perspectives on Massim exchange*, ed. J. W. Leach and E. Leach, 467–501. Cambridge: Cambridge University Press.

McArthur, J. M., R. W. Howarth, and T. R. Bailey. 2001. Strontium isotope stratigraphy, LOWESS Version 3: Best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology* 109:155–70.

Marlowe, F. 2004. Martial residence among foragers. *Current Anthropology* 45:227–84.

Morrison, K. D. 2006. Historicizing foraging in South Asia: Power, history, and ecology of Holocene hunting and gathering. In *Archaeology of Asia*, ed. M. Stark, 279–302. Malden, Mass.: Blackwell.

Mudar, K. M. 1995. Evidence for prehistoric dryland farming in mainland Southeast Asia: Results of regional survey in Lopburi Province, Thailand. *Asian Perspectives* 34:157–91.

Mudar, K. M., and V. C. Vincent. 2003. Subsistence changes and community-based craft production in prehistoric Central Thailand. In *Fishbones and glittering emblems: Southeast Asian archaeology 2002*, ed. A. Karlström and A. Källén, 149–61. Stockholm: Museum of Far Eastern Antiquities.

O'Leary, M. H. 1988. Carbon isotopes in photosynthesis. *BioScience* 38:328–36.

Oota, H., W. Settheetham-Ishida, D. Tiwawech, T. Ishida, and M. Stoneking. 2001. Human mtDNA and Y-chromosome variation is correlated with matrilocal versus patrilocal residence. *Nature Genetics* 29:20–21.

Passey, B. H., T. E. Cerling, G. T. Schuster, T. F. Robinson, B. L. Roeder, and S. K. Krueger. 2005. Inverse methods for estimating primary input signals from time-averaged isotope profiles. *Geochimica et Cosmochimica Acta* 69:4101–16.

Pietrusewsky, M., and M. T. Douglas. 2002. *Ban Chiang, a prehistoric village site in Northeast Thailand: The human skeletal remains.* Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology.

Pookajorn, S., and Staff. 1992. *The Phi Tong Luang Mlabri: A hunter-gatherer group in Thailand.* Bangkok: Odeon Store.

Post, D. M. 2002. Using stable isotopes to estimate trophic position: Models, methods, and assumptions. *Ecology* 83: 703–18.

Prowse, T., H. P. Schwarcz, S. Saunders, R. Macchiarelli, and L. Bondioli. 2004. Isotopic paleodiet studies of skeletons from the Imperial Roman-age cemetery of Isola Sacra, Rome, Italy. *Journal of Archaeological Science* 31:259–72.

Schoeninger, M. J., and M. J. DeNiro. 1984. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta* 48:625–39.

Seielstad, M. T., E. Minch, and L. L. Cavalli-Sforza. 1998. Genetic evidence for a higher female migration rate in humans. *Nature Genetics* 20:278–80.

Sillen, A., G. Hall, S. Richardson, and R. Armstrong. 1998. $^{87}Sr/^{86}Sr$ ratios in modern and fossil food-webs of the Sterkfontein Valley: Implications for early hominid habitat preference. *Geochimica et Cosmochimica Acta* 62:2463–78.

Sinsakul, S. 2000. Late Quaternary geology of the Lower Central Plain, Thailand. *Journal of Asian Earth Sciences* 18: 415–26.

Siripanith, S. 1985. An analytical study on pottery from the excavation of Ban Thakae, Muang District, Lopburi Province (in Thai). M.A. thesis, Silpakon University.

Tayles, N. 1999. *The excavation of Khok Phanom Di, a prehistoric site in Central Thailand.* Vol 5. *The people.* Society of Antiquaries Research Report 61.

Thompson, G. B. 1996. *The excavation of Khok Phanom Di, a prehistoric site in central Thailand.* Vol. 4. *Subsistence and environment, the botanical evidence.* Society of Antiquaries Research Report 53.

Tieszen, L. L., and T. Fagre. 1993. Effect of diet quality and composition on the isotopic composition of respiratory CO_2, bone collagen, bioapatite, and soft tissues. In *Prehistoric human bone: Archaeology at the molecular level,* ed. J. B. Lambert and G. Grupe, 121–55. Berlin: Springer-Verlag.

Trickett, M. A., P. Budd, J. Montgomery, and J. Evans. 2003. An assessment of solubility profiling as a decontamination procedure for the $^{87}Sr/^{86}Sr$ analysis of archaeological human skeletal tissue. *Applied Geochemistry* 18:653–58.

Van Klinken, G. J., H. van der Plicht, and R. E. M. Hedges. 1994. Bond $^{13}C/^{12}C$ ratios reflect (palaeo-), climatic variations. *Geophysical Research Letters* 21:445–48.

Vincent, B. 2004. *The excavation of Khok Phanom Di.* Vol. 6. *The pottery.* Society of Antiquaries of London Research Report 70.

Whipkey, C. E., R. C. Capo, O. A. Chadwick, and B. W. Stewart. 2000. The importance of sea spray to the cation budget of a coastal Hawaiian soil: A strontium isotope approach. *Chemical Geology* 168:37–48.

Wu, C., and S. Ishihara. 1994. REE geochemistry of the Southern Thailand granites. *Journal of Southeast Asian Earth Sciences* 10:81–94.