Megan A. Perry
Department of Anthropology
East Carolina University
Flanagan 231
Greenville, NC 27858 USA

Megan A. Perry

Crossing Jordan: Tracing Human Migration in Classical Period Jordan Using Strontium and Oxygen Isotopes

Introduction

Archaeologists traditionally track the movement of material culture or assess site patterning in order to quantify ancient migration patterns or mobility levels (e.g., Binford 1980; Hitchcock 1987; Kent 1991). Chemical signatures in human skeletal tissues such as strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotopes also have become additional powerful tools for investigating migration in ancient contexts. This paper discusses the applicability of these techniques in Jordan. First, the development of these two isotopic techniques and how they relate to human migration will be discussed. This will be followed by an assessment of the applicability of these techniques in Jordan, using data from the Nabataean site of Khirbat adh-Dharīḥ and the Byzantine site of Faynān.

Isotopes and Human Migration

The ratio of two strontium isotopes, ^{87}Sr to ^{86}Sr, reflects bedrock geological age. Strontium enters the food chain, and our skeletal tissues, through consumption of ground water, plant, and animal resources (Faure 1986; Faure and Powell 1972). Human dental enamel, once mineralized, retains the strontium isotope ratio absorbed from consumption of these resources during childhood dental development. Enamel in a particular tooth therefore reflects the strontium sources relied upon, and hence the geological region lived in, during its mineralization. An individual would be identified as an immigrant into a particular region based on a difference between their dental enamel vs. local $^{87}Sr/^{86}Sr$ values. Dental enamel of small mammals best reflects the local $^{87}Sr/^{86}Sr$ signature (Bentley 2006; Budd *et al.* 2000; Hoppe *et al.* 2003; Price *et al.* 2002), although researchers have relied on bedrock, soils, plants, and/or local water with varied success (Ezzo *et al.* 1997; Hodell *et al.* 2004; Schweissing and Grupe 2003; Sillen *et al.* 1995, 1998). The application of $^{87}Sr/^{86}Sr$ to investigate human migration has been applied in numerous contexts around the globe (e.g., Ericson 1985, 1989; Evans *et al.* 2006; Ezzo *et al.* 1997; Knudson and Price 2007; Knudson and Buikstra 2008; Montgomery *et al.* 2000, 2003; Price *et al.* 1994, 1998, 2006).

Oxygen isotopes vary according to climatologic and geomorphologic variables such as distance from the ocean, precipitation, temperature, elevation, and humidity/aridity (Gat and Lansgaard 1972; Yurtsever and Gat 1981). Similar to strontium isotopes, oxygen isotopes become incorporated into the mineral components of human bone (carbonate and apatite) through consumption of water sources and food (Luz and Kolodny 1989; Luz *et al.* 1984). Instead of local geology, these materials reflect the local environmental water, which is composed of both meteoric water falling as precipitation and recycled groundwater (Dansgaard 1964). The $\delta^{18}O$ signatures in human dental enamel therefore reflect the water source(s) that the individual relied upon during dental enamel development and mineralization (see Dupras and Schwarcz 2001; Evans *et al.* 2006; Knudson and Price 2007; Prowse *et al.* 2007; White *et al.* 2004).

Geologic and Climatic Setting of Western Jordan

Strontium isotopes' utility for understanding migration depends upon: 1) considerable heterogeneity in $^{87}Sr/^{86}Sr$ values between geologic/cultural zones, and 2) significant homogeneity in $^{87}Sr/^{86}Sr$ ratios within these areas. The Hashemite Kingdom of Jordan occupies a geologically diverse region categorized by seven distinct geologic provinces: the southern mountainous desert, the Jordan rift valley, the mountains and highlands east of the rift valley, the central plateau near al-Jafr and the Wādī as-Sirḥān system, the northern basalt fields, and the northeastern plateau near the Iraqi border (Bender 1975) (FIG. 1). Presumably strontium isotope variation would mirror variability in bedrock geology.

The probability that faunal remains recovered from archaeological contexts would accurately characterize regional geology in western Jordan was tested using 20 samples from 13 archaeological sites. Western Jordan was focused on during this initial phase due to its geologic complexity and plethora of ancient sites in this area. Western Jordan includes two of Bender's provinces: the Jordan rift valley and the mountains and highlands to the east.

Regional characterization of $^{87}Sr/^{86}Sr$ ratios in western Jordan relied upon dental enamel from 20 small rodents (*Rattus rattus, Myomimus personatus, Mus musculus,* and *Gerbilus dasyurus)* recovered from 13 archaeological sites in Jordan. Patterning of these data was tested using two techniques: 1) a t-test to compare strontium isotope ratio means between Bender's two geologic provinces to see if they were sufficiently heterogeneous, and 2) cluster analysis to identify patterns that may not conform to Bender's designations. First, the t-test did identify a significant difference in the strontium isotope ratio signature means between Bender's two provinces (mean difference = 0.0002, df=10.3, t=4.04, p=0.0022), but significant overlap existed between the two groups. Cluster analysis clarified this overlap by clustering strontium isotope values in into three north-south zones: the rift valley ($^{87}Sr/^{86}Sr$=0.70781-0.70786), the western highlands ($^{87}Sr/^{86}Sr$=0.70815-0.70834), and the wadi and mountain systems in between the valley and the highlands ($^{87}Sr/^{86}Sr$=0.70792-0.70810) (Perry et al. in press). Published data from Israel suggests that the western rift valley, and escarpment, and highlands follow essentially the same pattern as Jordan with the exception of the coastal region ($^{87}Sr/^{86}Sr$=0.70831-0.70925) and the Golan Heights ($^{87}Sr/^{86}Sr$=0.70529-0.70571) (Shewan 2004).

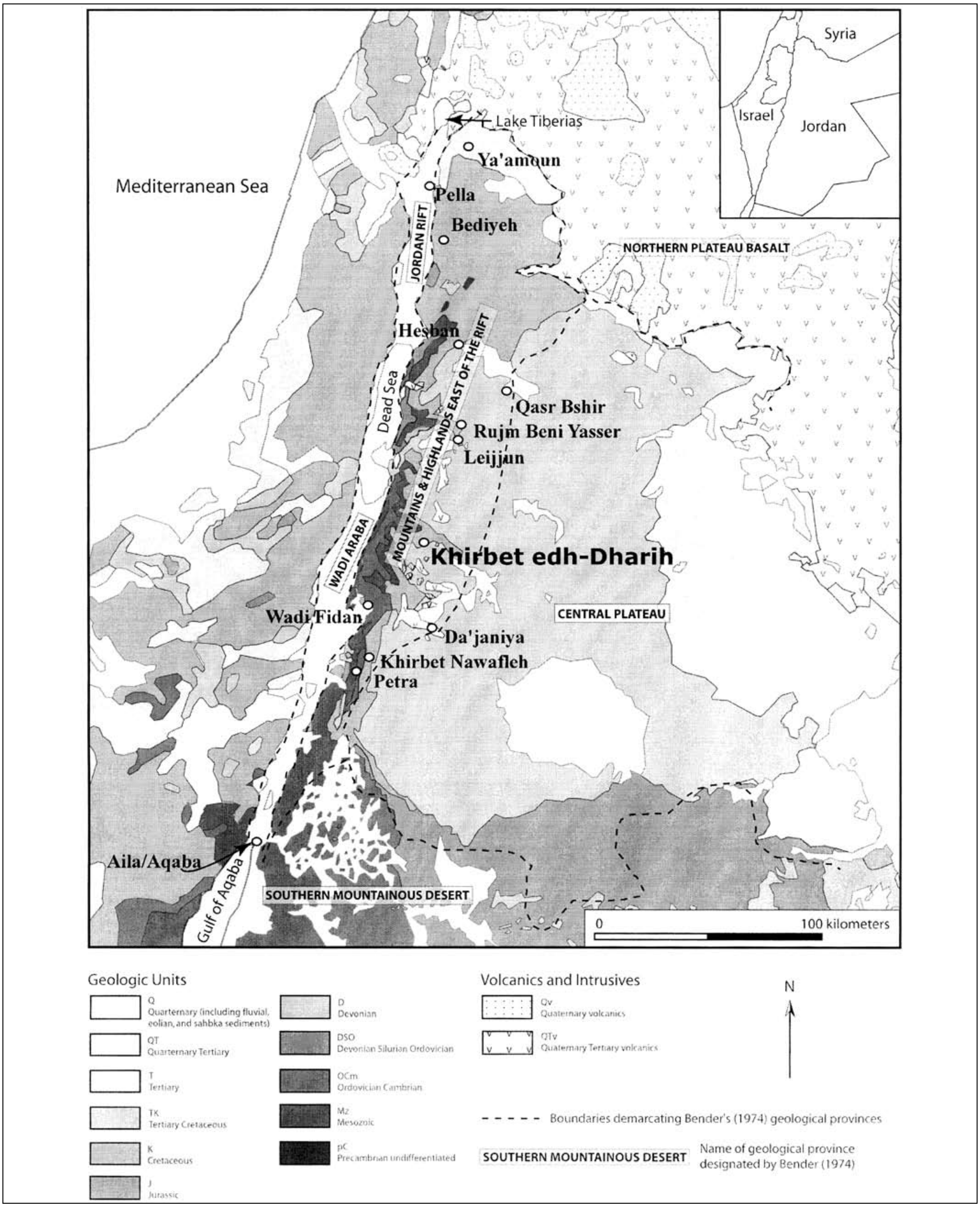
Oxygen isotopes' value for migration studies on the other hand generally depends upon regional variation in elevation, humidity, rainfall levels, and distance from major water bodies. The Levantine region generally follows a typical Mediterranean climate pattern with warm summers, mild winters, and seasonal rainfall lasting from September until April. As the systems spread inland from the Mediterranean into the mountainous regions in northern and central Israel, precipitation becomes continuously depleted of heavy isotopes (Gat and Dansgaard 1972). Rain in the lower lying areas on the other hand, such as the coastal plain and the Jordan Valley, is more enriched than in the higher elevations (Gat and Dansgaard 1972). This pattern reverses beyond the Jordanian side of the rift valley escarpment into the highlands, with increasingly lower precipitation $\delta\,^{18}O$ values as one moves from east to west (Bajjali and Abu-Jaber 2001). In the southern arid regions however, such as the Negev desert, precipitation $\delta\,^{18}O$ is strongly negative because of evaporation and relatively short duration of rainfall events (Gat and Dansgaard 1972).

Regional inhabitants additionally relied heavily on groundwater sources such as wells and aquifers in addition to constructed rainfall catchment features. Groundwater sources are largely replenished through surface runoff that varies from north to south. In the north, water is quickly absorbed into the surface. In the south on the other hand, surface runoff travels long distances over the loess groundcover, and as a result, is subject to greater evaporation and resulting enrichment (Gat and Dansgaard 1972). This combined effect of enriched precipitation and the relative importance of surface runoff as a water source in the south results in extremely enriched groundwater $\delta\,^{18}O$ values in southern Israel (Gat and Dansgaard 1972) (FIG. 2).

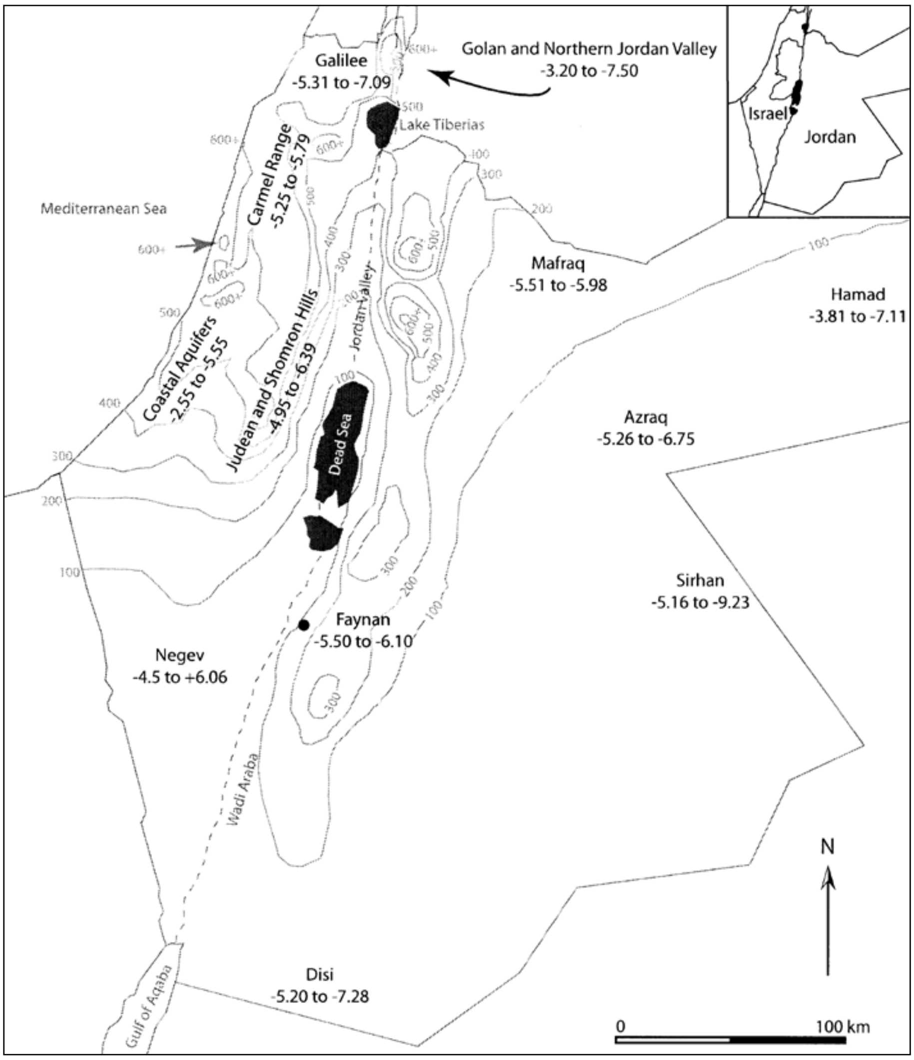
Thus, on the surface, Jordan seems to be an appropriate venue for isotopic investigations of ancient migration. Strontium isotope values vary strongly east to west, and oxygen isotopes have north-south variation as well as east-west variation. The efficacy of these techniques will be tested using isotopic data from two sites: Khirbat adh-Dharīḥ, and Khirbat Faynān (ancient *Phaeno*).

Example #1: Khirbat adh-Dharīḥ

Khirbat adh-Dharīḥ, located along the *Via Nova Traiana* north of Petra, was a small village and sanctuary during the Nabataean and Roman periods. Village residents included the family overseeing the sanctuary, possibly associated with a monumental family tomb discovered at adh-Dharīḥ, a large house near the sanctuary, and mentioned in an inscription from Khirbat at-Tannūr (al-Muheisen and Villeneuve 2005; Lenoble *et al*. 2001; Villeneuve and al-Muheisen 2003). Assuming that the



1. Map of Jordan showing bedrock geology and sampled sites (from Pollastro *et al*. 1997) in addition to geological regions identified by Bender (1974, 1975).

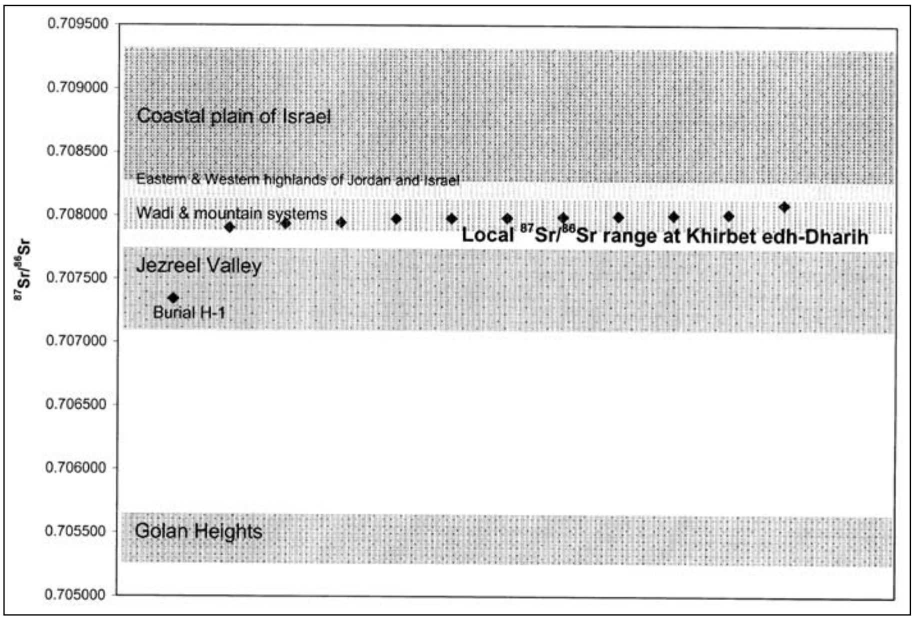


2. Isoline map showing mean annual precipitation (based on data from the Jordanian Ministry of Water and Irrigation, Palestinian Water Authority, and Israeli Hydrological Service, Middle East Water Data Banks Project. http://exact-me.org/overview/index.htm) with groundwater $\delta^{18}O$ variation in Jordan and Israel based on regional studies of Bajjali and Abu-Jaber (2001) and Gat and Dansgaard (1972).

religious sanctuaries were under centralized administrative control based in Petra, this family could have either been selected from the local population by authorities to administer the sanctuary or have been sent from an administrative center such as Petra. Excavators at the site hypothesize that Khirbat adh-Dharīḥ was settled by exiled elites from Petra. In this case, we used $^{87}Sr/^{86}Sr$ ratios of archaeological human enamel from adh-Dharīḥ to identify individuals, especially those in the monumental tomb, who did not originate from adh-Dharīḥ.

Dental enamel from the mid-crown of the first permanent molar of 12 adult individuals from the northern cemetery, southern cemetery, and monumental tomb at Khirbat adh-Dharīḥ, excavated by Yarmouk University, the Institut Français du Proche-Orient (IFPO), and Sorbonne University, was analyzed, reflecting residence from birth until approximately 2.5 years old (Moorrees *et al.* 1963a, 1963b). This sample includes one intact burial (V-5) from the monumental tomb (Tomb C1), likely interred in the years immediately following Roman annexation (Lenoble *et al.*, 2001:127-128). Two rodent dental enamel samples also were collected to establish the local $^{87}Sr/^{86}Sr$ value. The samples were processed at the Bioarchaeology Laboratory at East Carolina University and treated and analyzed at the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the University of North Carolina at Chapel Hill. Detailed results of these analyses are discussed in Perry *et al.* (in press).

Only one definite outlying value emerges through observing the distribution of the human dental enamel $^{87}Sr/^{86}Sr$ signatures (FIG. 3). This individual, an adult male buried in Tomb H in the Southern Cemetery, may have originated from the Jezreel Valley in northern Israel based on his



3. Results of $^{87}Sr/^{86}Sr$ analysis of the archaeological human dental enamel from Khirbat adh-Dharīḥ compared with ranges established by fauna and plants (Perry *et al.* in press; Shewan 2004).

$^{87}Sr/^{86}Sr$ signature ($^{87}Sr/^{86}Sr=0.70734$) (Shewan 2004). Comparing the remaining values with the range established from faunal dental enamel ($^{87}Sr/^{86}Sr=0.70783 \pm 0.0004$) only identifies one individual from the northern cemetery falling within the "local" range. The remaining 10 individuals from the northern cemetery, the southern cemetery, and the one individual from the monumental tomb have $^{87}Sr/^{86}Sr$ values slightly above the upper limit of the local range for adh-Dharīḥ. However, these individuals however fall within the values expected for the wadi systems and mountainous region to the east of the rift valley. These people thus originated from somewhere within the zone extending ca. 300km from north to south — and this could include adh-Dharīḥ or Petra. The faunal data therefore do not adequately reflect the broad range of actual strontium sources available at the site, which may vary from the local value through the consumption of strontium — and calcium — rich foods grown or raised in other regions. This can be clarified with further sampling of faunal dental and soil samples, in addition to detailed analysis of dietary sources and composition at the site. Other techniques, such as oxygen isotope analysis, may further clarify these results, as discussed below.

Example #2: Faynān

The example from Khirbat adh-Dharīḥ demonstrates the potential, and the limitations, of strontium isotope analysis in Jordan. Oxygen isotopes, however, often can clarify strontium isotope results. Recent analyses conducted by the author and Drew Coleman at University of North Carolina at Chapel Hill, assisted by Abdel Halim al-Shiyyab of Yarmouk University, on samples from the Byzantine cemetery at Faynān exhibits the potential of multiple isotopic techniques. The Byzantine Empire purportedly expended substantial funds and labor transporting prisoners to mining camps such as Faynān (*Phaeno*). The camp also certainly contained administrative staff or free mine laborers and their families, and possibly the families of the prisoners. The third - sixth century AD cemetery for instance held children under the age of three years whom Byzantine courts would have exempted, for example, from penalty (Robinson 1995). They thus lived with their parents, who resided at the camp for employment or punishment.

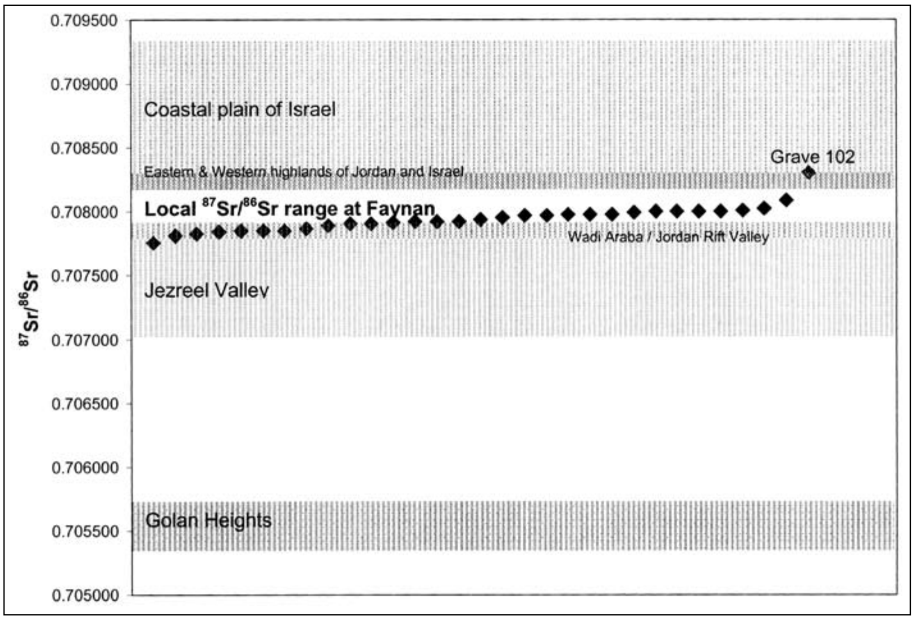
Dental enamel samples were collected from 31 of the 45 individuals excavated from Faynān's Southern Cemetery by Yarmouk University and the Council for British Research in the Levant (CBRL) in 1996 (Findlater *et al.* 1998). The sampled teeth from different individuals reflect the areas they lived in anywhere from 16 weeks *in utero* until 6.8 years of age. One rodent dental enamel and eight snail shell samples also were collected from Wādī Fīdān, ca. 10km to the west, to establish the local $^{87}Sr/^{86}Sr$ value. Strontium isotope analysis was performed at the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the University of North Carolina at Chapel Hill, and oxygen isotope analyses on enamel carbonate at the Stable Isotope Laboratory in the Department of Geosciences at the University of Arizona. The results from these analyses are discussed in more detail in Perry *et al.* (n.d.).

The estimated local $^{87}Sr/^{86}Sr$ value at Faynān based on local faunal enamel and snail shell samples ranges between $^{87}Sr/^{86}Sr$=0.70793-0.70814. Approximately half of the individuals from Faynān fall within this range, directly suggesting that they are of local origin (FIG. 4). The distribution of Sr isotope values, however, does not identify a clear boundary between individuals falling within the range and those just below it. According to the distribution of the values, only one 30-34 year-old male from Grave 102 ($^{87}Sr/^{86}Sr$=0.70830) is a true outlier.

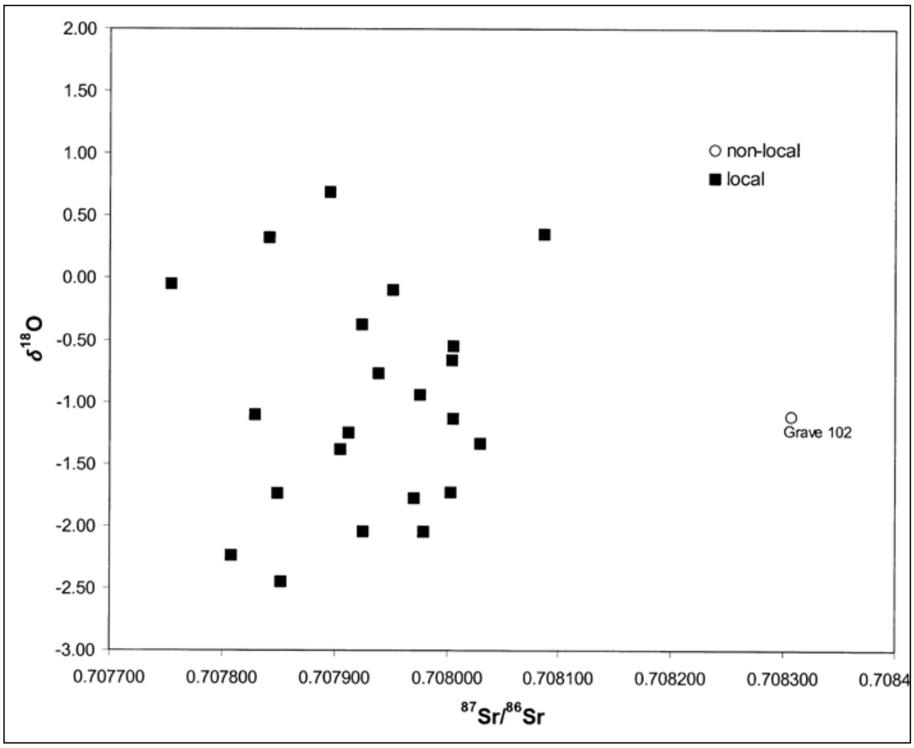
Therefore, similar to the Khirbat adh-Dharīḥ sample, the faunal and snail shell samples do not adequately reflect the local range of biologically-available strontium at the site. Furthermore we encounter the same problem interpreting the Faynān data as we do with the adh-Dharīḥ results — the two geologic regions represented by the $^{87}Sr/^{86}Sr$ values of Faynān residents stretch over 300km from north to south, and thus these individuals could have originated from any point within these zones. In addition there are other regions in the Levant that have geologic signatures similar to these two groups, such as the western (Israeli) side of the rift valley system. Oxygen isotopes may help elucidate whether or not these individuals originated in locales near Faynān, or in other areas with similar bedrock geology but a different elevation, distance from the coastline, precipitation pattern, or groundwater source.

Oxygen isotope analysis of 19 individuals from the southern cemetery at Khirbat Faynān reveals relative homogeneity in $\delta\,^{18}O$ values, and thus childhood water sources, in site residents (FIG. 5). The one possible non-local individual from Grave 102 has a $\delta\,^{18}O$ value of -1.12, not notably divergent from the other values. This person's $^{87}Sr/^{86}Sr$ signature indicates that they could have originated from areas to the north, such as the high plains in northwestern Jordan or the Judean Hills, the Carmel Range, or the Galilee regions in modern Israel and the West Bank (Shewan 2004). These regions generally receive greater rainfall and are in closer proximity to the Mediterranean then Faynān, and therefore should have water sources more depleted in $\delta\,^{18}O$. We plan to explore the $\delta\,^{18}O$ values at Faynān in more detail through comparing enamel carbonate $\delta\,^{18}O$ with enamel phosphate and soil carbonate $\delta\,^{18}O$ values to test for contamination or other factors that may have influenced the $\delta\,^{18}O$ values.

Strontium isotope values regardless do not imply that individuals were transported regularly from afar to staff and run the *Phaeno* mines. If prisoners were transported from the *Palaestina* provinces and surrounding regions, a wider array of $^{87}Sr/^{86}Sr$ values would be expected that reflect the varied geology of the coast and western highlands. The individual from Grave 102 could have been a prisoner or administrator transported to the camp under im-



4. Results of $^{87}Sr/^{86}Sr$ analysis of the archaeological human dental enamel from Khirbat Faynān compared with ranges established by fauna and plants (Perry *et al.* in press; Shewan 2004).



5. $\delta^{18}O$ values compared with $^{87}Sr/^{86}Sr$ signatures of individuals from Khirbat Faynān. The empty circle indicates the individual from Grave 102 with a non-local $^{87}Sr/^{86}Sr$ signature.

perial orders. He also could have been a miner born elsewhere, but forced to return to his hereditary homeland to work in the mine per Theodosius II's AD 424 decree (*Codex Theodosianus* 10.19.15). In this case, incorporating $\delta\,^{18}O$ data confirmed but did not necessarily broaden our interpretation of the strontium data. Combined oxygen and strontium isotope data indicate that *Phaeno* predominantly contained locally-derived individuals, suggesting that the mines were a locally-run venture staffed primarily by local residents.

Possible Confounding Factors

Strontium isotope ratios less accurately identify north-south movement than east-west migration in western Jordan based on results from analysis of faunal data from western Jordanian archaeological sites. Accurately characterizing local $^{87}Sr/^{86}Sr$ values is hindered by the small sample size of small mammals recovered from archaeological excavations in addition to a number of other confounding factors, discussed below. Furthermore, $\delta\,^{18}O$ values may not vary as strongly as expected in the region. Water catchment and storage, necessary in this arid environment, may dramatically influence $\delta\,^{18}O$ of consumed water that can mask expected climatological and geomorphological variation. Analyzing oxygen isotopes in local water and faunal samples would allow more accurate testing of $\delta\,^{18}O$ in ancient Jordanians. Furthermore, many factors besides contamination or local geology can influence an individual's $^{87}Sr/^{86}Sr$ signature. These factors include cultural vs. geological identification of "foreigners", the consumption of imported high-calcium and high-strontium foods, and climatological variables such as seasonal erosion and dust storms.

1) Would Strontium Isotopes Inaccurately Identify Foreigners?

One item to consider is whether or not strontium isotope heterogeneity across the region parallels ancient notions of "foreign-ness?" For example, individuals growing up in Wādī ʿAraba very near Faynān could be identified as "non-locals" based on strontium isotope ratios, but may not have been considered outsiders or foreigners by Faynān residents. Significant variation between regions may identify someone considered "local" inaccurately as a foreigner. Individuals identified as "local" at both Faynān and adh-Dharīḥ also may have been considered an outsider if they had originated from the northern sector of the geological zone runs 300km along the rift valley escarpment. Intra-regional homogeneity of $^{87}Sr/^{86}Sr$ values thus masks some indigenous cultural differences that may have existed between individuals. Therefore, careful construction of research questions considering these factors can strengthen the application of this technique. Furthermore, relying on other isotopes such as $\delta^{18}O$ and trace element concentrations (see Knudson and Price 2007) may clarify results from strontium isotopes.

2) Imported Diet

Dietary choices also may influence the $^{87}Sr/^{86}Sr$ signature of humans and must be considered in migration studies. Strontium and calcium-rich foods produce the majority of strontium in human skeletal tissue (see Burton and Wright 1995). Therefore, the consumption of imported foods high in these trace elements should be considered while interpreting human $^{87}Sr/^{86}Sr$ values. Meat provides more strontium to the local diet than cereal grains, for example (Lambert and Weydert-Homeyer 1993). Cereal grains, such as wheat, on the other hand have substantially greater concentrations of calcium than meat (Runia 1987), meaning that both sources consumed in equal amount may contribute similarly to bone Sr concentrations. Other high-calcium and high-strontium sources can include the treasured Roman condiment *garum* (fish sauce) that has been discovered at many inland Classical period sites such as Petra (Desse-Berset and Studer 1996; Studer 1994). Residents of inland urban centers and military forts also consumed fish from the Red or Mediterranean Seas (LaBianca 1990; Lernau 1986; Toplyn 2006). Dairy by-products from goats, sheep, and cattle can vary from the local expected $^{87}Sr/^{86}Sr$ value if they were herded long distances for trade with sedentary populations, such as at Aila (Parker 1996, 1998). Amphorae containing imported olive oil, wine, and other liquids, or pack animals used to transport goods also indicate the presence of other potentially calcium- and strontium-rich imported foods at many sites (e.g., Parker 2002, 2006; Toplyn 2006).

Water sources also have varied $^{87}Sr/^{86}Sr$ values, depending upon substrate geology and sediments they contain. Food production could similarly alter $^{87}Sr/^{86}Sr$ values, such as using imported grinding stones (Åberg *et al.* 1998) or additives to process food (Wright 2005). Any consideration of human (or rodent) $^{87}Sr/^{86}Sr$ values in thus must include any evidence for imported food and drink, extensive seafood consumption, or modes of food production in the archaeological record.

3) Climatic Variation

Intensity of seasonal dust storms can also influence strontium isotope ratios in western Jordan. Springtime low pressure systems originating in the Saharan desert (with $^{87}Sr/^{86}Sr$ ratios ranging from 0.7160-0.7192) send large *khamaseen* dust storms across the eastern Mediterranean and Near East. These storms variably influenced $^{87}Sr/^{86}Sr$ ratios during the past 220 kyr, producing intermittently higher $^{87}Sr/^{86}Sr$ values during dry periods (and thus more intensive atmospheric dust deposition) and lower $^{87}Sr/^{86}Sr$ ratios during wetter periods (Frumkin and Stein 2004; Krom *et al.* 1999). Thus biogenic strontium of organisms living during a period of intense dust storms may have a higher $^{87}Sr/^{86}Sr$ value than expected based on organisms that lived during wetter seasons.

Seasonal rainfall additionally results in considerable fluvial erosion in western Jordan, in particular in the wadi systems leading from the eastern highlands into the rift valley. Variation in annual rainfall amounts can result in variable annual erosion rates. Generally $^{87}Sr/^{86}Sr$ of alluvial material will combine, or “mix,” the $^{87}Sr/^{86}Sr$ of its sources (see Bentley 2006; Montgomery *et al.* 2007). Differential weathering of bedrock, not only due to relative elevation of strata but also relative contribution of bedrock components, may also influence $^{87}Sr/^{86}Sr$ values of alluvial wash at different points along the drainage system. This variation additionally can influence groundwater $^{87}Sr/^{86}Sr$ values seasonally or annually.

Conclusion

Regional characterization of $^{87}Sr/^{86}Sr$ ratios in western Jordan reveals that east-west migration patterns are best explored using strontium isotope analysis. Significant differences in $^{87}Sr/^{86}Sr$ values exist between the Wādī ‘Araba-Jordan rift valley, the mountains and wadi systems along the rift edge, and the highlands to the east of the rift. Strontium isotopes may not identify a migrant traveling from north to south within a geologic zone, such as along the *Via Nova Traiana*, the major Roman thoroughfare in the highlands area. Researchers are encouraged to utilize multiple chemical techniques to best characterize ancient population movement. Investigators additionally need to consider the presence of imported foods, especially those, which contain high amounts of calcium or strontium, the location of water storage features, and the intensity of dust storms and seasonal erosion in the area. Archaeological and historical evidence also should be incorporated in order to illuminate whether a geologically-defined "outsider" would in fact be classified as a "foreigner" by local populations. The studies presented here from Faynān and adh-Dharīḥ however demonstrate the utility and limitations of multiple chemical techniques in migration studies of archaeological populations.

Acknowledgments

The author would like to thank Fawwaz al-Khraysheh, Director-General of the Department of Antiquities of Jordan, and Abdel Halim al-Shiyyab of Yarmouk University for facilitating this research. Analysis of the Khirbat adh-Dharīḥ samples was made possible by François Villeneuve, Zeidoun al-Muheisen, and Françoise Le Mort, and study of the Faynān samples by Abdel Halim al-Shiyyab. I additionally would like to thank the many individuals who assisted in collection of faunal samples: Jerome Rose, Øystein LaBianca, Philip Edwards, S. Thomas Parker, Thomas Levy, Adolfo Muñiz, Abdel Halim al-Shiyyab, François Villeneuve, and Pierre and Patricia Bikai. David Dettman of the University of Arizona ran the $\delta\,^{18}O$ analyses, and Drew Coleman of the University of North Carolina at Chapel Hill ran the $^{87}Sr/^{86}Sr$ analyses. Lisa Leone, Tina Greene, and Timothy Shortley, Jr. of East Carolina University helped process the human dental enamel and faunal dental enamel samples. Jennifer Poole of University North Carolina at Chapel Hill assisted with all aspects of Sr sample preparation. This research was supported by an American Center of Oriental Research CAORC Senior Fellowship, a Joukowsky Family Foundation Research Grant, and an East Carolina University Creative and Research Activity Award.

Bibliography

Åberg, G., Fosse, G. and Stray, H. 1998. Man, Nutrition and Mobility: A Comparison of Teeth and Bone from the Medieval Era and the Present from Pb and Sr Isotopes. *The Science of the Total Environment* 224: 109-19.

Al-Muheisen, Z. and Villeneuve, F. 2005. Archaeological Research at Khirbat Adh-Dharih. *ADAJ* 49: 489-99.

Bajjali, W. and Abu-Jaber, N. 2001. Climatological Signals of the Paleogroundwater in Jordan. *Journal of Hydrology* 243: 133-47.

Bender, F. 1975. *Geology of the Arabian Peninsula - Jordan*. Washington, DC: USGPO.

Bentley, R.A. 2006. Strontium Isotopes from the Earth to the Skeleton: A Review. *Journal of Archaeological Method and Theory* 13: 135-87.

Binford, L. 1980. Willow Smoke and Dogs' Tails: Hunter-Gatherer Settlement Systems and Archaeological Site Formation. *American Antiquity* 45: 4-17.

Budd, P., Millard, A., Chenery, C., Lucy, S. and Roberts, C. 2004. Investigating Population Movement by Stable Isotope Analysis: A Report from Britain. *Antiquity* 78: 127-41.

Burton, J.H. and Wright, L.E. 1995. Nonlinearity in the Relationship between Bone Sr/Ca and Diet: Paleodietary Implications. *American Journal of Physical Anthropology* 96: 273-82.

Dansgaard, W. 1964. Stable Isotopes in Precipitation. *Tellus* 16: 436-68.

Desse-Berset, N. and Studer, J. 1996. Fish Remains from Ez-Zantur (Petra, Jordan). Pp. 381-387 in R.A. Stucky. (ed.), *Petra. Ez-Zantur: Ergibnesse Der Schweizerisch-Liechtensteinischen Ausgrabungen 1988-1992. Terra Archaeologica V. II*. Mainz: Von Zabern

Dupras, T.L. and Schwarcz, H.P. 2001. Strangers in a Strange Land: Stable Isotope Evidence for Human Migration in the Dakhleh Oasis, Egypt. *Journal of Archaeological Science* 28: 1199-208.

Ericson, J.E. 1985. Strontium Isotope Characterization in the Study of Prehistoric Human Ecology. *Journal of Human Evolution* 14: 503-14.

Ericson, J.E. 1989. Some Problems and Potentials of Strontium Analysis for Human and Animal Ecology. Pp. 252-259 in P.W. Rundel, R. Ehleringer and K.A. Nagy. (eds.), *Stable Isotopes in Ecological Research*. New York: Spring-Verlag

Evans, J.A., Chenery, C.A. and Fitzpatrick, A.P. 2006. Bronze Age Childhood Migration of Individuals near Stonehenge, Revealed by Strontium and Oxygen Isotope Tooth Enamel Analysis. *Archaeometry* 48: 309-21.

Ezzo, J.A., Johnson, C.M. and Price, T. 1997. Analytical Perspectives on Prehistoric Migration: A Case Study from East-Central Arizona. *Journal of Archaeological Science* 24: 447-66.

Faure, G. 1986. *Principles of Isotope Geology*. New York: John Wiley & Sons.

Faure, G. and Powell, J.L. 1972. *Strontium Isotope Geology*. New York: Springer-Verlag.

Findlater, G., el-Najjar, M., al-Shiyab, A.H., O'Hea, M. and Easthaugh, E. 1998. The Wadi Faynan Project:

The South Cemetery Excavation, Jordan 1996: A Preliminary Report. *Levant* 30: 69-83.
Frumkin, A. and Stein, M. 2004. The Sahara-East Mediterranean Dust and Climate Connection Revealed by Strontium and Uranium Isotopes in a Jerusalem Speleothem. *Earth and Planetary Science Letters* 217: 451-64.
Gat, J.R. and Dansgaard, W. 1972. Stable Isotope Survey of the Fresh Water Occurrences in Israel and the Northern Jordan Rift Valley. *Journal of Hydrology* 16: 177-212.
Hitchcock, R.K. 1987. Sedentism and Site Structure: Organizational Change in Kalahari Basarwa Residential Locations. Pp. 374-423 in S. Kent. (ed.), *Method and Theory for Activity Area Research*. New York: Columbia University Press
Hodell, D.A., Quinn, R.L., Brenner, M. and Kamenov, G. 2004. Spatial Variation of Strontium Isotopes ($^{87}Sr/^{86}Sr$) in the Maya Region: A Tool for Tracking Ancient Human Migration. *Journal of Archaeological Science* 31: 585-601.
Hoppe, K.A., Koch, P.L. and Furutani, T.T. 2003. Assessing the Preservation of Biogenic Strontium in Fossil Bones and Tooth Enamel. *International Journal of Osteoarchaeology* 13: 20-28.
Kent, S. 1991. The Relationship between Mobility Strategies and Site Structure. Pp. 33-59 in E.M. Kroll and T. Price. (eds.), *The Interpretation of Archaeological Spatial Patterning*. New York: Plenum Press
Knudson, K.J. and Price, T. 2007. Utility of Multiple Chemical Techniques in Archaeological Residential Mobility Studies: Case Studies from Tiwanaku- and Chiribaya-Affiliated Sites in the Andes. *American Journal of Physical Anthropology* 132: 25-39.
Krom, M.D., Cliff, R.A., Eijsink, L.M., Herut, B. and Chester, R. 1999. The Characterisation of Saharan Dusts and Nile Particulate Matter in Surface Sediments from the Levantine Basin Using Sr Isotopes. *Marine Geology* 155: 319-30.
LaBianca, Ø.S. 1990. *Sedentarization and Nomadization, Food System Cycles at Hesban and Vicinity in Transjordan*. Hesban 1. Berrien Springs, MI: Andrews University Press.
Lambert, J.B. and Weydert-Homeyer, J.M. 1993. The Fundamental Relationship between Ancient Diet and the Inorganic Constituents of Bone as Derived from Feeding Experiments. *Archaeometry* 25: 279-94.
Lenoble, P., al-Muheisen, Z. and Villeneuve, F. 2001. Fouilles de Khirbat adh-Dharih (Jordanie) I. Le Cimetière au Sud du Wadi Sharheh. *Syria* 78: 89-151.
Lernau, H. 1986. Fishbones Excavated in Two Later Roman-Byzantine Castella in the Southern Desert of Israel. Pp. 85-102 in D.C. Brinkhuizen and A.T. Clason. (eds.), *Fish and Archaeology: Studies in Osteometry, Taphonomy, Seasonality and Fishing Methods*. Oxford: BAR International SEries 294
Luz, B. and Kolodny, Y. 1989. Oxygen Isotope Variation in Bone Phosphate. *Applied Geochemistry* 4: 317-23.
Luz, B., Kolodny, Y. and Horowitz, M. 1984. Fractionation of Oxygen Isotopes between Mammalian Bone-Phosphate and Environmental Water. *Geochimica et Cosmochimica Acta* 48: 1689-93.
Montgomery, J., Budd, P. and Evans, J. 2000. Reconstructing the Lifetime Movements of Ancient People: A Neolithic Case Study from Southern England. *European Journal of Archaeology* 3: 370-85.
Montgomery, J., Budd, P. and Neighbour, T. 2003. Sr Isotope Evidence for Population Movement within the Hebridean Norse Community of Nw Scotland. *Journal of the Geological Society* 160: 649-53.
Montgomery, J., Evans, J.A. and Cooper, R.E. 2007. Resolving Archaeological Populations with Sr-Isotope Mixing Models. *Applied Geochemistry* 22: 1502-14.
Moorees, C.F.A., Fanning, E.A. and Hunt, E.E. 1963a. Formation and Resorption of Three Deciduous Teeth in Children. *American Journal of Physical Anthropology* 21: 205-13.
Moorees, C.F.A., Fanning, E.A. and Hunt, E.E. 1963b. Age Variation of Formation Stages for Ten Permanent Teeth. *Journal of Dental Research* 42: 1490-502.
Parker, S.T. 1996. The Roman Aqaba Project: The 1994 Campaign. *ADAJ* 40: 231-57.
—— 1998. The Roman ʻAqaba Project: The 1996 Campaign. *ADAJ* XLII: 375-94.
—— 2002. The Roman ʻAqaba Project: The 2000 Campaign. *ADAJ* 46: 409-28.
—— 2006. History of the Roman Frontier East of the Dead Sea. Pp. 527-584 in S.T. Parker. (ed.), *The Roman Frontier in Central Jordan: Final Report on the Limes Arabicus Project, 1980-1989*. Washington, DC: Dumbarton Oaks
Perry, M.A., Coleman, D.S. and Delhopital, N. in press. Mobility and Exile at 2nd Century A.D. Khirbet Edh-Dharih: Strontium Isotope Analysis of Human Migration in Western Jordan. *Geoarchaeology*.
Perry, M.A., Coleman, D.S., Dettman, D.L. and al-Shiyyab, A.H. n.d. Isotopic Evidence for the Transport of Byzantine Mining Camp Laborers into Southwestern Jordan. *Under review by the American Jour-*

nal of Physical Anthropology.

Pollastro, R.M., Karshbaum, A.S. and Viger, R.J. 1997. M*aps Showing Geology, Oil and Gas Fields and Geologic Provinces of the Arabian Peninsula: U.S. Geological Survey Open-File Report 97-470b*. U.S. Geological Survey, Denver, Colorado

Price, T., Grupe, G. and Schröter, P. 1998. Migration of the Bell Beaker Period of Central Europe. *Antiquity* 72: 405-11.

Price, T., Johnson, C.M., Ezzo, J.A., Ericson, J. and Burton, J.H. 1994. Residential Mobility in the Prehistoric Southwest United States: A Preliminary Study Using Strontium Isotope Analysis. *Journal of Archaeological Science* 21: 315-30.

Price, T., Tiesler, V. and Burton, J.H. 2006. Early African Diaspora in Colonial Campeche, Mexico: Strontium Isotopic Evidence. *American Journal of Physical Anthropology*.

Price, T.D., Burton, J.H. and Bentley, R.A. 2002. The Characterisation of Biologically-Available Strontium Isotopes for Investigation of Prehistoric Migration. *Archaeometry* 44: 117-35.

Prowse, T., Schwarcz, H.P., Garnsey, P., Knyf, M., Macchiarelli, R. and Bondioli, L. 2007. Isotopic Evidence for Age-Related Immigration to Imperial Rome. *American Journal of Physical Anthropology* 132: 510-19.

Robinson, O.F. 1995. *Penal Practice and Penal Policy in Ancient Rome*. London: Routledge.

Runia, L.T. 1987. Strontium and Calcium Distributions in Plants: Effect on Paleodietary Studies. *Journal of Archaeological Science* 14: 599-608.

Schweissing, M.M. and Grupe, G. 2003. Stable Strontium Isotopes in Human Teeth and Bone: A Key to Migration Events of the Late Roman Period in Bavaria. *Journal of Archaeological Science* 30: 1373-83.

Shewan, L. 2004. Natufian Settlement Systems and Adaptive Strategies: The Issue of Sedentism and the Potential of Strontium Isotope Analysis. Pp. 55-94 in C. Delage (ed.), *The Last Hunter-Gatherers in the near East*. Oxford: BAR International Series 1320

Sillen, A., Hall, G. and Armstrong, R. 1995. Strontium-Calcium Ratios (Sr/Ca) and Strontium Isotope Ratios ($^{87}Sr/^{86}Sr$) of *Australopithecus Robustus* and *Homo* Sp. From Swartkrans. *Journal of Human Evolution* 28: 277-85.

Sillen, A., Hall, G., Richardson, S. and Armstrong, R. 1998. $^{87}Sr/^{86}Sr$ Ratios in Modern and Fossil Food-Webs of the Sterkfontein Valley: Implications for Early Hominid Habitat Preferences. *Geochimica et Cosmochimica Acta* 62: 2463-73.

Studer, J. 1994. Roman Fish Sauce in Petra, Jordan. Pp. 191-196 in W. Van Neer. (ed.), *Fish Exploitation in the Past. Proceedings of the 7th Meeting of the ICAZ Fish Remains Working Group*. Musèe Royale de L'Afrique Centrale: Tervuren

Toplyn, M.R. 2006. Livestock and *Limitanei*: The Zooarchaeological Evidence. Pp. 469-513 in S.T. Parker. (ed.), *The Roman Frontier in Central Jordan: Final Report on the Limes Arabicus Project, 1980-1989*. Washington, DC: Dumbarton Oaks

Villeneuve, F. and Al-Muheisen, Z. 2003. Dharih and Tannur, Sancutaries of Central Nabataea. Pp. 83-100 in G. Markoe. (ed.), *Petra Rediscovered: Lost City of the Nabataeans*. New York: Harry N. Abrams

White, C.D., Longstaffe, F.J. and Law, K.R. 2004a. Exploring the Effects of Environment, Physiology and Diet on Oxygen Isotope Ratios in Ancient Nubian Bones and Teeth. *Journal of Archaeological Science* 31: 233-50.

Wright, L.E. 2005. Identifying Immigrants to Tikal, Guatemala: Defining Local Variability in Strontium Isotope Ratios of Human Tooth Enamel. *Journal of Archaeological Science* 32: 555-66.

Yurtsever, Y. and Gat, J.R. 1981. Atmospheric Waters. Pp. 103-42 in J.R. Gat and R. Gonflantini (eds.), *Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle*. Vienna: International Atomic Energy Agency