



## Resource utilisation and regional interaction in protohistoric Cambodia – The evidence from Angkor Borei

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### ABSTRACT

Angkor Borei is a protohistoric (ca. 500 BCE – 500 CE) site in southern Cambodia (Takeo Province), on the western edge of the Mekong Delta. Cambodia's protohistoric period, concurrent with the Iron Age elsewhere in mainland Southeast Asia, is a period characterised by major socio-political transformation: early state formation, incorporation into the South China Sea network, and urbanisation. First occupied in the mid-first millennium BCE, Angkor Borei became the delta's largest regional centre during the Funan period (c. 1st-6th century CE). This study builds on previous skeletal chemistry research, increasing the sample set by additional 15 individuals, to refine our understanding of the residential behaviour and exploitation strategies of the Angkor Borei mortuary sample. Using strontium, oxygen, carbon, and nitrogen isotope measurements from tooth enamel and bone, and incorporating bioavailable baseline strontium isotope data, we find that the majority of individuals have a childhood  $^{87}\text{Sr}/^{86}\text{Sr}$  signature consistent with locally acquired food resources. For those individuals with outlier  $^{87}\text{Sr}/^{86}\text{Sr}$  values, utilisation of the broader regional environment is suggested without the need to infer long-distance migration. The evidence for population stability at Angkor Borei during this dynamic period of increasing regional societal complexity indicates that the catalysts for change are manifold. Many factors are likely to have contributed to the genesis of early state society including social differentiation, cultural exchange, mercantile activity, residential mobility, and settlement growth, rather than one 'external' prime causative factor.

### 1. Introduction

Mainland Southeast Asia's societies underwent profound organisational change as they transitioned to history in the mid-first millennium BCE. Some villages nucleated into cities along the region's alluvial plains as they adopted South Asia-derived religions, while in coastal areas port-settlements were positioned to take advantage of increasingly cosmopolitan maritime trade networks linking Rome to China via Southeast Asia (Miksic and Goh, 2017: 147–227; Stark, 2006). These demographic, settlement, and ideological changes transformed the region by the mid-first millennium CE: Brahmi-derived writing systems, Indic-tinged art styles and institutionalised Indic religions formed foundations for newly-established states whose leaders inscribed their

largesse in stone. Some scholars, in their assessment of South and Southeast Asia trade connections have proposed a process involving two phases: the first (4th century BCE to 2nd century CE) involving the intermittent movement of goods and ideas, and the second (2nd–4th centuries CE) in which trade intensified, and it is argued, in the case of the Thai-Malay Peninsula, included the movement of foreign skilled craftsmen (Bellina and Glover, 2004; Ray, 1989). How this apparent dynamic and burgeoning regional interconnectivity looked in different parts of Southeast Asia, has become the focus of recent research (Carter, 2015; Favereau and Bellina, 2016; Hung et al., 2007, among others). Understanding the nature of change and increasing socio-political complexity during this period requires the detailed study of particular locations such as the Mekong Delta.

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Archaeological research in the Mekong Delta, begun in the mid-20th century by French colonial scholars (Malleret, 1959–63), offers one lens for viewing this process of transition. The delta is long seen as the heart of the early to mid-first millennium CE “Kingdom of Funan” that appears in Chinese reports. Chinese documents suggest that at its 3rd century CE peak, the Kingdom of Funan stretched approximately 3000 li (600 km) along its east–west axis, covered a total area of 6000 li (2000–2400 km), and housed at least one dozen urban centres (Pelliot, 1903). Recent archaeological research confirms the delta’s rich proto-historic record, which includes large settlement mounds in both southern Cambodia and Vietnam, linked into a delta-wide network through rivers, canals, and roads (Manguin, 2009; Manguin and Stark, in press; Stark, 2003). The focus of the present paper is the site of Angkor Borei located in Takeo Province in the Mekong Delta in Cambodia. This site is notable for its walls and moats enclosing 300 ha of urbanised settlement with a long history of occupation (Stark, 2001; Stark et al., 1999; Bishop et al., 2003a,b). Work described in this paper uses materials recovered from Angkor Borei during 1999–2000 excavations at Vat Komnou by the Lower Mekong Archaeological Project (Stark, 1998, 2003; Stark and Bong, 2001).

The study comprises the measurement of strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), oxygen ( $\delta^{18}\text{O}$ ) carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotopes in the skeletal remains of 15 individuals from the Vat Komnou mortuary assemblage.  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  is measured in (first or second) human molars and faunal enamel and  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  is measured in human bone collagen. This research builds on the previous work involving 10 individuals, only nine of which had reported  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Krigbaum et al., 2008; Ikehara-Quebral, 2010; Ikehara-Quebral et al., 2017). We now report analyses on a further 15 individuals, one of which was in the original series of 10 individuals (for this individual, Burial 36, we report the average of the two analyses). This study also incorporates  $^{87}\text{Sr}/^{86}\text{Sr}$  measured in plants and soils from the surrounding area, and archaeological faunal enamel recovered from the site to characterise local  $^{87}\text{Sr}/^{86}\text{Sr}$  variability.

This research broadens our understanding of residential behaviour and exploitation strategies at this early historic period site in southern Cambodia, at a pivotal period in the development of increasingly complex socio-political entities in the region. The paper presents, for the first time, environmental baseline isotopic data supporting a model of population stability at Angkor Borei. Furthermore, this research enhances the existing understanding of the Vat Komnou cemetery sample, addressing gaps in our current knowledge regarding demography, landscape use, cultural practices and health in the lower Mekong Basin during the dynamic Protohistoric Period.

## 2. Background

### 2.1. The site

The central mound of Angkor Borei is located at UTM 48P 497507 m E, 1214867 m N at approximately 5–10 m asl (Fig. 1). Archaeological research conducted since 1996 through the Lower Mekong Archaeological Project (LOMAP) has revealed evidence for early urbanisation associated with monumental construction and water control features within a c. 300 ha walled settlement (Stark, 2001; Stark et al., 1999; Bishop et al., 2003a,b). Subsequent excavation and survey has produced nearly identical artefact assemblages (e.g., Phon, 2004), which suggests that Angkor Borei may have been subdivided into multiple precincts. Recovered fauna represent broad-spectrum use of the local environment (Voeun et al., 2012). The dominant mammal in the faunal assemblage is the domesticated pig (*Sus scrofa*) with other domesticates including cattle (*Bos taurus* and *Bos indicus*) and chicken (*Gallus gallus domesticus*). Wild animals including deer, elephant, buffalo, tiger, cattle, crocodile, and fresh and brackish water fish species are present (Ikehara-Quebral et al., 2017, Table 3).

### 2.2. Environmental context

The geology of Cambodia is summarised in the United Nations, Economic and Social Commission for Asia and the Pacific, Atlas of Mineral Resources of the ESCAP Region (United Nations, 1993). It is diverse and comprises sedimentary formations, metamorphic and igneous rocks from the Precambrian through to the Quaternary (Sotham, 1997; Workman, 1977) (Fig. 2).

During the Protohistoric/Iron Age, most large Southeast Asian settlements were located in coastal areas, major floodplains and river valleys or in proximity to freshwater lakes (Stark, 1998, 2006). A key region during this period is the Mekong Delta, believed to be the centre of the “Kingdom of Funan” and home to several important centres including Óc Eo and Go Thap in southern Vietnam (Lê et al., 1995; Lê, 2005, 2006; Malleret, 1959–63, Manguin and Vo, 2000) and Angkor Borei in southern Cambodia (Stark, 2003).

The Mekong river, nearly 4,900 km in length, drains an area of approximately 800,000 km<sup>2</sup> from the Tibetan Plateau and passes through China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam to the South China Sea through the distributary channels of its delta (Gupta and Liew, 2007; Manh et al., 2015). Its average annual water discharge is 470 km<sup>3</sup> and modern (predam) sediment flux is 160 million tonnes (Kondolf et al., 2014; Ta et al., 2002: 1808). The delta itself, comprises an intricate system of rivers, channels and floodplains, and is one of the most complex and vulnerable river deltas in the world (Manh et al., 2015). It has prograded for approximately the last 6000 years and covers an area of approximately 70,000 km<sup>2</sup> in Cambodia and Southern Vietnam (Ta et al., 2002; Tamura et al., 2009). In the southern Cambodian lowlands, the site of Angkor Borei and surrounding area are located in a fluvial-deltaic environment containing a series of terraces, channels, paleochannels, backswamps (Bishop et al., 2003b: 360); two rivers, several tributaries, and more than 200 km<sup>2</sup> of ancient canals link the site to other proto-historic settlements such as Óc Eo located in modern Vietnam (Bishop et al., 2003a; Bourdonneau, 2003; Sanderson et al., 2003, 2007; Paris, 1931, 1941).

The elevation around Angkor Borei ranges from c. 2 to 10 m above sea level and the region is covered with Holocene alluvium comprising unconsolidated silt, clay and sand (Anderson, 1978; Stark et al., 1999:19). A 3.1 m core extracted from a reservoir on Angkor Borei’s eastern perimeter reveals a paleoenvironmental record stretching back to c. 2000 cal. Yr BCE (Bishop et al., 2003b). This record indicates the existence of a mangrove forest in the region with burned grasslands noted in the local environment for much of the first and second millennia BCE. Abrupt changes in the 5th to 6th centuries CE paleobotanical and sedimentation record suggest a reduction in grassland and the expansion of secondary forests (Bishop et al., 2003b), which may reflect altered land use or possibly abandonment of the area. This paleoenvironmental shift correlates closely with the decline of Angkor Borei as a regional center of “Funan” (Ishizawa, 1996).

### 2.3. Vat Komnou mortuary assemblage

In 1999 and 2000 excavations were focused near the edge of a cemetery mound at Vat Komnou which dates from 200 BCE to 200 CE (Stark, 2001). The remains of one hundred and eleven individuals (mostly in good to fair preservation) from 57 mortuary contexts were retrieved from an excavation unit designated ‘AB7’ measuring 5 × 2 m (Pietruszewsky and Ikehara-Quebral, 2006; Ikehara-Quebral, 2010; Ikehara-Quebral et al., 2017). The adult male to female ratio is 2:1, suggesting differential mortuary practices, immigration of male labourers, or out-migration of females (Ikehara-Quebral et al., 2017). Associated burial goods included ceramics, gold, glass and stone beads and faunal remains (Bong, 2003; Carter, 2010, 2012, 2015; Ikehara-Quebral et al., 2017; Voeun et al., 2012).

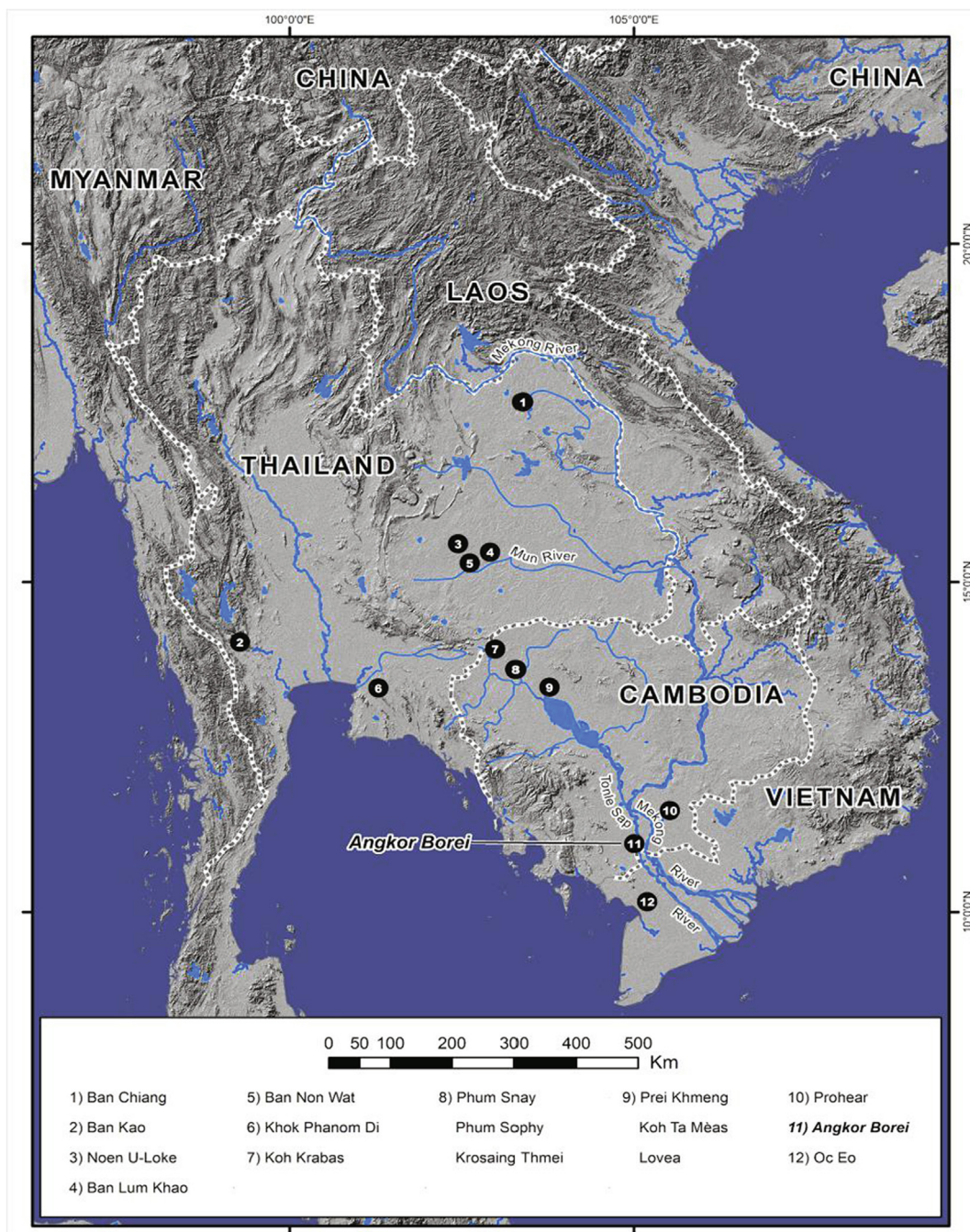


Fig. 1. Location of Angkor Borei.

#### 2.4. Health status of the Vat Komnou burial sample – conclusions from previous reports

A full assessment of the health indicators of the mortuary sample has been described in detail elsewhere (Ikehara-Quebral, 2010; Ikehara-Quebral et al., 2017). Table 1 of this paper describes the burials analysed in this present report and the previous study, including four individuals with culturally modified (filed) teeth, and provides a summary of pathology and non-metric traits recorded in the sampled individuals. Previously, Ikehara-Quebral and colleagues have shown that subadult (< 15 years of age) oral-dental health indicated good infant, childhood, and maternal health with adequate nutrient intake. The deciduous caries rate observed suggested a relatively greater reliance on carbohydrates early in life. The adult burial sample ( $\geq 15$  years of age) is reported to have been an increasing, nonstationary group with a

high total fertility rate. Mean stature calculated with Thai-Chinese regression formulae (Sangvichien et al., 1985) was 165.3 cm in males and 154.8 cm in females. Linear enamel hypoplasia (LEH) was fairly low (8.8% or 39/445 permanent teeth) indicating relatively little stress once individuals survived infancy. Observed dental pathology indicated a significantly greater number of males were affected by advanced periodontal disease than females, which may be attributed to the consumption of a high protein diet or betel (*Areca catechu*) nut chewing, and/or poorer oral hygiene. A low rate of carious teeth (5.0% or 25/497) and a moderate rate of advanced dental attrition (10.4% or 52/498) suggested the group consumed fibrous, abrasive foods (including betel quid) that helped remove plaque bacteria from the teeth.

The recorded occurrence of cribra orbitalia in the total sample was 35.7% (5/14 individuals). Two of 13 adult males (15.4%) were affected by porotic hyperostosis of the cranial vault while none of the adult

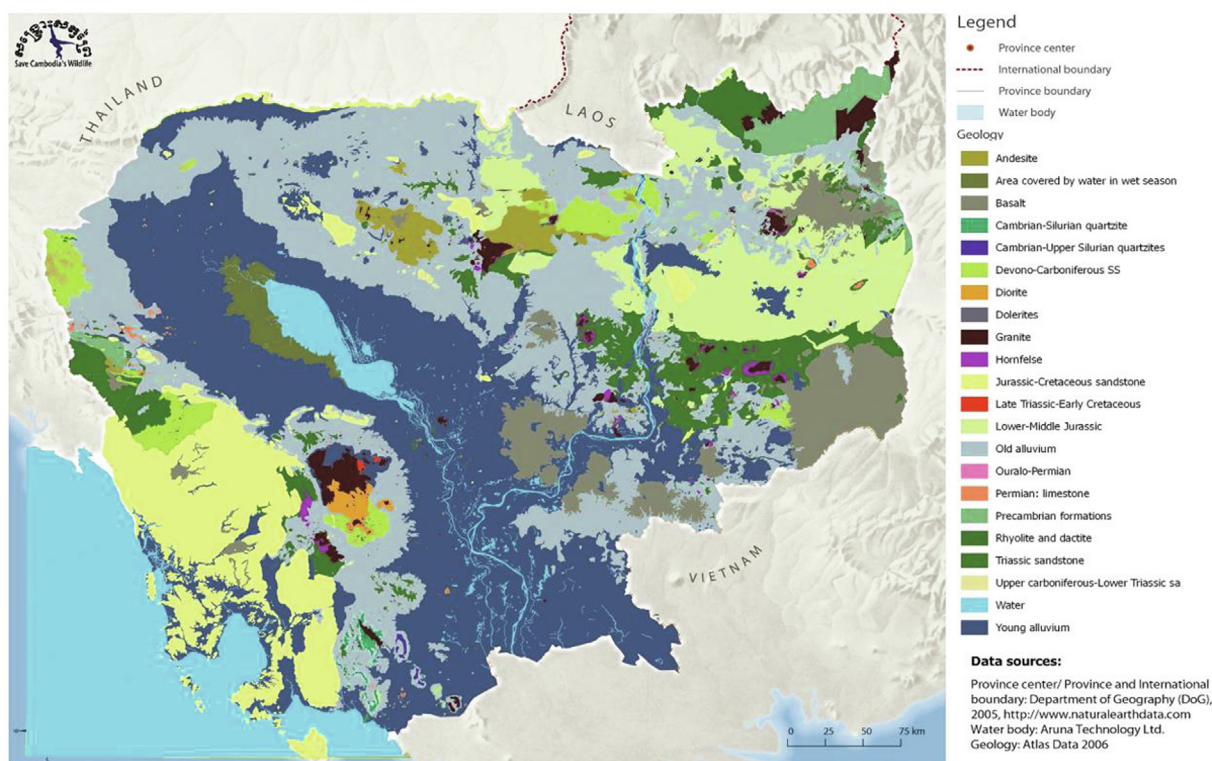


Fig. 2. Geology of Cambodia. Source: Open Development Cambodia <https://opendevelopmentcambodia.net/dataset/?id=geology-of-cambodia-2006>.

females were affected, and very few cases of infectious disease were observed in the sample. While degenerative changes in the male and female skeletons suggested a sexual division of labour by early adulthood, overall, the people laid to rest in the Vat Komnou cemetery were an active group who lived healthy lives during the dynamic period of emerging socio-political complexity in Cambodia.

### 2.5. Multi-isotopic analysis of human and faunal remains: (strontium, oxygen, carbon, nitrogen)

Strontium isotope ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) measured in human skeletal material are used in bioarchaeological investigations to increase our understanding of the residential behaviour and resource acquisition strategies of pre/historic communities (Bentley, 2006; Bentley et al., 2005, 2007, 2009; Budd et al., 2004; Cox et al., 2011; Slovak and Paytan, 2011 among others). Strontium has four naturally occurring isotopes ( $^{84}\text{Sr}$ ,  $^{86}\text{Sr}$ ,  $^{87}\text{Sr}$ ,  $^{88}\text{Sr}$ ).  $^{87}\text{Sr}$  is radiogenic, being produced by the radioactive decay of  $^{87}\text{Rb}$  which has a half-life of 48,000,000 years (Faure and Mensing, 2005). Strontium isotope ratios measured in rock, soil, and groundwater vary according to the age and composition of the underlying geology. This variability in  $^{87}\text{Sr}/^{86}\text{Sr}$  is carried with no measurable fractionation from weathered bedrock to vegetation and via diet to the teeth and bones of animals and humans where strontium substitutes for calcium.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios measured in human enamel preserve a record of the geological environment from which these individuals obtained their food during childhood as enamel forms in the early years of life, and unlike bone, is not remodelled. The values recorded in skeletal material however reflect *biologically available* strontium which may vary from whole rock and soil  $^{87}\text{Sr}/^{86}\text{Sr}$  values as a function of differential weathering, atmospheric deposition such as seaspray, rainfall and windblown dust, mixing processes between different strontium reservoirs and the use of modern fertilizer (Price et al., 2002; Sillen et al., 1998). To gauge the spatial variability of bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  in the study region, we have measured  $^{87}\text{Sr}/^{86}\text{Sr}$  of archaeological faunal enamel from animals recovered from the site and in

grasses and soil from the surrounding area.

Oxygen has three stable isotopes ( $^{16}\text{O}$ ,  $^{17}\text{O}$ ,  $^{18}\text{O}$ ). The ratio  $^{18}\text{O}/^{16}\text{O}$  expressed as  $\delta^{18}\text{O}$  varies in water sources according to altitude, latitude, precipitation, temperature and distance from the sea. Generally higher  $\delta^{18}\text{O}$  values are associated with warmer temperature, proximity to the ocean, and lower altitude and lower values are associated with lower temperature, inland location and higher altitude (Knipper et al., 2018:738). Measured in archaeological dental tissue  $\delta^{18}\text{O}$  provides a proxy for drinking water composition (and rainfall) and can be used to infer geographic location permitting examination of mobility strategies in past populations.

The analysis of carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotopes in human tissue is regularly used for the reconstruction of past diets. Carbon isotope ratios ( $\delta^{13}\text{C}$ ) in bone and teeth have been used to explore the relative proportion of  $\text{C}_3$  vs  $\text{C}_4$  plants in the diet or marine vs terrestrial foodstuffs. Plants following the  $\text{C}_3$  photosynthetic pathway (such as rice) are more depleted in  $^{13}\text{C}$  than those such as millet using the  $\text{C}_4$  pathway. Carbon isotope ratios measured in bone collagen reflect the main protein portion of the diet over the last years of an individual's life, while in dental enamel carbonate,  $\delta^{13}\text{C}$  reflects the whole diet during the period of enamel formation i.e., childhood (Ambrose and Norr, 1993). Nitrogen isotopes ( $\delta^{15}\text{N}$ ) measured in bone collagen increase with trophic level and can be used to indicate the proportion of different food resources in human diet.

## 3. Methodology

### 3.1. Strontium isotope ratios

#### 3.1.1. Enamel

Enamel samples were mechanically cleaned using a dental drill to remove any adhering residue and then ground using an agate mortar and pestle. A small sample (< 10 mg) was placed in a microcentrifuge tube and leached in 5% acetic acid for 8 h. Samples were rinsed 3 times with Milli-Q deionized water and then placed in Teflon beakers.

**Table 1**  
**Vat Konnou Isotope sample composition, skeletal markers and associated burial assemblage.**

Burial Number	Sex	This Study	Previous Study	Skeletal Markers	Burial Assemblage
AB 5	F	X	X	Persistence of metopic suture into adulthood, Carabelli's cusp, enlarged nutrient foramen in 2 hand bones and vertebral centra, mandibular tooth crowding, I1 Schmorl's node	Ceramics, glass beads
AB 13	M	X	X	Five left infraorbital foramina, persistence of infraorbital suture, well-developed zygomaxillary tubercle, LEH, peg shaped maxillary M3s, stained dental enamel, congenital absence of twelfth ribs, right hemi-sacralization L5, possible healed fractures of hyoid lesser horn and T2 & T3 spinous processes	Ceramics, 2 pig tooth pendants
AB 14	M	X	X	Enamel extension maxillary permanent right M2. CAL. 45 BC-AD 80 (dentine)	3 small orange pots and a larger orange pot with lid
ABM 16B	?M	X	X	Light enamel staining. LEH	Glass beads
AB 17	M	X	X	Poor oral-dental health, enlarged nutrient foramina of hand and foot bones indicating possible childhood anemia, stained dental enamel	Ceramics, glass bead
ABM 20A	?F	X	X	LEH	Glass beads
AB 22	?F	X	X	Light brown stains on dental enamel, dental caries	Ceramics, glass beads
ABM 22A	?	X	X	LHPC mandibular right deciduous canine, dental caries, enlarged nutrient foramen of metatarsal	Glass beads
AB 25	?M	X	X	Dental caries	Glass beads
AB 27	M	X	X	LEH, possible traumatic myositis ossificans of left posterior-superior tibial shaft	Cluster of 6 pots and glass beads
AB 28	F	X	X	Filed teeth, persistence of metopic suture into adulthood, thickened frontal and occipital bones, congenital absence of mandibular M3s, poor oral-dental health including dental caries, light enamel staining	Ceramics
ABM 31A	?F	X	X	Carabelli's cusp of maxillary deciduous m2, bilaterally	Glass beads
ABM 31B	?M	X	X	LEH, persistence of complete metopic suture	Glass beads
AB 32	M	X	X	Filed teeth, possible agnesis of mandibular M3s, moderate periapical cavity at root of the mandibular permanent right central incisor, septal aperture	Ceramics
ABM 33A	M	X	X	Dental caries, enamel staining	2 small pots
AB 33	?M	X	X	Dental caries, accessory cusp on posterior surface of permanent mandibular M3	2 small pots
AB 34	?	X	X	4-rooted maxillary permanent M2, Carabelli's cusp, septal aperture	2 small pots
AB 36	M	X	X	Filed teeth, periapical cavity at maxillary left C, LEH	Orange pottery anvil, glass beads, 2 pig tooth pendants
ABM 39A	?M	X	X	Enlarged nutrient foramen in three metatarsals, healed trauma in fourth metatarsal. 69–210 cal AD (bone)	Glass beads
ABM 40A	?M	X	X	Dental caries, Carabelli's cusp	
ABM 43B	M	X	X	Cribriform orbitalia, poor oral-dental health, dental caries, periapical cavities, tibial squatting facet, vault asymmetry, dental enamel staining of all teeth, evidence of right-handedness	2 small pots, 2 pig crania, glass beads
AB 44	F	X	X	Poor oral-dental health, possible agnesis of mandibular left M3, left hemi-spondylosis of L4, dental enamel staining of anterior teeth	Beads: 13 gold, 1 Carnelian and numerous glass; ceramics; unknown metal object
AB 47	M	X	X	Cribriform orbitalia, possible premature fusion of sagittal suture, dark staining of dental enamel	Ceramics
AB 48	F	X	X	Filed teeth, poor oral-dental health including dental caries, periapical cavity at root of the maxillary right 12	Ceramics, glass beads, garnet bead

### 3.1.2. Plants and soil

Plant (mostly grass) and soil samples collected from different geologic provinces across Cambodia have been analysed to create a baseline strontium isotope map of the region for bioarchaeological research and provenance studies (Shewan et al., *in press*). Results from southern Cambodia, near the site of Angkor Borei are incorporated here. As whole rock and soil  $^{87}\text{Sr}/^{86}\text{Sr}$  may vary from bioavailable strontium, we have included soil, plant (a direct measure of bioavailable strontium) and soil leachates (a proxy measure) for consideration.

Sample sites were geo-located with a hand-held GPS device with soil and grass sampled at the same location. Plant and soil samples were placed in porcelain crucibles and ashed for 8 h at 800 °C. 10–20 mg from each plant sample was placed in an acid cleaned Teflon beaker and digested in ultrapure concentrated nitric acid ( $\text{HNO}_3$ ) and for the soils the addition of hydrofluoric acid (HF). Strontium was separated and concentrated using Sr-Spec ion exchange columns. For soil leachates 1 gm of soil was placed in a centrifuge tube with 1 ml ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) shaking the suspension overnight to extract the bioavailable strontium component. Following digestion, Sr was separated and concentrated using Sr-Spec ion exchange columns.

Following strontium separation  $^{87}\text{Sr}/^{86}\text{Sr}$  was measured in all samples using two Thermal Ionisation Mass Spectrometers (TIMS) at the Research School of Earth Sciences at the Australian National University (ANU), Canberra (a MAT261 and a Thermo Finnigan Triton mass spectrometer). During the period of analysis 36 measurements of SRM987 on the MAT261 yielded an average  $^{87}\text{Sr}/^{86}\text{Sr}$  value of  $0.71023 \pm 5$  (1 sigma); The long-term mean value for SRM987 for the TRITON was  $0.710244 \pm 1$  (N = 85). The results have been normalised to the SRM987 value of 0.710275 to compare directly with the previous study.

### 3.2. Oxygen and carbon: Enamel

Enamel samples were ground to a fine powder using an agate mortar and pestle and leached to remove secondary carbonate. Stable isotope analyses ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) of the carbonate phase in human and faunal tooth enamel were conducted on an automated individual-carbonate reaction Kiel Device coupled to a Finnigan MAT-251 isotope ratio mass spectrometer at the Research School of Earth Sciences, ANU. Approximately 4–5 mg of each powdered enamel sample was reacted with 103%  $\text{H}_3\text{PO}_4$  at 90 °C to liberate sufficient  $\text{CO}_2$  for isotopic analysis. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values are reported as per mil (‰) deviations relative to the Vienna PeeDee Belemnite (VPDB) standard. The corrected samples have been normalised such that NBS 19 yields d13 Cvpdb (+1.95‰) and d18Ovpdb (-2.20‰) and NBS 18 yields d13Cvpdb (-5.00‰) and d18Ovpdb (-23.00‰). As the acid-water fractionation factor for oxygen isotopes in the carbonate phase of tooth enamel is unknown, we cannot normalise the measured  $\delta^{18}\text{O}$  values to the VPDB scale in the strict sense. This is the case with other studies of oxygen in tooth enamel. As such,  $\delta^{18}\text{O}$  values measured on  $\text{CO}_2$  liberated from tooth enamel carbonate by acidification are not directly comparable to those measured on  $\text{CO}_2$  liberated from calcite standards of equivalent  $\delta^{18}\text{O}$  values (Fraser et al., 2008). As a result, while our tooth enamel  $\delta^{18}\text{O}$  values are internally consistent, they cannot be strictly compared with  $\delta^{18}\text{O}$  values measured on tooth enamel apatite or data produced by microbeam analysis techniques such as laser ablation and secondary ion mass spectrometry.

### 3.3. Carbon and nitrogen: bone

For each sample, a small bone fragment was cleaned with a Dremel drill. Collagen was purified according to well established methods with samples sequentially treated with 0.5 M HCL (4 rinses), 0.1 M NaOH (30 min), and 0.5 M HCL (1 h) with rinsing with ultrapure water between each step (Brock et al., 2010). The sample is then submerged in 8–10 ml of 0.001 M HCL (pH 3), sealed and placed in oven at 70C for

20 h. Stable isotopes were measured at the Australian National University in an ANCA GSL connected to a Sercon 20–22 Isotope Ratio Mass Spectrometer (IRMS) operating in continuous flow mode against an in-house gelatin reference. Values were scaled against USGS40, USGS41, IAEA-C6 and IAEA-600. Standard indicators have been used to assess collagen preservation including collagen yield, carbon and nitrogen contents and C:N ratios (2.9–3.6).

## 4. Results

### 4.1. Plants and soil

Situated on the western edge of the lower Mekong Basin, Angkor Borei is located 5–10 m above sea level on a marine terrace. The region is covered with Young Alluvium. These Quaternary sediments are widespread throughout Cambodia and are composed of grits, pebbles, sand, silt and claystone, reaching over 200 m in thickness in some areas. In close proximity to the site are areas of Old Alluvium (mostly composed of claystone, silt and sand, overlying lateritized or conglomerate beds), and outcrops of granite, triassic sandstone, and hornfels. Further afield, Cambrian-Upper Silurian quartzite, rhyolite, diorite and basalt can be found (see Fig. 2).

$^{87}\text{Sr}/^{86}\text{Sr}$  measured in plants, soil leachates and soil selected from locations in southern Cambodia near the Angkor Borei region (Fig. 3) reflect the complex geological environment of the Mekong delta. While the depositional environment has been modified through time and by modern hydrological events and anthropogenic activity, useful information can be gleaned from the isotopic data concerning the spatial variability of biologically available strontium. Soil samples range from 0.71573 to 0.72094 (mean  $\pm$  SD,  $0.71780 \pm 0.00187$ ); Leachates range from 0.71008 to 0.71999 (mean  $\pm$  SD,  $0.71419 \pm 0.00288$ ) and plant samples range from 0.71070 to 0.71928 (mean  $\pm$  SD,  $0.71327 \pm 0.00242$ ) (Table 2). Recorded average Mekong River water  $^{87}\text{Sr}/^{86}\text{Sr}$  is 0.71052 (Pearce et al., 2015).

As reported in many studies, whole rock and soil  $^{87}\text{Sr}/^{86}\text{Sr}$  values can vary significantly from the isotopic value of bioavailable strontium values taken up by living organisms. This is confirmed in the present study where soil values varied significantly from plant samples ( $p < 0.001$ ). Soil leachates (used to approximate labile strontium) are expected to resemble more closely those results obtained from vegetation, although some variation is likely. In this study, while differences exist between the plants and soil leachates, they are not statistically significant ( $p = 0.57$ ) (data presented in Table 2).

### 4.2. Fauna

The isotopic results for the six archaeological faunal samples are presented in Table 3 and Fig. 4. The mean ( $\pm$  SD) strontium isotope ratio for the faunal specimens is  $0.71167 \pm 0.00073$  with values ranging from 0.71069 to 0.71247. Those species with an expected larger home range (wild cattle and elephant), incorporating strontium from wider sources exhibit more radiogenic values ( $0.71230 \pm 0.00019$ ) than the smaller, lower mobility animals ( $0.71104 \pm 0.00033$ , difference  $p < 0.005$ ) who likely fed in the local environment in close proximity to the humans.  $^{87}\text{Sr}/^{86}\text{Sr}$  of the plant samples obtained within approximately 50 km of the site are aligned with those values obtained from the archaeological fauna ( $p$  value for the difference is 0.14, ns). For four of the faunal samples it was possible to also obtain  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from the carbonate phase of the tooth enamel. These values range from  $-3.76$  to  $-7.37$  and  $-6.93$  to  $-13.62$  respectively.

### 4.3. Human isotopic data

The isotopic results for the 15 new human skeletal samples are presented in Table 4.

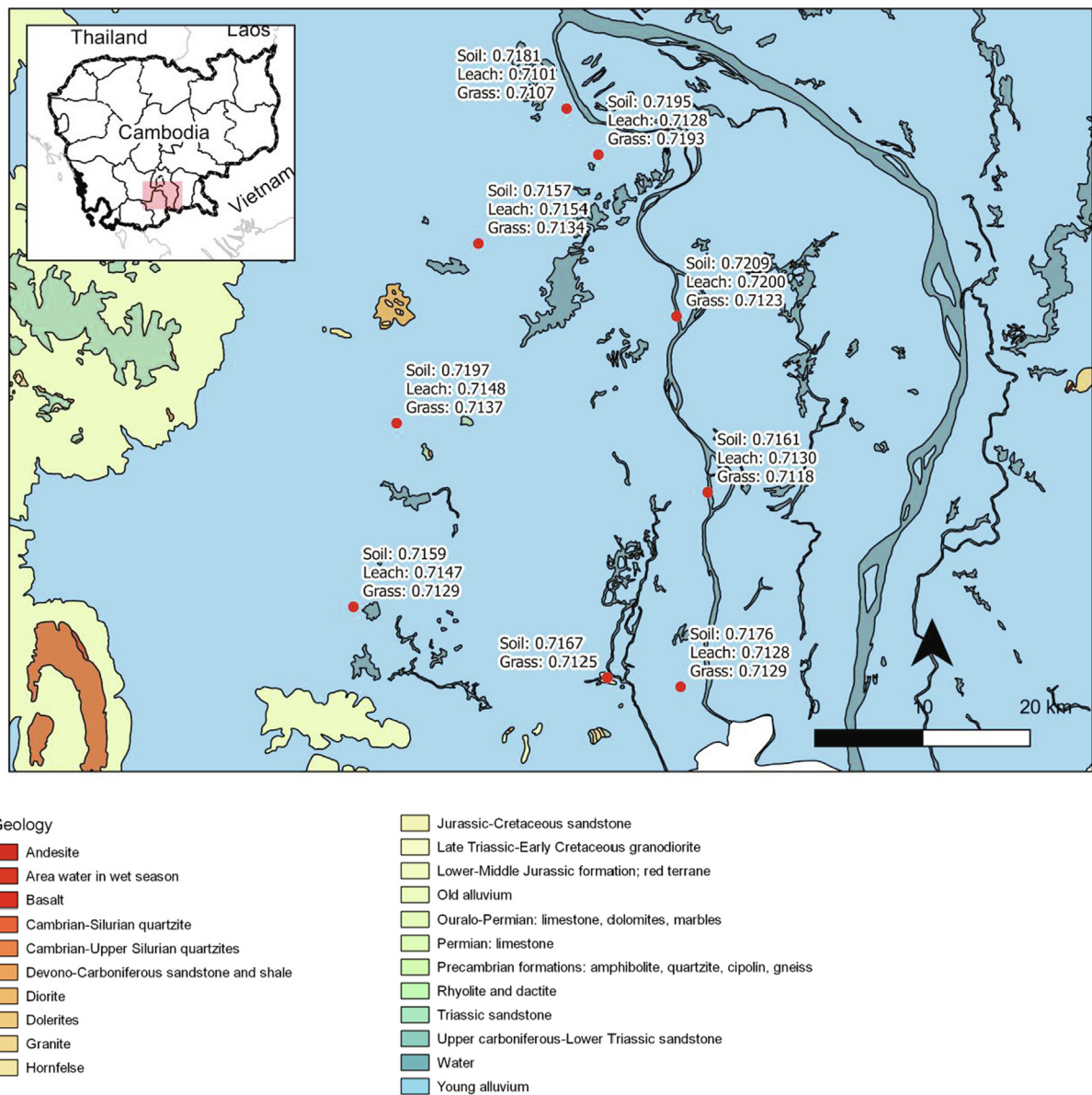


Fig. 3. Plant and soil <sup>87</sup>Sr/<sup>86</sup>Sr values from southern Cambodia.

We have combined these results with analyses conducted previously (Ikehara-Quebral et al., 2017) (Table 5 included below for reference).

4.3.1. Combined results

The mean ( ± SD) strontium isotope ratio for all human individuals from both studies (n = 23) is 0.71045 ± 0.0013. The <sup>87</sup>Sr/<sup>86</sup>Sr values

appear to be mainly (n = 16) clustered around 0.711 (see Fig. 4), with six individuals with lower <sup>87</sup>Sr/<sup>86</sup>Sr values (Burials 13, 16B, 20A, 28, 32 and 48, ranging between 0.70826 and 0.70963) and one more radiogenic outlier Burial 33 (0.71455), a ?male individual aged between 12 and 15 years of age.

The oxygen isotope values for the 23 human individuals range from

Table 2  
<sup>87</sup>Sr/<sup>86</sup>Sr measured in plants, soil leachates and soils from the Mekong Delta region.

Lab number	<sup>87</sup> Sr/ <sup>86</sup> Sr Grass	± 2 s.e.	<sup>87</sup> Sr/ <sup>86</sup> Sr Leachate	± 2 s.e.	<sup>87</sup> Sr/ <sup>86</sup> Sr soil	± 2 s.e.
225	0.71070	0.00001	0.71008	0.00002	0.71805	0.00003
226	0.71338	0.00005	0.71544	0.00003	0.71573	0.00003
227	0.71368	0.00001	0.71476	0.00002	0.71965	0.00003
228	0.71291	0.00001	0.71467	0.00002	0.71592	0.00004
229	0.71251	0.00003	nd	0.00002	0.71668	0.00003
230	0.71291	0.00002	0.71280	0.00002	0.71759	0.00002
231	0.71178	0.00002	0.71301	0.00002	0.71613	0.00001
232	0.71227	0.00002	0.71999	0.00003	0.72094	0.00004
233	0.71928	0.00004	0.71280	0.00001	0.71949	0.00002

nd = no data.

**Table 3**  
Isotope values in archaeological faunal enamel from Angkor Borei.

Sample	Species	$^{87}\text{Sr}/^{86}\text{Sr}$ recalculated to 0.710275	$\pm 2$ s.e.	$\text{d}^{18}\text{O}$ ‰ (VPDB) enamel	$\text{d}^{18}\text{O}$ ‰ (SMOW) enamel	$\text{d}^{13}\text{C}$ ‰ (VPDB) enamel
AB3133	Dog <i>Canis</i> sp.	0.71108	0.00002	-7.37	23.31	-12.97
AB2809	Pig <i>Sus scrofa</i>	0.71135	0.00008	-6.19	24.53	-13.62
AB3223	Rodent <i>Rattus</i> sp.	0.71069	0.00003	-6.34	24.37	-11.71
AB2383	Elephant <i>Elephas maximus</i>	0.71210	0.00002	nd	nd	nd
AB3221	Cattle <i>Bos</i> sp.	0.71234	0.00003	nd	nd	nd
AB3A81	Gaur <i>Bos gaur</i>	0.71247	0.00005	-3.76	27.04	-6.93

Nd = no data.

-2.92 to -6.79. These values are plotted against the strontium isotope values in Fig. 5.

Carbon and nitrogen isotope values are consistent in both studies. The combined sample values are plotted in Fig. 6 and reflect a diet dominated by  $\text{C}_3$  food resources. The  $\delta^{13}\text{C}$  values for 21 individuals range from -20.37 to -19.12‰ (Mean -19.72  $\pm$  0.39) and the  $\delta^{15}\text{N}$  values range from 9.2 to 11.52‰ (Mean 10.07  $\pm$  0.56).

## 5. Discussion

### 5.1. Previous isotope study

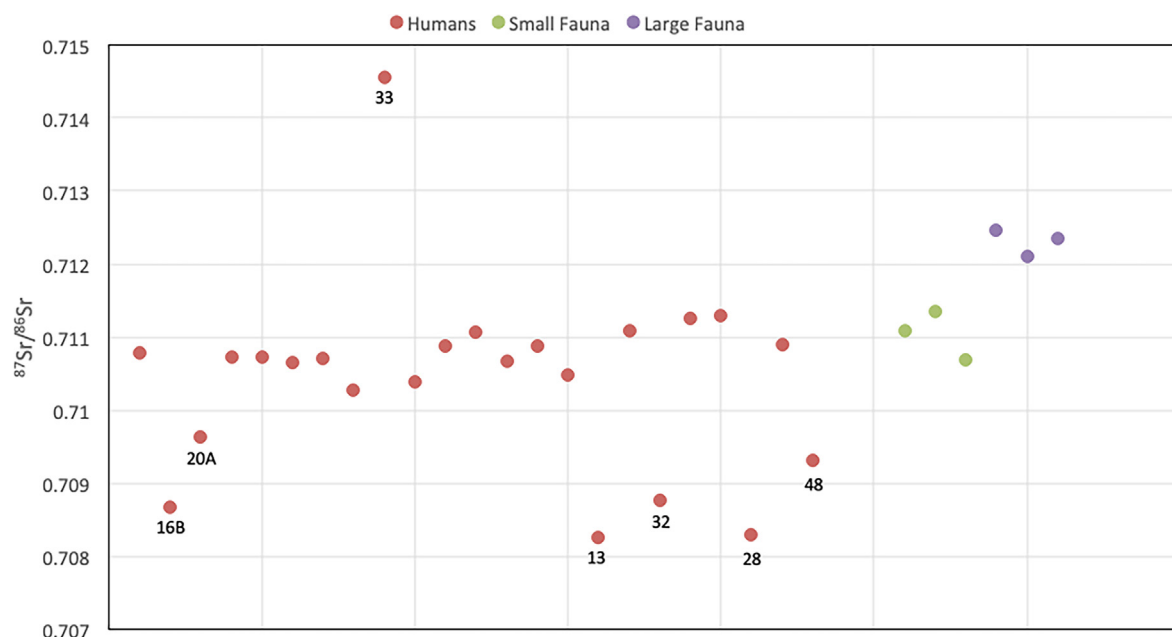
Krigbaum et al. (2008) conducted various stable isotope analyses on human rib bone and molar tooth enamel sampled from 10 of the most complete Vat Komnou individuals with results as summarised in Table 5 (see Ikehara-Quebral et al., 2017:191-236). In this first isotope study, intragroup analysis of the Vat Komnou  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios suggested two geographic origins: one group with elevated ratios the authors suggested may have emigrated from the north and one presumed local group (Krigbaum et al., 2008). The burials that formed the two isotope clusters were not spatially distinct from the other burials in the cemetery but exceptions to the “head pointing SW” burial orientation and a wider assortment of beads were noted in the presumed non-local group

and may represent social status markers (Ikehara-Quebral, 2010:43-44). The second isotope cluster, discerned as the local group, included three of the four Vat Komnou individuals that displayed purposeful dental filing of the anterior teeth.

Based on analyses of both bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , bone apatite  $\delta^{13}\text{C}$ , and  $\Delta^{13}\text{C}$  bone collagen-apatite spacing, Krigbaum et al. (2008) suggested the Vat Komnou inhabitants consumed relatively less terrestrial protein, but with a relatively greater reliance on fish and estuarine/riverine protein compared to Ban Chiang in northeast Thailand (King and Norr, 2006) and two Neolithic samples from China (Hu et al., 2006; Pechenkina et al., 2005). There is little or no evidence of a  $\text{C}_4$  diet at Vat Komnou. A diet dominated by  $\text{C}_3$  food resources, which would include rice, was suggested by  $\delta^{13}\text{C}$  between about -20.5‰ and -18‰ in bone collagen at Vat Komnou, supplemented by some terrestrial protein and substantial riverine/estuarine protein. This is consistent with the environmental setting of Angkor Borei in the Mekong Delta. Contemporary Southeast Asia sites on the Khorat Plateau’s Mun River, like Noen U-Loke (King et al., 2014), illustrate a similar pattern.

### 5.2. Present research

With a larger human sample and the inclusion of faunal material and environmental baseline  $^{87}\text{Sr}/^{86}\text{Sr}$  values, we are able to refine and



**Fig. 4.**  $^{87}\text{Sr}/^{86}\text{Sr}$  values of human and faunal tooth enamel (outliers labelled by burial number).

**Table 4**  
Isotope values in bone and enamel from Vat Komnou human skeletons (this study).

Bur No	Sex, Age (yr)	Tooth	$^{87}\text{Sr}/^{86}\text{Sr}$ recalculated to 0.710275	$\pm 2$ s.e.	$\delta^{18}\text{O}$ ‰ (VPDB) enamel	$\delta^{18}\text{O}$ ‰ (SMOW) enamel	$\delta^{13}\text{C}$ ‰ (VPDB) enamel	$\delta^{13}\text{C}$ ‰ (VPDB) bone coll	$\delta^{15}\text{N}$ ‰ (AIR) Bone coll
14	M, 35–40	M1-26	0.71078	0.00001	-5.1	25.66	-14.01	nd	nd
16B	?M, 20–35	M1-26	0.70868	0.00001	-4.67	26.09	-12.99	-20.0	9.44
20A	?F, 10–12	M1-16	0.70963	0.00002	-3.77	27.02	-13.89	nd	nd
22A	?, 6–8	M1-36	0.71073	0.00004	-5.43	25.31	-13.74	-19.75	9.72
25	?M, 9.5–11	M2-17	0.71072	0.00002	-6.07	24.65	-13.44	-19.41	10.49
27	M, 20–35	M2-17	0.71066	0.00001	-4.48	26.29	-13.7	-19.36	10.27
31A	?F, 3–5	M1-16	0.71070	0.00002	-6.03	24.70	-13.57	-19.41	9.65
31B	?M, 25–35	M1-16	0.71028	0.00004	-6.69	23.95	-13.53	-19.73	9.79
33	?M, 12–15	M1-36	0.71455	0.00003	-5.45	25.29	-14.35	-20.31	9.64
33 A	M, 20–35	M1-46	0.71038	0.00001	-6.46	24.25	-14.38	-20.12	9.66
34	?, 11–13	M1-16	0.71088	0.00002	-6.41	24.3	-13.65	-19.16	9.88
36*	M, 35–45	M2-47	0.71106	0.00003	-2.92	27.55	-13.39	-20.37†	10.77†
39A	?M, 20–50	M2-47	0.71067	0.00002	-6.24	24.47	-14.02	nd	nd
40A	?M, 5–6	M1-46	0.71087	0.00001	-5.59	25.15	-13.28	-19.58	9.20
43B	M, 45–55+	M1-16	0.71048	0.00004	-6.79	23.91	-14.2	-19.54	9.92

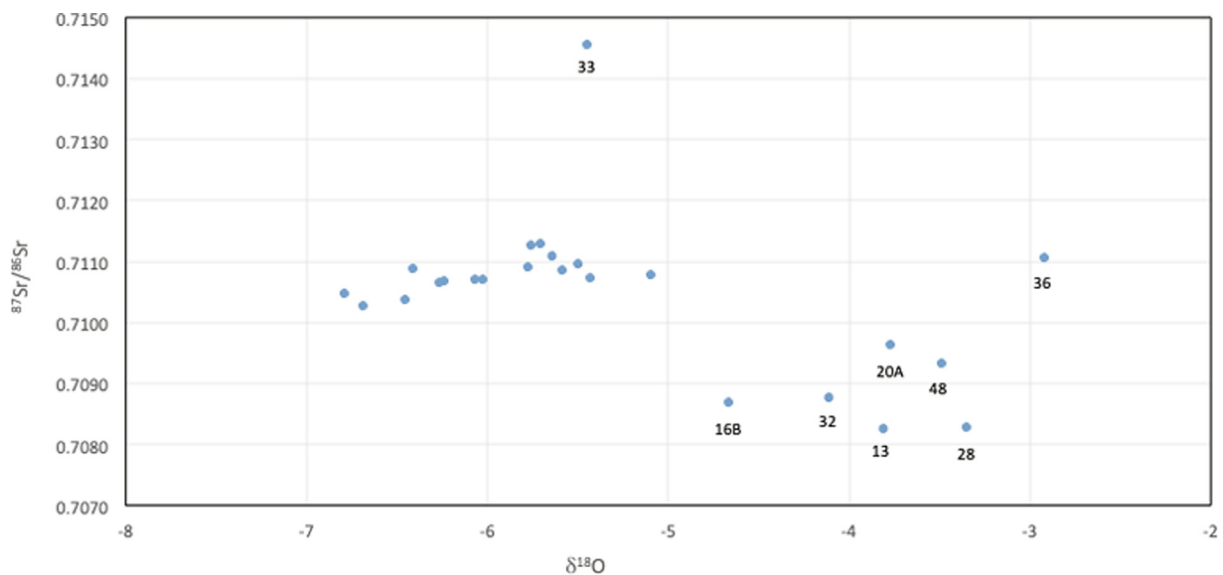
nd = no data; M = Male, F = Female, ? = probable. \*Burial 36 (analysed in both studies) is presented as the average of both analyses. † poor collagen preservation: low %C and %N.

**Table 5**  
Isotope values in bone and enamel from Vat Komnou skeletons (previous study 2008, 2017).

Bur. No.	Sex	Age (Years)	Bone Collagen and Apatite					C:N	Tooth Enamel Apatite			
			$\delta^{13}\text{C}_{\text{co}}$ (‰ vs. VPDB)	$\delta^{15}\text{N}_{\text{co}}$ (‰ vs. AIR)	$\delta^{13}\text{C}_{\text{ap}}$ (‰ vs. VPDB)	$\delta^{18}\text{O}_{\text{ap}}$ (‰ vs. VPDB)	$\Delta^{13}\text{C}_{\text{ap-co}}$ (‰ vs. VPDB)		$^{87}\text{Sr}/^{86}\text{Sr}$	$\delta^{13}\text{C}_{\text{en}}$ (‰ vs. VPDB)	$\delta^{18}\text{O}_{\text{en}}$ (‰ vs. VSMOW)	$\delta^{18}\text{O}_{\text{en}}$ (‰ vs. VPDB)
13	M	25–35	-20.20	9.72	-11.19	-6.19	9.01	2.99	0.70826	-13.61	26.98	-3.81
17	M	30–35	-19.16	10.21	-11.46	-5.72	7.70	3.02	0.71108	-13.64	25.10	-5.64
32	M	19–25	-19.60	11.52	-11.99	-6.01	7.61	2.98	0.70877	-13.27	26.67	-4.11
36	M	35–45	-20.11	10.84	-11.26	-5.97	8.85	3.06	0.71097	-13.42	28.25	-2.58
47	M	25–35	-19.63	10.06	-11.82	-5.85	7.81	3.03	nd	-13.11	25.24	-5.50
5	F	19–21	-19.50	10.67	-11.40	-6.19	8.10	2.97	0.71126	-12.98	24.97	-5.76
22	?F	20–35	-19.90	9.47	-11.86	-5.98	8.04	3.04	0.71129	-13.10	25.02	-5.71
28	F	30–35	-19.93	10.29	-12.77	-5.76	7.16	3.02	0.70829	-13.37	27.46	-3.35
44	F	35–45	-19.12	10.87	-12.47	-6.11	6.65	3.00	0.71090	-13.04	24.95	-5.78
48	F	30–35	-20.29	10.13	-11.57	-6.05	8.72	3.06	0.70932	-13.83	27.31	-3.49

Isotope data from Krigbaum et al. (2008); table from Ikehara-Quebral et al. (2017:205).

co = bone collagen; ap = bone apatite; en = tooth enamel; nd = no data; M = Male, F = Female, ? = probable.



**Fig. 5.**  $\delta^{18}\text{O}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$  values of human tooth enamel (outliers labelled by burial number).

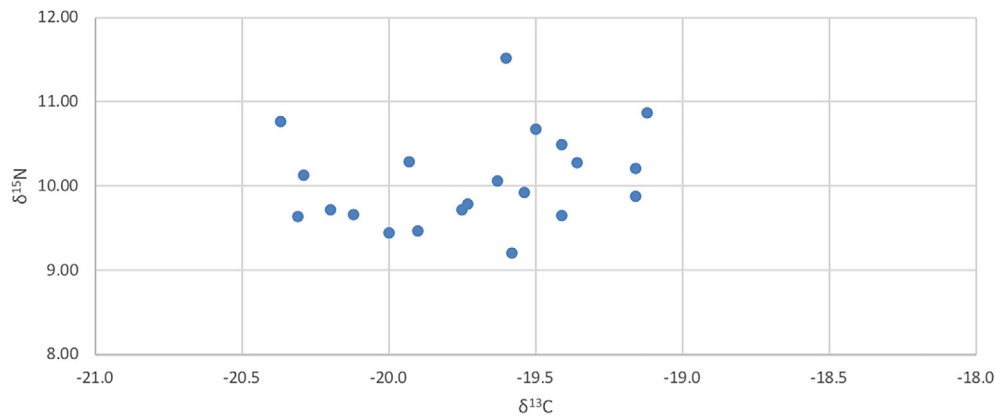


Fig. 6.  $\delta^{13}\text{C}$  vs  $\delta^{15}\text{N}$  values of human bone collagen.

extend our understanding of the Vat Komnou mortuary sample. While the previous study identified two possible clusters of individuals, with the non-local group identified as those with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  values, we are now able to re-evaluate this interpretation in consideration of the faunal, environmental, and additional human values presented in this new study, and observation of the geologic environment beyond the immediate Angkor Borei region. Our analysis indicates that the Vat Komnou sample shows evidence for both local geographic origin (individuals with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  values) and exploitation of the broader regional environment (individuals with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values).

The  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the 23 individuals range from 0.70826 to 0.71455 which is consistent with the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the small fauna ( $0.71104 \pm 0.00033$ ) recovered from the site (p value for the difference is 0.45, ns). Within the 23 individuals there is one tightly clustered group of 16 individuals that we interpret as being local (see Fig. 4) with values ranging between 0.71028 and 0.71129. Six of the 23 individuals showed lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values and may represent a separate group. When these are plotted against the oxygen isotope values, there is further support for this (Fig. 5) in that all six individuals with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values also have more positive  $\delta^{18}\text{O}$  values (-4.67 to -3.35). While we cannot use these data to pinpoint a precise location for the origin of the people, we have noted a small sample nearby with similar less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values (unpublished data), and together with the presence of geology likely to exhibit lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values such as basalt and diorite in the broader region (Fig. 2), there is no need to infer long-distance migration to explain the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of these six individuals. Furthermore, while oxygen isotopes can be useful to interrogate intra-group observations, oxygen isotope locational data in this tropical region is problematic (Cox et al., 2011). Modern Global Natural Isotopes in Precipitation (GNIP) records for Bangkok (Thailand) and Dong Hoi (Vietnam) show monthly variation in  $\delta^{18}\text{O}$ ; from -2.01 to -8.35 and -1.94 to -9.27 respectively (IAEA/WMO, 2019). These variations are greater in magnitude than the differences we see between different samples in this study. Similarly large variation in  $\delta^{18}\text{O}$  has been described between seasonal growth rings in trees in southern Cambodia (Zhu et al., 2012), showing that biological uptake can capture widely varying oxygen isotope values, even from a single location.

Among the 23 individuals, one has a significantly higher  $^{87}\text{Sr}/^{86}\text{Sr}$  value (0.71455) though with a  $\delta^{18}\text{O}$  value well within the range of the predominant oxygen ( $\delta^{18}\text{O}$ ) cluster. As areas of more radiogenic geology are found both in close proximity to the site and in the broader region, the most parsimonious explanation is that this individual may have been sourcing food from areas with higher  $^{87}\text{Sr}/^{86}\text{Sr}$  values such as granite or sandstone found nearby.

It is interesting to note that among the six individuals with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values are three of the four Angkor Borei individuals identified with intentional dental filing (Ikehara-Quebral et al., 2017). While

purposeful dental filing may denote kinship identity or perhaps shared social status (Domett et al., 2013), there is little evidence in terms of the material culture interred with the Vat Komnou mortuary sample to suggest or quantify differential wealth or status. With the exception of Burial 44, a non-outlier (adorned with gold and carnelian beads), the remaining burials are similar in terms of grave goods with most primary burials accompanied by ceramics and/or glass beads (Table 1). It has been noted however that the site suffered from extensive looting prior to excavation resulting in the loss of a rich array of material culture (Stark, 1998:191).

The range of strontium isotopic values derived from Angkor Borei skeletal material and faunal remains indicates that the individuals interred at the Vat Komnou cemetery utilised both the immediate and the region's broader environment and resources. A growing body of archaeological evidence suggests that the Mekong Delta was a dynamic social arena during the early first millennium CE (Manguin and Stark, in press), and Angkor Borei was one of its most important regional centres. Linked by canals and rivers to the South China Sea coast, archaeological investigation of the site attests to expansive regional interactional systems and mercantile activity.

Evidence for trade and interregional interaction is demonstrated by the presence of exotic grave goods such as glass and stone beads and by similarities in material culture with other regional urban centres (Carter, 2010, 2012, 2015; Stark and Fehrenbach, 2019). A few centuries later, Chinese documentary records reported significant foreign populations in the region (Wheatley, 1961:17), a claim that some researchers in peninsular Thailand support with evidence for presence of South Asian craft production technologies (Bellina, 2003).

While long-distance mobility or migration does not appear to characterise the Vat Komnou mortuary sample analysed in this study, this does not preclude significant mobility within similar geological provinces such as the vast alluvium covered lowlands of Cambodia. In areas of homogenous geology or spatially separated areas of similar geology and strontium isotopic characterisation, movement will not be perceptible using these methods.

## 6. Conclusion

While archaeological evidence has demonstrated expansive regional interaction, this study finds no conclusive support for long-distance migration of people at this critical juncture in protohistory. Rather, in the context of the faunal and plant samples analysed in this study and consideration of the broader geologic variability of the region, it would appear that the mortuary sample exhibits evidence for local geographic origin and wider regional utilisation. This does not however obviate potentially significant mobility within similar geological provinces, nor the exploitation of food resources from spatially separate, but isotopically similar locales. It does however suggest that the trajectory to

statehood is driven by myriad factors and that evidence for increasing socio-political complexity can be demonstrated through expanding trade and exchange, settlement growth and mobility, and social differentiation.

Most sampled humans were indistinguishable from the small low mobility fauna, and those individuals with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures may have been accessing food resources from less radiogenic areas observed within the broader catchment area of the site. Plausible areas, based on sampling and geological maps, can be inferred within 30–50 km of the site.

Future research might usefully be directed to higher resolution environmental sampling around Angkor Borei to further refine diet catchment  $^{87}\text{Sr}/^{86}\text{Sr}$  variability. This would include the analysis of additional vegetation samples in and around the site and further sampling of small fauna from the same stratigraphic context as the human burials. A comparison between the results obtained from the Vat Komnou mortuary assemblage with that from other known Protohistoric/Iron Age sites in Cambodia will be undertaken shortly. This future analysis will facilitate a comparative assessment of population dynamics and resource acquisition strategies throughout Cambodia during this period of increasing socio-political complexity prior to the rise of the Angkorian state.

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