An Application of Strontium Isotope Analysis to Caribbean Contexts: Promises and Problems

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Abstract: Strontium (Sr) isotope analyses are currently being applied to human remains from archaeological contexts throughout the world to address questions of past mobility and migration. As part of the NWO-funded VICI project "Communicating Communities", we are in the process of applying this approach to Caribbean archaeological collections. Towards this end, we are constructing a database of strontium isotope variation across the Caribbean through the analysis of geological, faunal, and botanical remains from most of the islands of the Greater and Lesser Antilles. This data is generated for the purposes of comparison with, and interpretation of, Sr isotope data derived from several large human skeletal assemblages. This paper deals specifically with the potential promises and problems of using strontium isotope analysis in this region of the world. These potentials are discussed within the framework of our preliminary data of pan-regional isotopic variation and are illustrated by several specific case studies.


Resumen: Los análisis del isótopo del estroncio (Sr) se están aplicando actualmente a los restos humanos de contextos arqueológicos en el mundo entero para tratar cuestiones de la últimas movilidad y migración. Como parte del NWO-financiado VICI proyecto "Communicating Communities", estamos en curso de aplicación de este acercamiento a las colecciones arqueológicas del Caribe. Hacia este extremo, estamos construyendo una base de datos de la variación del isótopo del estroncio a través del Caribe con el análisis de restos geológicos, fáunicos, y botánicos la mayor parte de de Las Antillas Mayores y Las Antillas Menores. Estos datos se generan para los propósitos de la comparación con, y la interpretación, de los datos del isótopo del senilor derivados de varias ensambladuras esqueléticas humanas grandes. Este papel se ocupa específicamente de las promesas y de los problemas potenciales de utilizar análisis de isótopo del estroncio en esta región del mundo. Estos potenciales se discuten en el marco de nuestros datos preliminares de la variación isotópica circum-regional y son ilustrados por varios estudios de caso específicos.
Understanding Migrations and Mobility in the Ancient Caribbean

Migration and mobility are core concepts in such varied disciplines as demography, sociology, and geography and thus are important foci for attempts to understand multiple aspects of past human behavior from an archaeological perspective. Migrations and migration-related processes have been evoked as explanations for various patterns of cultural change and variation in the pre-Columbian Caribbean (Berman and Gnivecki 1993; Berman and Gnivecki 1995; Booden, et al. 2008; Coppa, et al. 2008; Hofman, et al. 2007; Hoogland and Hofman 1993, 1999; Keegan 1995; Keegan and Diamond 1987; Rodriguez Ramos 2007; Rouse 1986, 1989, 1992; Siegel 1991) and more recently the topic of migration has itself become a subject of investigation within this context [for an extensive review of the topic of migration in the Caribbean, see (Curet 2005)].

In general, the vast majority of archaeological approaches to migration and mobility, in the Caribbean and beyond, can be characterized as macro-scalar. In this context, macro-scalar refers to the long-term, cumulative effects of migration and from an archaeological perspective these are most evident through observations of changing distributions of various phenomena in the material record. These macro-scalar approaches can be characterized on the basis of their source data for example; material culture, settlement patterns, environment, foodways, landscape, and bioarchaeology for example.

Less common are micro-scalar approaches to understanding human migrations and mobility, examples of these would include such geochemical methods as trace element and especially isotopic analyses. These approaches differ from macro-scalar ones in part due to their focus on the individual. The analysis and associated identification of a particular behavioral process, in this case migration, is done on the level of the individual and this process can be repeated for multiple individuals and groups permitting a bottom-up approach (Hakenbeck 2008) to elucidating patterns of human mobility. From this perspective, micro- and macro-scalar approaches can be seen as complementary approaches to similar phenomena. This paper presents the preliminary results of a large-scale isotopic study of human remains from the Caribbean from a micro-scalar perspective, embedded within a broader pan-Caribbean research program concerning human interaction, mobility and exchange.

**Principles of Strontium Isotope Research**

This paper focuses specifically on Sr isotope analysis and its potentials and promises for addressing issues of human migration and mobility in the ancient Caribbean. There are four naturally-occurring isotopes of strontium of which only $^{87}$Sr is radiogenic. $^{87}$Sr is produced by the radioactive decay of $^{87}$Rb, with a half-life of 4.75 X 10$^{10}$ years (Pollard, et al. 2007). Globally, the ratio of $^{87}$Sr/$^{86}$Sr is variable and it varies according to three main factors, "(1) the $^{87}$Sr/$^{86}$Sr at time the rock crystallized, $t = 0$, (2) the $^{87}$Rb/$^{86}$Sr ratio, which is directly proportional to the Rb/Sr ratio in most cases, and (3) the time $t$ elapsed since formation." (Bentley 2006).

Strontium often enters the food chain through the transport of weathered soil minerals into plant tissues. It then moves through the food chain as herbivores and omnivores consume plants and as carnivores consume them, and so on. Although there is a known reduction of strontium concentrations (relative to calcium) as one moves up the food chain (Burton and Price 2000), this reduction does not alter the strontium isotope ratio.
Bioapatite or Ca$_{10}$(PO$_4$)$_6$(OH)$_2$ is the primary mineral component of human bone and enamel (Burton 2008). Fully formed human dental enamel is approximately 97-99% calcium hydroxyapatite (White and Folkens 2005). Because strontium and calcium are somewhat chemically similar, strontium can and does replace calcium within the crystalline structure of bioapatite (Bentley 2006). Unlike bone, enamel does not undergo remodeling after maturation and mineralization and is highly resistant to diagenic alteration or contamination, and thus it preserves the biogenic signal of its formation and development (Budd, et al. 2000). As the time of formation and development of human teeth are fairly well-known (Hillson 1996), the analysis of the Sr isotope signal from a tooth will provide information concerning the geochemical environment of that individual's youth, from several months in utero until ~ 14 years of age depending on the tooth (White and Folkens 2005).


**Caribbean Biogeochemistry**

The primary sources of strontium into any particular ecosystem can be divided into geological and non-geological sources. In most cases, the geological source is the largest contributor of strontium into plant tissues (Bentley 2006) through the primary weathering of soil minerals. However, research into various environmental systems indicates that atmospheric contributions of strontium can be quite substantial (Pozwa, et al. 2002; Pozwa, et al. 2000; Pozwa, et al. 2004). Non-geological sources are atmospheric and hydrological in nature; and a significant non-geological source of strontium in coastal areas comes from the sea (Hodell, et al. 2004; Montgomery, et al. 2003). Marine effects can be derived from sea-spray; or marine-derived strontium in rainwater; or through the direct consumption of marine resources by animal organisms.

In order to interpret strontium isotope data it is therefore necessary to have a good understanding of the geology of the area of a site/settlement as well as an awareness of potential non-geological sources of strontium into a skeletal assemblage. The geology of the Caribbean is extremely complex, but a few comments on it will suffice for our purposes [for a more extensive discussion see (Dengo and Case 1990)]. The northern Lesser Antilles island arc, from Saba to Guadeloupe, is divided into two parallel archipelagoes the Volcanic Caribbees to the west and the Limestone Caribbees to the east. In the southern Lesser Antilles island arc from Dominica to Grenada these two formations merge (Roobol and Smith 2004). Most of the other islands of the West Indies can be characterized as composite islands, containing some combinations of uplifted marine sediment, volcanic deposition, and in some cases contributions from older crustal material.
Fortunately, a wealth of strontium isotope data already exists for much of the Lesser Antilles in the context of research publications on the geological origins and tectonic history of many of the volcanic islands (Davidson 1985; Davidson 1987; Roobol and Smith 2004; van Soest, et al. 2002; White, et al. 1985; White and Patchett 1984). The marine strontium signature is known and is stable over short time periods; it does fluctuate over geological time but this fluctuation or variation has been resolved to the extent that an approximation of the Sr isotope signal of a marine carbonate or limestone deposit can be derived from an estimate of the time period of its formation (deposition) and vice versa (Hess, et al. 1986; Howarth and McArthur 1997; McArthur, et al. 2001; Richter, et al. 1992; Veizer, et al. 1999).

Thus, for most of the islands of the Lesser Antilles and some regions of the Greater Antilles, the background geological Sr isotope ranges and that of modern (and ancient) seawater are already known. Therefore, we can use some simple mixing models to constrain the limits of Sr isotope ranges for given islands or regions of the Caribbean using geological Sr isotope data and that of the sea as the two main sources of Sr into an ecosystem (Bentley 2006). In fact, any given organism, which subsists solely or primarily on local food resources (terrestrial and/or marine), must have a Sr isotope value which falls somewhere between the marine and terrestrial values for that locale.

The first application of strontium isotope analysis to human remains in the Caribbean to address questions of human mobility is quite recent (Booden, et al. 2008). This analysis was carried out on the late ceramic age skeletal assemblage from the site of Anse à la Gourde, Guadeloupe (Delpuech, et al. 2001; Hofman, Delpuech, et al. 2001; Hofman, Hoogland, et al. 2001; Hoogland, et al. 2001). This site is located on the island of Grand-Terre which is one of the Limestone Caribbees and whose surface is covered by uplifted Pliocene and Quaternary limestone (Booden, et al. 2008). The Sr isotope signal of this formation is essentially identical to modern seawater and marine resources. Therefore, any locally grown or raised biological organism will have a $^{87}\text{Sr}/^{86}\text{Sr}$ signature very close to (.7092) (Howarth and McArthur 1997; McArthur, et al. 2001). In fact, analysis of soils from burial pits, archaeological fauna, and the majority of the individuals from this site all have $^{87}\text{Sr}/^{86}\text{Sr}$ values which fall into a very restricted range similar to that of modern seawater. Interestingly, 14 of the 50 individual humans sampled were identified as non-local (Booden, et al. 2008). What is evident from this project is that multiple lines of evidence pointed to the same estimate of the local range and that this narrow and restricted range made it possible to clearly identify a substantial number of non-locals. We suspect that similar geochemical environments, i.e. relatively uniform carbonate platforms, will yield similar results.

**Preliminary Results of Ongoing Case Studies**

The complexities of interpreting strontium isotope data from other contexts in the Caribbean, e.g. from volcanic and composite islands can be illustrated by 2 case studies. The first case study is from the site of Kelbey's Ridge 2, Saba. This is a late ceramic age site from which seven individuals, both adults and children, were excavated by the University of Leiden (Hofman and Hoogland 1991; Hoogland 1999; Hoogland and Hofman 1993). Saba is a geologically young, oceanic volcano and the expectation is that the bedrock and soils should possess a fairly low, non-radiogenic, Sr isotope signature. This expectation is supported by Sr isotope analysis of whole rocks from Saba, carried out by other researchers; mean $^{87}\text{Sr}/^{86}\text{Sr} = .70386$, range .70376-.70406 (Roobol and Smith 2004) as well as our results of analysis of whole rocks and soils; mean
$^{87}\text{Sr}/^{86}\text{Sr} = .704489$, range .703791-.706255. However, Sr isotope signatures from seven human individuals from the site of Kelbey's Ridge, as well as 10 archaeological rice rat samples from similar deposits at this site all possess much higher Sr isotope values; mean $^{87}\text{Sr}/^{86}\text{Sr} = .708264$, range .707699-.70890, than would be expected from the geochemical environment of Saba.

Considering multiple lines of evidence in our estimation of the local range, we propose that these higher than expected values are the result of marine influences either directly through the consumption of marine resources by both humans and rats at this site and/or indirectly through the deposition of sea-spray or marine-influenced rainwater into the local soils and hence into the local ecosystem. This pattern is similar to the elevated Sr values obtained from sheep enamel from Iceland, an island with similar geological characteristics to Saba (Price and Gestsdottir 2006). Interestingly, one result from a land snail at Kelbey's Ridge, $^{87}\text{Sr}/^{86}\text{Sr} = .70717$, provides a value intermediate between the measured terrestrial geological values and the known marine signature. In this case, the lower geological values around .7038 should represent the lower values contributing to the local range and the modern marine signature of .709175 would delimit the upper value. Any and all plants and animals living on Saba should then fall somewhere in this range depending in part on the micro-local influences of marine precipitation and the relative consumption of marine resources. Unfortunately, this rather wide range of Sr isotope values would make it relatively difficult to identify any non-locals in the Saban archaeological record. In fact, our range of measured values from humans and fauna from Saba are nearly an order of magnitude greater than the estimated local range for Anse a la Gourde, Guadeloupe (Booden, et al. 2008). Nevertheless, we are currently in the process of systematically analyzing a large number of botanical, faunal, and geological samples collected from various parts of the island of Saba to obtain a better understanding of the local Sr isotope variation on a small, volcanic island.

Our second case study comes from El Chorro de Maíta, Cuba. This site near the northeastern coast of Cuba contains both late pre-contact and early-contact period components (Valcárcel Rojas and Rodríguez Arce 2005). A large cemetery was excavated there in the 1980's by the Departamento Centro Oriental de Arqueología under the direction of José M. Guarch Delmonte, and this excavation has been expanded in recent years (Valcárcel Rojas and Rodríguez Arce 2005). The geology of the island of Cuba is highly complex but the site itself lies upon the edge of a large carbonate shelf dated to the middle Eocene (Pardo 1970). The Sr isotope measurements of oceanic carbonate from the Eocene are stable around .7077 and we expect that the terrestrial contribution to the local ecosystem around this site to be close to this value. However, owing to the site's proximity to the coast and by association various potential sources of marine Sr, the 2 main sources of Sr for El Chorro de Maíta provide minimum and maximum Sr signatures of .7077-.709175, respectively. Initial results derived from local faunal samples allow us to tentatively suggest .708-.709 as an estimate of the local range, which will be further constrained as more data becomes available. Because we are in the early stages of analysis of this collection, we report here only on the analysis of 51 human individuals, 3 pigs, and 2 hutia with further results forthcoming [all Sr isotope values for humans and maamals reported herein are derived from samples of dental enamel according to protocols which can be found in (Booden, et al. 2008)].

As expected the majority (38; n=51) of our results fall within the estimated local range [see Figure 5]. The presence of 13 non-locals (25%) amongst this burial population is suggestive of substantial immigration to this site and similar to migration patterns derived from other sites including; Anse a la Gourde, Guadeloupe. One outlier at .711033 +/- .000013 (2SE) was
obtained from an adult male. This relatively radiogenic value was confirmed by a second analysis which gave a similar result. Remarkably, this same individual was found to be different from the rest of the skeletal collection from El Chorro de Maitá both morphologically and because he clearly lacked the intentional cranial modification common throughout the rest of this burial population (personal communication, Valcárcel Rojas 2009).

In addition, Sr signatures from 3 pig enamel samples [CMfa1=.706171, CMfa2=.707353, CMfa3=.707477] were clearly much lower than the rest of the measured values and far lower than what would be expected given the known geology of this region. This lower value cannot be accounted for by any marine influence, which would tend to raise the signal closer to ~.7092. It is possible that these pigs originated from elsewhere within Cuba as the isotopic variation of strontium within Cuba is not well known at this time. However, the fact that this site has a proto-historic component, it is also possible that this pig represents an early example of the importation of domesticated livestock into the New World and suggests that this species may not be an ideal candidate for estimating the local range of strontium isotope signals in this archaeological context.

Conclusions

A few points concerning the application of strontium isotope analysis to address questions of ancient Caribbean mobility require further elaboration. First, as suggested by experts in the field of Sr isotope analysis, it is often necessary to estimate the local range for the area around an archaeological site, in order to interpret Sr isotope data and to identify non-locals amongst skeletal populations (Bentley, et al. 2004). This is best accomplished using all available lines of evidence ranging from the geological literature to analysis of local water, soil, rock, plant, and animal samples. The analysis of dental enamel from archaeological faunal samples has been proposed as perhaps the best indicator of the local range, although the choice of which species is best made on a case by case basis depending on the geographical, geological, and cultural contexts of a given site (Price 2002). Furthermore, owing to the fact that so many archaeological sites in the Caribbean are near the coast, it is necessary to closely examine the multiple, potential marine influences upon the Sr isotope data in this region. Our preliminary results indicate that the 'visibility' of non-locals will be masked in certain regions by large ranges/high variance in Sr isotope values, for example as found on the island of Saba. This pattern may prevail on other small, oceanic, volcanic islands and suggests that our ability to identify non-locals is variable and dependent on a multitude of factors, which may make the interpretation of human mobility more difficult in some regions relative to others.

Nevertheless, fascinating results have already begun to emerge from the application of this approach to archaeological collections. Our data and that from previously published work from Leiden University (Booden, et al. 2008) reveal some interesting patterns concerning ancient human mobility in the Caribbean. Considering that isotopic assessments only provide minimum estimates of the number of non-locals, owing to the possibility that some non-locals possess Sr isotope values similar to the local signal, the rate of mobility appears substantial with 26 out of 101 (25.7%) individuals tentatively identified as non-locals. When broken down by age category; adults appear highly mobile 22 out of 84 (26.2%) identified as non-local, while sub-adults (mainly infants and children) are expectedly less mobile with only 2 out of 17 (11.8%) individuals analyzed being deemed non-local. These results are derived from multiple Caribbean
skeletal collection including the published data of (Booden, et al. 2008). More detailed treatments of the analysis and results from these other individual collections are forthcoming. We would like to point out that the inclusion of a broad array of complementary, comparative data from numerous sources both enables and enriches our interpretations. For example the data from morphological and osteological analysis, concerning genetic affinity and the practice of cranial modification; radiocarbon dating of individual human remains; and material culture analysis and archaeometric sourcing of grave goods are essential for interpretations of human and animal mobility at the site of El Chorro de Maita, Cuba. Lastly, it is apparent that this type of micro-scalar approach to ancient migrations with a focus on the movement of individuals (both human and animal) requires the analysis of a large number of samples from different regions and time periods in order to reveal patterns of mobility from the bottom-up.

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Figure 1. Map of the Caribbean, indicating several sites included in our research project
Figure 2. Map of Eastern Caribbean, indicating location of Kelbey’s Ridge 2, Saba.

Figure 3. Chart of Strontium isotope data from Kelbey’s Ridge, Saba.
Figure 4. Map of Cuba, indicating location of the site of El Chorro de Maita.

Figure 5. Chart of Strontium isotope data from El Chorro de Maita, Cuba.
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<thead>
<tr>
<th></th>
<th>N= # analyzed</th>
<th># of non-locals</th>
<th>% of group</th>
</tr>
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<tbody>
<tr>
<td>Adults</td>
<td>106</td>
<td>34</td>
<td>32.1%</td>
</tr>
<tr>
<td>Children</td>
<td>32</td>
<td>3</td>
<td>9.4%</td>
</tr>
<tr>
<td>Total</td>
<td>138</td>
<td>37</td>
<td>26.8%</td>
</tr>
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Figure 6. Summary of Sr results compiled from several skeletal assemblages.
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