Local People or Masked Mobility: Results of Strontium Isotope Analysis of Human Teeth

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Introduction

The Late and Final Pre-Pottery Neolithic B/ C (Late PPNB/ Final PPNB/ PPNC) was characterised by fundamental changes in human communities of the Near East with the hypertrophic expansion, transformation and/ or abandonment of the so-called mega-sites, and possible emergence of pastoralist communities (*e.g.*, Rollefson 2000; Fujii 2009; Makarewicz 2014; Miller *et al.* 2019; Goring-Morris and Belfer-Cohen 2020; Kafafi 2022). The accelerated population dynamics during the 8th millennium (with the establishment of settlements up to 16ha) had been unprecedented in the central and southern Levant, with many of the Late PPNB settlements being established on hitherto unbuilt land. The apparently "sudden" increase in population densities stimulated the formulation of migration models that would postulate resettlements of people, from the west into the central Jordanian Highlands and to the southern Levant (Gebel 2004; Rollefson 2010). However despite the extensive exchange of raw-materials and artefacts (*e.g.*, Purschwitz 2017; Alarashi *et al*. 2018; Gebel *et al.* 2022), the first results of genetic and isotope analyses as well as the investigation of non-metric traits of teeth, point to rather circumscribed communities with limited genetic exchange, at least for social groups in the southern Levant (Alt *et al.* 2013, 2015; Lazaridis *et al*. 2016; Feldman *et al*. 2019; Skourtanioti and Feldman this volume).

The geological conditions of the Greater Petra Area (where Ba`ja is located) and of the East-West transect in the Levant, seemed promising to investigate the role of human mobility in these socio-economic developments, using strontium (Sr) isotope analysis (Fig. 1). Intensive surveys in the modern states of Israel, and of northern and central Jordan started to explore and map the regional variations of bioavailable Sr during the last decades (Shewan 2004; Perry *et al*. 2008; Moffat *et al.* 2020; Santana *et al.* 2021). Yet for the southern Levant, comprehensive applications of this method are still rare. With few exceptions (Alt *et al.* 2013; Balasse *et al.* 2014), the number of local comparative samples or the number of tested individuals is rather low. Conclusions have been further hampered by hydrological, climatic and geological factors in the arid environments, which make the interpretation of Sr isotope data of human samples very difficult without contemporary local comparative data.

On a micro-perspective, the Late PPNB settlements with their high population densities meant major social challenges for early Neolithic communities (see contributions in Benz *et al.* 2017). How these local groups defined their relations and managed their interaction on a micro-(household) and macro-(regional and supra-regional) scale, was one of the main questions of the *Household and Death Project.* The setting of Ba`ja near a geological border between the (Pre-) Cambrian sandstone mountains and calcareous bedrock, and evidence of intensive herding of goats and sheep, made it seem a very promising site to establish a comprehensive set of data in order to identify mobility patterns. Considering the two above-mentioned research themes of the *Household and Death Project*, the aims of the Sr isotope analysis were twofold:

On a micro-level, we tried to gain more information on the composition of household communities at the site. Did they include locals and individuals from abroad? Were there differences according to buildings? Were there sexual differences in mobility patterns? Were some individuals specialised/ segregated from the others by their mobility patterns? Did cultural attributes corroborate with differences in Sr isotope ratios?

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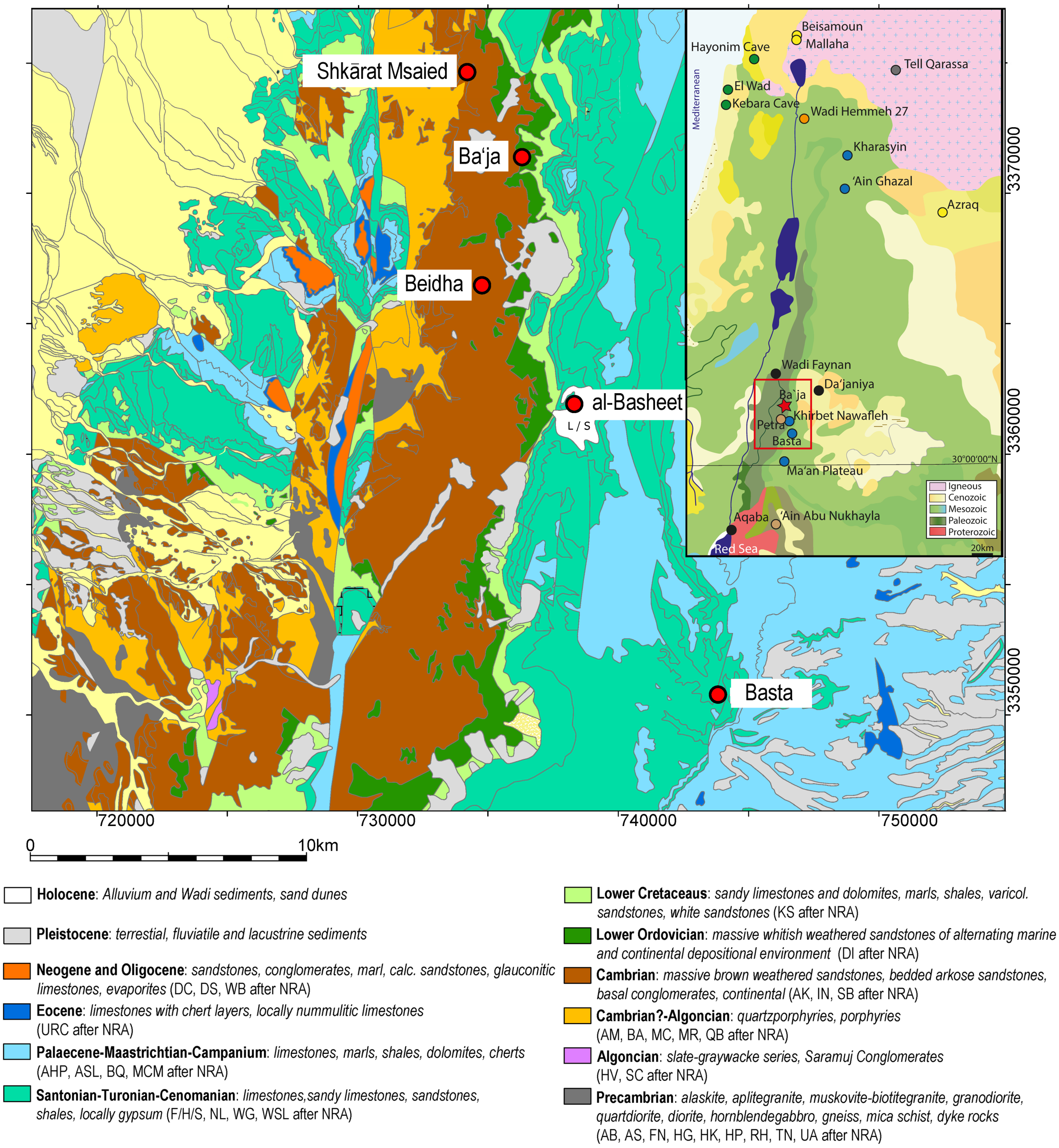

Fig. 1 Geological setting of major Pre-Pottery Neolithic B sites in southern Jordan (main map), and location of reference sites (top right). (Map: C. Purschwitz, Ba'ja N.P. based on the compilation of data from Bender 1968; Barjous 1988a, b; Ibrahim and Rashdan 1988; Rabba' 1991; Kherfan 1998; Tarawneh 2002; overview (right corner) by M. Benz based on the geological map provided as free-ware by the CGMW project of International Geological Map of Middle East [IGMME]).

On a macro-level, we tried to identify or exclude possible areas from which non-local people at Ba`ja may have immigrated.

Material and Methods

With two exceptions (Burial CG1, Individual VI), all the samples (n_{total}=19, MNI=18, Table 2) were collected in the frame of the *Household and Death Project* during three field seasons in 2016, 2018, and 2019. Individual VI of the collective burial had been already excavated in 2005 (Gebel *et al.* 2006). Thirteen of the sampled individuals are subadults who can be further classified as infans Ia (0-2 years; n=3), infans Ib (3-5 years; n=4), infans II (6-11 years; n=2), adolescent (12-19 years; n=3), and sub-adult without further specification (n=1). In comparison, adult and mature individuals are underrepresented and comprise four male individuals and one female.

To minimise diagenetic influence on the Sr isotope ratios, only tooth samples were analysed. Direct radiocarbon dating of human remains failed due to the poor preservation of bone collagen, however their stratigraphic context allows an attribution to the second phase of the settlement occupation dated to the Late PPNB around 7200-6850 cal BCE (see Purschwitz and Benz Vol I).

All the human samples come exclusively from Area C, while samples from Area A (one female adult) and D (an unstudied collective burial) were unavailable for this study. In Area B, no human remains have been uncovered so far. Samples from Area C comprise nine different burial contexts (C=Area C; G=grave+number) in five rooms (CR5/6, CR17, CR28.2, CR36.1 and CR35 from east to west, Table 2). They include two single subadult burials (CG4 and CG7), one single male adult burial (CG10), three double subadult burials (CG2 [Loc. CR5:54] CG5 [Loc. CR6:23a], and CG8 [Loc. C10:405, Individual II]), one collective/ multiple burial of four subadults (CG9 [Loci CR28.2:122a/ 122b), and two collective burials (CG1 [Individual 40/ VI, 2 teeth] and CG11 [9 individuals for the Loci No. see Table 2]). Individuals from the collective Burial CG12, Room CR34 (Gebel *et al.* 2006), were unavailable for this study. Due to the ongoing anthropological analyses, not all individuals were sampled. Most of the samples (n=9) were taken from the collective Burial CG11 in Room CR17, which was repeatedly used as a burial place. Except for the young adult male (CG10), samples of adult individuals come exclusively from collective burials (CG1 and CG11). The quantity and quality of "grave goods" and the elaboration of the burial constructions varies considerably between the different interments. Whereas CG7, CG9, and CG10 are the most sophisticated interments regarding burial rituals, construction, grave goods, and ornaments, the double Burial CG8 represents the simplest grave: a pit covered with one stone slab and with no grave goods at all. Between these extremes, various forms of elaboration and more or less costly ornamentations of corpses existed (for a more detailed description and precise location of the contexts see Benz *et al.* this volume).

Archaeological remains from wild animals of different species and sizes, including gazelle, pig/ boar, fox, donkey and small mammals served as comparison samples (Table 3). Wild fauna was chosen in order to avoid any possible bias of the data due to mobile herding patterns that may have led to mixed signals. Whenever possible, we sampled tooth enamel. In the case of a marten, an additional bone sample of the mandible was tested. The donkey is also represented by a sample from a scapula.

Methodological Background

The geochemical basics of Sr isotope analysis have been extensively described elsewhere (Bentley 2006), and the application of this method to archaeological human remains has become part of the standard repertoire of anthropological investigations to identify mobility patterns and migrations (*e.g.*, Knipper *et al.* 2012, 2014; Moffat *et al.* 2020; Santana *et al.* 2021). It therefore suffices to describe the method briefly and to identify difficulties that occurred in studies of the Near East. Generally, the isotopic composition of Sr ($^{87}Sr/^{86}Sr$) stored in rocks relates to the types and ages of the geological units. Due to weathering, Sr becomes biologically available, is taken up by plants, animals and humans, and substitutes for Ca, which is a main element in the hydroxyapatite of human and animal teeth and bones. Geologically older formations (>100 million years old) contain usually more radiogenic Sr with isotope ratios of above 0.710 (*e.g.*, granites), while younger geological units (<1-10 million years old) tend to have less radiogenic (lower) values of below 0.706 (*e.g.*, quaternary basalts) (Scheeres 2014). This rough correlation holds true when the bedrock extends directly to the surface, soil cover is negligible, and dust, sediment or water transport from other areas is minimal. Especially in arid environments (as they are typical for the study area), aeolian transport of sediments may mask the local signal of the bedrock considerably (Moffat *et al*. 2020). Moreover, investigations of speleothems revealed that the relative contribution of Sr from aeolian dust and (calcareous) bedrock to the labile Sr changed over time. Together with other proxies, these changes may imply changes of climatic conditions, *i.e.*, changes in the amount of aeolian transport of sediment and in precipitation (Ayalon *et al.* 1999; Frumkin and Stein 2004). Whether such effects were large enough to influence the isotopic composition of the biologically available Sr to an extent that is relevant for the interpretation of data from human and animal teeth (regarding residential changes and mobility) depends on the specific

Table 1 $^{87}Sr/^{86}Sr$ ratios of the NBS 987 standard run with the samples.

Standard	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ 2σ	n	Period of analysis	Certified value, resp. interlaboratory mean	References
NBS-987 after Sr separation	0.71025	0.00001	2	28.09.2021	0.71034 ± 0.00026 (2 SD)	https://www-s.nist.gov/srmors/certificates/987.pdf
NBS-987	0.71024	0.00001	10	28.09.2021	0.71034 ± 0.00026 (2 SD)	https://www-s.nist.gov/srmors/certificates/987.pdf

contexts. In any case, for the interpretation of Sr isotope ratios of human remains, a comprehensive database of local comparative samples is indispensable. They should originate from archaeological contexts of the same archaeological and climatological period as the material in question. Samples that cover climatically different periods, may mimic higher mobility rates, even though differences might be caused by different climatic regimes (*e.g.*, like the climatic differences between the Younger Dryas and the Early Holocene, *cf.* Santana *et al.* 2021).

Sample Preparation and Analyses

Sample preparation followed the methods described in Knipper *et al.* (2012, 2014) and Benz *et al.* (2019). They comprised the following steps:

Enamel fragments were cut from the tooth crowns using a diamond-coated cutting disc attached to a dental drill, and all surfaces and remaining dentin were removed using diamond-coated milling bits. The samples were ground in an agate mortar. 11 to 12mg of sample material were weighed into sample tubes and pre-treated in successive steps with 1.8ml of Milli-Q water, 1.8ml of 0.1M acetic acid buffered with lithium acetate (pH *c.* 4.5) and were washed three times with 1.8ml of H_2O. During each of these steps the samples were placed into an ultrasonic bath for 10 minutes. The objective of the pre-treatment procedure was to remove diagenetic carbonates. Samples were dried afterwards overnight (50°C) and ashed in order to remove remaining organic components (3h at 850°C).

All subsequent steps were carried out under clean lab conditions. The samples were dissolved in nitric acid (3 N HNO3), and the Sr was separated using *Sr-Spec* ion exchange resin. Sr concentrations were determined using a *Quadrupol ICP* mass spectrometer, the solutions were diluted, and the isotope ratios were determined using a *High Resolution-Multi Collector-Inductively Coupled Plasma-Mass Spectrometer* (HR-MC-ICP-MS; *Neptune* at the Institute for Geosciences of the University of Frankfurt). The raw data were corrected according to the exponential mass fractionation law to $^{88}Sr/^{86}Sr$=8.375209. Blank values were less than 10pg Sr during the whole clean lab procedure, including digestion, Sr separation and measurement. Average values of NBS-987 standards that were run with the samples match the certified values (Table 1).

Results

Generally the $^{87}Sr/^{86}Sr$ ratios of the human enamel samples exhibited a very narrow range – between 0.70804 and 0.70814 (Table 2, Appendix 1, Fig. 2) with a median and average of 0.70809 (MNI 18). An adult male yielded the lowest value, whereas the highest value was found in a tooth of a child of the age group infans Ib. The animal teeth and bones yielded isotope values between 0.70810 and 0.70829, of which the highest value (representing a scapula of a donkey) (MA-190955) appears clearly separated from the majority of the data and is considered to be an outlier. It was excluded from the statistics due to the wide foraging range of this animal. The remaining values vary between 0.70810 (pig enamel) and 0.70815 (small mammal; *Procavia capensis*) and have a median and an average of 0.70813 (n=8) (Tables 3-4). In one instance, a marten, two samples were taken: one from the mandible bone and one of a tooth. Both samples gave the same signal within the analytical uncertainty (MA-211535/ 205700).

The overall variation of the dataset is remarkably small, and many data are identical within the analytical precision. Consequently, differences between subgroups of the dataset are also marginal. Indeed, the data of the subadult individuals (avg. 0.70809±0.000013; n=13) overlap widely with those of the adult males (avg. 0.70808±0.00003; n=4). The $^{87}Sr/^{86}Sr$ ratio of 0.70806 of the only sample of a female adult is also indistinguishable from the males (Fig. 2). The relatively large number of subadult

Table 2 Sample IDs of human teeth from Ba`ja for strontium isotope analyses: contexts and results. ID No refers to the numbers given in the field by the anthropologist to either single bones or to articulated bones.

Sample ID	Context	Burial ID	Skeletal element	Age	Age Class	Sex	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ 2σ	Remarks
MA-172897	Room CR35; Loc. C10:405	CG8	Tooth 75	3-4yrs	infans Ib	?	0.70811	0.00001	Individual II
MA-172898	Room CR35 Loc. C10:408	CG10	Tooth 48	25-35yrs	adult	m	0.70812	0.00001	
MA-204350	Room CR6; Loc. CR6:23a	CG5	Tooth 36	3-4yrs	infans Ib	?	0.70814	0.00002	Individual I
MA-204351	Room CR36.1; Loc. C1:46	CG7	Tooth 47	8±2yrs	infans II	f?	0.70808	0.00002	Individual Loc. C1:46
MA-204352	Room CR6; Loc. CR6:48	CG4	Tooth 47	7±2yrs	infans II	?	0.70810	0.00002	Individual CR6:48
MA-204353	Room CR5; Loc. CR5:54	CG2	Tooth 26	1-2yrs	infans Ia	?	0.70809	0.00002	Individual Loc. CR5:54
MA-204354	Room CR28.2; Loc. CR28.2: 122b	CG9	Tooth 26	3-4yrs	infans Ib	?	0.70808	0.00002	Individual Loc. CR28.2:122b
MA-204355	Room CR28.2; Loc. CR28.2:122a	CG9	Tooth 46	3+yrs	infans Ib	?	0.70809	0.00002	Individual Loc. CR28.2:122a
MA-204356	Room CR17; Loc. *CR17:117b*	CG11	Tooth 47	15±3yrs	adolescent	?	0.70809	0.00002	Mandible ID No12 (BJ18)
MA-204357	Room CR17; Loc. CR17:127	CG11	Tooth 46	2yrs±8mon	infans Ia	f (aDNA)	0.70811	0.00002	ID No 19
MA-204358	Room CR17; No 91a	CG11	Tooth 38	adult	adult	f	0.70806	0.00002	ID No 91a
MA-204359	Room CR17; Loc. CR17:133/ 135	CG11	Tooth 38	adolescent	adolescent	?	0.70807	0.00003	ID No 100
MA-204360	Room CR17; Loc. CR17:133	CG11	Tooth 46	0±2mon	infans Ia	?	0.70810	0.00002	ID No 101
MA-204361	Room CR17; Loc. CR17:130	CG11	Tooth 27	adult	adult	m (aDNA)	0.70809	0.00002	Skull in eastern wall
MA-204362	Room CR17; No 91b	CG11	Tooth 38	12±3yrs	adolescent	?	0.70809	0.00002	ID No 91b
MA-204363	Room CR17; Loc. CR17:115	CG11	Tooth 37	matur	matur	m	0.70807	0.00002	ID No 21
MA-204364	Room CR35; Loc. C 10:152 E	CG1	Tooth 46	18-22yrs	adult	m>f	0.70805	0.00002	Individual 40/VI
MA-204365			Tooth 48				0.70804	0.00002	
MA-205643	Room CR17. *CR17:117b*	CG11	Tooth 46	subadult	subadult	?	0.70808	0.00002	Mandible ID No 46; (BJ18)

individuals and the detailed anthropological investigation allowed exploring possible differences within this group. Again however, all of these subgroups exhibited very similar data ranges – with infans Ia: 0.70809-0.70811 (mean: 0.70810, n=3), infans Ib: 0.70808-0.70814 (mean: 0.70811, n=4), infans II: 0.70808-0.70810 (mean: 0.70809, n=2), adolescents: 0.70807-0.70809 (mean: 0.70808; MNI=3).

Furthermore, variation can be explored according to burial contexts (Fig. 3). From the collective Burial CG11 in Room CR17, the remains of nine individuals were sampled including two adult males and the adult female as well as subadult individuals between the age groups infans Ia and adolescent. The $^{87}Sr/^{86}Sr$ ratios of their tooth samples cover most of the spectrum of the human data at the site (0.70806 to 0.70811), without remarkable breaks in the sequence of data, or apparent outliers (Fig. 4). Room CR35 yielded the skeletons of the adult male with the lowest $^{87}Sr/^{86}Sr$ ratio among all samples (CG1), as well as a child from a double burial (CG8) and the adult male, whose enamel had very similar, slightly more radiogenic $^{87}Sr/^{86}Sr$ ratios,

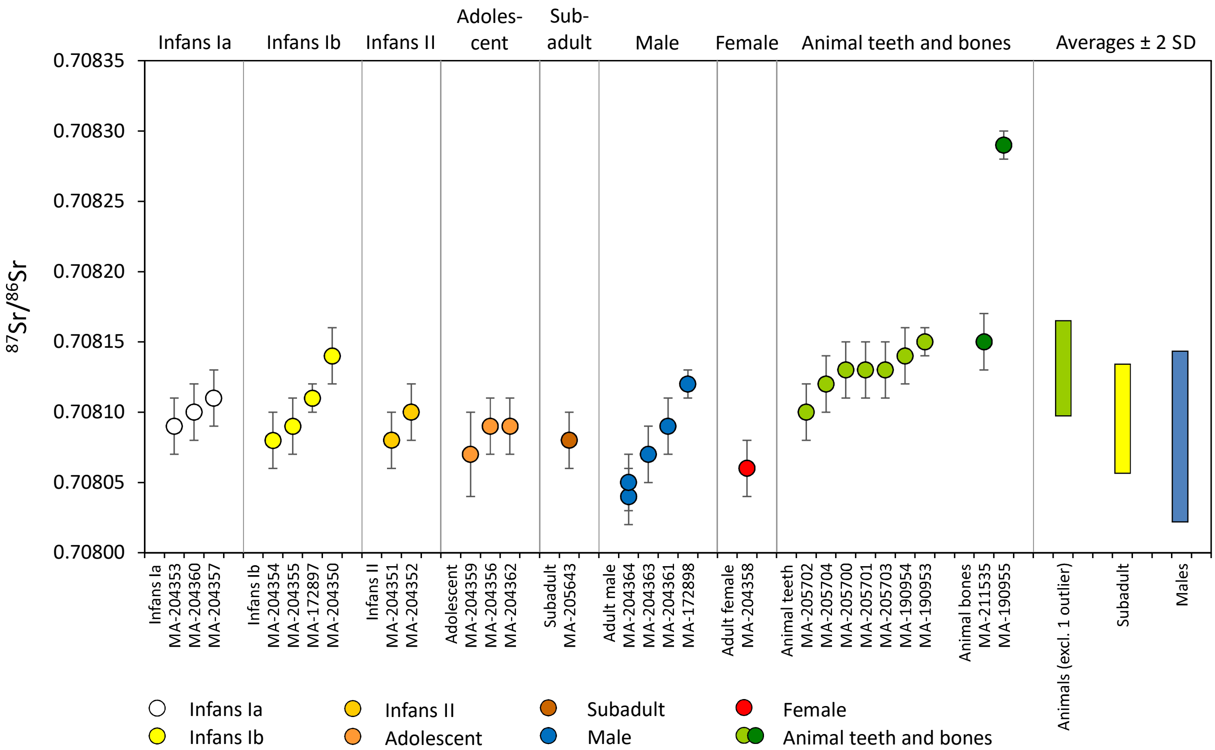

Fig. 2 Strontium isotope ratios of human enamel samples sorted according to age and sex, and animal teeth and bones from Ba`ja. (Graph: C. Knipper, Ba`ja N.P.)

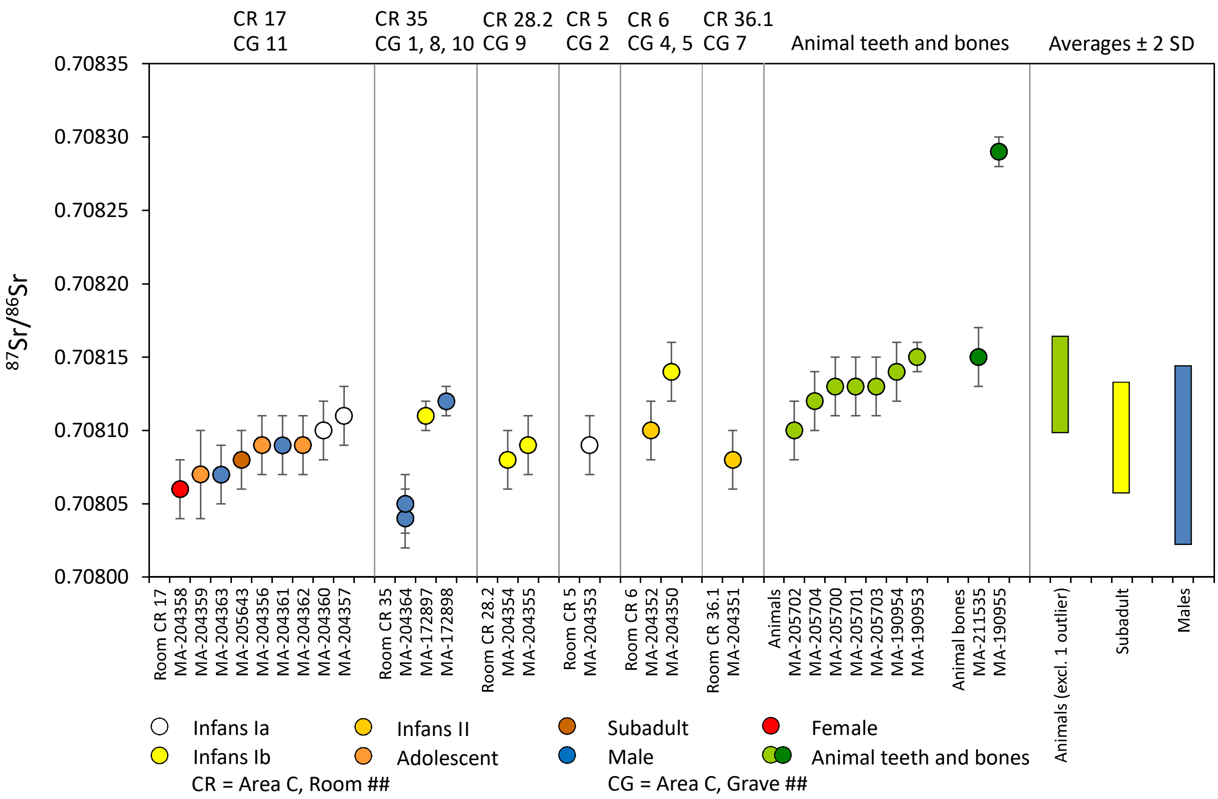

Fig. 3 Strontium isotope ratios of human enamel samples sorted according to burial contexts (rooms and graves). Data of animal teeth and bones from Ba`ja are given for comparison. (Graph: C. Knipper, Ba`ja N.P.)

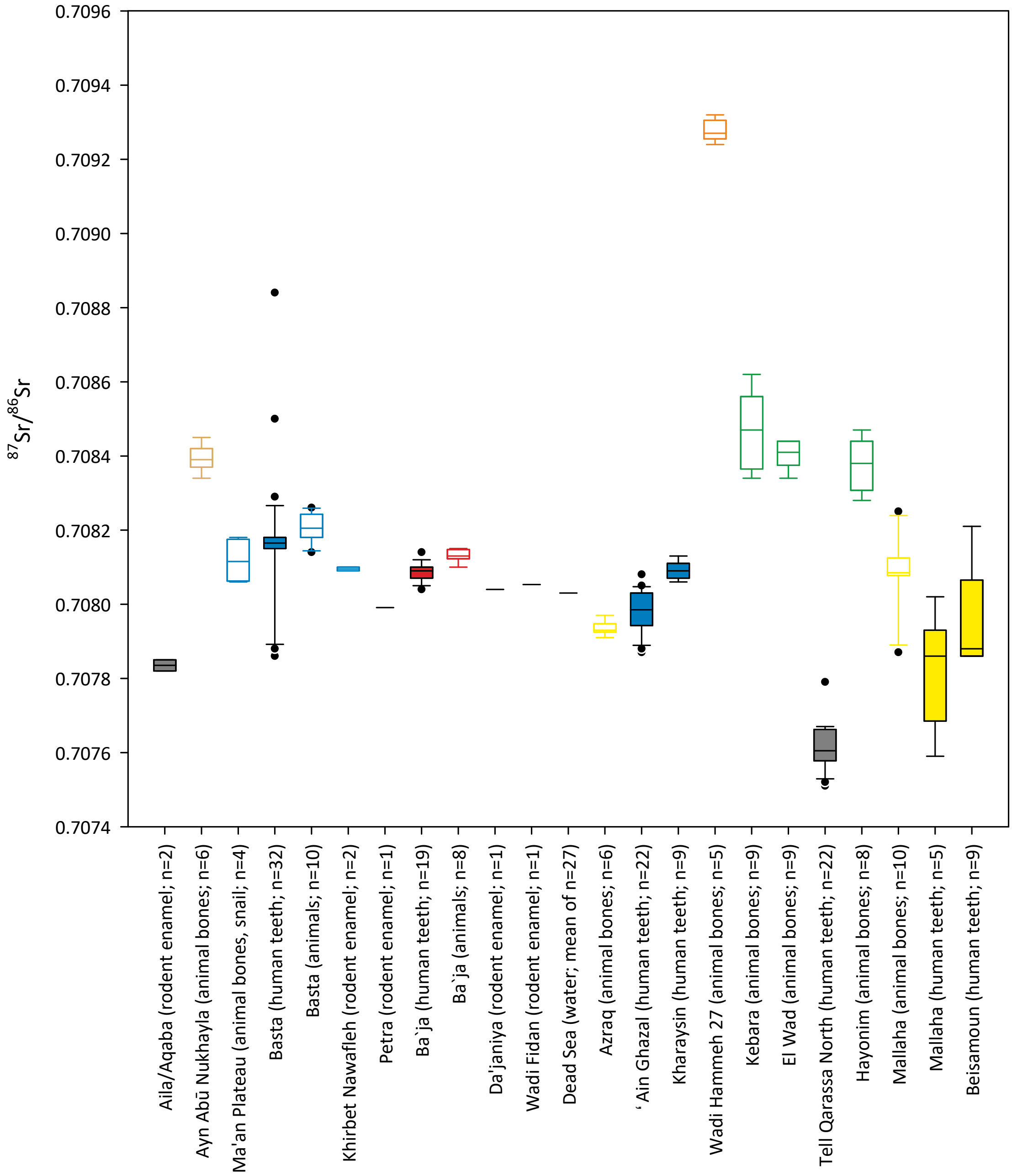

Fig. 4 Box plot of strontium isotope data of Natufian and early Holocene sites in the Near East, sorted from south to north. White boxes=animal bones/ teeth/ geological reference samples, coloured boxes=human teeth, red=samples from Ba`ja, rosé=(Pre-)Cambrian sandstones, blue=Cretaceous limestone, green=limestone Mediterranean Area, grey=predominantly Quaternary basalts, yellow=Quaternary basalts and limestone, grey=indet. or mixed geological context (*cf.* Appendix 1). (Graph: C. Knipper, Ba`ja N.P.)

and who was buried in a very elaborate grave (CG10). Furthermore, CG9 in Room CR28.2 contained the remains of two subadults of the age group infans Ib, whose $^{87}Sr/^{86}Sr$ ratios are identical within the analytical uncertainty (0.70808 and 0.70809). All other data represent inhumations either from double burials (CG2, CG5) or single interments (CG4, CG7), and are very similar to those of the other burials.

Discussion

Despite the geological variability of the local environment around Ba`ja, the $^{87}Sr/^{86}Sr$ ratios of the human teeth fall into a very narrow range with a difference (dif.) of only 0.0001 between the lowest and the highest value (range: 0.70804-0.70814; n=19; Figs. 2-4, Table 4). One outlier excluded, the range of $^{87}Sr/^{86}Sr$ values of

Table 3 Sample IDs of animal teeth and bones from Ba`ja for strontium isotope analyses: contexts, species identifications, and results; frgms.=fragments.

Sample ID	Context	Species	Skeletal element	^{87}Sr / ^{86}Sr	^{87}Sr / ^{86}Sr 2σ
MA-190953	Test Unit 2	*Procavia capensis*	Tooth frgms.	0.70814	0.00001
MA-190954	Loc. C12:18	*Procavia capensis*	Tooth frgms.	0.70815	0.00002
MA-190955	Loc. C12:30	*Equus africanus*	*Scapula*	0.70829	0.00001
MA-205700	Room BNR 31; Loc. B12:21; F.no. 24171	*Martes foina*	Molar	0.70813	0.00002
MA-205701	Room BNR 22/23 Loc. BNR22:102; F.no. 64139	*Vulpes* sp.	*Caninus*	0.70813	0.00002
MA-205702	Room BNR 22/23 Loc. BNR23:111; F.no. 64039	*Sus* sp.	*Caninus*	0.70810	0.00002
MA-205703	Room BNR 22/23 Loc. BNR 23:112; F.no. 64132	*Gazella* sp.	Molar 3	0.70813	0.00002
MA-205704	Room CR6. Loc. CR6:38; F.no. 114083	*Rodentia* sp.	Teeth frgms.	0.70812	0.00002
MA-211535	Room BNR31. Loc. B12:21; F.no. 24171	*Martes foina*	*Mandibula*	0.70815	0.00002

the faunal remains is even smaller with 0.00005 (range: 0.70810-0.70815; n=8). Consequently, the standard deviations of the human and the animal datasets are also very small (0.00002 in both cases; Table 4) and almost identical with the analytic uncertainties.[1] Table 4 summarises the descriptive statistics and Fig. 4 presents box plots of Sr isotope data from other sites in the Near East, which only cover a comparatively small portion of the global scale of variation of $^{87}Sr/^{86}Sr$ ratios. However, despite this restriction the datasets from the individual sites do not overlap completely with each other. This observation goes along with limited variations within the datasets, which are often similar or only slightly larger than those found at Ba`ja (*e.g.*, Tell Qarassa n=22, dif.=0.00028; Tell Kharaysin n=9, dif.=0.00007; ‘Ain Ghazal n=22, dif.=0.00021; Beisamoun n=5, dif.=0.00035 [Santana *et al.* 2021]; Basta n=32, dif.=0.0008 [Alt *et al.* 2013]). Similar observations of limited variation of the Sr isotope data from archaeological sites in the Near East have been made by other authors, despite microregional geological diversity (Gregoricka 2013; Knipper and Maus 2018).

Only the Middle PPNB site of Kharaysin in the northern Central Highlands of Jordan (SD_{human}=0.00002, n=9) (Santana *et al.* 2021) and the animal bone samples from Azraq (Shewan 2004) show a similarly low variability. In contrast, as highlighted by Santana *et al.* 2021, samples from the Natufian site of Mallaha had a rather high variability.

A Sr isotope mapping project in the modern state of Israel revealed largely overlapping isotopic compositions of Sr extracted from rocks and soils of different geological ages and compositions, including carbonates, granites, rhyolites (typically more radiogenic) as well as basalts (typically less radiogenic) (Moffat *et al.* 2020). In addition, it appears that aeolian dust from calcareous bedrock or sea spray homogenise the biologically available Sr, especially in dry climatic conditions. These equalising effects may make residential mobility between geologically diverse regions isotopically invisible. Moreover, cultural or economic factors such as specific dietary and land use regimes or herd management into other areas, may also have had an effect (Makarewicz 2014). Therefore, the interpretation of Sr isotope data regarding human or animal mobility requires solid estimations of the local ranges of the bioavailable Sr, roughly contemporary with the

[1] Median values were preferred in this study because they are more robust against outliers. Modern comparative samples were not considered unless no other values were available (*cf.* Santana *et al.* 2021: S2). Modern contamination and other biasing factors might blur the original early Holocene values.

Table 4 Ranges of strontium isotope ratios of major archaeological sites in the central and southern Levant, mean, median, ranges, and standard deviations (sorted from lowest to highest SD values). Values in grey were excluded, either because they were outliers, or they were discarded by the authors of the respective study. All references are given in Appendix 1; SD=standard deviation.

Site name	Min.	Max.	Mean	Median	Range	SD
Ba`ja (n=8, animal teeth/ bones)	0.70810	0.70815 0.70829	0.70813	0.70813	0.00005	0.00002
Ba`ja (n=19, human teeth)	0.70804	0.70814	0.70809	0.70809	0.00010	0.00002
Azraq (n=6, animal bones)	0.70791	0.70794	0.70794	0.70793	0.00003	0.00002
Kharaysin teeth (n=9, human teeth)	0.70806	0.70813	0.70809	0.70809	0.00007	0.00002
Wadi Hemmeh 27 (n=5, animal bones)	0.70924	0.70932	0.70928	0.70927	0.00008	0.00003
Ayn Abu Nukhayla (n=6, animal bones)	0.70838	0.70845	0.70839	0.70839	0.00007	0.00003
El Wad (n=9, animal bones)	0.70834	0.70844	0.70841	0.70841	0.00010	0.00004
Basta (n=10, animal bones)	0.70814	0.70826	0.70821	0.70820	0.00012	0.00004
‘Ain Ghazal (n=22, human teeth)	0.70787	0.70808	0.70798	0.70799	0.00021	0.00005
Tell Qarassa North (n=22, human teeth)	0.70751	0.70779	0.70762	0.70761	0.00028	0.00006
Ma`an Plateau (n=4, shells, animal bones)	0.70806	0.70818	0.70811	0.70811	0.00012	0.00006
Hayonim (n=8, animal bones)	0.70828	0.70847	0.70837	0.70838	0.00019	0.00007
Mallaha (n=10, animal bones)	0.70765 0.70787	0.70825	0.70809	0.70809	0.00038	0.00009
Kebara (n=9, animal bones)	0.70834	0.70862	0.70846	0.70847	0.00028	0.00011
Basta (n=32, human teeth)	0.70799	0.70884	0.70819	0.70816	0.00084	0.00014
Mallaha (n=9, human teeth)	0.70759	0.70802	0.70782	0.70786	0.00043	0.00014
Beisamoun (n=5, human teeth)	0.70786	0.70821	0.70795	0.70788	0.00035	0.00015
Mallaha (n=9, animal bones)	0.70787	0.70825	0.70809	0.70809	0.00038	0.00016
Petra (n=2, rodent enamel)	0.70771	0.70799				
Aila/ Aqaba (n=2, rodent enamel)	0.70782	0.70785				
Da‘janiya (n=1, rodent enamel)	0.70804					
Wadi Faynan (n=1, rodent enamel)	0.70805					
Khirbet Nawafleh (n=2, rodent enamel)	0.70809	0.70810				

investigated human remains (excluding mobile animals which browse/ graze in a wide area, *e.g.*, gazelle, ibex, donkey). For example, in areas with large ranges of bioavailable Sr, *e.g.*, the Golan Heights or the Hula Basin, individuals may appear to have been mobile, although the data reflect the variations of the local Sr isotope signals (Table 4; Moffat *et al.* 2020: 3649; *cf.* Santana *et al.* 2021; see Appendix 1: Mallaha). In contrast, in areas with low variability of the bioavailable Sr, numbers of non-local individuals and the role of mobility may be underestimated. This may have been the case at Basta (MNI 22, n=32), where the local values appear to be very homogeneous (Alt *et al.* 2013, *cf.* Table 4). Considering that a comprehensive overview of bioavailable Sr for the southern Levant is still lacking, and several areas may be indistinguishable isotopically, the interpretation of the data of this study should be considered preliminary and restricted.

Variations Among Households (Micro-Level)

The animal remains have been analysed to provide an estimate of the isotopic composition of the local, biologically available Sr. They include the teeth of small to medium-sized wild species that are supposed to have foraged near the site. Formally, $^{87}Sr/^{86}Sr$ values of human teeth that fall into the range of two standard deviations from the average of the faunal values (0.70810 to 0.70816) may be considered to be of a local origin. This estimation is based on the assumption that the food and drink humans consumed during childhood when their teeth formed, was procured from the same habitat in which the animals foraged. Applied to the dataset from Ba`ja, the $^{87}Sr/^{86}Sr$ ratios of the teeth from four individuals (including three subadults and an adult male) fall into the range of the animal teeth. The enamel samples of fourteen individuals – among them subadults, adult males, and an adult female – yielded slightly less radiogenic Sr isotope signals. However, because the values of the human samples are rather continuously distributed, and the difference between those that fall into and those that fall below the animal data is marginal, interpreting the lower values as indicators of a non-local origin does not seem reasonable. Moreover, the range of two standard deviations from the averages of the subadult individuals (0.70806 to 0.70813) and the adult males (0.70802 to 0.70814) overlap largely and cover the values of the single adult female. Only the infans Ib individual MA-204350 exhibited a $^{87}Sr/^{86}Sr$ ratio that was slightly more radiogenic than the described range of the subadults of all age categories. However, because it falls perfectly into the isotopic range of the samples of the faunal remains, it should also be considered local. Overall, the distribution of the human data indicates a group of individuals that exploited food sources and water from a shared area of land use.

The large portion of subadults, including several individuals who deceased only shortly after birth (infans Ia) and had only little time for residential changes, implies that the majority of the data does represent the local population at the site. Restricted variation among the data of subadults, and indications that they may serve as a representative estimate of the local bioavailable Sr, have been previously described (Alt *et al*. 2014; Knipper *et al*. 2018, 2020) and seem to be compelling for Ba`ja as well. The marginal difference to the $^{87}Sr/^{86}Sr$ of the animals – if it is a meaningful difference at all – may have resulted from slight differences between the habitats in which the animals foraged, and those humans exploited for food and drink. Varied use of the landscape around settlements by humans and animals may be related to environmental factors, such as soil fertility or humidity, so that the Sr that was biologically available to different species may be dominated by varied geological units (Brönnimann *et al*. 2018; Knipper *et al.* 2018). Especially arable land or habitats, in which plants grew that may have been gathered or harvested by humans for food, were often restricted to certain areas of the landscape and unlikely to have been evenly distributed around settlements.

With regard to age and sex, there is no pronounced difference between the subadults of different age categories. Furthermore the data of all subadults combined vary within the same spectrum as for those of the males. Similar data distributions of adult males or females and subadults are generally consistent with patri- or matrilocality (Knipper *et al*. 2017; Mittnik *et al.* 2019). At Ba`ja however, it was impossible to gain information on residential rules and sex-related mobility patterns because our study is biased, comprising only one sample of a female adult (Fig. 2). Overall, there is no segregation observable between burial locations within the site, which suggests that resource procurement and consumption or mobility patterns were rather consistent among all individuals (Fig. 3). The inhumations of the collective Burial CG11 in Room CR17 cover almost the whole range of Sr isotope data, without any remarkable grouping, breaks in their data distribution, or outliers. The limited variation of the $^{87}Sr/^{86}Sr$ ratios of the samples does not indicate that any individual was originally foreign to this group. The isotope ratios of the individuals buried in Room CR35 (CG1, CG8, CG10) have a similar range to those in Room CR17 between the lowest value 0.70804 and 0.70812. One of the males (CG1/ MA-204364) appears to be separated by his low values, whereas the $^{87}Sr/^{86}Sr$ ratios of the other male and the child are very similar and more radiogenic. However, the absolute difference among these data is so small, that it does not seem to be justified to conclude that the three individuals procured food and drink from different habitats during their childhood. The almost identical data of both subadults from the multiple/ collective Burial CG9 is remarkable and in agreement with being raised on food that was procured from the same habitat.

Regarding possible correlations of Sr ratios with the ornamentation of corpses, both individuals who were associated with perforated large mother-of-pearl rings (MA-204351 and MA-204360) revealed identical Sr isotope values within analytical uncertainty (0.70808 and 0.70810). However, in light of the narrow range of the subadults (0.70807-0.70814), this observation should also not be overvalued.

As the overall variation of the Sr isotope values at Ba`ja is very small, differentiation over time can only be marginal. Indeed, the dataset did not reveal any noteworthy trends of chronologically changing isotopic signals. Within the sequence of inhumations in the collective Burial CG11, a sample from the final burial layer of an about 2-year-old infant (MA-204357) yielded a rather high value (0.70811±0.00002), whereas the contemporary mature male individual (MA-204363) exhibited a rather low value (0.70807±0.00002). Individuals from the lower levels of the burial sequence (MA-204359/ MA-205643/ MA-204360) covered the range between 0.70807 and 0.70810.

The overall similarity of the samples is underlined by the lacking correlation of burial rituals with Sr isotope values. There is no correlation of Sr isotope ratios with the amount or quality of burial goods either, nor with the elaboration of burial constructions. The most lavishly decorated and elaborate burials (CG10 and CG7) show no Sr isotope ratios out of the ordinary, nor do they differ from ordinary burials without elaborate grave constructions and hardly any grave goods (CG2, CG8). Burials with daggers (CG1, CG10) also cover the whole range, with CG1 at the lowest end and CG10 near the highest end. It should be noted that the latter individual, who is the most lavishly decorated adult (Benz *et al.* 2019), is the only adult whose $^{87}Sr/^{86}Sr$ ratio clearly falls into the isotopic range of the faunal remains, perhaps underlining his special role, even though the differences to the other male adults were hardly greater than the analytical uncertainties.

Changes of residence during childhood could not be detected, which is however also largely due to the availability of samples and structure of the dataset. Only for one male (CG1, Ind. VI, Loc. C10:152) from the five adult individuals whose remains were recovered at Ba`ja, was it possible to analyse the first and third molar (MA-204364, Molar 46; MA-204365, Molar 48). Both samples gave almost identical results, and do not indicate any noteworthy changes in the area from which food and drink were procured – from birth to about three years (Molar 1 [46]), and from about seven years until adolescence (Molar 3 [48]). The results indicate residential continuity during this person's childhood.

The homogeneity of the data of the human teeth implies that the settlement of Ba`ja was occupied year-round and that it was not only a seasonal site. If that would have been the case, more varied and lower isotopic values within the infants Ia could have been expected. However, bulk analyses of enamel (as they were carried out in this study) lack the temporal resolution of the data that would be necessary to draw more secured conclusions on seasonal mobility. Such investigations require taking sequences of multiple samples from the same teeth that can reflect gradual variation of the isotopic composition of the strontium that was metabolised during the time of enamel formation of that specific tooth. However, the existing data from Ba`ja attest to a very homogeneous landscape regarding the biologically available strontium. Therefore, it seems unlikely that a series of samples placed between the tip and the base of a tooth crown would detect any variation that would be large enough to give evidence of the exploitation of food resources from geologically different habitats and to detect seasonal mobility.

Despite the observed homogeneity, household-based characteristics of diet or resource procurement/ mobility cannot be totally excluded, mostly, because we lack information from other areas of the site (*e.g.*, Area D see Gebel and Hermansen 2001). It is also possible that different households procured food from different habitats or plots of land that are isotopically indistinguishable. For the time being, the data of Ba`ja did not reveal any remarkable differentiation according to age, sex, or burial place, even though infants had $^{87}Sr/^{86}Sr$ ratios slightly more similar to animals than the adults. The small offset between the isotopic ratios of the humans and of the animals may have been caused by slight differences in the geological properties of the areas that contributed to the biologically available Sr that was incorporated in their respective tissues.

Regional Variations (Macro-Level)

Generally as mentioned above, Sr isotope ratios of early Neolithic sites in the Near East display rather little variation. This attests to little variation of the isotopic composition of the bioavailable Sr in general, and to primarily local populations with only minor evidence for migration or mobility (Alt *et al.* 2013; Santana *et al.* 2021). The data from Ba`ja corroborate these observations (Figs. 2-4, Table 4).

The site of Ba`ja is situated in a geologically variable area of Cambrian (541-485.4mya), Ordovician (485.4-443.8mya) and Cenomanian (99.6-93.6mya) sandstone formations, for which more radiogenic biologically available Sr can be expected than in the geologically younger Santonian-Turonian limestone area (about 94-83mya) where the site of Basta is situated (Fig. 4, Appendix 1). Extractions of the labile Sr from Pre-Cambrian granites near Timna/ Eilat exhibited Sr isotope ratios of (ISO45) 0.711296±0.000007 and (ISO44) 0.740718±0.000014 (Moffat *et al*. 2020), which are in contrast to the much lower Sr ratios from the skeletal remains of the Ba`ja individuals that appear typical for areas dominated by limestone (see Moffat *et al.* 2020). Limestone formations are very close to Ba`ja, east of the site (1-5km). Because Sr substitutes for Ca as a trace element, Sr concentrations are generally much higher in carbonate rocks than in silicate rocks. Therefore, it is likely that Sr of carbonate origin would dominate the bioavailable Sr of the area. Moreover, due to the dry climate conditions, aeolian transport distributes calcareous sediment particles, so that they contribute to the biologically available Sr beyond the outcrops of the limestone units themselves. Such an overprint of the surface layers by Sr of calcareous origin may reduce the isotopic variation of the Sr occurring deeper down in the bedrock units.

However, these values corroborate earlier observations suggesting there was no *in situ* supply of water close to the site of Ba`ja. The next fossil water sources for Ba`ja are at about 1-5km to the east, in the Na‘ur-Fuhays/ Hummar/ Shu‘ayb Wadi as-Sir limestone formation (Gebel 2004; Kinzel 2013). The limestone plateau east of Ba`ja and the valley bottom west of the site were suitable areas for cultivation, while arable land within the sandstone rock area is insufficient to support a densely populated village like Ba`ja.

Ranges of bioavailable Sr characteristic of sites at the edge of the eastern mountain area (close to the eastern escarpment of the Wadi Araba such as Wadi Faynan) match with the lower ranges of the samples from Ba`ja. Samples from the Cretaceous limestone mountains Khirbet Nawafleh (Perry *et al.* 2008) and the Ma’an Plateau (Balasse *et al.* 2014) show an almost identical range as the Ba`ja animal samples and as the upper range of the Ba`ja human samples. It can thus be suggested that the value of the local wild animals reflects indeed the local value of the area, underlining that bioavailable Sr was mainly determined by the adjacent limestone formations.

Samples from Ba`ja overlap considerably with samples from limestone areas such as Basta, even though the latter tend to be slightly higher (s. below) (Table 4), matching perfectly well with the characteristic ranges of the eastern mountain area of Jordan which were identified by Perry *et al.* as “Cluster 3” (ranges between 0.70815-0.70834). Similarly human teeth from the Late PPNB site of Karaysin (Central Highlands, Cretaceous limestone) cover an almost identical range as the Ba`ja samples (Santana *et al.* 2021). Animal reference samples from ‘Ain Mallaha have a similar median but include herded animals (sheep/ goat) and wide ranging *Gazella gazella,* which may have caused a shift in values of the Cretaceous eastern steppe region. Consequently, individuals from these regions who may have immigrated to Ba`ja would probably remain undetected in Sr isotope ratios.

Geological samples from the western side of the southern Jordan valley also partly fall into this range but tend to be higher (Moffat *et al.* 2020). Samples from Aqaba, the Dead Sea, and Petra yielded lower ranges compared to the individuals from Ba`ja (Stein *et al.* 1997; Perry *et al.* 2008), whereas bioavailable Sr from Ayn Abū Nukhayla, Wadi Rum, are – expectedly due to their geologically older environments of (Pre-)Cambrian sandstones – higher (0.70838-0.70845) (Balasse *et al.* 2014). Most of the northern Jordanian sites and geologically younger sites tend to have lower Sr isotope ratios. However, the rather high values of Upper Cretaceous limestone, Travertine, and even Quaternary basalts in the northern Jordanian region and Israelian cost, appear puzzling and need further investigation.[2] If people from these regions would have migrated to Ba`ja, they should be detected by different Sr isotope ratios.

Tracing mobile pastoralism with Sr isotope values of human teeth is difficult, because (a part of) the resources may have been procured or exchanged from areas other than the pasture-land. Analyses of oxygen isotope ratios may help to detect mobility in east-west directions. It should also be recalled that Sr isotope ratios in teeth only represent dietary intake during the formation of the teeth up until the age of about 15 years in humans. If mobility in animal husbandry is a central research question, it is highly advisable to analyse animal teeth: Serial sampling of high-crowned teeth may detect changes in the isotope composition of Sr along tooth crowns, that result from feeding in locations of variable geological properties.

In sum, it is rather improbable that immigration to Ba`ja from geologically older, *e.g.*, southern desert or steppe areas or younger formations like the Upper Cretaceous limestone of the Mount Carmel Mountain rages took place. However, incoming people from the limestone plateaus in the southeast and north may remain undetected due to the dominance of the limestone signal in the bioavailable Sr of Ba`ja.

Concluding Notes and Prospects

Our investigations on 18 individuals from Ba`ja, comprising 19 human enamel samples and eight comparative samples from contemporary local animal teeth and bones, point to a very local homogenous population. The $^{87}Sr/^{86}Sr$ ratios of local animals vary in a narrow range, which overlaps on average with the slightly less radiogenic isotopic data from the human samples. The differences between the samples from humans and local wild animals are however so small, that it is not conclusive to interpret the human data as representing non-local signals. We rather suggest that humans sourced their food slightly offset from the niches that wild animals used. The different types of bedrock around the site may be responsible for these differences, which appear much smaller than expected (based on the types of bedrock alone).

The data of subadults and adults are very similar and do not include any outliers or breaks in the data distribution. This homogeneity and the low number of adults, especially of females, also precludes the possibility to identify any clear differences in mobility or migration due to age or sex. The large number of subadults with only local signals underscores the local appearance of the population and the year-round occupation of the site.

The data match perfectly well with values recorded for the eastern Cretaceous limestone steppe area (Khirbet Nawafleh/ Ma‘an Plateau; Perry *et al.* 2008; Belasse *et al.* 2014). This suggests that supposedly Sr-rich aeolian dust from these areas masked the local (Pre-)Cambrian signal. The biologically available Sr thus appears to be dominated by Sr of calcareous origin. Therefore, the isotopic signals of the animal and human remains, investigated in this study, represent the local biologically available Sr much better than estimations based directly on the bedrock units. They confirm slight but distinct differences to the likewise narrow data ranges in the more southern and western areas (Alt *et al.* 2013; Balasse *et al.* 2014; Moffat *et al.* 2020).

On a regional scale, the isotope ratios of the skeletal remains from Ba`ja differ from the biologically available Sr in the Jordan Valley, the northern basaltic areas, and from Mediterranean Upper Cretaceous limestone zones (Fig. 4; Shewan 2004; Perry *et al.* 2008; Moffat *et al.* 2020; Santana *et al.* 2021). Therefore, the sampled individuals probably did not originate from these areas. In contrast, reported data ranges from the Central Transjordanian Highlands and the Cretaceous mountains to the east overlap with those found at Ba`ja, and

[2] The very high values for Wadi Hemmeh 27 (Shewan 2004) were excluded in Fig. 4 to illustrate the other sample ranges well (for the data see Appendix 1).

non-local individuals from these areas would possibly remain isotopically undetected. The identification of people from the northern Negev is possible but the range of modern geological samples is rather wide and archaeological samples have not been available (Moffat *et al*. 2020).

To conclude, our results confirm that Sr isotope analyses may provide evidence for mobility, even though overlapping isotope ratios with limestone areas at various distances from the site may mask the evidence for non-local individuals. The very homogeneous Sr isotope ratios of the human teeth, without any clearly divergent values, supports the idea of a territorially confined community (Gebel 2017). However mobility into or by non-local individuals from isotopically similar landscapes, such as the eastern steppe areas but also from the escarpments of the Wadi Araba, cannot be excluded. Intensive exchanges within these areas are supported by the procurement of chert, artefacts, semi-precious minerals, and by close cultural similarities (see Purschwitz 2017, Gebel *et al*. 2022; Alarashi and Benz this volume; Gebel a this volume; Gerlitzki and Martin this volume).

A more precise evaluation of the role of Ba`ja within the settlement network of the Greater Petra Area requires a denser network of comparative human and animal data from archaeological contexts. The Sr isotope data from Ba`ja underline the great importance of local archaeological comparative samples to characterise the biologically available Sr with as little as possible influence from modern factors such as climate change, imported fodder, fertilisers *etc*. Furthermore, multi-isotope approaches as applied by Santana *et al.* (2021) may contribute to identifying regional mobility from the eastern Cretaceous Highlands. Multi-isotope studies and serial sampling of animal teeth may provide evidence for mobile pastoralism, which cannot be identified by Sr isotope data from human teeth alone.

Future investigations will also need to evaluate a more comprehensive sample, which should especially include more adult individuals. Moreover, human remains from other areas of the site should be tested in order to evaluate whether the suggested homogeneity is due to the restricted provenience of the human samples of this study (only from Area C), or whether it is a general characteristic of the former inhabitants of the site. Similarly, because of the temporal restriction of the human remains to the Late PPNB period, it remains unknown whether changes in mobility occurred during the final occupation phase (PPNC).

The only adult male who was buried in a single inhumation with a dagger, is – so far – also the only adult whose Sr isotope signal falls into the range of the faunal remains. However, until more adults are tested, this correlation remains anecdotic, especially because the isotopic signals from the other adults are only marginally lower. Enlarging the sample with more adult individuals seems necessary in order to validate our observations.

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Appendix 1

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