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ORIGINAL PAPER

Strontium isotope evidence for long-distance immigration into the Byzantine port city of Aila, modern Aqaba, Jordan

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Abstract The ancient Red Sea maritime port of Aila was a major economic and manufacturing center during the 1st century B.C. through the Islamic era. The increased importance of Red Sea trade in the 4th century A.D. in addition to the arrival of a Roman legion in Aila also would suggest an increase in civilian residents arriving in the city for largely economic reasons. Strontium isotope analysis is used to identify any non-locally-born individuals within two mid-4th to early - 5th century A.D. cemeteries in the city (total $N=46$). However, this assessment of population mobility requires an accurate estimate of the "local" strontium isotope value at Aila, a calculation made difficult through extensive food importation that occurred in this oasis city. Local faunal values combined with archaeological and historical evidence of local food production and food importation and childhood dietary practices were used to contextualize the human values within the Aila sample subjected to isotope analysis ($N=22$). These sources suggest that the local signature of Aila ranges between $^{87}Sr/^{86}Sr=0.7076142–0.708643$, and only four individuals within the cemeteries were local to Aila. Most of the other individuals had $^{87}Sr/^{86}Sr>0.7100$, values unmatched in studies of bioavailable strontium in the Levant, Turkey, Egypt, Iraq, and the Persian Gulf. The lack of strontium dietary sources in southwestern Asia mirroring this signature suggests that many people buried at Aila hailed from great distances, supporting Aila's role as a major trade center during the Byzantine period.

Keywords Strontium isotopes · Geology · Diet · Migration · Byzantine · Jordan

Introduction

Extensive textual and material cultural evidence demonstrates the wide reach of Roman and Byzantine economy and trade, a sphere that includes northern Africa, India, Ethiopia, the Arabian Peninsula, most of Europe, and even China. Southwestern Asia provided overland links between Rome and its partners to the East, with cities such as Petra in Jordan and Palmyra in Syria serving as major trade entrepots from at least the 2nd century B.C. Concerted attempts to capitalize on seasonal monsoon winds during the 1st century A.D. increased the importance of maritime trade between Rome and the east (McLaughlin 2010). Red Sea trading ports such as Berenike, Myos Hormos, and Clysma in Egypt and Aila in Jordan thus served as major import and export centers after this period (Fig. 1; Tomber 2008). Excavations in Aila from 1994 until 2002 sought to explore the port's role in manufacturing and the economy of the empire from the 1st century B.C. until the 7th century A.D. (Parker 2006, 2015). In addition to material evidence of imported goods confirming Aila's role in international trade, excavation also uncovered two mid-4th to early-5th century A.D. cemeteries containing 46 individuals just outside of the ancient city wall. These skeletal remains provide evidence not only of health and disease at Aila but also, through isotopic analysis of dental enamel, the identification of immigrants within the population, providing further evidence of Aila's role in international and regional trade. Strontium isotope ratios in human dental enamel

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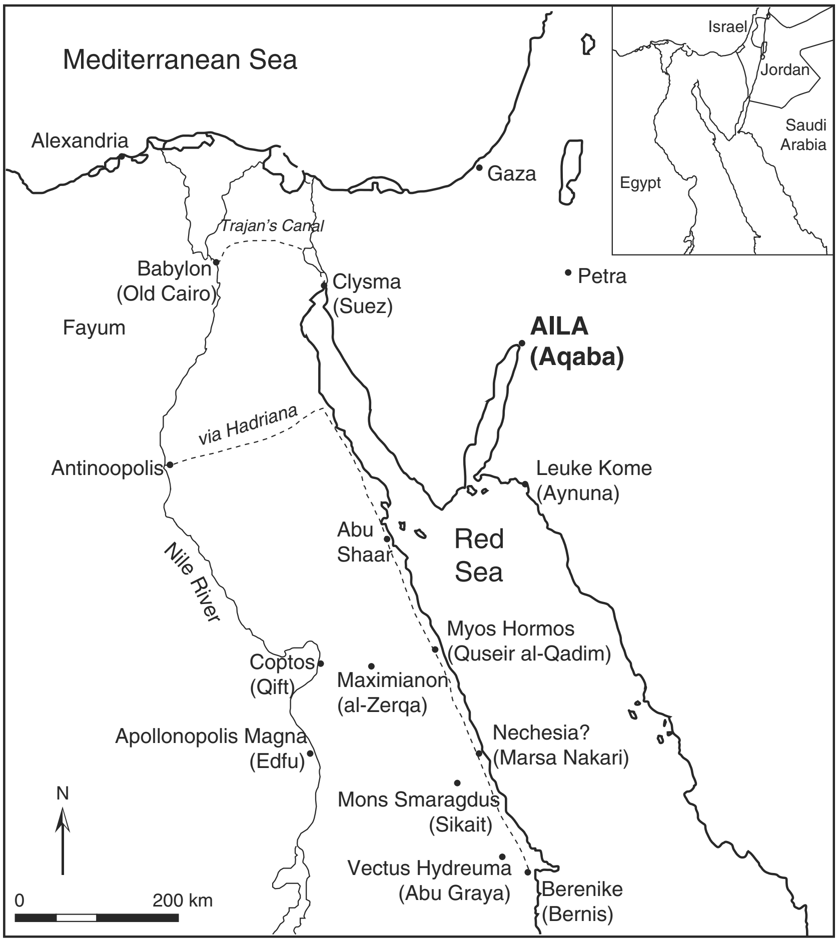

Fig. 1 Location of Aila on the Red Sea showing major trade centers of the Roman period

reflect the origins of food and water consumed during childhood enamel mineralization. Generally this is used to identify non-local individuals who immigrated into a region since childhood. This method has the greatest success in regions of moderate geological variability and local food production. However, as with many sites in Jordan, interpretation of isotopic indicators of migration is clouded by likely importation of dietary sources from multiple regions of the province, empire, or even long-distance imperial trading partners. Aila's excessively arid environment meant food production at a local level could not support the port's population, particularly after the arrival of the 10th Roman Legion in the 4th century. Therefore, childhood diets reflected in the dental enamel of local individuals probably contain a mixture of imported and locally-produced foods.

Here we interpret the strontium isotopic diversity of 4th–5th century Aila within the context of strontium isotope data from local archaeological rodents and herd animals, along with survey evidence for ancient local agricultural production, faunal and paleobotanical evidence of diet, and expected levels of isotopic diversity based on other Roman sites. This case study demonstrates the importance in incorporating multiple sources in assessing the presence of immigrants at a site with potentially diverse imported dietary sources.

The ancient port city of Aila

The northern tip of the Gulf of Aqaba in the Red Sea, encompassing the modern cities of Eilat, Israel and Aqaba, Jordan, has seen almost constant occupation from the Chalcolithic period through the modern era. The Aqaba region exemplifies the geological diversity seen along the rift valley system in the Levant (Figs. 2 and 3). The site sits on a coastal plain that is bisected by the Dead Sea transform fault, and thus the western side of the Araba valley is offset to the south by approximately 107 km (Freund 1965). To the east and southwest of the site rise some of the oldest formations in the region: the Precambrian basement outcrop of the Arabian Shield composed of quartz diorite, schist, gneiss, and granite cross-cut by mafic and felsic dikes (Bentor 1985; Kessel et al. 1998; Rashidan 1988). Formations to the northwest of Aqaba/Eilat include a series of Cretaceous sedimentary formations forming the western side of Wadi Araba (Beyth et al.

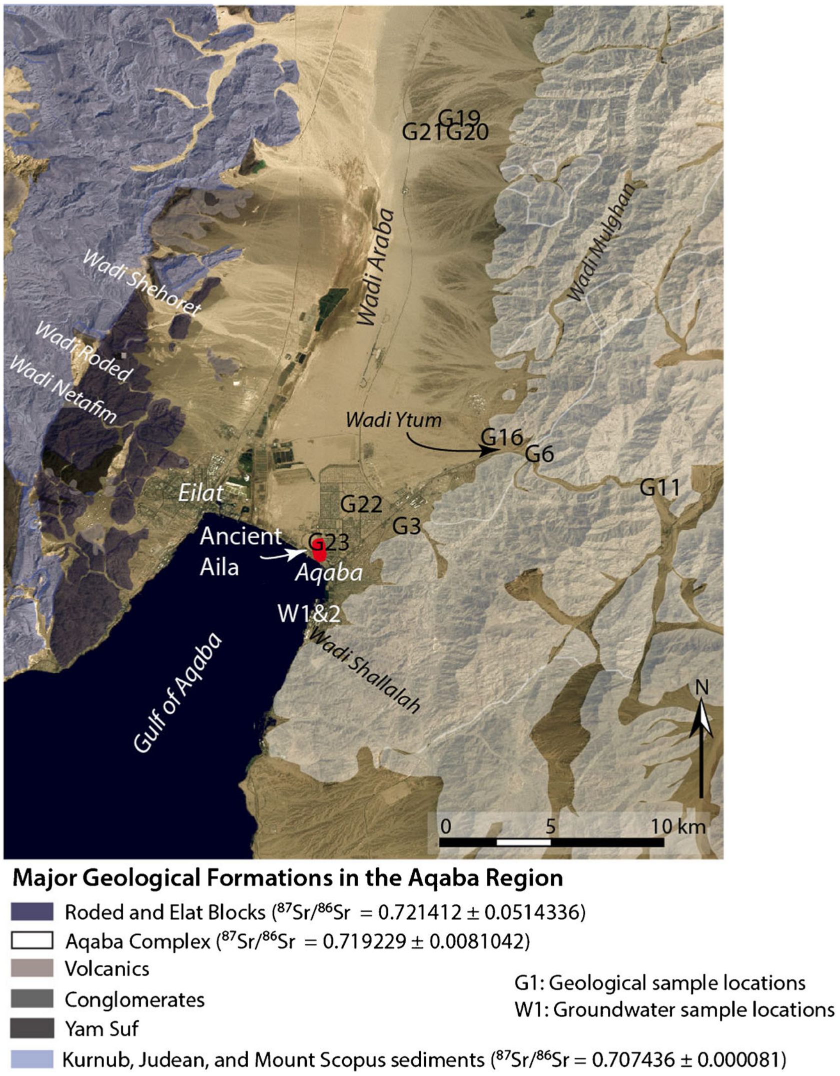

Fig. 2 The primary geological formations surrounding the Aqaba/Elat coastal plain and locations of geological and water samples analyzed in this study

2011). Erosion from the western and eastern range fronts has caused the creation of alluvial fans in the wadis to the north (Wadi Araba), east (Wadi Yutum), and west (Wadis Natafim, Roded, and Shehoret) of Aila that date from the Pleistocene to the Holocene, with the earlier deposits lying closer to the mountains (Beyth et al. 2011; Niemi and Smith 1999; Niemi 2013). The site of Aila sits on a valley floor characterized by the Quaternary alluvial deposits and beach sediments (Allison and Niemi 2010; Niemi 2013; Slater and Niemi 2003). Strontium isotope ranges for these geological regions are presented in Table 1.

The settlement denoted as "Aila" was established at the head of the Gulf of Aqaba in the 1st century B.C. while the region was part of the Nabataean kingdom that was centered at the overland trade center of Petra ca. 125 km to the north. Parker (2013) surmises that establishing a Red Sea port would have allowed the Nabataeans to maintain a hold on maritime-traded goods and compete with Rome's revitalized Red Sea ports in its new province of Egypt. Aila had the additional benefit of serving overland routes running through Nabataean agricultural villages in the Negev desert to Gaza on the Mediterranean coast (Erickson-Gini 2006; Parker and Smith 2013).

Although the excavated portions of Aila only provide a glimpse of the city's history, the archaeological evidence clearly supports its role as a trade and manufacturing center. From its inception in the late 1st century B.C., Aila was involved with the industrial manufacturing of raw goods in addition to the trade and consumption of imported ceramics, amphorae, and glass (Parker 2006). The early 4th century A.D. marked greater economic stimulation, largely due to the transfer of the *legio X Fretensis* from Jerusalem to Aila (*Not Dig Or* 34.30, Seeck 1876; Parker 2009, 2015), the possible intensification of maritime trade in the late 3rd century A.D. (Tomber 2008:69), and the increased interest of travelers in nearby Christian holy sites of the Sinai (Antoninus Placentius *Itinerarium* p. 49, Geyer 1965). In-house craft and food production continued. Large-scale ceramic production, including the unique Aila amphorae

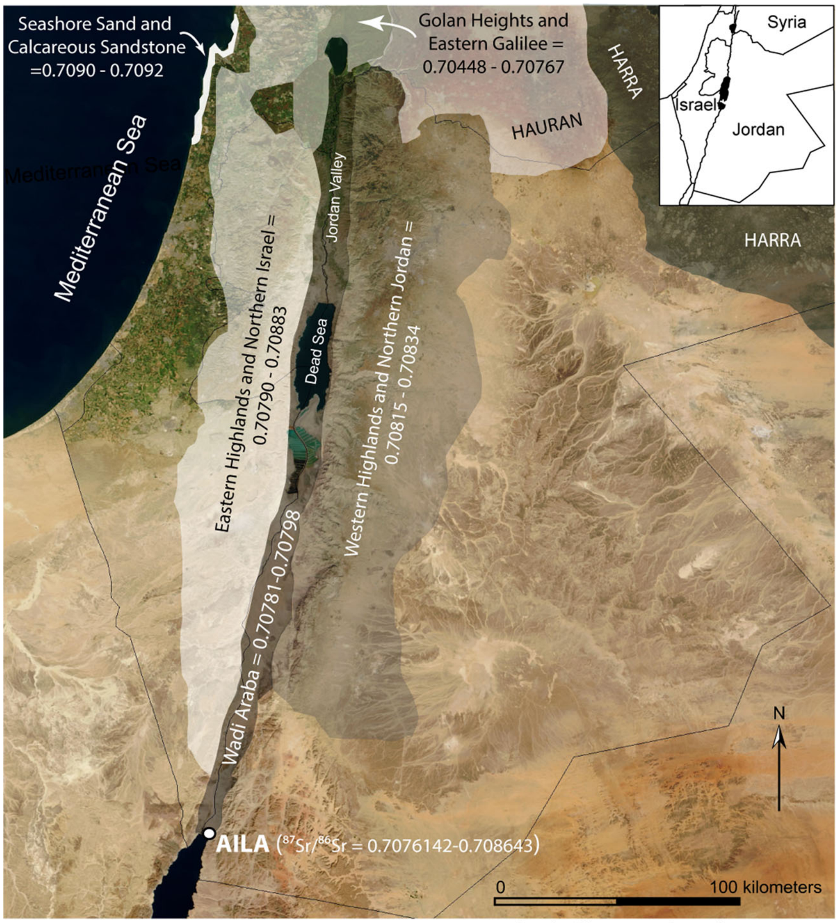

Fig. 3 Map of bioavailable strontium isotope values from the Levant from Hartman and Richards 2014; Perry et al. 2008, 2009; Shewan 2004

Landsat image courtesy of www.nasa.gov

that have been found in other Red Sea ports in Ethiopia, Egypt and Yemen, occurred at the site, along with metal and glass processing and the production of the fish sauce *garum* (Parker 2013; Van Neer and Parker 2007). As discussed below, Aila also may have supported some small-scale oasis-style agriculture despite the site's searing summer temperatures and ca. 35 mm per annum rainfall (Jordan Water Authority 1980:226–227). However, the possible doubling of the port's population with the arrival of the Roman legion would have increased the city's reliance on imported foodstuffs, not only from the immediate region but also Egypt, as indicated by artifactual evidence (Parker 2006, 2015).

The exact location of the 4th century legionary fortress has not been identified, and it likely lies underneath the modern city. After the arrival of the legion, the city was enclosed by a fortified wall in the late 4th to early 5th century, and city inhabitants began using two areas to the north of the wall for interment of the dead. Other as-of-yet unidentified cemeteries clearly served the population during this period, not only based on the needs of a city of Aila's size but also on the discovery of a fragmentary mid-6th century Greek funerary inscription from another location of the city (Schwabe 1953), possibly originating from a more ornate cemetery. The "Area A" cemetery was established directly outside of the city wall and was used for the burial of 32 adults and children. Another contemporaneous cemetery, "Area M", was located ca. 230 m north of the city wall, within a series of domestic complexes abandoned during the early 4th century; another 14 individuals were excavated from this locale. It appears that the Area A cemetery was excavated completely; however, the true extent of the Area M cemetery is unknown.

The Areas A and M cemeteries adhered to the same burial program, one that also is reflected in most of southern Jordan from the Nabataean through the Byzantine periods (Lenoble et al. 2001; Perry 2007; Perry and Jones 2008; Perry et al. 2007, 2013; Mattingly et al. 2007). The graves, concentrated along an ENE-WSW axis, consisted of shafts 0.65–0.70 m deep occasionally finished with a mud brick cist tomb to surround the corpse at the bottom. The bodies were interred in an extended position surrounded by cloth shrouds, as indicated by the organic residue surrounding the bodies and textile imprints on the bones. Grave goods were few and consisted only of simple beaded jewelry. In some cases, the remains of a mud brick grave marker were found at the ground level

Table 1 Ages and ^{87}Sr/^{86}Sr values of whole bedrock and alluvium samples near Aila

Published studies	Age	N	^{87}Sr/^{86}Sr	
Aqaba complex	630–80 Ma[1]	61	0.719229 ± 0.008104[2,3,4]	
Composite dikes in Aqaba complex	573–559 Ma[3]	10	0.728679 ± 0.021889[3]	
Roded and Elat blocks	813–630 Ma[5]	33	0.721412 ± 0.051433[6,7,8]	
Dikes in Roded/Elat blocks	609–532 Ma[5]	9	0.704230 ± 0.000308[9]	
Yam Suf	Cambrian[5]	–	–	
Kurnub, Judea, and Mount Scopus sediments	Cretaceous[5]	57	0.707436 ± 0.000081[10]	
This study	Age	Sample Number	Corrected ^{87}Sr/^{86}Sr[11]	Sr ppm
Aqaba complex	Precambrian			
Yutum formation		G13	0.731191	76.1258
Urf porphyritic		G17	0.711462	96.9819
Urf porphyritic		G18	0.7114162	316.9438
		overall	0.724182 ± 0.011035	
Aqaba complex—composite dike	Precambrian	G15	0.706178	501.4054
East Aqaba alluvium	Pleistocene–Holocene	G3	0.717267	130.9622
Wadi Ytum alluvium	Pleistocene–Holocene	G6	0.711338	302.7244
		G11	0.715288	335.6723
		G16	0.709937	422.7384
		overall	0.712188 ± 0.002775	
Wadi Araba alluvium	Pleistocene–Holocene	G19	0.708886	406.2051
		G20	0.708910	383.3446
		G21	0.707995	374.8245
		overall	0.708597 ± 0.000521	
Aqaba city center playa	Quaternary	G22	0.710965	307.7231
		G23	0.710468	296.9637
		overall	0.710717 ± 0.000351	

[1] Ibrahim and McCourt 1995

[2] Brook et al. 1990; Jarrar et al. 2003

[3] Jarrar et al. 2004

[4] Jarrar et al. 2008

[5] Beyth et al. 2011

[6] Stein and Goldstein 1996

[7] Weissman et al. 2013

[8] Eyal et al. 2004

[9] Katz et al. 2004

[10] Veizer et al. 1999 (expected based on age of formation)

[11] Data standardized to long term running mean NBS 987 = 0.710270 ± 0.000014

contemporary with the burials. Nothing in the cemetery suggests that it was associated with the legion, thus it contained the civilian population of Aila. Date of the burials was provided by secondary ceramic and numismatic artifacts from within the tomb fill and stratigraphy sealing the top of the grave shaft, which both provide a Late Byzantine *terminus ante queum* for cemetery use, although it is conceivable that the cemetery was used into the Early Islamic period. At any rate, the cemetery in Area A, and presumably Area M, went out of use sometime before the construction of domestic structures outside of the city wall in the 7th century.

Previous demographic and paleopathology studies of the Aila sample collected frequencies of non-specific stress indicators, such as periostitis, dental enamel hypoplasias (DEHs), and porotic hyperostosis, in addition to signs of identifiable infectious conditions and other pathologies related to biomechanical stress (osteoarthritis, vertebral osteophytosis, and trauma) (Perry 2002; see references therein in addition to Larsen 2015 for descriptions and etiology of these conditions). Analysis of the demographic and paleopathology profiles of the Aila sample discovered a relatively low frequency of adults dying with active malnutrition or infection. Many infants and children, especially newborns, perished with active periostitis and porotic hyperostosis, suggesting they suffered from conditions leading to systemic infection and megaloblastic anemia in the period before death. In addition, children had a significantly higher percentage of DEHs than adults. Therefore, only children at Aila, particularly infants and newborns, were exposed to unhealthy environments in terms of poor nutrition and/or high levels of infectious disease.

Aila served as a gateway between the Roman west and the Red Sea, Arabian Peninsula, and India. In addition, it functioned as a station for pilgrims visiting Mount Sinai and other Christian holy places. The extensive economic reach of Aila is attested to by the material culture at the site, and the city's vibrant economy is provided by evidence of manufacturing and other locally-based activities, and the presence of a military legion. What is not clear from the material cultural or the textual data is whether or not Aila absorbed outsiders to support its economic and trade activities. Here, strontium isotope ratios are used to identify immigrants into the population.

Strontium isotopic reflections of migration

Strontium (Sr) is an alkaline earth element that exists in geological deposits. The ratio of isotopes strontium-87 to strontium-86 in bedrock reflects the age of the formations, with older formations having higher ratios and younger formations having lower ratios (Faure 1986; Faure and Powell 1972). Strontium enters the food chain through groundwater and plants and is absorbed into other organisms as these sources are consumed. Strontium has an electron configuration similar to calcium (Ca) and thus often replaces calcium in bones and teeth of humans and other vertebrates upon consumption.

Since the 1960s, archaeological chemists realized that the Sr abundance in skeletal tissues, particularly in relation to Ca, can provide insight into the composition and sources of prehistoric diets (Schoeninger 1979; Sillen 1981; Toots and Vorhees 1965). Strontium isotopes ^{87}Sr and ^{86}Sr, however, do not undergo similar fractionation as elemental Sr as they move through the food chain. On the other hand, since these ratios of these isotopes are related to geological age, they can vary by geological location. As such, comparing ^{87}Sr/^{86}Sr in dental enamel, which forms during childhood and does not undergo remodeling, can reflect ^{87}Sr/^{86}Sr of childhood dietary sources, and by proxy, the geological region in which a person spent their childhood (e.g., Ericson 1985, 1989; Price et al. 1994; Sealy et al. 1991). This dental enamel isotope signature can be compared to the local value of the region where the individual died and was buried to identify an individual as an immigrant to the area.

Such assessment also needs to consider how strontium from different geological and dietary sources can differentially impact bone strontium. Differential weathering and varied Sr ppm concentrations of bedrock result in disproportionate contributions of these strontium sources to the bioavailable strontium at a site (Bentley 2006). In addition, atmospheric sources of Sr can comprise a significant contribution to local strontium, perhaps overriding the signatures of slow-weathering bedrock (Hartman and Richards 2014; Hodell et al. 2004). Development of an isotope mixing model for potential strontium sources entering a local environment can demonstrate the differential impact of foods deriving from soils with varied strontium concentrations (e.g., Beard and Johnson 2000; Montgomery et al. 2007; Montgomery 2010).

In addition, foods vary in their abundances of strontium and thus will differentially impact the overall strontium in the body, and hence, the resulting ^{87}Sr/^{86}Sr value. This effect also is strongly linked with Ca abundance in foods, which is why the ratio of Sr to Ca in bone tissues can be used in to identify meat vs. plant ratios in ancient diets. Calcium, which is chemically similar to strontium, biopurifies as it moves up the food chain, meaning that strontium and other elements such as barium and lead are essentially removed from the food chain at each successive level (Burton et al. 2003; Elias et al. 1982). However, foods with high Sr and/or Ca abundances can effectively "swamp" the impact of lower Sr or Ca foods in the diet (Burton and Wright 1995; Runia 1987; Schoeninger and Peebles 1981). In addition, absorption of Sr in foods high in both Sr and Ca, such as milk or seafood, is suppressed due to the body's preferential absorption of calcium (Burton and Wright 1995; Burton and Price 1999).

The implications for the differential impact of dietary sources on Sr isotope ratios in bone because of the Sr concentrations of the soil substrate or Sr and Ca concentrations in the food itself is significant. For example, if Aileans were consuming equal proportions of high Sr foods such as imported cereals and high Ca (resulting in decreased strontium absorption) milk products from local sheep, their ^{87}Sr/^{86}Sr ratios will reflect the source of the imported grains, with the sheep products having little effect on Sr (see Burton and Wright 1995; Burton and Price 2000; Montgomery et al. 2005). In addition, differential consumption of or access to these imported grains could result in individuals at Aila having a range of values between these two end-members (although likely clustering at the end anchored by the grains because of their higher Sr ppm value than other sources).

These issue can be overcome through establishing a local "biologically-available" spectrum, the range reflecting that within which local humans presumably would fall based on foods generally consumed at the site. Soil and bedrock strontium signatures, particularly when the samples are completely dissolved during preparation, have little relationship with biologically-available strontium (Bentley 2006; Blum et al. 2000; Knudson et al. 2014; Price et al. 2002). Instead this range can be established through testing local flora or archaeological fauna dental enamel, which better average bioavailable strontium contributions to the environment (Bentley et al. 2004; Evans and Tatham 2004; Ezzo et al. 1997; Hartman and Richards 2014; Hodell et al. 2004; Price et al. 2002; Sillen et al. 1998). Human bone may also provide an indication of the local strontium level, presuming the individual had lived at the site during the last few years of life (Price et al. 1994). However, numerous studies of diagenetic contamination of bone vs. dental enamel in humans have found that the porosity of bone results in more extensive post-burial contamination from surrounding soils and groundwater than the dense crystalline structure of enamel (Beard and Johnson 2000; Budd et al. 2000; Chiaradia et al. 2003; Grupe et al. 1997; Hoppe et al. 2003; Evans and Tatham 2004). Therefore, dental enamel of fauna, rather than bone, typically is used for establishing this local value. Human bone pre-treatment through leaching the bone in acetic acid may remove diagenetic strontium in bone hydroxyapatite (e.g., Sealy et al. 1991; Sillen 1986), but human bone should be used only to supplement local range data derived from better-preserved dental enamel sources (Bentley 2006).

Previous investigations of migration using strontium isotope ratios in Jordan have demonstrated the difficulty in establishing a local value range that accurately reflects “local” humans. Investigations at Khirbet edh-Dharih (Perry et al. 2008) and Khirbet Faynan (Perry et al. 2009, 2011) discovered that archaeological rodent dental enamel provides a very limited range compared to the human dental enamel values. At Khirbet edh-Dharih ($N = 12$), only one individual had a ^{87}Sr/^{86}Sr range that actually fell within that provided by local rodent samples, with all but one obvious non-local having values higher than the “local” range. In addition, eight out of 31 individuals from Khirbet Faynan had values lower than the “local” range, and one obvious non-local had a value higher than the normally distributed local values. In the end, the clearest indicator of “local” vs. “immigrant” status was statistical outliers to the normal distribution of human samples (e.g., Wright et al. 2005), rather than a local value established by fauna.

To address this issue, multiple indicators of the “local” bioavailable strontium at Aila are used for comparison with human values, in addition to assessment of likely sources of bioavailable strontium in the Ailaean environment. Rodent dental enamel along with human bone samples from the Aila burials, which reflect strontium sources during the last years of life, provide a baseline local strontium range for Aila. In addition, strontium isotope values of sheep/goat dental enamel, identifying areas of grazing, and archaeological survey data on agricultural sites provided the geographic breadth of potential local food production. This evidence was coupled with archaeological and historical evidence for food importation that supplied the civilian population buried within these cemeteries. Finally, levels of isotopic diversity in Roman-period sites with similar levels of population mobility and food importation contextualized the level of isotopic variation seen in humans and faunae at Aila. The inclusion of multiple data sources provide a nuanced view of how local and imported food sources impact the bioavailable strontium at Aila and a careful identification of possible immigrants into the site.

Materials and methods

Human dental enamel samples were collected from 22 adult individuals buried in the Byzantine Areas A and M cemeteries at Aila (Table 2). Eight of the sampled individuals came from Area M and 14 individuals came from Area A. Age and sex had already been determined by Perry using the methods in Buikstra and Ubelaker (1994; see Perry, 2002: 89, 96). The selected sample contains 11 adult females, seven adult males, and three adults of indeterminate sex, and one adolescent 14–16 years of age. The teeth sampled were 17 first molars (reflecting residence from birth to 2.5 years of age) and six second molars (reflecting residence from 3.8 to 6.6 years of age) (Moorees et al. 1963). One of these individuals sampled (A.9:34) had both the first and second molars tested. Two archaeological rodent dental enamel samples and two modern groundwater samples were analyzed to establish the local range for Aila. In addition, strontium isotope of human bone from five individuals in the A and M cemeteries, reflecting residence during the few years before death, were used to confirm the fauna-established local range. These were coupled with eight archaeological sheep/goat dental enamel to identify from where this food source originated. In addition, presented here are ^{87}Sr/^{86}Sr values from nine completely dissolved samples from strategically sampled alluvial deposits surrounding the western side of the rift valley, in addition to four samples of whole bedrock randomly sampled from two different granitic formations in the Aqaba Complex (Yutum and Urf formations).

Bone and enamel samples from five individuals (A.9:34, A.14:8, A.14:37, and M.8:12) were prepared and mechanically cleaned at Geochron Laboratories in Cambridge, MA, USA. The strontium isotope analysis was then conducted at the Isotope Geochemistry and Geochronology Laboratory in the Department of Earth, Atmospheric, and Planetary Sciences at Massachusetts Institute of Technology in 2001. Ground bone and enamel samples were treated with purified

Table 2 Demographic and paleopathological information on burials from Aila included in this study

Burial	Age	Sex	Periostitis	Osteoarthritis (OA)/vertebral osteophytosis (VOP)	Dental enamel hypoplasias (age of development)
A.9:6	30–34 years	Male	none	none	3–5 years of age
A.9:9	Young adult	Probable female	none	none	none
A.9:15	20–25 years	Probable female	none	none	Birth–6.5 years of age
A.9:34	20–25 years	Female	none	none	none
A.9:58	35–39 years	Female	none	none	none
A.10:10	Adult	Male	none	OA in shoulder and elbow; VOP in lumbar and thoracic vertebrae	none
A.13:10 (a)	14–16 years	Indeterminate	none	none	2–6 years of age
A.13:10 (b)	Adult	Indeterminate	none	none	3–6 years of age
A.14:8	25–29 years	Female	none	none	1.5–4 years of age
A.14:18	16–18 years	Probable female	none	none	4–5.5 years of age
A.14:21	18–25 years	Indeterminate	none	none	none
A.14:37	35–29 years	Female	none	none	5.5 years of age
A.15:36	16–20 years	Probable male	none	none	none
A.17:33	Adult	Probable male	none	none	none
M.2:19	Indeterminate	Indeterminate	none	none	none
M.2:39	Adult	Female	none	none	1.5–6 years of age
M.2:57	Old adult	Probable female	Femur, rib, and humerus	OA in vertebrae, shoulder, elbow, wrist, and hand; VOP in thoracic and lumbar vertebrae	none
M.2:61	40–44 years	Male	Skull	OA in lumbar vertebrae; VOP in cervical, thoracic, and lumbar vertebrae	none
M.4:58	40–44 years	Male	none	OA in shoulder; VOP in cervical, thoracic, and lumbar vertebrae	none
M.6:18	>60 years	Male	none	OA in shoulder, elbow, hand, and knee; VOP in cervical, thoracic, and lumbar vertebrae	none
M.7:21	40–44 years	Female	none	OA in thoracic, lumbar, and cervical vertebrae, shoulder, elbow, wrist, and knee VOP in cervical, thoracic, and lumbar vertebrae (two thoracics wedged)	2–6 years of age
M.8:12	Young adult	Female	none	none	none

$HlClO_4$ and dissolved in 500 μL of 3.5 M HNO_3, after which they were added to a Sr-specific resin bed and repeatedly washed in 3.5 N HNO_3. The samples were dried then loaded onto Rhenium filament with 1 μL of 1 M H_3PO_4 and 1 μL of $TaCl_5$ and dried at 3.0 amps. The samples were run on a VG-54 mass spectrometer in dynamic faraday mode at ^{88}Sr-3 V.

Table 3 ^{87}Sr/^{86}Sr values of human and archaeological fauna skeletal tissues and modern groundwater

Burial/context	Sample type	Age	Sex	Tooth analyzed	Corrected ^{87}Sr/^{86}Sr[1]
A.9:6	Human enamel	30–34 years	Male	RM_1	0.708043
A.9:9	Human enamel	Adult	Probable female	LM_1	0.711583
A.9:15	Human enamel	20–25 years	Probable female	LM_1	0.709723
A.9:34	Human enamel	20–25 years	Female	LM_1	0.709112
A.9:34	Human enamel	20–25 years	Female	M2	0.708919
A.9:34	Human bone	20–25 years	Female	–	0.708113
A.9:58	Human enamel	35–39 years	Female	LM_1	0.708771
A.10:10	Human enamel	Adult	Male	RM_1	0.712553
A.13:10 (a)	Human enamel	14–16 years	Indeterminate	LM^1	0.712970
A.13:10 (b)	Human enamel	Adult	Indeterminate	LM_2	0.711430
A.14:8	Human enamel	25–29 years	Female	LM^1	0.709394
A.14:8	Human bone	25–29 years	Female	–	0.708271
A.14:18	Human enamel	16–18 years	Probable female	RM_2	0.713190
A.14:21	Human enamel	18–25 years	Indeterminate	RM_1	0.710379
A.14:37	Human enamel	35–29 years	Female	RM^1	0.708016
A.14:37	Human bone	35–29 years	Female	–	0.707868
A.15:36	Human enamel	16–20 years	Probable male	RM_1	0.712413
A.17:33	Human enamel	Adult	Probable male	RM^1	0.710409
M.2:19	Human enamel	Indeterminate	Indeterminate	RM^1	0.712130
M.2:39	Human enamel	Adult	Female	LM^1	0.710955
M.2:57	Human enamel	Old adult	Probable female	LM^1	0.707986
M.2:61	Human enamel	40–44 years	Male	RM_1	0.711469
M.4:58	Human enamel	40–44 years	Male	M^2	0.708693
M.4:58	Human bone	40–44 years	Male	–	0.707965
M.6:18	Human enamel	>60 years	Male	RM^1	0.717060
M.7:21	Human enamel	40–44 years	Female	LM_2	0.712608
M.8:12	Human enamel	Young adult	Female	M^2	0.707768
M.8:12	Human bone	Young adult	Female	–	0.707840
M.3:55	Rodent enamel	–	–	Canine	0.707813
J.22:47	Rodent enamel	–	–	Canine	0.707844
J.20:43	Sheep/goat enamel	–	–	M1	0.708042
J.20.36	Sheep/goat enamel	–	–	M1	0.708124
J.20:43	Sheep/goat enamel	–	–	M1	0.708114
J.5:2		–	–	P1	0.707999

Table 3 (continued)

Burial/context	Sample type	Age	Sex	Tooth analyzed	Corrected ^{87}Sr/^{86}Sr[1]
	Sheep/goat enamel				
J.11:46	Sheep/goat enamel	–	–	P2	0.707731
J.11:0	Sheep/goat enamel	–	–	M2	0.708012
J.21:45	Sheep/goat enamel	–	–	M2	0.708451
J.22:31	Sheep/goat enamel	–	–	P1	0.707816
Well near castle (sample P1)	Groundwater	–	–	–	0.707608
Well near castle (sample P2)	Groundwater	–	–	–	0.707324

[1] Data standardized to long term running mean NBS 987 = 0.710270 ± 0.000014

All ratios are normalized to ^{86}Sr/^{88}Sr = 0.1194 and are reported relative to a value of 0.710270 ± 0.000014 (2σ) for the NBS 987 standard. External reproducibility for strontium runs is typically <20 ppm based on 100 dynamic cycles of data collection.

The remaining dental enamel, faunal enamel, water, and geological samples were prepared for analysis in the Bioarchaeology and Geology Laboratories at East Carolina University, and all isotopic analysis were completed at the Isotope Geochemistry Laboratory at UNC Chapel Hill. The dental enamel in each human and sheep/goat tooth was sectioned using a Dremel saw, and a small piece at least 10 mg was cleaned using a carbide burr to remove any soil and dental dentine. The rodent canine enamel surface also was mechanically cleaned, and then the underlying enamel surface was burred down to the amelo-dentinal junction to collect enamel powder along the length of the canine. The bulk dental enamel samples were subjected to cleaning through repeated washing with distilled water, after which the tooth enamel was dissolved in 500 μL of twice distilled 7 N HNO_3 and then evaporated and redissolved in 250 μL of 3.5 N HNO_3. Solid geological samples were reduced using standard rock-crushing equipment and 50–100 mg were placed into beakers for complete dissolution. Water samples (~525 μL) were placed directly into beakers. All samples were spiked with concentrated ^{84}Sr. Solid geological samples were dissolved in a sealed beaker on a hotplate in HF/HNO_3, then dried and redissolved in HCl.

All samples (including water) were dried a final time and dissolved in 500 μL of 3.5 M HNO_3 in preparation for column chromatography. Isolation of Sr was accomplished using a resin bed of approximately 35 μL of EiChrom Sr-Spec™ resin. Following collection of Sr, all samples had 1 μL of concentrated H_3PO_4 added and were dried prior to loading. Samples were loaded on single rhenium filaments with $TaCl_5$ and analyzed in triple-dynamic multicollector mode with ^{88}Sr-3 V (10^{-11}Ω resistor) on the VG Sector-54 housed in the Department of Geological Sciences at the University of North Carolina. All ratios are normalized to ^{86}Sr/^{88}Sr = 0.1194 and are reported relative to a value of 0.710270 ± 0.000014 (2σ) for the NBS 987 standard. Internal precision for strontium runs is typically ±0.000012 to 0.000018 % (2σ) standard error based on 100 dynamic cycles of data collection.

The local ^{87}Sr/^{86}Sr range at Aila was computed by using ±2σ of the mean of faunal samples following Price et al. (2002). Subgroup comparisons of mean strontium isotope values were analyzed by age-at-death (<35, 35–50, >50 years), sex (males vs. females), burial location (Area A vs. Area M cemeteries), presence of pathologies (periostitis, osteoarthritis, vertebral osteophytosis, fractures, or dental enamel hypoplasias), and tooth type (M1 vs. M2) using a Mann-Whitney test for non-normally distributed samples in JMP 11.0 (SAS Corporation, Cary, NC). A Gaussian kernel density distribution using Sheather and Jones's (1991) data-based bandwidth of the human dental enamel Sr values was created using the "density" function in R (R Core Team 2015). Kernel density distributions are a data smoothing technique used to estimate the probability density function to better understand the distribution a continuous random variable.

Results

The local Sr value at Aila

Assessment of archaeological rodent dental enamel recovered from archaeological deposits at Aila indicated a biologically available range of ^{87}Sr/^{86}Sr = 0.707793–0.707880 [0.707837 ± 0.00004 (2σ); Perry et al. 2008] (see Table 3). Samples from sheep/goat dental enamel present a slightly broader range of $^{87}Sr/^{86}Sr = 0.707602$–$0.708470$ [0.708036 ± 0.00043 (2σ)]. The human bone values have a range essentially matching the sheep/goat range, of $^{87}Sr/^{86}Sr = 0.707651$–$0.708372$ [0.708011 ± 0.00036 (2σ)]. The entire range of bioavailable strontium at Aila represented by both rodent and sheep/goat fauna is $^{87}Sr/^{86}Sr = 0.7075779$–$0.7084145$, which does not change notably with the addition of the human bone values (0.707614–0.708388). Modern groundwater values average slightly lower, at 0.70747 ± 0.0004 (2σ). The reported value for ocean water is $^{87}Sr/^{86}Sr = 0.709178$ relative to 0.710250 for NBS-987; (Kuznetsov et al. 2012).

Archaeological human dental enamel samples

The archaeological human dental enamel samples display an extremely wide range of $^{87}Sr/^{86}Sr$ values, averaging 0.7108 ± 0.00229 (1σ) (Table 3). Descriptive statistics of the sample display a generally normal distribution, with a normal quantile plot identifying one definite outlier ($^{87}Sr/^{86}Sr = 0.7171$) at the upper end of the distribution and perhaps two slight outliers ($^{87}Sr/^{86}Sr = 0.7078$ and 0.7080) at the lower end (Fig. 4). The Shapiro-Wilk test for normality indicates that the distribution just reaches normality ($W = 0.924854$, $p = 0.0959$). Removing the obvious outlier (burial M.6:18) adjusts the normality somewhat ($W = 0.923083$, $p = 0.1000$). The other values however do not converge around the normal line, and both the normal quantile plot and a histogram of the human strontium values indicate a possible binomial distribution. A non-parametric probability density function using a Gaussian kernel density distribution confirms this bimodal pattern by identifying two density peaks in the data at 0.708833 and 0.711897 (Fig. 5). Testing differences in Sr isotope means by sex, age-at-death, presence of pathologies, and tooth analyzed (i.e., first vs. second molar, which reflect different ages during childhood) using a Mann-Whitney test did not indicate any significant difference in these subsamples (Table 4). In addition, no difference existed between mean strontium isotope values in the burials in Area A vs. Area M. The 20–25-year-old female, who had both the M1 and M2 tested, showed a 0.0002 decrease in strontium isotope value between the two teeth, suggesting that her dietary sources changed between birth–2.5 and 3.8–6.6 years of age.

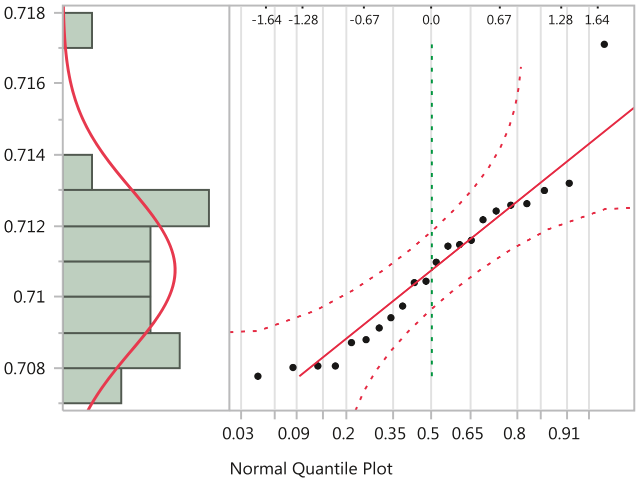

Fig. 4 Histogram and normal quantile plot of the human $^{87}Sr/^{86}Sr$ values from Aila

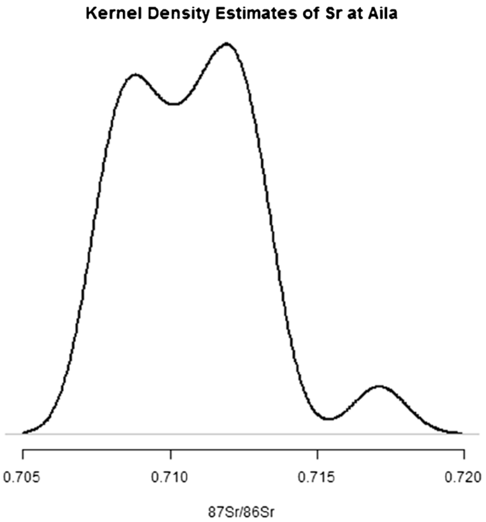

Fig. 5 Kernel density distribution of Aila $^{87}Sr/^{86}Sr$ data

Geological samples

Analysis of nine geological samples from alluvial fans and four whole bedrock samples collected to the west and northwest of Aila were added to the isotopic profile of the Aqaba region to characterize how erosion from diverse geological bedrock features would affect strontium of the soils where any local agriculture could have occurred. As noted in Table 1, the eastern and western sides of the rift valley contain formations dating from the Precambrian to the Cretaceous periods. Strontium isotope analysis of some alluvial fans near Aqaba (such as samples G3 and G7) indeed reflect the high strontium isotope values of their more direct source, the granites of the Aqaba Complex ($^{87}Sr/^{86}Sr = 0.719229 \pm 0.008104$ in published sources, $^{87}Sr/^{86}Sr = 0.724182 \pm 0.011035$ in this study). While the alluvial fan from below Jabal ash-Shahbi (sample G3) has a relatively high value at $^{87}Sr/^{86}Sr = 0.71727$, samples of alluvial fans along Wadi Ytum range slightly lower ($^{87}Sr/^{86}Sr = 0.712188 \pm 0.002775$), as do the values from the Aqaba city center plain ($^{87}Sr/^{86}Sr = 0.710717 \pm 0.000351$). Alluvial deposits from farther north in Wadi Araba (G19, G20, and G21; $^{87}Sr/^{86}Sr$ 0.708597 ± 0.000521) mirror the Cretaceous sediments on the western slope ($^{87}Sr/^{86}Sr = 0.707436 \pm 0.000081$), despite their location close to the Precambrian granites of the Aqaba Complex. These

Table 4 Result of comparisons of $^{87}Sr/^{86}Sr$ in the Aila sample by age, sex, age of tooth development, cemetery, and presence of bone lesions

	Subgroups	*N*	Mean	S.D.	Mann-Whitney results
Sex	Male	7	0.711527	0.003011	$Z = 0.99623$; $p = 0.3191$
	Female	11	0.709909	0.001898	
Age-at-death	<35	9	0.710332	0.002062	<35 vs. 35–50: $Z = -0.533333$, $p = 0.5938$;
	35-50	5	0.709911	0.002005	
	>50	2	0.712546	0.006449	35–50 vs. >50: $Z = 0.00000$, $p = 1.0000$;
					<35 vs. >50: $Z = 0.117851$, $p = -0.90562$
Tooth phase	M1	15	0.711160	0.002366	$Z = -1.12785$, $p = 0.2594$
	M2	7	0.709900	0.001988	
Cemetery	Area A	14	0.710570	0.001801	$Z = -0.03413$, $p = 0.9728$
	Area M	8	0.7110859	0.003074	
Periostitis?	Yes	2	0.709727	0.002463	$Z = -0.77875$, $p = 0.4361$
	No	19	0.710832	0.00054	
Osteoarthritis/vertebral osteophytosis?	Yes	7	0.711833	0.003001	$Z = 1.08177$, $p = 0.2794$
	No	14	0.710174	0.001804	
Fractures?	Yes	6	0.712102	0.002840	$Z = 1.20667$, $p = 0.2276$
	No	15	0.710177	0.001946	
DEHs?	Yes	9	0.710703	0.002016	$Z = 0.33889$, $p = 0.7385$
	No	13	0.710798	0.002535	

geological Sr isotope values do not reflect bioavailable strontium; however, they do reflect the broad range of strontium in geological strata upon which local plants would have grown, which could be mirrored in a wide range of human values providing these formations have similar strontium abundances.

The overall distribution of the geological strontium is largely skewed to the left. ($^{87}Sr/^{86}Sr = 0.71433 \pm 0.0262$, median $= 0.70749$). A strontium "mixing model" (Montgomery et al. 2007) can indicate which geological strontium sources will contribute more significantly to the bioavailable strontium absorbed by plants and consumed by animals. The linear model created by comparing $^{87}Sr/^{86}Sr$ of bedrock vs 1/Sr (ppm) of the geological samples presented here along with published data clearly indicates that environmental strontium will be impacted more by lower strontium values with higher strontium concentrations [i.e., lower 1/Sr(ppm) values] at Aila (Fig. 6).

Discussion

The results from the Aila human dental enamel samples indicate quite clearly that many individuals buried at Aila had a strontium level much different from, and generally higher than, the local rodents or sheep/goats consumed at the site. Two primary explanations exist for this discrepancy: (1) there were a large number of immigrants living at the Aila, or (2) the rodent and sheep/goat values do not adequately represent all biologically-available sources of strontium at Aila. How, then, to determine if these are immigrants, or local individuals are consuming a broad array of imported and local foods?

Expected level of isotopic variation

The first level of assessment needs to address whether or not such a broad array of strontium isotope values as seen at Aila (0.7108 ±0.00229) has been observed in other communities within the Roman and Byzantine Empires, who may have similar levels of food importation and/or population mobility. In Roman Britain, slightly smaller standard deviations of human values have been reported, such as ±0.0013 in Gloucester (Chenery et al. 2010), ±0.0011 in Catterick (Chenery et al. 2011), ±0.0010 in

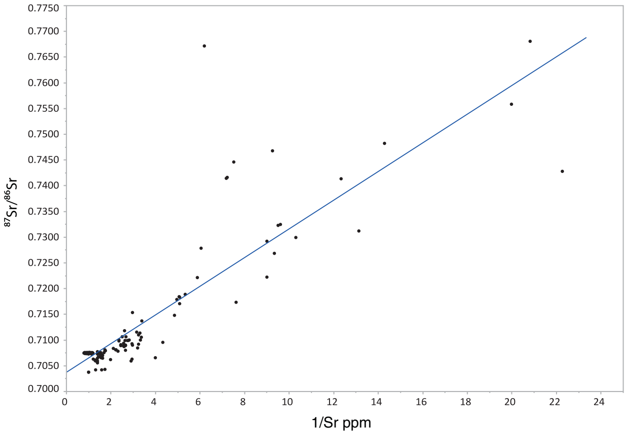

Fig. 6 Geological $^{87}Sr/^{86}Sr$ and Sr concentration data from Aila's region demonstrating the end-members and differential contribution of different geological elements to environmental strontium. The three values with the highest $^{87}Sr/^{86}Sr$ and lowest concentrations were not included

Winchester (Eckardt et al. 2009; Evans et al. 2006), and ±0.0012 in York (Leach et al. 2009, 2010; Muldner et al. 2011). A village associated with a Roman castellum in Bavaria had a similarly high human range of ±0.0013 (Schweissing and Grupe 2003). While these ranges are greater than those seen in the Near East, as discussed below, they are still below Aila's. Removing the potential non-locals from each Romano-British and Bavarian sample based on the estimated local $^{87}Sr/^{86}Sr$ range, the standard deviation of the sample decreases to ±0.0003 at Winchester, ±0.0005 at Catterick, ±0.0005 in Bavaria, and ±0.0007 at York (Gloucester $^{87}Sr/^{86}Sr$ values all fall within the "local" range, and after removing non-locals based on $\delta^{18}O$ results from the sample, the range remains at ±0.0013).

Examples from Rome and the eastern provinces of the Roman and Byzantine Empires also have narrower human $^{87}Sr/^{86}Sr$ ranges than Roman Britain or Bavaria. Values from the environs of Imperial-period Rome show slightly smaller ranges of ± 0.0008 for Casal Bertone and ± 0.0008 for Castellaccio, and removal of the non-locals from each site provides decreased standard deviations of ±0.0004 and ±0.0005, respectively (Killgrove 2010). Near Eastern populations, such as St. Stephen's Monastery in Jerusalem (± 0.0007) (Sheridan and Gregoricka 2015), Barsinia in northern Jordan (± 0.0001) (al-Shorman and el-Khouri 2011), and Khirbet edh-Dharih (± 0.0002) (Perry et al. 2008) and Khirbet Faynan (± 0.0001) (Perry et al. 2009) in southern Jordan, have even narrower ranges. The standard deviation of the St. Stephen's sample (±0.0001) and the Khirbet Faynan standard deviation (±0.00002) both decrease when only including locals established by the fauna range. The one studied region with a similarly high variation as Aila is the Indus Valley trade center of Harappa in the 3rd–2nd millennium B.C. , with a standard deviation of ±0.0035 (Kenoyer et al. 2013).

Do broad human value 1σ ranges tend to occur at sites with relatively large 2σ ranges in fauna values? In contrast to the broad overall $^{87}Sr/^{86}Sr$ values of humans at Aila, the local fauna-based local range is quite narrow (±0.00004 2σ). Only two individuals (M.8:12 and M.2:57) fall just on the upper border of the local range, with the other individuals having much higher values. Expanding this local range to include the sheep/goat values (±0.00043 2σ) only adds two more individuals, A.14:37 and A.9:6, to the local human sample. Other fauna-based 2σ local ranges in the Near East also are much narrower than the plant-based ranges in Roman Britain, such as ±0.0004 at St. Stephen's, ±0.0005 at Barsinia, and ±0.0001 at Khirbet edh-Dharih, compared to ±0.0045 at Gloucester, and ± 0.0017 at Catterick (although Winchester has a more comparable range of ±0.0004, and Bavaria, which has a local range based on human bone values, had a standard deviation of ±0.0007). Harappa has a fauna 2σ range similar to Roman Britain (±0.0022). In general, the narrow Near Eastern local ranges would suggest a relatively homogeneous origin of food sources (as expressed by the fauna) compared to Roman Britain or Bavaria. With the exception of Aila, the relatively narrow overall human $^{87}Sr/^{86}Sr$ ranges also suggest Near Eastern humans consumed similar diets composed of foods from the same mixture of locales, particularly after removing "non-locals" from the sample. In many cases, the heterogeneity of the Romano-British "local" humans can be explained by local geological diversity (e.g., Chenery et al. 2010), and other sites with more homogenous local human values relied on diets from a limited region (e.g., Chenery et al. 2011).

The geological diversity of Aila's surroundings, extending from Precambrian to Cretaceous bedrock with alluvial soils combining these sources, may support the conclusion that the human heterogeneity could stem from exploiting resources from geologically diverse regions all relatively close to Aila (Fig. 3). However, the linear relationship between $^{87}Sr/^{86}Sr$ of the local geology and strontium concentration levels of the geological samples [expressed here as 1/Sr (ppm); Fig. 6] indicates that, as expected, formations with lower strontium isotope values have higher concentrations of strontium. As a result, even if food sources from an array of geological locales in Aila were consumed in equal proportions, the items from areas with greater strontium ppm levels would drive the human's overall strontium value to the lower end of the strontium isotope signature spectrum.

The broad range of human values also could reflect importing foods from diverse regions through long-distance trade, or the importation of humans themselves directly from diverse regions through immigration. The fact that most human values fall outside of the local Aila range would indicate that immigration from different regions created the isotopic diversity at the site, similar to the conclusion at Harappa (Kenoyer et al. 2013), but it is possible that the small fauna sample is not reflecting all of the dietary sources at Aila. Archaeological evidence on local food production, evidence for food importation, and information on childhood diet may help address this issue.

Local food production

Ongoing research into the archaeobotanical and zooarchaeological evidence from Byzantine period Aila suggests that limited food production did occur at the site or within its hinterland (Parker 2015). Local agriculture likely followed the model of oasis agrosystems that revolved around date palms (Parker 2015; Ramsay et al. n.d.). Easily accessible ground water just below the surface meant that small family or community gardens could exist within the city, as they do today near the older sections of modern Aqaba. This level of subsistence horticulture could have produced the chickpeas, grapes, lentils, olives, dates, and figs that show up in the archaeological record (Parker 2006). In addition, fish and shellfish make up a large portion of the faunal remains recovered from archaeological deposits at the site (Parker 2006, 2015), not surprising given the site's location. Some local species, such as tuna and lizardfish, also were used to produce a high-quality *garum*, or fish sauce, at the site during the 1st century A.D. (Van Neer and Parker 2007), an activity that continued through the Byzantine period.

Agricultural weeds, millet, and wheat and barley chaff and grains recovered from archaeological deposits at Aila support local grain harvesting (Parker 2015), but grain production likely was environmentally limited. Archaeologists have not been able to clearly define the extent of the city's *territorium* that would have directly provided agricultural-based subsistence to its inhabitants (Parker 2006). One would assume, based on the patterns seen at other sites in Wadi Araba that relied on desert agriculture such as Faynan, Yotvata, and Bir Madhkur, that larger fields would be located in areas with extensive water runoff within 5–10 km of the settlement (Smith 2005; Meshel 1989; Newson et al. 2007; Ramsay and Smith 2013). At Aila, logical positions would include the alluvial fans along the main trunk road (*via nova Traiana*) through Wadi Yutum, along the wadis on the eastern and western sides of the city, in addition to locations north of the city in Wadi Araba. Extensive archaeological surveys have documented agricultural fields and water catchment systems within 20 km of Aila, but these have been dated from the 5th through 3rd millennia B.C., and show no clear reuse during later periods (Avner 1990; Siegel 2009; Smith 2013). In addition, large agricultural fields at Evrona, 10 km to the north of Aila in Wadi Araba, and Yotvata, about 25 km to the north of the city, were cultivated during the 8th through 10th centuries A.D. (Avner and Magness 1998), but no evidence of earlier large-scale agricultural activities have been noted in that area. As pointed about by Ashkenazi and colleagues (2012), most desert agricultural endeavors in the region were primarily for local consumption.

Aila not only needed grain to support its human population, but also to provide fodder for animals. In fact, the only evidence at Aila for the agricultural by-products supporting local agricultural production mentioned above has been found carbonized in burned animal dung (Parker 2015), meaning there is no direct evidence for local agriculture to feed this city's humans. The strontium isotope evidence for sheep and goats indicate that they were grazed elsewhere (see below), but likely also had to be fed once arriving "on the hoof" into the city. Parker (2015) suggests that grain for animal fodder may have been imported on the stalk to Aila, which had to be processed on-site, and herd animals consumed the grain and any associated agricultural by-products within the shipment. Parker concludes that humans at Aila likely had to supplement their locally-produced crops with imported grains, particularly after the arrival of the legionary garrison at the beginning of the 4th century (Parker 2015).

Evidence for food importation

Extensive archaeological evidence at Aila, including imported amphorae and other ceramics, attests to its role in regional trade from the 3rd century A.D., and possibly as early as the 1st century A.D. (Parker 2006; Ward 2007). After Roman annexation in the early 2nd century, Aila became integrated with Rome's extensive trade networks that linked the Mediterranean to a large portion of Europe, northern Africa, and western Asia. These connections increased through the 3rd century A.D., particularly with Egypt due to the reopening of Trajan's canal from the Nile to the Red Sea port of Clysma (Papaconstantinou 2012). Accordingly, Egyptian amphorae and Egyptian Red Slip (ERS) ceramics began appearing in Aila in the 3rd century (Parker 2009).

The population size for Aila in the 3rd century is not clear, although the city from the 1st century had significant amount of domestic structures, supporting Strabo's identification of Aila as a "*polis*" during this period (Parker 2009; Strabo *Geography* 16.2.30, 16.4.4). Regardless, the arrival of the *legio X Fretensis* in the early 4th century, numbering 1000–2000 military personnel plus their families, would have significantly increased the city population and its food needs (Parker 2015). Perhaps it is no coincidence that the numbers of Egyptian amphorae and ERS increase dramatically at Aila around this period.

As outlined above, Aila's regional environment meant that grains such as wheat and barley likely had to be imported in order to support the local civilian population, especially after arrival of the military component in the 4th century. Agricultural yields from sites in the southern Negev, Wadi Araba, or other arable areas within 100 km of Aila potentially could not support both their local population and livestock (Ashkenazi et al. 2012; Mattingly et al. 2007:344-345), let alone provide a surplus for Aila. The legion's presence meant that some food arrived in Aila as part of the *annona militaris* (Parker 2015), goods collected from civilian populations in the empire that were then redistributed to supply military units beginning in the 3rd century A.D. Parker surmises that the lack of Egyptian ceramics to the north of Aila suggest the port city was their final destination, and they probably contained some of the *annona militaris* destined for the legion.

Egypt served as one of Rome's primary "bread baskets" during the 1st and 2nd centuries A.D. (Erdkamp 2005; van Minnen 2000), with centers of grain agriculture located in the Fayum oasis and the fertile Nile valley and delta (Bagnall 1995). Agricultural yields during this period supported the local population and covered taxes to Rome (van Minnen 2000). During the 4th century, however, agricultural yields in Egypt had dropped according to papyrological evidence, partly due to environmental issues, such as in the Fayum (Bagnall 1985), and largely due to an earlier population decline that left a diminished labor force for agricultural production (van Minnen 2000, 2007). In order to fulfill increased taxation and the new *annona militaris* requirements as the result of 3rd century Diocletianic reforms (van Minnen 2000), most agricultural land was turned over to wheat production (Hickey 2007). Some scholars surmise, based on papyrological evidence, that wheat diminished as a market crop during this period and was only grown for local consumption and taxation purposes, and instead farmers focused on crops such as flax used for textile production and viniculture for market production (see Hickey 2007). However, others note that the 4th century marks aggregation of a populace not directly involved in food production into urban areas (van Minnen 2007), which may have integrated former members of small, discrete communities into the broader agricultural economy (Bagnall 2005). Therefore, it is possible that this economic shift altered wheat's path to more distant markets that is invisible in the available papyri. Furthermore, agricultural production, including wheat, increases in Egypt during the 5th and 6th centuries with the development of new irrigation technologies, which expanded cultivation into more marginal areas (Hickey 2007; Papaconstantinou 2012).

Thus, Egypt still seems to be a large source of grain in the 4th century for military support, including the legion at Aila, but the ability of the civilian population to purchase wheat through long-distance contacts during this period remains less clear. The individuals discussed here were buried in an apparently non-military cemetery, and may not have had access to military resources. Effects of any purported shifts in wheat production for market sale on Aila unfortunately cannot be tracked through traditional indicators of trade, such as amphorae, since grains were transported primarily in sacks (Erdkamp 2013:270) that are rarely preserved in the archaeological record. On the other hand, if one uses the presence of Egyptian amphorae and ERS as a proxy for grain exchange with Egypt, the importation of Egyptian goods into Aila increases significantly in the 4th century. Grain sacks originating from Egypt destined for Aila's civilians could have been included within the ships' cargoes, but this can only be confirmed through isotopic investigation of charred grains found within archaeological deposits at Aila (following Bogaard et al. 2014), an important direction for future research.

Assuming that wheat from Egypt served as a significant food source for Aila's residents, their strontium isotope values would be impacted by the signatures of the primary areas of wheat production, the Nile valley and delta. Most of the Nile sediments transported by the river and deposited in its floodplain originate in Ethiopia (Krom et al. 2002), and along the river's way to the Mediterranean travels through areas of crystalline basement rocks, volcanic, and sandstones, along with alluvial sediments (Krom et al., 2002; Said 1981). The ^{87}Sr/^{86}Sr of sediments in the Nile delta since 6000 BP fluctuates between 0.7088 and 0.7073 due to flow level variation and differential inputs from the rivers' two sources. For sediments deposited between 2200 and 950 BP, the period of interest here, the ^{87}Sr/^{86}Sr value hovers near ~0.7075 (Krom et al. 2002). Strontium isotope studies of human dental enamel from the ancient Nile cities of Thebes and Memphis indicate that bioavailable strontium of 0.70777 ± 0.00027 closely matches the soil signature (Buzon and Simonetti 2013).

Other potential sources of imported food are sheep, goats, and other livestock. Zooarchaeological analysis has indicated that these herd animals were elsewhere and brought to the city "on the hoof" for sale and consumption (Lowrey personal communication; Parker 2001, 2015). Strontium isotope analysis of eight archaeological sheep/goat dental enamel samples from Aila (^{87}Sr/^{86}Sr = 0.7080 ± 0.0004) indicates that those ending up at Aila were herded at least seasonally in the more fertile highland regions to the east and west of Wadi Araba, which are characterized by ^{87}Sr/^{86}Sr ranges of 0.7079–0.70883 (Perry et al. 2008; Perry and Parker 2015). Seasonal transhumance of sheep and goats following this upland/lowland pattern was documented in 19th century Jordan (van der Steen 2013).

Aila's location on the Red Seas was economically strategic enough to overlook the relative lack of local resources. That city residents relied heavily on imported foods that could have traveled along these routes is not surprising. Thus, the broad array of human values at Aila could stem from differential access to these imported resources, and these imported foods simply are not reflected in the rodent values from the excavated portions of Aila. On the other hand, evidence for imported foods at the site does not preclude the presence of numerous non-locally-born residents as well.

Rodent sampling bias

The sample of rodents that serve to establish a local value at Aila admittedly is small, and that alone may intrinsically result in statistical error in our local range determination or diagenetic contamination. On the other hand, external factors may be hindering the ability of rodents to capture the variety of food sources at the site. One reason for the discrepancy between human and rodents strontium isotope values at Aila may result from age-related dietary choices. The dental enamel investigated in the Aila sample comes from the first and second molars, teeth in which the enamel forms between birth to 2.5 years of age (for first molars) or 3.8 to 6.6 years of age (second molars) (Moorees et al. 1963). The strontium isotopes therefore not only reflect childhood residence, but also to the same extent, geological origins of items consumed during childhood. Rodents at Aila, presumably representing the foods available for consumption by all city residents, may not be eating the same array of items as children at Aila, some of whom may have been breastfeeding or in the process of being weaned.

Written recommendations on infant feeding and weaning by Roman physicians such as Oribasius (4th century A.D.) and Soranus (1st century A.D.) were followed well into the later Byzantine and Early Islamic periods (Laskaratos and Poulakou-Rebelakou 2003), but how much women on the imperial frontiers followed Greco-Roman medical practices is unclear. Suggestions include feeding a baby honey mixed with water or goat's milk immediately after birth and then having a wet nurse provide milk for a 20-day period afterwards, as the mother's breast milk was thought to be of poor quality until then (Bourbou and Garvie-Lok 2009). Weaning itself should be very gradual, with increased portions of softened cereals, vegetables, and eggs given from 6 months until at least 2 years of age, at which point the child would focus on eating solid foods (Bourbou and Garvie-Lok 2009). Isotopic evidence of weaning from 5th–7th century eastern Mediterranean skeletal samples suggests that children were in fact weaned from 6 months to 3 years of age (Bourbou and Garvie-Lok 2009; Dupras et al. 2001; Gregoricka and Sheridan 2012). However, variation has been noted in components of the weaning or post-weaning childhood diet, regarding the plants vs. animal protein (Dupras et al. 2001; Gregoricka and Sheridan 2012). Based on this research we can expect to see children at Aila fully weaned by 3 years of age and relying on varied diets, but primarily on C_3 plants such as wheat, barley, legumes, and fruit and on milk and other by-products from animals that consumed these foods. Babies still being largely breastfed should reflect the $^{87}Sr/^{86}Sr$ of the mother or wet nurse, since strontium isotopes do not undergo fractionation (Ericson 1985; Sealy et al. 1991). However, there is the possibility that the mother's body may harbor strontium absorbed during the few previous years, rather than that only absorbed during the period of lactation. Thus, her movement between regions in the years before giving birth could impact the breastfeeding infant's $^{87}Sr/^{86}Sr$ value. Once the infant begins the gradual transition away from breast milk to more solid food, they would be exposed to a combination of locally-produced and imported foods, but this may or may not be in the same proportions as adults. Further isotopic analysis of the Aila sample could clarify differences in childhood vs. adult diets, but the poor preservation of collagen in these skeletal materials (based on attempts at ^{14}C dating) limits this investigation.

As noted by Bentley (2006) and Horn and Müller-Sohnius (1999), diagenetic contamination of skeletal tissues through ground water infiltration will shift their measured values to the ground water signature, resulting in a decreased standard deviation. While rodent dental enamel, like human enamel, should reflect a biogenic in vivo absorption of strontium, it is possible that the dental enamel was contaminated, or despite following best practices, dental dentine, which is more susceptible to contamination, was included in the enamel sample. This could explain a narrow standard deviation for the Aila local value.

The other extrinsic source of bias in our rodents may stem from the type of archaeological deposits providing the samples. The choice of excavation areas for the Roman Aqaba Project was largely dictated by the availability of open lots and/or land within the modern city. The location of the late 4th–early 5th century city wall and contemporary structures indicate that most of the ancient city (along with any legionary fortress) lies underneath modern development and has yet to be explored. Both rodents analyzed here come from archaeological deposits outside of the city wall. It is possible that these rodents did not have access to a random sample of the imported and local foods consumed by the human population residing within the city, and thus their $^{87}Sr/^{86}Sr$ does not reflect that of human residents.

So are these immigrants? or cosmopolitan locals?

The civilian individuals who died and were buried in the two cemeteries explored at ancient Aila in the 4th-5th centuries A.D. clearly consumed food from extremely varied geological locales during childhood. Whether these were locals eating foods imported from many different regions or immigrants originating from many different regions has been explored through assessing the expected level of variation of non-rural Roman settlements in the provinces, identifying which foods could have been produced locally or imported, and possible explanations for the lack of a similar variability in the archaeological fauna used to establish the local range. Aila's diverse local geology includes extremely old granitic formations of the Aqaba complex with high strontium isotope values along with primarily Quaternary alluvial deposits having much lower values. While bedrock values do not translate directly into the potential range of bioavailable strontium at a site, Aila's geological diversity could be represented in a wide range of local human values. Indeed, none of the human values fall outside of the range provided by soil and bedrock in the area. However, the varied Sr abundances in geological sources indicate that they did not contribute equally to the bioavailable strontium. Other natural sources could contribute to higher-than-expected local human values at Aila. $^{87}Sr/^{86}Sr$ of local precipitation may strongly be influenced by the precipitation's seawater source ($^{87}Sr/^{86}Sr \sim 0.7092$; Bentley 2006) in addition to any water-solubilized dust, which in this region often originates in the Sahara ($^{87}Sr/^{86}Sr = 0.7160–0.7192$) (Frumkin and Stein 2004; Hartman and Richards 2014; Krom et al. 1999). The lack of substantial precipitation at Aila implies that this effect is minimal. However, sea spray could impact local bioavailable values (Hodell et al. 2004; McManus et al. 2013; Montgomery and Evans 2006; Whipkey et al. 2000). Seawater ($^{87}Sr/^{86}Sr = 0.709178$ relative to 0.710250 for NBS-987; Kuznetsov et al. 2012) in contact with consumed foods, or even salt mined from the Red Sea, could result in slightly higher Sr ratios in foods that people consumed at the site. Sodium (Na) concentrations in the air surrounding Eilatsuggest that aeolian-derived sea spray impacts the Red Sea coast at levels similar to those seen in the Mediterranean coast of Israel (Chen et al. 2008). How much this sea spray impacts local bioavailable strontium has not been examined, although Herut and colleagues (1993) found that anywhere from 3 to 100 % of strontium isotopes in rainfall on the Mediterranean coast derive from sea spray. In general, however, aeolian dust particles have a more profound effect on strontium than aeolian sea spray (Anker et al. 2007; Frumkin and Stein 2004).

Three different sources provided some estimation of the local value at Aila. The narrow 2σ range provided by the two rodents falls in between the two lowest human values at the site. Expanding this local range to include all available sources (rodent enamel, sheep/goat enamel, and human bone) results in the inclusion of individuals with the four lowest strontium isotope values. Human bone is more susceptible to diagenetic alteration than dental enamel, but all human bone values fall below the values of local groundwater and the soils within central Aqaba within which they were buried. In addition, only considering the rodent-based local value would suggest that the sheep/goats at Aila where being raised elsewhere and brought to the city “on the hoof,” corroborating the zooarchaeological interpretations. However, they have almost the same range as the human bone values. The most parsimonious explanation for the slight discrepancy between the rodent values and the human bone and sheep/goat values likely is bias due to the small size of the rodent sample.

The local diet at Aqaba probably was based on consumption of imported wheat from the Nile valley in Egypt supplemented by some local fruits and legumes in addition to local fish and other marine resources. Children at Aila may have had a diet limited to the imported grains, milk from sheep/goats or cattle, eggs from local chickens, and perhaps a few locally-produced fruits, vegetables, and legumes, based on textual recommendations and C and N isotope data from other sites. Of these foods, grains and other plant products that have high Sr concentrations will contribute more to their strontium values. The possible influence of grains imported from the Nile Valley (^{87}Sr/^{86}Sr = 0.70777 ± 0.00027; Buzon and Simonetti 2013) is reflected in Aila’s rodent dental enamel range (^{87}Sr/^{86}Sr = 0.707837 ± 0.00004).

This rodent-based range falls below human bone values from Aila (0.708011 ± 0.00036), which may result from, as mentioned above, differential access to dietary sources between these two groups. For instance, the slightly higher human bone values may be influenced by foods originating from areas with higher bioavailable values, such as Wadi Araba north of Aila (^{87}Sr/^{86}Sr = 0.70793–0.70813) and the eastern and western highlands on either side of the valley (^{87}Sr/^{86}Sr = 0.70790–0.70883) (Hartman and Richards 2014; Perry et al. 2008, 2009; Shewan 2004). Strontium-rich plant foods from these sources would drive the human values slightly higher than the rodents, presuming the rodents did not have access to these items. In addition, the sheep/goats consumed at Aila (^{87}Sr/^{86}Sr = 0.708036 ± 0.00043), likely raised outside of the city in more fertile areas and herded in for sale, mirror the higher bioavailable strontium in these regions. Milk from these animals probably did not strongly impact dietary Sr, as it is also high in Ca that the body will uptake preferentially over Sr. However, the source of these animals may represent economic links to areas that could have produced other food items for Aila. Therefore, the local bioavailable strontium range at Aila probably is best reflected by a combination of these three sources, the human bone range, the rodent dental enamel range, and the sheep/goat enamel range ^{87}Sr/^{86}Sr = 0.7076142–0.708643. This would include four of the individuals within this sample, M.8:12, M.2:57, A.14:37, and A.9:6, with the rest falling above this range. This range also matches that of geological features with the highest Sr abundances at Aila that would more strongly influence local bioavailable strontium.

Confirmation of “local” values clustering at the lower end of the human Sr spectrum seen at Aila can be further demonstrated by the density peaks in the data provided by the kernel density distribution. This would be based on the supposition that the density of strontium isotope observations would increase around the local range, and any non-locals would have randomly distributed strontium values, particularly if they immigrated from a wide array of regions. Density peaks occurred at ^{87}Sr/^{86}Sr = 0.708833 and ^{87}Sr/^{86}Sr = 0.711897, implying that two main subgroups can be identified based on distribution of the data. The lower peak contains some individuals falling within the range established by fauna and human bone, in addition to others with values slightly higher. However, there are few dietary inputs at Aila that fall above 0.7088, suggesting some individuals contributing to the second density peak at 0.7119 of the distribution may not be local.

Accepting that the above range reflects local bioavailable strontium, a majority of the individuals buried in these two cemeteries Aila were not locally-born. For instance, if burial M.6:18, a >60 year-old male with ^{87}Sr/^{86}Sr = 0.7171, spent his childhood in Aila, he would have had to consume almost exclusively foods with strontium values *above* 0.7171 to be able to swamp local sources with high Sr abundances and much lower ^{87}Sr/^{86}Sr values (see Montgomery and Evans 2006). This is not likely in this geological context.

Therefore, careful parsing of the data suggests that most of the individuals at Aila were immigrants into the port city, assuming that, as children before and after weaning, Ailaean children (or those from whom they breastfed) were consuming a mix of grains primarily imported from Egypt, milk from sheep and goats raised elsewhere but brought to Aila markets, and other locally-produced fruits and legumes produced in Aila's oasis gardens. The tooth analyzed (first vs. second molar) can reflect pre-vs. post-weaning diets. As noted above the first molar reflects residence/diet from birth to 2.5 years of age when the child has not been completely weaned, and the second molars from 3.8 to 6.6 years of age, or the period after weaning. No differences in dietary sources were noted between these two ages in this sample, indicating a very slow and gradual transition to solid foods during infancy. However, intra-individual variation can be seen in the 0.0002 decrease in Sr isotope values between the first and second molars of A.9:34, the 20–25-year-old female, which may suggest some dietary shift pre- and post-weaning, although this value falls under the general % standard error in these samples. However, no significant differences in strontium isotope values emerged by comparing males and females, different age categories, location of burial, and presence of pathologies.

It is notoriously difficult to identify from where immigrants originated (Price et al. 2002), particularly in a seaport potentially drawing individuals from points along the extensive trade networks of the Byzantine Empire. In addition to Egypt and northern Africa, as noted above, maritime trade occurred with the Persian Gulf and India, and overland trade linked Aila to the Mediterranean (Tomber 2008). Studies of bioavailable strontium through analysis of fauna and plants (and plant ash used in glass-making) in the Levant, Iraq, Turkey, the Persian Gulf, and Egypt, while not exhaustive, have not identified a region displaying values as high as those seen within most Aila immigrants (Bogaard et al. 2014; deGryse et al. 2010; Ganio et al. 2013; Gregoricka 2013a, b, 2014a, Gregoricka et al. 2014; Hartman and Richards 2014; Henderson et al. 2005, 2009, 2010; Leslie et al. 2006; Perry et al. 2008, 2009, 2011; Sheridan and Gregoricka 2015; Shewan 2004). On the other hand, inland North African samples from Niger (Stojanowski and Knudson 2014) and inland Libya (di Lernia and Tafuri 2013) fall over 0.7110. Elsewhere, values above 0.7090 have been reported in Pakistan (Gregoricka 2013a, b), higher than 0.7100 in Europe (e.g., Borić and Price 2013; Chenery et al. 2010, 2011; Eckardt et al. 2009; Evans et al. 2006; Gregoricka et al. 2014; Leach et al. 2009, 2010; Schweissing and Grupe 2003; Waterman et al. 2014), and above 0.715 within the Indus River system (Kenoyer et al. 2013).

Thus, while the birthplace of the non-local individuals who died at Aila cannot be identified, those with $^{87}Sr/^{86}Sr$ >0.7090 clearly originated a significant distance from immediate southwestern Asia, a theory that can be explored further through additional isotope testing. Their reasons for being at Aila also cannot be ascertained through these data, but the range of sexes and ages of these individuals may suggest no one narrative can explain their presence. Despite their diverse origins, and any resulting diversity in traditional burial practices, the non-local individuals buried in Areas A and M were not treated differently in death from the locally-born residents. The residents of the Byzantine seaport of Aila buried in these two cemeteries thus represent a population who traveled a significant distance in their lifetime to the city.

Conclusions

Therefore, careful assessment of dietary sources of strontium and the local bioavailable strontium range indicate that the diverse strontium isotope values at ancient Aila reflect individuals emigrating from many different locales. Four individuals growing up at Aila were probably fed grains, perhaps softened bread or cereals made from wheat and barley imported from areas such as Egypt as indicated by the archaeological and historical evidence, and have the lowest strontium isotope values in this sample ($^{87}Sr/^{86}Sr = 0.7076–0.7080$). The other 19 may have been drawn to Aila and settled there for economic reasons, or been part of the extensive maritime and overland trade networks within which the city was embedded, and because they died en route or upon arrival, Aila happened to be their final port of call.

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