archaeometry

Archaeometry ••, •• (2020) ••–•• doi: 10.1111/arcm.12557

BASELINE BIOAVAILABLE STRONTIUM ISOTOPE VALUES FOR THE INVESTIGATION OF RESIDENTIAL MOBILITY AND RESOURCE-ACQUISITION STRATEGIES IN PREHISTORIC CAMBODIA*

L. G. SHEWAN†
School of Earth Sciences, University of Melbourne, Melbourne, VIC, Australia

R. A. ARMSTRONG
Research School of Earth Sciences, The Australian National University, Canberra, ACT, Australia

D. O'REILLY
School of Archaeology and Anthropology, The Australian National University, Canberra, ACT, Australia

Strontium (Sr) isotope ratios ($^{87}Sr/^{86}Sr$) measured in human skeletal material can increase one's understanding of the residential behaviour and resource-acquisition strategies of past populations. The paper maps bioavailable $^{87}Sr/^{86}Sr$ variation in 183 plant and soil samples across Cambodia. Bioavailable $^{87}Sr/^{86}Sr$, as measured in plants, differs significantly between four major geological units. The data set will support future investigations of skeletal material from Cambodian archaeological sites. Baseline $^{87}Sr/^{86}Sr$ data should be applied judiciously to skeletal populations, and in concert with other lines of evidence, to identify potential geographical outliers rather than to ascribe specific locations from which individuals may have moved.

KEYWORDS: CAMBODIA, STRONTIUM ISOTOPES, BASELINE MAP, PALEOMOBILITY

INTRODUCTION

Cambodia has long held archaeological interest (Corre 1879; Mansuy 1902; Mourer 1994), where the primary focus has been on the rise and fall of the Khmer Empire centred on Angkor (Fletcher *et al*. 2006). Much of what is known about the Angkorian civilization is derived from the magnificent religious monuments, artworks and inscriptions, and, in recent years, from the exquisitely detailed record of landscape modification obtained from high-resolution airborne laser scanning technology (Evans and Fletcher 2015; Evans 2016; O'Reilly *et al*. 2017). In the past 20 years, more research has been undertaken at archaeological sites that predate the foundation of the Angkorian Empire (802 CE), and specifically about the populations who lived in these pre-state societies (Stark 1998, 2004, 2006; Ly 1999; Albrecht *et al*. 2000; Dega 2001; Phon 2004; Pottier *et al*. 2004; O'Reilly *et al*. 2008, in press; Reinecke *et al*. 2009; Yasuda 2013; O'Reilly and Shewan 2015, 2016a, 2016b). The majority of the excavated prehistoric sites in Cambodia date to the Iron Age (*c*.500 BCE–500 CE). This is a period of transformational change, characterized by increasing socio-political complexity, burgeoning interregional trade, technological transfer and developments in settlement use (Carter 2010; O'Reilly and

*Received 6 July 2019; accepted 5 March 2020
†Corresponding author: email louise.shewan@unimelb.edu.au

Shewan 2015, 2016a, 2016b; O'Reilly *et al*. 2017; Pryce *et al.* 2017). In the absence of epigraphic evidence for this period, knowledge about pre-state social organization, health, diet, material culture and mercantile activity is gleaned from residential and mortuary contexts, including human and faunal skeletal assemblages and the accompanying grave goods.

The measurement of strontium (Sr) isotope ratios (^{87}Sr/^{86}Sr) ratios in human tooth enamel from skeletons interred in Iron Age mortuary contexts is used to enhance one's understanding of human settlement behaviour and resource-acquisition strategies in this dynamic period before the rise of the Angkorian Empire. However, in isolation, these isotopic measurements are of limited value unless baseline biologically available Sr variation is characterized throughout the study region, around the archaeological sites and surrounding areas. The paper presents the first baseline map of biologically available Sr isotope ratios from selected regions in Cambodia. It has also compared the sample values between four major geological units (Jurassic–Cretaceous sandstone, basalt, young alluvium and old alluvium) in the sampled regions. The database is intended as a preliminary assessment of the spatial variation in bioavailable ^{87}Sr/^{86}Sr and will be updated as further sampling is completed and with the addition of archaeological faunal enamel from archaeological contexts. For the assessment of individual archaeological sites and human skeletal populations recovered from these contexts, it is advisable to use multiple lines of data. These include, where feasible, higher resolution ^{87}Sr/^{86}Sr environmental sampling, archaeological faunal enamel from the same region, use of other isotopic systems and consideration of the material culture assemblage associated with the burials in order to facilitate robust archaeological interpretation and understanding.

SR ISOTOPES

Sr has four naturally occurring isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr). ^{87}Sr is radiogenic and produced by the radioactive decay of ^{87}Rb (rubidium), which has a half-life of 48 million years (Faure and Mensing 2005). Sr isotope ratios measured in rock, soil and groundwater vary according to the age and composition of the underlying geology of the region. In general, for rocks that are old ($>$ 100 mya) with high Rb/Sr ratios such as old granites, the isotopic ratio is high ($>$ 0.710). In geologically young rocks (1–10 mya) with low Rb/Sr ratios, the ^{87}Sr/^{86}Sr is low ($<$ 0.706). As a high-mass element, this variability is carried with no measurable fractionation from weathered bedrock to vegetation and via the diet to the teeth and bones (biological apatite) of animals and humans where Sr substitutes for calcium (Ca) (Bentley 2006).

Sr isotope ratios have been used in a wide variety of archaeological, palaeontological, ecological and modern source-tracing investigations (e.g., Ericson 1985, Price *et al.* 1994a, 1994b; Sealy *et al*. 1995; Capo *et al*. 1998, Sillen *et al*. 1998; Hoppe *et al*. 1999; Beard and Johnson 2000; Blum 2000, Montgomery *et al*. 2000; Bentley 2006; Budd *et al*. 2004; Hoddell *et al*. 2004; Shewan 2004; Bentley *et al*. 2005, 2007, 2009; Slovak and Paytan 2011; Bataille and Bowen 2012; Evans *et al*. 2012; Laffoon *et al*. 2012; Willmes *et al*. 2018 among others). In bioarchaeological research, the methodology has become increasingly used to identify non-local individuals in (pre)/historic mortuary populations and to investigate residential mobility and migration patterns.

The interpretation of isotopic values measured in human skeletal material requires the assessment of regional Sr isotope variability in the study region. While geological maps are a useful starting point to infer isotopic Sr variability in the study region, they reflect bedrock geology and not the ^{87}Sr/^{86}Sr ratios available to living organisms. Biologically available ^{87}Sr/^{86}Sr may deviate significantly from whole rock ratios due to differential weathering of the source material, mixing processes, atmospheric deposition such as dust, rainfall and sea spray, and the use of fertilizers with potentially variable Sr concentrations and ratios (Aberg 1995, Sillen *et al*. 1998; Poszwa *et al*. 2004; Willmes *et al*. 2018). To gauge local biologically available Sr, $^{87}Sr/^{86}Sr$ ratios have variously been measured in plants, soils, soil leachates, water and faunal teeth from archaeological deposits (Evans and Tatham 2004; Maurer *et al*. 2012; Kootker *et al*. 2016). Ideally, all sample types should be included, but this is not always feasible.

Here we provide the first baseline map of biologically available Sr from selected locations in Cambodia (Fig. 1) based on plant and soil specimens sampled from areas near known Iron Age sites and other regions. The study is restricted to areas accessible by road. Ongoing collection and analysis will extend sample coverage (particularly to the east) and will permit future updates of the database. The baseline map is intended as a resource for future bioarchaeological and zooarchaeological research and investigations concerned with material culture provenance.

GEOLOGICAL SETTING

Cambodia covers an area of approximately 181,000 km^2 and is divided into 25 provinces (including Phnom Penh). Topographically, much of Cambodia consists of a lowland plain with the majority of the country at an elevation < 100 masl. The plain is framed by the Dangrek Mountains to the north-west (highest peak, 753 masl), the Damrei (Elephant) Mountains to the south (highest peak, 1081 masl), the Krâvanh (Cardamom) Mountains to the south-west (highest peak, 1813 masl), and a high plateau in the north-east reaching heights > 1500 masl.

The dominant water features include the Mekong River and its tributaries, and the Tonle Sap lake and river system. The Mekong flows southward from the Tibetan Plateau through mountain gorges and valleys from China, Myanmar, Thailand, Laos and through the lowlands of Cambodia and Vietnam, debouching in the Mekong Delta into the South China Sea. The river drains a total area of approximately 800,000 km^2, with a long-term average sediment flux estimated to be about

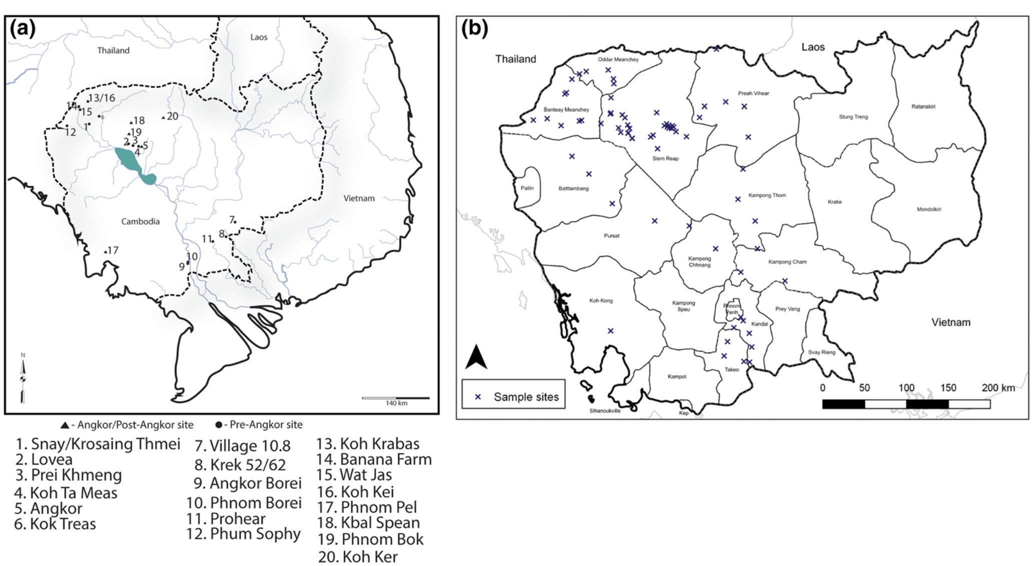

Figure 1 *(a) Locations of a selection of prehistoric, protohistoric and historic archaeological sites in Cambodia; and (b) sample location sites. [Colour figure can be viewed at wileyonlinelibrary.com]*

144 ± 34 million tonnes per year (Kondolf *et al*. 2018). The Mekong joins with the Tonle Sap River near Phnom Penh, and during the rainy season (May–September) excess sediment-laden water in the Mekong drains into the Tonle Sap (Great Lake) by reverse flow, flooding the alluvial plains surrounding the lake (Penny 2006). With the dry season, the water of the Tonle Sap flows back down the Tonle Sap River into the Mekong.

While geological research in Cambodia dates from the end of the 19th century, geological information about Cambodia has steadily increased since the establishment of the Cambodian Department of Geology and Mines in 1985 (Sotham 1997). The stratigraphy of Cambodia is summarized in the United Nations' Economic and Social Commission for Asia and the Pacific (ESCAP), Atlas of Mineral Resources of the ESCAP Region (United Nations 1993) and other reviews (Sotham 1997; Workman 1977). The geology is diverse and comprises sedimentary formations, metamorphic and igneous rocks from the Precambrian through to the Quaternary (Sotham 1997) (Fig. 2). While there are no dated Precambrian rocks in Cambodia, Precambrian–Proterozoic metamorphic units including gneiss, amphibolites and schist can be found in the north-east of the country and near the western border near Pailin. Cambrian argillites are recorded in Stung Treng province dated by a Trilobite specimen. Cambrian to Ordovician micaceous quartzite outcrops can be found in the south-west with Cambro-Silurian age schist and quartzite units found in the north-east and near the Laos–Cambodia border. Devonian to Carboniferous sandstone and shale can be found in the east, west and south-west of Cambodia and near Kratie, with Upper Carboniferous–Permian limestone represented in Stung Treng province and the Kampot area. The marine Permian limestone is recorded in Banteay Meanchey and Battambang in the west and in Kampot in the south. Mesozoic deposits cover a large part of the region. Triassic rocks are common and include shale, sandstone, breccia, conglomerate,

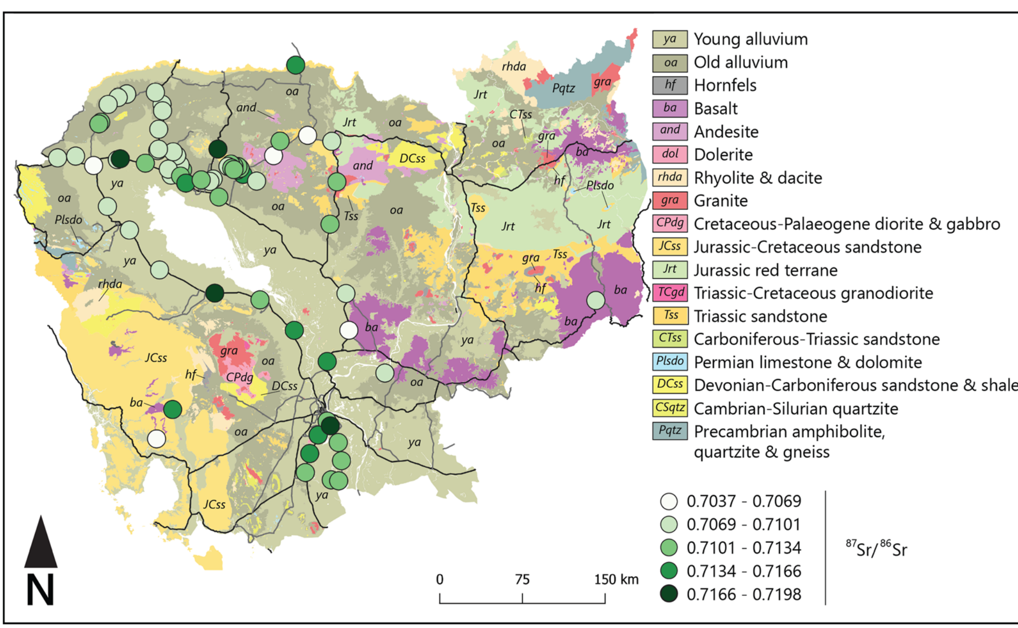

Figure 2 *Geology of Cambodia with bioavailable $^{87}Sr/^{86}Sr$ values from modern plants. Source: Map based on data from Open development Cambodia (https://opendevelopmentcambodia.net/dataset/?id=geology-of-cambodia-2006). [Colour figure can be viewed at wileyonlinelibrary.com]*

limestone and some volcanic deposits such as andesite, rhyolite and dacite. The early Triassic is considered to be more marine in character with continental phases more common in the late Triassic. In western Cambodia, Triassic units have been found in Pailin, Pursat and Kompong Speu, and in the east in Preah Vihear and Kratie.

The main characteristic unit of the Lower-Middle Jurassic is the *Terrain Rouge* comprising conglomerates, sandstones and siltstones of continental origin occupying large areas of eastern Cambodia and extending into north central Cambodia with isolated outcrops in the west. This series can > 2000 m in thickness. The Upper Jurassic–Cretaceous includes the *Gres Superieures* (upper sandstone) sequence represented in the south-western Cardamom Mountain region and northern Cambodia, including Phnom Kulen and the Dangrek Range, with isolated outcrops in Kratie and Stung Treng. This series consists mostly of quartz-rich sandstone and conglomerates that can > 2000 m in thickness. Volcano-sedimentary rocks of Jurassic age, comprising rhyolites, dacites and tuffs, are represented in western Cambodia in Pursat.

The central plains are mostly covered by alluvial deposits of Quaternary to Recent age, with protruding hard rocks. Neogene–Quaternary sediments are referred to as old alluvium. These sediments, varying in thickness, from thin to > 8 m, are composed mostly of claystone, silt and sand, overlying lateritized or conglomerate beds. Young alluvium Quaternary sediments, generally occupying lowland regions of the central alluvial plain, 0–40 masl, are widespread and contain grits, pebbles, sand, silt and claystone. This alluvium can reach > 200 m in thickness in some areas.

Intrusive suites of Paleozoic to Paleogene age are represented in the north-east, Preah Vihear, Kompong Chnang and Pursat, and in the south near Kampot. Volcanic rocks include Neogene–Quaternary basalts (occurring mostly in the east, but also near Pailin, Preah Vihear and the Cardamom Mountains) and Permian–Mesozoic rhyolites, dacites and andesites.

METHODOLOGY

Sr isotope ratios

Plant and soil samples were collected from a range of geological provinces across Cambodia. Plant specimens consisted of shallow rooted grasses and were taken a few centimetres away from soil samples which were collected at depths between 0 and 5 cm. Sample sites were concentrated in the western part of the country, in regions where archaeological research is being conducted by the authors (Fig. 1). We also sampled in other areas accessible by road. Access to eastern Cambodia was limited at the time of collection. Further sampling and analysis will become possible as other regions are explored. Sample sites were geolocated with a hand-held global positioning satellite device; samples were dried and transported to Australia for analysis. Sample sites were classified into four categories, including Jurassic–Cretaceous sandstone ($n = 12$), basalt ($n = 4$), young alluvium ($n = 38$) and old alluvium ($n = 20$), based on their location compared with geological maps (United Nations 1993). In addition, a single sample came from an area of exposed granite.

Plant and soil samples were placed in porcelain crucibles and ashed for 8 h at 800°C. A total of 10–20 mg from each plant sample were placed in an acid-cleaned Teflon beaker and digested in ultrapure concentrated nitric acid (HNO_3), and for the soils the addition of hydrofluoric acid (HF). Sr was separated and concentrated using Sr-Spec ion-exchange columns. For soil leachates, 1 g of soil was placed in a centrifuge tube with 1 ml of ammonium nitrate (NH_4NO_3), shaking the suspension overnight to extract the bioavailable Sr component. Following digestion, Sr was separated and concentrated using Sr-Spec ion-exchange columns. $^{87}Sr/^{86}Sr$ was measured using thermal ionization mass spectrometry on two mass spectrometers over a period of several years at the Research School of Earth Sciences, Australian National University. The earliest samples were analysed using a Finnigan MAT261 (with the samples loaded onto Ta filaments), and the later samples using a Thermo Finnigan Triton mass spectrometer (with the samples loaded with TaF onto Re filaments). All analyses were corrected for mass fractionation using $^{86}Sr/^{88}Sr = 0.1194$, and the $^{87}Sr/^{86}Sr$ ratios were monitored by frequent analyses of the NBS standard SRM987. The averages over the relevant periods for the two mass spectrometers were 0.71023 ± 0.00003 (2 SD (standard deviation); $n = 30$) for the Mat261 and 71025 ± 0.00002 (2 SD; $n = 74$) for the Triton. All values are reported normalized to 0.71023. Samples were compared using paired and unpaired Student's *t*-tests as appropriate.

RESULTS

Plant and soil samples were analysed from 76 locations (Fig. 2 and Table 1). As has been demonstrated in various studies in other regions, whole rock and soil Sr values do not necessarily correlate with the bioavailable Sr (Sillen *et al*. 1998; Price *et al*. 2002; Evans and Tatham 2004). We have confirmed this finding in a monsoonal environment by measuring $^{87}Sr/^{86}Sr$ in bulk soils and comparing these results with $^{87}Sr/^{86}Sr$ values obtained from leached soils and plants. In the 45 locations where we had all three sample types (soil, leachate, grass), we performed a two-tailed Student's *t*-test for paired samples. This showed soil samples to be highly significantly different to plant samples (soil $= 0.71341 \pm 0.00634$ compared with plants $= 0.71062 \pm 0.00310$, $p = 0.0005$). Analyses of soil leachates were intermediate, at 0.71172 ± 0.00391 between plants (0.71062 ± 0.00310, $p = 0.042$) and soil (0.71341 ± 0.00634, $p = 0.02$). These observed differences between leachates and plants are consistent with previous reports from other regions (Maurer *et al*. 2012; Willmes *et al*. 2018).

Plant samples

The range of $^{87}Sr/^{86}Sr$ ratios for plants across the study region varied from 0.7037 to 0.7198 (Fig. 2). Generally, the most radiogenic $^{87}Sr/^{86}Sr$ ratios were measured in grasses growing on areas of Jurassic–Cretaceous sandstone and granite, while the least radiogenic values were recorded in plants growing on basalt (Figs 2–5). The highest average $^{87}Sr/^{86}Sr$ values were recorded in plant samples from Jurassic–Cretaceous sandstone (mean ± SD = 0.7131 ± 0.002), which was significantly higher than both basalt (0.7054 ± 0.002, $p < 0.0001$) and old alluvium (0.7094 ± 0.002, $p < 0.0001$), but not significantly different to young alluvium (0.7116 ± 0.003, $p = 0.14$, n.s.). Plant samples from basalt areas produced the lowest $^{87}Sr/^{86}Sr$ values and significantly different from the three other geological units (sandstone $p < 0.0001$; young alluvium $p = 0.0003$ and old alluvium $p = 0.002$). In addition, although considerable $^{87}Sr/^{86}Sr$ overlap exists between plant samples taken from young and old alluvium, the difference between them was significant (0.7116 ± 0.003 versus 0.7094 ± 0.002, $p = 0.004$) (Table 2).

DISCUSSION

Cambodia is dominated by the broad central plain surrounding Tonle Sap Lake and the Mekong River and its tributaries, covered with Quaternary sediments with isolated hills of basement rocks. Areas surrounding the plain comprise metamorphic, sedimentary, volcanic and intrusive

Table 1 *Plant, soil and leachate $^{87}Sr/^{86}Sr$ for Cambodia*

Sample	*East UTM 48 N*	*North UTM 48 N*	*$^{87}Sr/^{86}Sr$ soil*	*±2SE*	*$^{87}Sr/^{86}Sr$ soil leachate*	*±2SE*	*$^{87}Sr/^{86}Sr$ grass*	*±2SE*	*Geology*
24	463931	1351134	0.71891	0.00004	0.71327	0.00003	0.71344	0.00001	Young alluvium
25	432790	1378818	0.71198	0.00001			0.71283	0.00004	Young alluvium
26	391782	1384925	0.74238	0.00001	0.71665	0.00008	0.71655	0.00002	Young alluvium
27	341614	1406037	0.70937	0.00005	0.70838	0.00001	0.70829	0.00001	Young alluvium
28	314262	1442020					0.70753	0.00001	Young alluvium
30	294333	1463508	0.70771	0.00002			0.70790	0.00002	Young alluvium
35	281832	1500704	0.70730	0.00002	0.70754	0.00001	0.70644	0.00002	Young alluvium
36	303356	1506006	0.71106	0.00002	0.71079	0.00001	0.70933	0.00002	Young alluvium
37	249120	1507683	0.70665	0.00002	0.70706	0.00001	0.70696	0.00002	Old alluvium
38	288336	1540123	0.71130	0.00001	0.71000	0.00001	0.71036	0.00002	Old alluvium
39	311867	1565562	0.70748	0.00002			0.70798	0.00002	Old alluvium
40	343931	1556366	0.70770	0.00001			0.70876	0.00002	Old alluvium
41	339958	1514275	0.70963	0.00001			0.70891	0.00002	Young alluvium
42	352089	1491960	0.70929	0.00004	0.70917	0.00005	0.70952	0.00001	Young alluvium
43	395480	1472074	0.71568	0.00001			0.71313	0.00001	Young alluvium
44	417364	1492652	0.72005	0.00002			0.71391	0.00001	Jurassic–Cretaceous sandstone
45	445168	1509711	0.70380	0.00001	0.70367	0.00002	0.70375	0.00002	Basalt
46	476056	1528171	0.71825	0.00002	0.71332	0.00001	0.70546	0.00002	Old alluvium
47	497966	1522709	0.70858	0.00001			0.70710	0.00002	Old alluvium
48	502642	1485920	0.70405	0.00001	0.70508	0.00002	0.71273	0.00001	Granite
49	496377	1447318	0.71117	0.00002	0.71304	0.00002	0.71089	0.00001	Old alluvium
50	490446	1410852	0.71002	0.00006	0.71097	0.00001			Young alluvium
51	510815	1384564	0.71142	0.00001	0.70916	0.00002	0.70809	0.00001	Young alluvium
52	513515	1351168	0.70428	0.00003	0.70468	0.00001	0.70440	0.00001	Basalt
53	493790	1322789	0.71816	0.00001	0.71311	0.00001	0.71447	0.00001	Young alluvium
201	365488	1484809	0.71458	0.00001	0.71388	0.00002	0.71363	0.00001	Young alluvium
202	361056	1491121	0.71233	0.00002	0.71102	0.00006	0.71158	0.00001	Young alluvium
203	362621	1496713	0.71148	0.00001	0.71113	0.00002	0.71159	0.00002	Young alluvium
204	360396	1501001	0.70985	0.00001	0.70983	0.00002	0.70985	0.00002	Young alluvium

(*Continues*)

205	357207	1509698	0.70828	0.00002	0.70769	0.00002	0.70900	0.00001	Old alluvium
206	354048	1513179	0.70946	0.00002	0.70880	0.00002	0.70858	0.00002	Old alluvium
207	349563	1497479	0.71074	0.00001	0.70940	0.00001	0.70913	0.00001	Young alluvium
208	409225	1497076	0.71468	0.00002	0.71236	0.00002	0.71188	0.00001	Jurassic–Cretaceous sandstone
209	411970	1496413	0.71679	0.00001	0.71572	0.00003	0.71558	0.00001	Jurassic–Cretaceous sandstone
210	414718	1498185	0.71681	0.00002	0.71210	0.00004	0.71208	0.00002	Jurassic–Cretaceous sandstone
211	412891	1499726	0.71674	0.00002	0.71794	0.00002	0.71331	0.00001	Jurassic–Cretaceous sandstone
212	409088	1500325	0.71513	0.00002	0.71543	0.00001	0.71224	0.00001	Jurassic–Cretaceous sandstone
213	406261	1502056	0.71305	0.00002	0.71500	0.00002	0.71191	0.00002	Jurassic–Cretaceous sandstone
214	403698	1499865	0.72115	0.00002	0.72041	0.00002	0.70838	0.00001	Jurassic–Cretaceous sandstone
215	429729	1486580	0.70765	0.00002	0.72042	0.00002	0.70765	0.00001	Old alluvium
216	328765	1502868	0.70995	0.00002	0.71091	0.00002	0.71091	0.00002	Young alluvium
217	340725	1515663	0.71042	0.00001	0.70909	0.00002	0.70813	0.00007	Young alluvium
218	340898	1533711	0.71141	0.00002	0.71024	0.00002	0.70972	0.00002	Old alluvium
219	344380	1550520	0.70849	0.00002	0.70783	0.00002	0.70854	0.00002	Old alluvium
220	337829	1567155	0.71142	0.00001	0.71099	0.00004	0.70838	0.00001	Old alluvium
222	304086	1562599	0.71038	0.00001	0.71003	0.00003	0.70970	0.00002	Old alluvium
223	294991	1556299	0.71191	0.00002	0.70892	0.00002	0.70850	0.00001	Young alluvium
224	286515	1538562	0.71142	0.00002			0.71175	0.00002	Old alluvium
225	493757	1268894	0.71805	0.00003	0.71008	0.00002	0.71070	0.00001	Young alluvium
226	485569	1256212	0.71573	0.00003	0.71544	0.00003	0.71338	0.00005	Young alluvium
227	477962	1239325	0.71965	0.00003	0.71476	0.00002	0.71368	0.00004	Young alluvium
228	473938	1222064	0.71592	0.00004	0.71467	0.00002	0.71291	0.00002	Young alluvium
229	497435	1215394	0.71668	0.00003			0.71251	0.00003	Old alluvium
230	504255	1214532	0.71759	0.00002	0.71280	0.00002	0.71291	0.00002	Young alluvium
231	506770	1232821	0.71613	0.00001	0.71301	0.00002	0.71178	0.00002	Young alluvium
232	503875	1249379	0.72094	0.00004	0.71999	0.00003	0.71227	0.00002	Young alluvium
233	496620	1264563	0.71949	0.00002	0.71280	0.00001	0.71928	0.00004	Young alluvium
300	387378	1486315					0.70950	0.00002	Old alluvium

(*Continues*)

302	365560	1484741			0.71339	0.00002	Young alluvium
303	365551.43	1484819.17			0.71300	0.00002	Young alluvium
304	365519.75	1484817.42			0.71320	0.00002	Young alluvium
306	365509.02	1484833.77			0.71370	0.00002	Young alluvium
Chi Phat	338939	1252691	0.70344	0.00001	0.70449	0.00005	Basalt
Dve	379447	1487696			0.71286	0.00002	Old alluvium
E. Valley	737652	1378266			0.70867	0.00001	Basalt
Koh Ker	451056.5	1522888.7			0.71326	0.00002	Old alluvium
Kspean	394636.1	1515685.2			0.71782	0.00001	Jurassic–Cretaceous sandstone
Kulen A8	407105	1498417	0.71749	0.00002	0.71177	0.00002	Jurassic–Cretaceous sandstone
Kulen Stg	409129	1497064			0.71266	0.00001	Jurassic–Cretaceous sandstone
P. Bok 2 g	390220	1488476			0.70804	0.00001	Old alluvium
P. Vihear	465241	1591750			0.71541	0.00002	Jurassic–Cretaceous sandstone
Phum Lovea	360707.2	1491086.7	0.71172	0.00003	0.71160	0.00001	Young alluvium
Phum Snay	305967.3	1506846.5			0.71977	0.00002	Young alluvium
Phum Sophy	265455	1509283			0.70869	0.00005	Young alluvium
Prei Khmeng	365560	1484741	0.71542	0.00002	0.71340	0.00001	Young alluvium
Wat Moha	546199.3	1312279			0.70920	0.00002	Young alluvium

UTM, universal transverse mercator

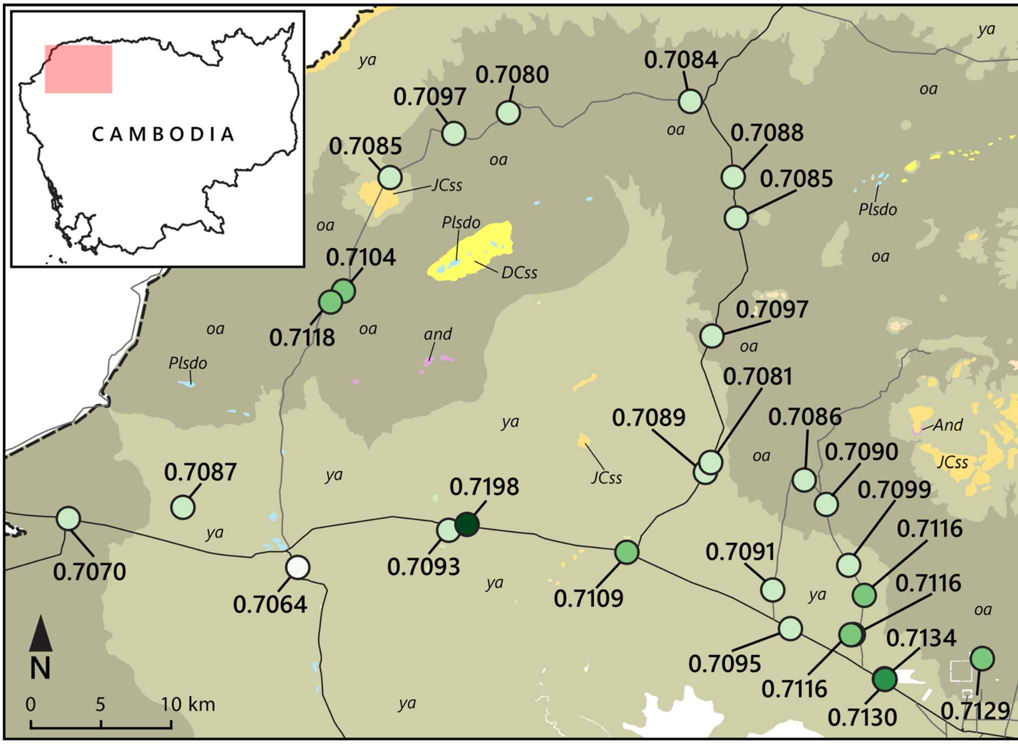

Figure 3 *North-west Cambodia: $^{87}Sr/^{86}Sr$ measurements of plant samples. The main geological units are young alluvium (light green) and old alluvium (green) with other units identified according to Fig. 2 legend. Source: Map based on data from Open development Cambodia (https://opendevelopmentcambodia.net/dataset/?id=geology-of-cambodia-2006). [Colour figure can be viewed at wileyonlinelibrary.com]*

rocks of different ages and composition (Sotham 1997; Workman 1977). While ideally $^{87}Sr/^{86}Sr$ baseline maps for archaeological provenance studies might usefully compare all possible samples types including whole rock, soil, soil leachates, ground water, flora, archaeological and modern faunal enamel, this is not always practicable. The present study used plant samples to approximate bioavailable $^{87}Sr/^{86}Sr$ variability across the region. In areas where we analysed plants, soils and soil leachates from the same location, considerable divergence was recorded between plant, soil and soil leachate $^{87}Sr/^{86}Sr$ values, questioning the utility of using soil leachates in this region to approximate the bioavailable $^{87}Sr/^{86}Sr$.

The study has identified that plant $^{87}Sr/^{86}Sr$ ratios generally reflect the surface geology of the region and can discriminate between different lithologies. Furthermore, we find sufficient variation in bioavailable $^{87}Sr/^{86}Sr$ within the region to investigate the residential mobility of past populations using Sr isotope analysis of skeletal material. Plants growing on Jurassic–Cretaceous sedimentary units in areas such as the Phnom Kulen Plateau, the Dangrek ranges and the Cardamom Mountains had $^{87}Sr/^{86}Sr$ values that ranged from 0.7084 to 0.7156. Lying south of the Dangrek Mountains and approximately 30 km north of Angkor, the Kulen region of north central Cambodia was an important quarry source during the Angkorian period (Carò *et al*. 2010; Carò and Im 2012). Plants sampled from areas of basalt including locations in the Cardamom Mountains (south-west Cambodia) and north and central Cambodia display lower $^{87}Sr/^{86}Sr$ values:

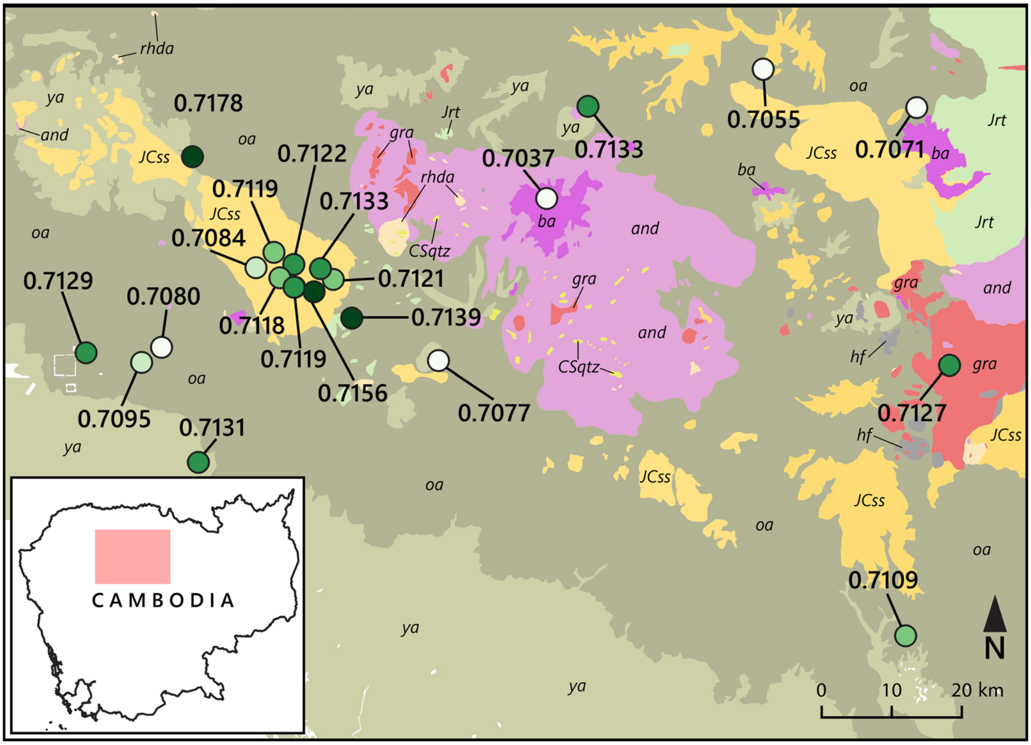

Figure 4 *North central Cambodia: $^{87}Sr/^{86}Sr$ measurements of plant samples. The major geological units are marked (see Fig. 2 legend for geological unit abbreviations). Source: Map based on data from Open development Cambodia (https://opendevelopmentcambodia.net/dataset/?id=geology-of-cambodia-2006) [Colour figure can be viewed at wileyonlinelibrary.com]*

0.7047, 0.7037 and 0.7044, respectively. A value of 0.7087 measured in a single plant specimen from the basaltic area in Mondolkiri (eastern Cambodia) presents a higher $^{87}Sr/^{86}Sr$ value. This may simply reflect a different rock composition (not measured) or may include Sr from other sources, including Quaternary laterite deposits found in close proximity (Piilonen *et al*. 2018) or the presence of weathered soils modified by atmospheric input (precipitation and dust).

Plant samples growing on old and young alluvium displayed the widest range of $^{87}Sr/^{86}Sr$ values, as would be expected given the range of source components in the alluvium and fluctuation in river discharge, sedimentation rates and river course over time (Fig. 6). $^{87}Sr/^{86}Sr$ measured in plants growing on young alluvium (sand, silt, clay and some gravel) ranged from 0.7064 to 0.7198 and generally increased in value from north to south, though no definitive gradient is discernible, and outliers exist. Plants growing on old alluvium (sand, silt, clay, laterite and gravel) ranged from 0.7055 to 0.7133, reflecting different sources of Sr in the alluvial composition.

In areas of specific archaeological interest, where human skeletal samples will be analysed to examine residential behaviour and landscape utilization, the $^{87}Sr/^{86}Sr$ baseline plant data will be supplemented with the analysis of archaeological faunal enamel. Using animals that fed locally, and obtained from the same area and stratigraphic contexts as the human burial assemblage, will help to refine local catchment $^{87}Sr/^{86}Sr$ variability. $^{87}Sr/^{86}Sr$ measured in the enamel of

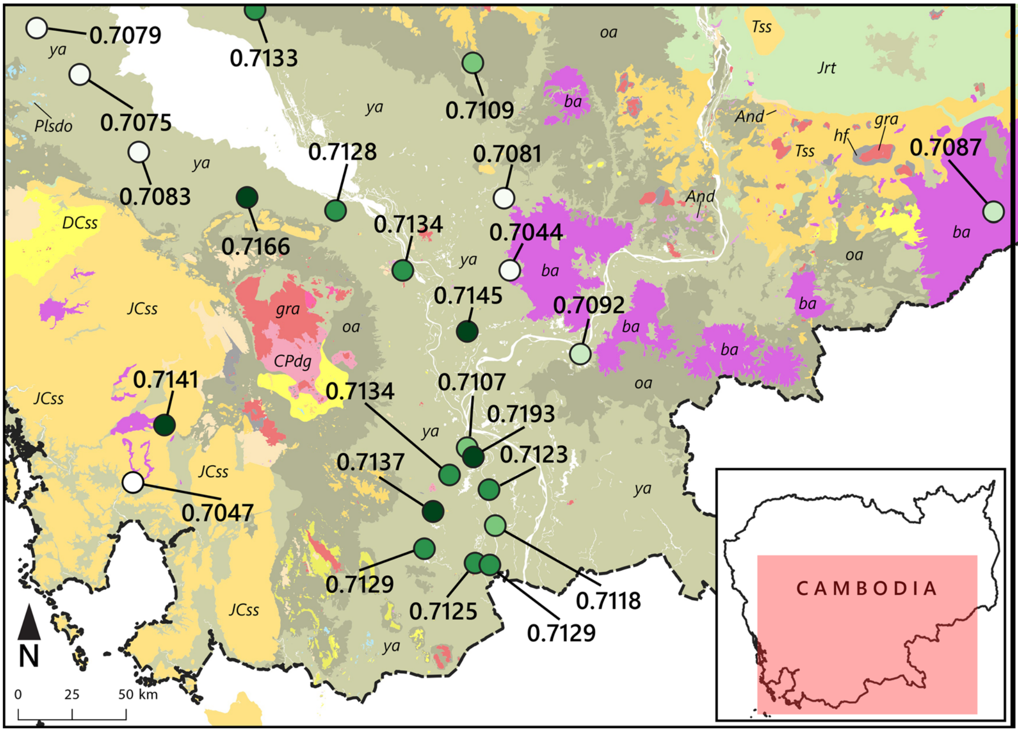

Figure 5 *Central and southern Cambodia: $^{87}Sr/^{86}Sr$ measurements of plant samples. The major geological units are marked (see Fig. 2 legend for geological unit abbreviations). Source: Map based on data from Open development Cambodia (https://opendevelopmentcambodia.net/dataset/?id=geology-of-cambodia-2006) [Colour figure can be viewed at wileyonlinelibrary.com]*

individuals interred at the investigated archaeological sites will be compared with the local Sr isotope signature to identify individuals who may be geological outliers to the region rather than to nominate a specific childhood origin.

Table 2 *Comparison of plant $^{87}Sr/^{86}Sr$ between geological provinces.*

	Old alluvium	*Young alluvium*	*Basalt*	*Sandstone*
Mean	0.7094	0.7116	0.7054	0.7131
SD	0.002	0.003	0.002	0.002
Old alluvium		0.004	0.002	0.0001
Young alluvium			0.0003	0.14
Basalt				0.0001

Values are mean and standard deviation of plant $^{87}Sr/^{86}Sr$ values. *p*-values are compared by a two-tailed unpaired Student's *t*-test.

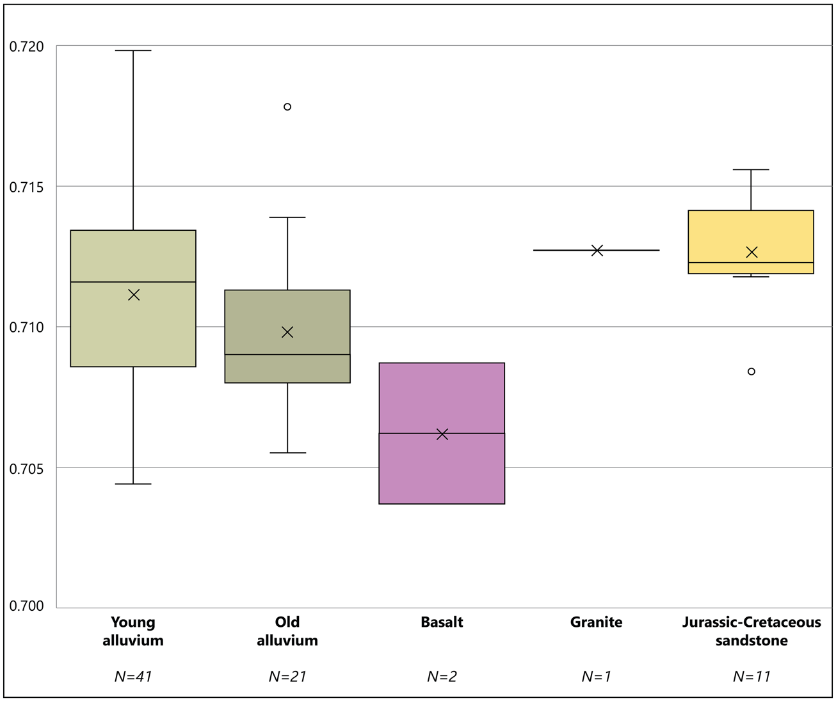

Figure 6 *Box plot of the bioavailable* $^{87}Sr/^{86}Sr$ *variation by geological provinces. Central lines indicate medians; × = mean; shaded boxes represent the interquartile range; and stems whiskers are the highest and lowest values. [Colour figure can be viewed at wileyonlinelibrary.com]*

Archaeological landscape

Archaeological research was conducted by the authors at Iron Age (*c*.500 BCE–500 CE) sites in Banteay Meanchey at Phum Sophy and Phum Snay (O'Reilly and Pheng 2001; O'Reilly *et al*. 2008, 2015), in Siem Reap province at Lovea and Prei Khmeng (O'Reilly and Shewan 2015, 2016a, 2016b; O'Reilly *et al*. 2017, in press), and at a historic jar/coffin site named Phnom Pel in Koh Kong province (Beavan *et al*. 2012) (Fig. 1). In Banteay Meanchey province (north-west Cambodia), the Iron Age sites of Phum Sophy and Phum Snay are situated within young alluvium (mean = 0.7117 ± 0.003). With the aid of this Sr baseline map, in conjunction with Sr isotope values measured in archaeological fauna enamel recovered from the sites, it may be possible to identify potential geological outliers among the excavated human burials, should individuals have exploited food resources from more radiogenic areas such as Jurassic–Cretaceous regions or less radiogenic basaltic locations.

The Iron Age sites of Lovea and Prei Khmeng are located some 60 km south-east of Phum Sophy and Prei Khmeng in Siem Reap province. While also situated within young alluvium, plant samples taken in close proximity to these sites display higher $^{87}Sr/^{86}Sr$ values, overlapping with more radiogenic Jurassic–Cretaceous regions to the north. As a result of this confluence, it may be more difficult to discern discrete human utilization of these different geological areas, as significant mobility within regions of similar isotopic range, or indeed between spatially separated but similar isotopic regions, will not be perceptible. However, exploitation of less radiogenic areas such as regions of basalt and andesite will potentially be detected.

In Koh Kong province, the 15th–17th-centuries jar/coffin site of Phnom Pel (Beavan *et al*. 2012) is located in the Cardamom Mountains, a region composed of Upper Cretaceous sedimentary formations (*Grès Supérieurs*) with outcrops of fine-grained basalt (unpublished data). It should be possible to gauge whether this population, whose remains are contained in large ceramic storage jars and wooden log coffins, spent their childhood mostly within the dominant Jurassic–Cretaceous local environment or accessed resources from less radiogenic locales such as the areas of basalt within the Cardamom ranges and regions beyond.

Future research will usefully be directed at more intensive sampling around the archaeological sites of interest to enhance resolution and in areas not yet sampled.

CONCLUSIONS

In order to assess the residential mobility and resource-acquisition strategies of past populations using Sr isotope analysis of human enamel, regional maps of the bioavailable $^{87}Sr/^{86}Sr$ are required. Studies in other regions have relied on various types of samples to approximate local and regional $^{87}Sr/^{86}Sr$ variability including plants, soils, soil leachates, water and faunal remains, against which to compare $^{87}Sr/^{86}Sr$ in skeletal remains. In this study, we measured $^{87}Sr/^{86}Sr$ values in vegetation samples from across the region in an effort to create a baseline map of the bioavailable $^{87}Sr/^{86}Sr$ for Cambodia. This database will assist in the examination and interpretation of skeletal material recovered from archaeological mortuary deposits excavated by the authors and will provide a useful resource for other provenance studies. The results of this study show that biologically available $^{87}Sr/^{86}Sr$ ratios, as measured in plant samples, on average reflect the surface geology of the region and can be used to assist in the characterization of the local $^{87}Sr/^{86}Sr$ signature. To refine local $^{87}Sr/^{86}Sr$ values for archaeological regions of interest further and to examine the mobility and habitat exploitation patterns of the individuals interred at these sites, we will use this baseline database in combination with the analysis of faunal enamel preserved in the same archaeological contexts as the skeletal population. Future research will result in more comprehensive coverage of the region with updates of the map as further regions in Cambodia are explored.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Ministry of Culture and Fine Arts (MoCFA) and the APSARA Authority of Cambodia for their support and cooperation. They thank the Australian Research Council for supporting the research through the Discovery Grants programme (grant numbers DP0984968 and DP110101997). The authors are grateful to Mr Suy Pov and Bou Rithy for their support in the field and for assistance with the sample collection; and to Stefan Vollgger (Geodimensional) for assistance with mapping. The authors also thank the anonymous reviewers for their constructive comments which have improved the manuscript.

REFERENCES

Aberg, G., 1995, The use of natural strontium isotopes as tracers in environmental studies, *Water, Air, and Soil Pollution*, **79**, 309–22.

Albrecht, G., Haidle, M., Chhor, S., Heang, L. H., Heng, S., Heng, T., Mao, S., Sirik, K., Som, S., Thuy, C., and Vin, L., 2000, Circular earthwork Krek 52/62: Recent research on the prehistory of Cambodia, *Asian Perspectives*, **39**(1–2), 20–46.

Bataille, C. P., and Bowen, G. J., 2012, Mapping 87Sr/86Sr variations in bedrock and water for large scale provenance studies, *Chemical Geology*, **304**, 39–52.

Beard, B. L., and Johnson, C. M., 2000, Strontium isotope composition of skeletal material can determine the birth place and geographic mobility of humans and animals, *Journal of Forensic Science*, **45**(5), 1049–61.

Beavan, N., Halcrow, S., McFadgen, B., Hamilton, D., Buckley, B., Tep, S., Shewan, L., Sokha, O., Fallon, S., Miksic, J., Armstrong, R., O'Reilly, D., Domett, K., and Chhem, R., 2012, Radiocarbon dates from jar and coffin burials of the Cardamom Mountains reveal a unique mortuary ritual in Cambodia's late- to post-Angkor period (15th–17th centuries), *Radiocarbon*, **54**(1), 1–22.

Bentley, R. A., 2006, Strontium isotopes from the earth to the archaeological skeleton: A review, *Journal of Archaeological Method and Theory*, **13**, 135–87.

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

Bentley, R. A., Tayles, N., Higham, C. F. W., Macpherson, C., and Atkinson, T., 2007, Shifting gender relations at Khok Phanom Di, Thailand, *Current Anthropology*, **48**, 301–14.

Bentley, R. A., Cox, K., Tayles, N., Higham, C. F. W., Macpherson, C., and Hayes, T., 2009, Community diversity at ban Lum Khao: The chemical evidence, *Asian Perspectives*, **48**, 79–97.

Blum, J. D., Taliiaferro, H. E., Weisse, M. T., and Holmes, R., 2000, Changes in Sr/ca, Ba/ca and 87Sr/86Sr ratios between trophic levels in two forest ecosystems in the northeastern USA, *Biogeochemistry*, **49**, 87–101.

Budd, P., Millard, A., Chenery, C., Lucy, S., and Roberts, C., 2004, Investigating population movement by stable isotope analysis, *Antiquity*, **78**, 127–41.

Capo, R. C., Stewart, B. W., and Chadwick, O. A., 1998, Strontium isotopes as tracers of ecosystem processes: Theory and methods, *Geoderma*, **82**(1–3), 197–225.

Carò, F., and Im, S., 2012, Khmer sandstone quarries of Kulen Mountain and Koh Ker: A petrographic and geochemical study, *Journal of Archaeological Science*, **39**(5), 1455–66.

Carò, F., Douglas, J. G., and Im, S., 2010, Towards a quantitative petrographic database of Khmer stone materials. Koh Ker style sculpture, *Archaeometry*, **52**(2), 191–208.

Carter, A. K., 2010, Trade and exchange networks in iron age Cambodia: Preliminary results from a compositional analysis of glass beads, *Bulletin of the Indo Pacific Prehistory Association*, **30**, 178–88.

Corre, A., 1879, Rapport Sur les objects de l'age de la Pierre polie et du bronze recueillis à Som-Ron-sen (Cambodge) et note annese Sur des instruments en Pierre polie et en bronze trouvés aux environs de Saigon, *Excursions et Reconnaissances. École Française d'Éxtreme Orient, Saigon.*, **1**, 79–91.

Dega, M., 2001, *Prehistoric Circular Earthworks of Cambodia*, PhD thesis, Department of Anthropology, University of Hawai'i, Manoa.

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

Evans, D., 2016, Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia, *Journal of Archaeological Science*, **74**, 164–75.

Evans, D., and Fletcher, R., 2015, The landscape of Angkor wat redefined, *Antiquity*, **89**(348), 1402–19.

Evans, J. A., and Tatham, S., 2004, Defining "local signature" in terms of Sr isotope composition using a tenth- to twelfth-century Anglo-Saxon population living on a Jurassic clay-carbonate terrain, Rutland, UK, in *Forensic geoscience: Principles, techniques and applications, vol. 232* (eds. K. Pye and D. J. Croft), 237–48, Geological Society of London, Special Publications, London.

Evans, J. A., Chenery, C. A., and Montgomery, J. A., 2012, Summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain, *Journal of Analytical Atomic Spectrometry*, **27**, 754–64.

Faure, G., and Mensing, T. M., 2005, *Isotopes: Principles and applications*, 3rd edn, John Wiley and Sons Inc, Hoboken, New Jersey.

Fletcher, R., Penny, D., Barbetti, M., Pottier, C., Than, H., Chan, K., and Someaneath, K., 2006, The greater Angkor project 2005–2009: Issues and program, in *Uncovering Southeast Asia's past: Selected papers from the 10th international conference of the European Association of Southeast Asian Archaeologists* (eds. E. Bacus, I. Glover, and V. Piggot), 347–54, The National University of Singapore, Singapore.

Hoddell, D. A., Quinn, R. L., Brenner, M., and Kamenov, G., 2004, Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: A tool for tracking ancient human migration, *Journal of Archaeological Science*, **31**, 585–601.

Hoppe, K. A., Koch, P. L., Carlson, R. W., and Webb, S. D., 1999, Tracking mammoths and mastodons: Reconstruction of migratory behavior using strontium isotopes, *Geology*, **27**, 439–42.

Kondolf, G. M., Schmitt, R. J. P., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T. A., Gibson, S., Kummu, M., Oeurng, C., Rubin, Z., and Wild, T., 2018, Changing sediment budget of the Mekong: Cumulative threats and management strategies for a large river basin, *Science of the Total Environment*, **625**, 114–34.

Kootker, L. M., van Lanen, R. J., Kars, H., and Davies, G. R., 2016, Strontium isoscapes in the Netherlands. Spatial variations in 87Sr/86Sr as a proxy for palaeomobility, *Journal of Archaeological Science: Reports*, **6**, 1–3.

Laffoon, J. E., Davies, G. R., Hoogland, M. L. P., and Hofman, C. L., 2012, Spatial variation of biologically available strontium isotopes (87Sr/86Sr) in an archipelagic setting: A case study from the Caribbean, *Journal of Archaeological Science*, **39**, 2371–84.

Ly, V., 1999, Samrong Sen; *Early Workshop of Material Culture in the Flooded Area of the Tonle Sap River, Kompong Chhnang, Cambodia*, Ph.D. Thesis, Sophia University, Tokyo.

Mansuy, H., 1902, *Stations Préhistoriques de Samrong-Sen et de Longprao (Cambodge)*, F. G. Schneider, Hanoi.

Maurer, A.-F., Galer, S. J. G., Knipper, C., Beierlein, L., Nunn, E. V., Peters, D., Tütken, T., Alt, K. W., and Schöne, B. R., 2012, Bioavailable $^{87}Sr/^{86}Sr$ in different environmental samples—Effects of anthropogenic contamination and implications for isoscapes in past migration studies, *Science of the Total Environment*, **433**, 216–29.

Montgomery, J., Budd, P., and Evans, J., 2000, Reconstructing the lifetime movements of ancient people, *European Journal of Archaeology*, **3**, 370–85.

Mourer, R., 1994, Contribution a l'étude de la prehistoire du Cambodge, in *Recherches Novelles Sur le Cambodge* (ed. F. Bizot), Études Thématiques I, École Française d'Éxtreme Orient, Paris.

O'Reilly, D., and Pheng, S., 2001, Recent excavations in Northwest Cambodia, *Antiquity*, **75**, 265–6.

O'Reilly, D., and Shewan, L., 2015, A report on the 2011–2012 excavation of Lovea: An iron age, moated settlement in Cambodia, *Archaeological Research in Asia*, **1–2**, 33–47.

O'Reilly, D., and Shewan, L., 2016a, Phum Lovea: A moated precursor to the Pura of Cambodia. Socio-political transformation from iron age settlements to early state society, *Journal of Southeast Asian Studies*, **47**(3), 468–83.

O'Reilly, D., and Shewan, L., 2016b, Prehistoric mortuary traditions in Cambodia, in *The Routledge handbook of bioarchaeology in Southeast Asia and the Pacific Islands* (eds. M. Oxenham and H. Buckley), 45–67, Routledge, New York.

O'Reilly, D., Domett, K., and Sytha, P., 2008, The excavation of a late prehistoric cemetery in Northwest Cambodia, *Udaya*, **7**, 1–6.

O'Reilly, D., Shewan, L., Domett, K., Newton, J., Evans, D., Vuthy, V., and Beavan, N., 2015, The excavation of Phum Sophy 2009–2010: An iron age site in north-west Cambodia, *Journal of Indo-Pacific Archaeology*, **39**, 57–73.

O'Reilly, D., Evans, D., and Shewan, L., 2017, Airborne LiDAR prospection and archaeological investigations at Lovea, an iron age moated settlement in Central Cambodia, *Antiquity*, **91**, 947–65.

O'Reilly, D., Shewan, L., Domett, K. and An S., in press, Revisiting Prei Khmeng: The excavation of an iron age settlement and cemetery in Cambodia. Asian Perspectives.

Penny, D., 2006, The Holocene history and development of the Tonle Sap, Cambodia, *Quaternary Science Reviews*, **25**, 310–22.

Phon, K., 2004, Phnom Borei project: Phnom Borei and its relationship to Angkor Borei. Unpublished Report. Phnom Penh.

Piilonen, P. C., Sutherland, F. L., Danišík, M., Poirier, G., Valley, J. W., and Rowe, R., 2018, Zircon Xenocrysts from Cenozoic alkaline basalts of the Ratanakiri Volcanic Province (Cambodia), Southeast Asia—Trace element geochemistry, O-Hf isotopic composition, U-Pb and (U-Th)/he geochronology—Revelations into the underlying lithospheric mantle, *Minerals*, **8**, 556. https://doi.org/10.3390/min8120556.

Poszwa, A., Ferry, B., Dambrine, E., Pollier, B., Wickman, T., Loubet, M., and Bishop, K., 2004, Variations of bioavailable Sr concentration and $^{87}Sr/^{86}Sr$ ratio in boreal forest ecosystems: Role of biocycling, mineral weathering and depth of root uptake, *Biogeochemistry*, **67**, 1–20.

Pottier, C., Phin, V. S., Heng, T., Chhay, R., and Demeter, F., 2004, Koh ta Méas, un site inédit dans le baray occidental, *Udaya*, **5**, 167–91.

Price, T. D., Johnson, C. M., Ezzo, J. A., Ericson, J., and Burton, J. H., 1994a, Residential mobility in the prehistoric Southwest United States: A preliminary study using strontium isotope analysis, *Journal of Archaeological Science*, **21**, 315–30.

Price, T. D., Grupe, G., and Schröter, P., 1994b, Reconstruction of migration patterns in the bell beaker period by stable strontium isotope analysis, *Applied Geochemistry*, **9**, 413–17.

Price, T. D., Burton, J. H., and Bentley, R. A., 2002, The characterization of biologically available strontium isotope ratios for the study of prehistoric migration, *Archaeometry*, **44**(1), 117–35.

Pryce, T. O., O'Reilly, D., and Shewan, L., 2017, Copper-base metallurgy in late iron age Cambodia: Evidence from Lovea, *Journal of Archaeological Science: Reports*, **13**, 395–402.

Reinecke, A., Vin, L., and Seng, S., 2009, *The first Golden age of Cambodia: Excavation at Prohear*, DAI KAAK, Bad Langensalaz, Germany.

Sealy, J., Armstrong, R., and Schrire, C., 1995, Beyond lifetime averages: Tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons, *Antiquity*, **69**, 290–300.

Shewan, L., 2004, Natufian settlement systems and adaptive strategies: The potential of strontium isotope analysis, in *The last hunter–gatherer* (ed. C. Delage), 55–94, BAR International Series, Oxford.

Sillen, A., Hall, G., Richardson, S., and Armstrong, R., 1998, 87Sr/86Sr ratios in modern and fossil food-webs of the Sterkfontein Valley: Implications for early hominid habitat preference, *Geochimica et Cosmochimica Acta*, **62**, 2463–73.

Slovak, N. M., and Paytan, A., 2011, Applications of Sr isotopes in archaeology, in *Handbook of environmental isotope geochemistry* (ed. M. Baskaran), 743–68, Springer, Heidelberg.

Sotham, S., 1997, Geology of Cambodia. C.C.O.P, *TEC Bulletin*, **26**, 13–23.

Stark, M., 1998, The transition to history in the Mekong delta: A view from Cambodia, *International Journal of Historical Archaeology*, **2**(3), 175–203.

Stark, M., 2004, Pre-Angkorian and Angkorian Cambodia, in *Southeast Asia: From prehistory to history* (eds. I. Glover and P. Bellwood), 89–119, RoutledgeCurzon, New York.

Stark, M., 2006, Early mainland southeast Asian landscapes in the first millennium AD, *Annual Review of Anthropology*, **35**, 407–32.

United Nations, 1993, *Economic and social commission for Asia and the Pacific (ESCAP), atlas of mineral resources of the ESCAP region, volume 10*, Cambodia, Explanatory brochure, New York.

Willmes, M., Bataille, C. P., James, H., Moffat, I., McMorrow, L., Kinsley, L., Armstrong, R. A., Eggins, S., and Grün, R., 2018, Mapping of bioavailable strontium isotope ratios in France for archaeological provenance studies, *Applied Geochemistry*, **90**, 75–86.

Workman, D. R., 1977, Geology of Laos, Cambodia, South Vietnam and the eastern part of Thailand. *Overseas Geological and Mineral Resources*. No. 50, 1–34. HMSO, London.

Yasuda, Y. (ed.), 2013, *Water civilization: From Yangtze to Khmer civilizations, advances in Asian human–environmental research*, Springer, Tokyo.