Long-distance exchange in the precolonial Circum-Caribbean: A multi-isotope study of animal tooth pendants from Puerto Rico

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ABSTRACT

This study explores the feasibility of using combined strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotope analyses of archaeological animal remains from Puerto Rico to investigate precolonial networks of exchange in the Circum-Caribbean. Culturally modified teeth (pendants) of animals including jaguar (*Panthera onca*), peccary (*Tayassu pecari*), and tapir (*Tapirus terrestris*) none of which is native to the Antilles were analyzed to investigate their geographic origins. The strontium isotope results were compared to extant databases and spatial models of biosphere $^{87}Sr/^{86}Sr$ variation for the Circum-Caribbean. The oxygen isotope results were compared to available bioapatite ($\delta^{18}O_{ap}$) and precipitation ($\delta^{18}O_{prec}$) data sets. Although it is not possible to pinpoint a specific origin based on the isotope data alone, based on comparative analyses from various mainland areas, we tentatively propose that: the two jaguar teeth have clearly distinct origins, with one possibly originating from the Guiana Shield Region of northeastern South America and the other possibly from the Southern Lowlands of Mesoamerica, Central America, or northwestern South America; and that the peccary and tapir teeth have similar isotope values and both may have originated from northern coastal South America, the Metamorphic Province of northern Central America, or the Maya Mountains of Belize. These results indicate that the modified teeth of different mainland species were widely circulated amongst the indigenous societies of the Neotropics, with some objects apparently being transported over a thousand kilometers from the source area to the location of final deposition. The diverse origins of these artifacts support the proposition that objects with distant origins were highly valued by precolonial Caribbean peoples, including the tooth pendants of exotic mainland fauna.

1. Introduction

Traditional models of Caribbean culture history are in general agreement that the first settlers of the insular Caribbean may have originated from multiple regions of Central and/or South America as early as ca. 5000 BC; that the first ceramic-making horticulturalists migrated to the insular Caribbean (ca. 500 BC) from northeastern South America; and that long term interactions continued to occur between the inhabitants of this region and those of the Antilles over the subsequent centuries (Boomert, 2000; Rouse, 1986, 1992; Siegel, 1991). In contrast, alternative models of Caribbean prehistory proposed over the last two decades tend to stress divergent and/or multiple origins for different cultural and ethnic groups that migrated into the islands; multi-linear and reticulate modes of cultural evolution and change; and the diversity of cross-community articulations over space and time (Hofman et al., 2007, 2010, 2011; Laffoon, 2012; Rodríguez Ramos, 2010; Rodríguez Ramos and Pagán Jimenez, 2006).

In recent years, the application of a wide range of archaeological methods and theories have contributed to a growing body of evidence indicating that interactions occurred amongst and between different peoples and regions of the Caribbean islands and the surrounding mainland regions through time since the initial occupation of the archipelago (Boomert, 2000; Hofman et al., 2008a, 2011; Hofman and Hoogland, 2011; Laffoon, 2012,

2013; Rodríguez Ramos, 2010, 2011, 2013). These multiple lines of evidence indicate that interactions and articulations existed between pre-Columbian societies of the insular Caribbean and multiple regions of the surrounding continental mainland. These areas include not only northeastern South America but also northern South America, the Isthmo-Columbian region (or Intermediate Area), and Mesoamerica (reviewed in Rodríguez Ramos, 2011). Thus, the extant body of evidence supports the notion that migrations and interactions were more variable, diverse and complex than proposed by traditional models of Caribbean culture history and indicate the need for further research into the nature of these dynamic relationships and how these varied temporally and spatially. In other words, although there is clear evidence that precolonial island peoples interacted with numerous and wide-ranging mainland groups, the nature, frequency, intensity, timing, and importance of these interactions are as yet not well understood and continue to be the focus of much ongoing research (e.g. Hofman et al., 2011; Rodríguez Ramos, 2013).

Ultimately, much of the current evidence for alternative linkages between island societies and regions of surrounding continents rests on the presence of clearly exotic or nonlocal raw materials and artifacts recovered from insular Caribbean archaeological sites. In recent years, there has been considerable progress in material and artifact provenance studies in the broader region (Descantes et al., 2008; García-Casco et al., 2013; Harlow et al., 2006; Hofman et al., 2008b; Knippenberg, 2006; Martinón-Torres et al., 2007; Meniketti, 2011; Pavia et al., 2013; Schertl et al., 2012) but much work remains to be done particularly in the exploration of the origins of many of the foreign objects recovered from the archaeological record of the insular Caribbean. One particular class of artifact that is particularly well-suited to intensified research is animal remains (Laffoon et al., 2013a). Owing to the principles of island biogeography, namely that the West Indies (or Antilles sensu stricto[1]) have been spatially separated from the surrounding mainland(s) for several million years, the late Holocene terrestrial fauna of the insular Caribbean is commonly characterized by a general lack of biodiversity and a nearly complete absence of medium- and large-bodied mammals (Newsom and Wing, 2004; Woods and Sergile, 2001). However, zooarchaeological analyses of island faunal assemblages have identified the remains of a number of non-native species recovered from precolonial archaeological sites in the insular Caribbean (Antczak, 1995; Boomert, 2000; deFrance and Newsom, 2005; Giovas et al., 2011; Keegan, 1996; Narganes Storde, 1985; Newsom and Wing, 2004). The presence of most, if not all, of these specimens can be directly attributed to human agency and are thus anthropochorous (Masseti, 2011), representing examples of either species translocations or the long-distance exchange and acquisition of animal skeletal remains. Perhaps, the most widely occurring example of this phenomena is the introduction of the domestic dog (Canis familiaris) into the islands by indigenous peoples, which likely occurred multiple times dating back to at least 500 BC (Newsom and Wing, 2004; Wing, 2001).

Some of the rarest of the non-native species discovered in precolonial insular Caribbean contexts are jaguar (Panthera onca), peccary (Tayassu pecari), and tapir (Tapirus terrestris). To our knowledge, jaguar teeth have been found at only three sites in the Antilles: La Hueca-Sorcé, Vieques (Narganes Storde, 1985, 2005); Punta Candelero, Puerto Rico (Rodríguez López, 1991); and Pearls, Grenada (Keegan, 1996). Excluding multiple sites on Trinidad and Tobago (Steadman and Jones, 2006; Wing and Reitz, 1982), which are within the natural range of collared peccaries (Pecari tajacu), and numerous peccary bone artifacts found on the off-shore Venezuelan Los Roques archipelago (Antczak, 1995; Antczak and Antczak, 2006), the distribution of peccary remains in the Caribbean archaeological record is sparse and only represented by isolated finds at La Hueca-Sorcé, Vieques (Narganes Storde, 1985, 2005); Upton, Jamaica (Fandrich, 1991); Calivigny, Grenada (Wing, 1968); and Grand Bay, Carriacou (Giovas et al., 2011). Tapir remains are even rarer, with the only documented specimens[2] having been recovered from Dos Mosquises, Los Roques (Antczak, 1995) and La Hueca-Sorcé, Vieques (Narganes Storde, 1985, 2005). Given the highly restricted distribution of these taxa in the archaeological record of the insular Caribbean and the fact that all three of them have been recovered at the site of La Hueca-Sorcé, Vieques undoubtedly raises many questions concerning the origins of these artifacts and the mechanisms by which they came to be deposited so far from the possible source regions, especially considering that the Vieques Passage region (separating eastern Puerto Rico from Vieques) is located several hundred kilometers from the natural ranges of any of these three taxa.

Thus far, no complete sets of skeletal remains of these animals have been recovered from archaeological deposits in the insular Caribbean. In fact, nearly all of the specimens of jaguar, tapir, and peccary teeth found in Antillean (sensu stricto) contexts consist of culturally modified artifacts (i.e. perforated and/or incised). This pattern suggests that the skeletal remains of these animals were transported as artifacts or isolated skeletal elements (Antczak, 1995; Newsom and Wing, 2004). Furthermore, the fact that these remains were modified, and in most cases likely represent objects of personal adornment, signals that they may represent one of several classes of objects or 'social valuables' that were widely circulated amongst and between precolonial island and mainland communities of the Circum-Caribbean (Boomert, 1987, 2000; Hofman et al., 2007, 2010, 2011; Hofman and Hoogland, 2011; Mol, 2007; Oliver, 2009; Rodríguez Ramos, 2010, 2013).

Although zooarchaeological analyses have clearly identified the presence of continental fauna at various pre-Columbian sites and islands within the insular Caribbean, no assessment of their origins at finer scales has been attempted, especially for the three large-bodied mammals sampled for this study (jaguar, tapir, and peccary) that have very widespread distributions throughout the New World. The southernmost extent of the former ranges of all three of these animals is roughly north-central Argentina but the northernmost extent is quite variable. For instance, while Tapirus terrestris is limited to South America, the Tayassu pecari roughly extends to southern Mexico,[3] while that of Panthera onca projects into the southern United States (Emmons and Feer, 1997; Fittkau, 1969). Although isolated fossil remains of these taxa have been found outside of these ranges, particularly in Pleistocene deposits (e.g. Carr, 2012), the reported historical ranges probably roughly coincide with those that existed during the Ceramic Age (~500 BC to AD 1500) indigenous occupation of the insular Caribbean. Nevertheless, although the presence of these artifacts in insular Caribbean contexts clearly attests to engagements between island and mainland societies, identification of the origins of these specific artifacts at finer spatial scales (i.e. regional as opposed to continental) should contribute to current archaeological debates concerning interactions

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[1] Trinidad, Tobago, Aruba, Bonaire, Curaçao, and many of the coastal Venezuelan islands are technically part of the insular Caribbean but are not considered part of the Caribbean bioregion as they are situated on an extension of the South American continental shelf, were at one time connected to the mainland by a land bridge during lower sea levels, and thus have terrestrial faunal biodiversity that is overall more similar to the mainland than to the Antilles.

[2] In addition to the previously documented non-native faunal remains reported from the site of Pearls (Keegan, 1996), a small collection of faunal remains from Grenada recovered by avocational archaeologists includes a number of dog, opossum, seal, and tapir skeletal elements that are currently the focus of zooarchaeological and isotopic analyses.

[3] Although the range of collared peccaries includes Trinidad and possibly Tobago (and later introduced populations can also be found on Cuba), white-lipped peccaries are not reported to have inhabited these islands in precolonial times.

between different island and mainland peoples.

Archaeological faunal remains representing two perforated jaguar canines, an incised and perforated tapir molar, and a perforated peccary canine were sampled from two sites in the northern Caribbean: La Hueca-Sorcé, Vieques and Punta Candelero, Puerto Rico (Fig. 1). These sites are of particular interest because they are one of the few locations where the remains of these particular animals have been recovered, and where both Saladoid and Huecoid cultural deposits co-occur. Most Early Ceramic Age (ca. 500 BC to AD 600) deposits in the Antilles are categorized as Saladoid, the bearers of which are widely believed to have migrated from the lower Orinoco to the northeastern Caribbean starting around 500 BC and settled most of the insular Caribbean from Puerto Rico to the southern Lesser Antilles over the subsequent centuries (Rouse, 1992). Multiple lines of evidence, including broad-scale differences in ceramics, flaked and ground stone tools, lapidary work, and stylistic motifs indicate that the Huecoid is a distinct cultural tradition (Chanlatte Baik, 1981, 1983; see also Oliver, 1999). Huecoid assemblages are less common and more spatially restricted than Saladoid and are primarily known from a relatively small number of sites from Puerto Rico and the northern Lesser Antilles (Bonnissent, 2008; Hofman and Hoogland, 1999). Based on a comparative analysis of multiple aspects of material culture, the eastern foothills of the Andes have been proposed as the most likely area of origin for the Huecoid (Narganes Storde and Chanlatte Baik, 2005; Narganes Storde, 1985). An Isthmo-Colombian origin has also been proposed for certain exotic lithic materials, plants, and metal alloys recovered from Huecoid deposits in the Antilles (Rodríguez Ramos, 2010, 2013; Rodríguez Ramos and Pagán Jimenez, 2006).

Based on the 'lifeline model' originally proposed by Kirch (1988) for Pacific island societies and later applied to the Caribbean (Hofman et al., 2011; Keegan, 2004; Watters, 1982), owing in part to the uncertainties and risks associated with colonization, migrant groups will often attempt to maintain contacts and linkages with parent communities even over long-distances and for extended periods of time. Thus, since Saladoid and Huecoid communities in the Antilles have distinct ancestral origins from widely separated areas of mainland South America, it is also plausible that the exotic or foreign components of their material culture assemblages may also have distinct origins. Based on the assumptions of the lifeline model, this premise may hold true independently of the mechanism of acquisition, i.e. whether these objects were brought directly to the islands by first-generation migrants, acquired directly by islanders from the mainland, or subsequently exchanged between island and mainland groups. As such, the exotic animal tooth pendants associated with these different cultural deposits are ideally suited to an explicit investigation of provenance utilizing multiple isotope analysis. The isotope data from these samples are interpreted in reference to extant isotopic data sets and spatial models of isotope variation for the tropical Americas. This study provides an independent yet complementary perspective on pan-Caribbean patterns of precolonial animal resource acquisition, exchange, and deposition.

2. Principles of strontium and oxygen isotope analyses

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) obtained from dental enamel can be used to investigate geographic origins because $^{87}Sr/^{86}Sr$ in the biosphere varies spatially in relation to that of
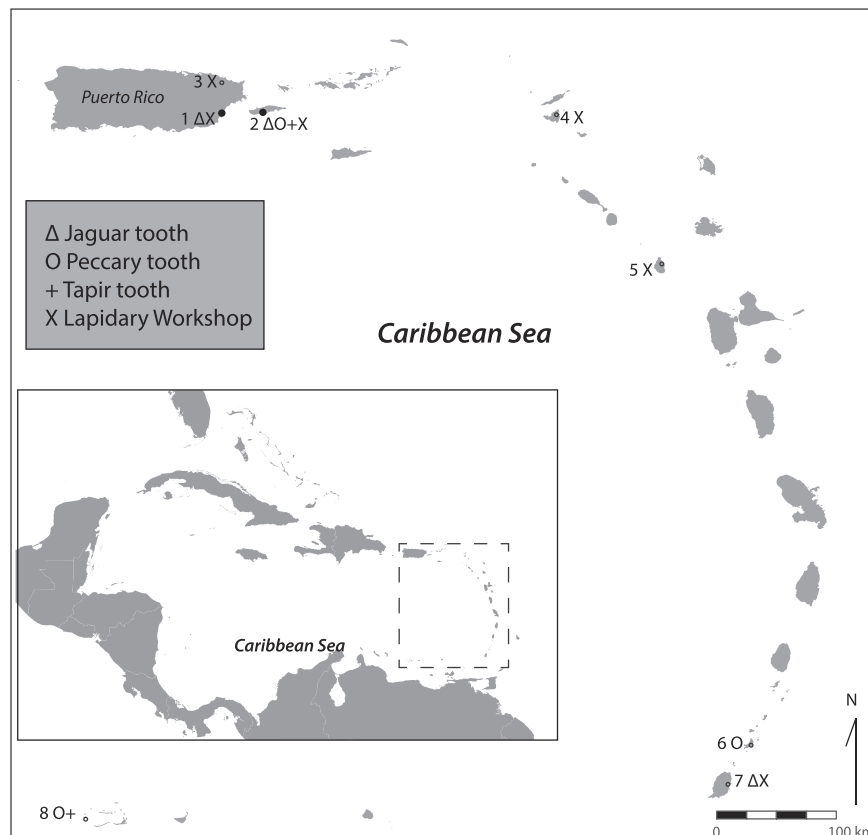
Fig. 1. Map of the eastern Caribbean showing the location of the sites mentioned in the text with tooth pendants of exotic fauna and/or lapidary workshops. Sites: (1) Punta Candelero, (2) La Hueca/Sorcé, and (3) Hacienda Grande, Puerto Rico; (4) Hope Estate, St. Martin; (5) Trants, Montserrat; (6) Grand Bay, Carriacou; (7) Pearls, Grenada; (8) Dos Mosquises, Los Roques Archipelago (Venezuela).

the underlying geology and environmental conditions. Strontium (Sr) in consumed water, plant and animal tissues is incorporated into skeletal tissues primarily by substituting for calcium (Ca) in the mineral phase of bones and teeth. Unlike light stable isotopes (e.g. carbon, nitrogen, oxygen), strontium is not substantially fractionated by naturally occurring biochemical processes at low temperatures (Blum et al., 2000; Price et al., 2002) (cf. Knudson et al., 2010). Thus, the strontium isotope composition of dental enamel represents the weighted average of consumed bioavailable $^{87}Sr/^{86}Sr$ during the period of tissue growth and development and it does not vary significantly between different (local) trophic levels. Enamel $^{87}Sr/^{86}Sr$ records the Sr ingested during the time of crown formation and mineralization, which varies according to tooth type and, unlike bone, enamel does not continuously remodel throughout life (Hillson, 1996). Furthermore, relative to bone, teeth are generally recovered in better states of preservation, particularly in tropical locations, and dental enamel is also less susceptible to diagenic alteration (Budd et al., 2000; Hoppe et al., 2003; Lee-Thorp and Sponheimer, 2003; Trickett et al., 2003).

Of the four naturally occurring isotopes of Sr, ^{87}Sr is the only one that is radiogenic, being produced by the radioactive decay of ^{87}Rb with a half-life of $\sim 4.88 \times 10^{10}$ years (Faure and Mensing, 2005). The $^{87}Sr/^{86}Sr$ of geological materials is thus primarily a function of time and the original rubidium/strontium (Rb/Sr) composition of the parent material. In most continental settings, the underlying bedrock is the primary proximate source of Sr to the local biosphere via mineral weathering. However, the lithosphere is not the only source of Sr to the biosphere, as atmospheric sources (precipitation, sea-spray, dust) of Sr can be substantial contributors to the pool of bioavailable Sr depending on a wide variety of climatic, geographic, and environmental conditions. For example, marine-derived Sr has been shown to be a large source of Sr to terrestrial coastal ecosystems (Kennedy et al., 1998; Laffoon et al., 2012; Vitousek et al., 1999; Whipkey et al., 2000). As bedrock weathering is commonly the dominant source of Sr to local biospheres, the $^{87}Sr/^{86}Sr$ of local geological materials can often be used as a first order approximation of local biosphere $^{87}Sr/^{86}Sr$, however, these data have to be considered critically and in light of a wide variety of complicating factors (Bataille et al., 2012; Bern et al., 2005; Pett-Ridge et al., 2009). In many geographic settings, especially island and coastal areas including Hawaii (Whipkey et al., 2000); Iceland (Price and Gestsdóttir, 2006); Vanuatu (Bentley et al., 2007); and the Isle of Skye, Scotland (Evans et al., 2009); but also in inland continental regions such as the southwestern U.S. (Graustein and Armstrong, 1983), clear discrepancies have been reported between bedrock $^{87}Sr/^{86}Sr$ and bioavailable $^{87}Sr/^{86}Sr$ values. In much of the Circum-Caribbean, these differences are often sufficiently large (as high as 0.005 or more) to lead to inaccurate conclusions concerning geographic provenance (Bataille et al., 2012; Laffoon et al., 2012; Pestle et al., 2013) and as such we are not able to simply rely on geological $^{87}Sr/^{86}Sr$ datasets as direct proxies for bioavailable $^{87}Sr/^{86}Sr$ for this study area.

Oxygen isotope ratios ($\delta^{18}O$) in archaeological skeletal remains have also been widely used in human and animal provenance studies (e.g. Balasse et al., 2002; Bell et al., 2009; Bentley et al., 2007, 2005; Budd et al., 2004; Dupras and Schwarcz, 2001; Evans et al., 2006; Knudson, 2009; Knudson et al., 2009; Müller et al., 2003; Schroeder et al., 2009; Somerville et al., 2010; Stuart-Williams et al., 1996; Turner et al., 2009; White et al., 2007, 2000, 1998). The principle of this method is based on the premise that $\delta^{18}O$ of skeletal bioapatites, both the carbonate (CO_3) and phosphate (PO_4) components, is related to that of body water (Longinelli, 1984; Luz and Kolodny, 1985; Luz et al., 1984; Podlesak et al., 2008), which in turn is reflective of the combined sources (liquid water, water in food, and atmospheric O_2) and losses (liquid water, water vapor, expired CO_2) of body oxygen. However, body water

$\delta^{18}O$ is also influenced by a number of other factors including diet, climate, thermophysiology, and behavior (Bryant et al., 1994; Kirsanow and Tuross, 2011; Kohn, 1996; Longinelli, 1984; Podlesak et al., 2008; Schoeninger et al., 2002; Sponheimer and Lee-Thorp, 1999). Inter-species variation in the relationship between environmental and body water has also been observed (Bryant and Froelich, 1995; Cerling et al., 1997; Kohn et al., 1996; Kohn, 1996; Martin et al., 2008; Schoeninger et al., 2002; Sponheimer and Lee-Thorp, 1999; Wang et al., 2008). However, as Bell and colleagues (2010:683) note, this so-called 'species effect' (Longinelli, 1984) is a misnomer "since differences are related to behavior and physiology rather than to phylogeny per se".

Several observations concerning patterns of $\delta^{18}O$ amongst and between terrestrial mammals are of particular relevance for this study. The first is that because mammals larger than approximately 1 kg have relatively constant internal body temperatures (ca. 37 °C) (Cossins and Bowler, 1987), the $\delta^{18}O$ of body water ($\delta^{18}O_{bw}$) and thus bioapatite "varies with ingested water and oxygen fluxes only and not with environmental temperature" (Bryant and Froelich, 1995:4523). Secondly, because of the inverse correlation between potential errors of water flux rates and body size and because consumed water comprises a larger proportion of the overall oxygen intake amongst large-bodied mammals, their $\delta^{18}O$ are more suitable as paleo-climatic indicators (Bryant and Froelich, 1995). Additionally, for most obligate drinkers, drinking water is likely the primary contributor to overall body water $\delta^{18}O$ (Bryant and Froelich, 1995; Kirsanow and Tuross, 2011; Kohn, 1996; Longinelli, 1984; Luz and Kolodny, 1985; Luz et al., 1984; Podlesak et al., 2008; Schoeninger et al., 2002) and in non-arid climates drinking water generally reflects that of average meteoric water (surface water derived from precipitation) (Longinelli, 1984), which is the likely predominant source of most consumed water in many geographic locations, including much of the Neotropics. Oxygen isotopes in precipitation ($\delta^{18}O_{prec}$) and meteoric water vary globally according to a multitude of factors such as altitude, latitude, and distance from coast or primary source of atmospheric water vapor. At smaller spatial scales (e.g. in the tropics), $\delta^{18}O$ of rainwater is also potentially highly influenced by other factors such as the amount of rainfall, temperature, and relative rates of evapo-transpiration that can vary both spatially and temporally at multiple scales (Bowen and Revenaugh, 2003; Dansgaard, 1964; Gat, 1980; Lachniet and Patterson, 2009; Rozanski et al., 1993).

Seasonal variation in $\delta^{18}O$ is likely 'averaged out' in bulk enamel samples that will generally represent several months or years of growth depending on the species and tooth type.[4] Long term climatic variation can have a pronounced effect on $\delta^{18}O$ values and can complicate comparisons between modern and archaeological data. Oxygen isotope results from a wide variety of sample materials have been used as paleo-climate proxy data for the Neotropics (e.g. Beets et al., 2006; Curtis et al., 2001; Curtis and Hodell, 1993; Hodell et al., 1991; Lachniet et al., 2007; Van Breukelen et al., 2008). Evaluation of these datasets reveals that although long-term changes in $\delta^{18}O$ have occurred throughout the Holocene, the range of variation over the last two millennia does not generally exceed $\sim 2‰$ and that $\delta^{18}O$ values from the same age as the samples analyzed herein (ca. AD 150 to 400) are quite similar to values obtained from modern samples. Spatial, as opposed to temporal, variation in $\delta^{18}O$ of precipitation and surface waters in the Neotropics is primarily influenced

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[4] The enamel formation periods for the taxa studied herein are not well known but given the bulk sampling strategy that was employed, whereby enamel from roughly the exterior surface to the enamel-dentine juncture was extracted, we expect that these will be fairly representative of the overall period of formation and capture at least some degree of any (potential) seasonal variation.

by differences in elevation and distance from the coast (Jones et al., 2000; Lachniet and Patterson, 2002, 2006, 2009).

In summary, the interpretation of oxygen isotope values derived from skeletal bioapatites is very complex and requires attention to a wide variety of potential complicating factors and processes. Nevertheless, previous research has clearly demonstrated that $\delta^{18}O$ of biogenic apatites display sufficient geographic variation and correlate (to varying degrees) with measured or expected $\delta^{18}O$ values in precipitation or local water sources to be potentially informative for human and animal provenance studies in the Circum-Caribbean (Laffoon et al., 2013b; Price et al., 2010; Schroeder et al., 2009; Somerville et al., 2010; Warinner et al., 2012; White et al., 2001, 2007, 2000, 2004, 2002, 1998; Wright et al., 2010).

3. Strontium and oxygen isotope variation in the Circum-Caribbean

3.1. Strontium isotope variation

In this section we briefly summarize strontium isotope variation in the New World tropics. Here, we limit our summary to an area of the Neotropics ranging from approximately the Tropic of Cancer to the Equator. This area encompasses not only much of the known geographic distributions of the three taxa analyzed for this study but also the geographic regions most likely to have had trade or exchange interactions with precolonial Antillean communities. Owing to the vast spatial scale of this area, it is only possible to characterize strontium isotope variation in very general terms. The limited available data indicate broad spatial patterning of both geological and bioavailable $^{87}Sr/^{86}Sr$ at scales that can be readily distinguished relative to the precision of isotope measurements. For example, the absolute difference between the lowest and highest $^{87}Sr/^{86}Sr$ ratios obtained directly from enamel apatite samples within this region is *ca.* 0.03, which is more than three orders of magnitude greater than the typical analytical error (~ 0.00001) of strontium isotope measurements.

There is also enormous variation in the availability of comparative Sr isotope data (especially for bioavailable $^{87}Sr/^{86}Sr$) within this study area. For example, in the last decade, much of Mesoamerica (the Maya region in particular) has been fairly well characterized in terms of $^{87}Sr/^{86}Sr$ variation both through studies that explicitly focused on spatial mapping and through a large number of local and regional case studies (Bataille et al., 2012; Hodell et al., 2004; Price et al., 2012, 2008, 2010, 2007, 2000, 2006; Thornton, 2011; White et al., 2007; Wright, 2005; Wright et al., 2010). Large $^{87}Sr/^{86}Sr$ datasets now exist for a wide variety of sample materials including human and animal bioapatites, plant, water, soil and rock samples ranging from northern Mexico to northwestern Honduras.

In Mesoamerica, the lowest $^{87}Sr/^{86}Sr$ ratios (ca. 0.7038 to 0.705) derive from the Volcanic Highlands and Pacific Coast regions. The Southern Lowlands are primarily underlain by older (Miocene to Eocene) marine carbonates and have $^{87}Sr/^{86}Sr$ ratios that range from ca. 0.7070 to 0.7085. The carbonate deposits that characterize much of the eastern Maya region range in age from older to younger (from south to north) and thus the Northern Lowlands have somewhat higher $^{87}Sr/^{86}Sr$ ratios ca. 0.7080 to 0.7092. The Metamorphic Province of Mesoamerica (extending into northern Central America) is situated between the Volcanic Highlands and the Southern Lowlands regions, and possesses much more variable, and in isolated pockets much higher, $^{87}Sr/^{86}Sr$ ratios ranging from ca. 0.704 to as high as 0.720, although mean values are generally much lower (~ 0.7074) (Hodell et al., 2004). The Maya Mountains of southern Belize, underlain by both igneous and metamorphic deposits, represent one of the only other areas of Mesoamerica

with $^{87}Sr/^{86}Sr$ ratios exceeding ~ 0.7095, with reported $^{87}Sr/^{86}Sr$ ratios ranging from ca. 0.712 to 0.715 (Hodell et al., 2004).

Unfortunately, the quantity of reported bioavailable $^{87}Sr/^{86}Sr$ values from most of Central America and northern South America is much lower and consists primarily of a small number of isolated case studies (e.g. Poszwa et al., 2002). This lack of data clearly hinders a comparative analysis and any attempt at identifying specific origins for the samples analyzed for this study. However, we argue that broad scale patterns of spatial variation of bioavailable strontium isotopes can still be inferred from the extant evidence. Owing in part to this lack of comparative data, Bataille and Bowen (2012) have developed a multi-source mixing model and associated map of predicted bioavailable $^{87}Sr/^{86}Sr$ variation for the Circum-Caribbean (Fig. 2). This model was tested on large extant databases of bioavailable $^{87}Sr/^{86}Sr$ from Mesoamerica and the Caribbean and the model predicts well observed $^{87}Sr/^{86}Sr$ ratios in these regions (MAE = 0.00040, RMSE = 0.00087 and MAE = 0.00014, RMSE = 0.0010, respectively). Although such models require further development, they represent a definite improvement over solely relying on geological $^{87}Sr/^{86}Sr$ data as a proxy for bioavailable $^{87}Sr/^{86}Sr$ and reveal broad patterns of spatial variation at sub-continental or regional scales.

3.2 Oxygen isotope variation

As previously mentioned, there are many potential complications associated with comparing carbonate oxygen isotope values obtained from archaeological skeletal materials with oxygen isotope ratios of modern precipitation. Some of these complications include for example, variations in the relative contributions of different oxygen fluxes to the body, the effects of nursing on skeletal $\delta^{18}O$, and compounded errors associated with the regression formulas used for the conversion of carbonate oxygen isotope values ($\delta^{18}O_c$) to associated drinking water values ($\delta^{18}O_{dw}$). Thus, considerable caution is required in the interpretation of skeletal $\delta^{18}O$ data in the context of archaeological provenance studies in general and comparisons between modern precipitation $\delta^{18}O$ and archaeological carbonate $\delta^{18}O$ data more specifically (Bell et al., 2009, 2010; Millard and Schroeder, 2010; Pellegrini et al., 2011; Pollard et al., 2011).

There are two main sources of comparative oxygen isotope data for the study region in question: (1) an extant dataset of bioapatite ($\delta^{18}O_{ap}$) obtained from the analyses of archaeological skeletal materials (as is the case with strontium, this is primarily represented by data from Mesoamerica); and (2) long term measurements of oxygen isotopes in precipitation ($\delta^{18}O_{prec}$) from various monitoring stations, which are available from the Global Network of Isotopes in Precipitation (GNIP) database (IAEA/WMO, 2013) [see also, http://www.iaea.org/index.html]. In addition, a recent regionalized model of $\delta^{18}O_{prec}$ spatial variation has been developed by researchers from the International Atomic Energy Agency (IAEA, 2013; Terzer et al., 2013). A modified version of this map displaying spatial variation of $\delta^{18}O_{prec}$ for the study area is presented in Fig. 3.

Mean $\delta^{18}O_{prec}$ measurements from lower altitude (<500 m amsl) monitoring stations along the northern and northeastern coast of South America such as Cayenne, French Guiana ($-1.8‰$) and Maracay, Venezuela ($-3.0‰$); are broadly similar, while slightly lower mean $\delta^{18}O_{prec}$ values are reported for measuring stations in coastal/lowland areas further to the west at Barranquilla, Colombia ($-4.5‰$) and Howard AFB, Panama ($-4.1‰$), although the overall ranges of $\delta^{18}O_{prec}$ display substantial overlap. Even lower mean $\delta^{18}O_{prec}$ values are reported for somewhat more inland and moderate altitude ($\sim 500–1000$ m amsl) locations in Central America at Santa Maria, Costa Rica ($-5.5‰$) and San Salvador, El Salvador ($-6.2‰$), while the lowest $\delta^{18}O_{prec}$ values in the larger
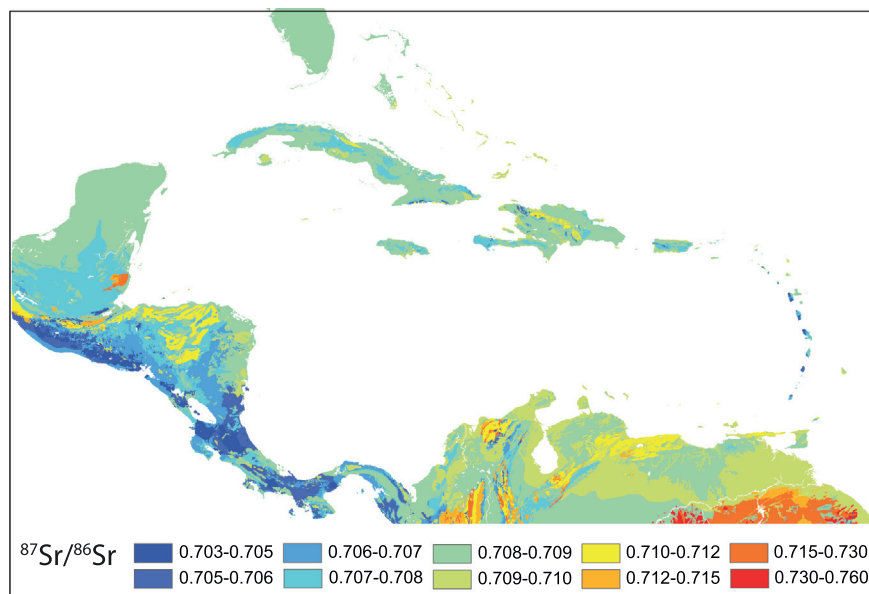
Fig. 2. Spatial model of bioavailable $^{87}Sr/^{86}Sr$ variation in the Circum-Caribbean. This map is based on a multiple-source mixing model which considers variable contributions to the average bioavailable $^{87}Sr/^{86}Sr$ for different areas and has been tested on large empirical datasets from Mesoamerica and the insular Caribbean. Despite some deviation from measured values for certain areas and a general lack of fine-scale (local) spatial resolution, this map provides a broad indication of patterns of $^{87}Sr/^{86}Sr$ variation at large spatial scales. Map adapted from original in Bataille et al. (2012).
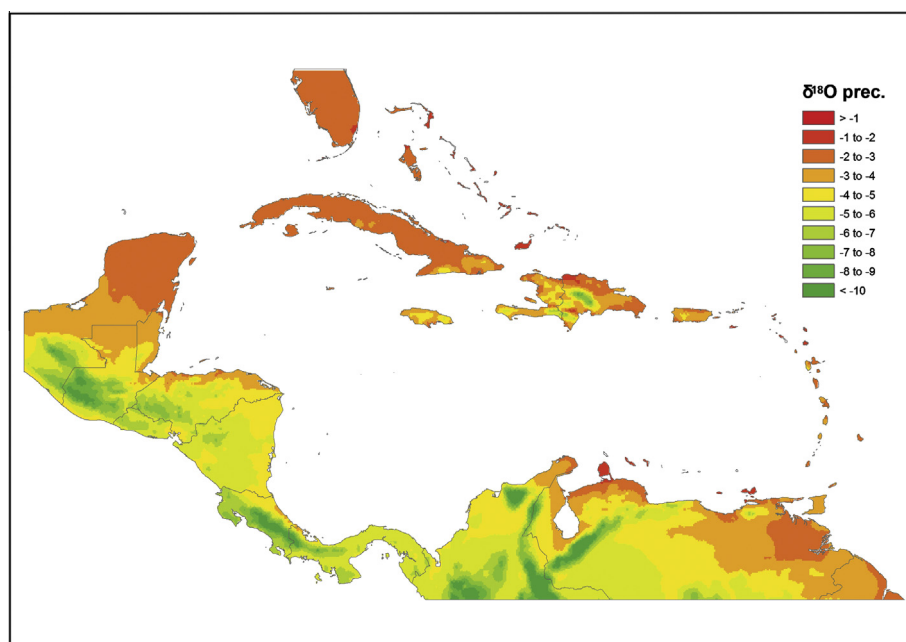
Fig. 3. Map of mean annual $\delta^{18}O_{prec}$ variation in the Circum-Caribbean. $\delta^{18}O_{prec}$ data are reported relative to VSMOW and derive from the International Atomic Energy Agency: RCWIP (Regionalized Cluster-Based Water Isotope Prediction) Model available at http://www.iaea.org/water (IAEA, 2013; Terzer et al., 2013). Map modified from the original by Till Sonnemann.

macro-region can be found at even higher altitude (>2000 m amsl) inland locations such as Sacramento, Costa Rica (−7.4‰) and Bogota, Colombia (−8.7‰), although these latter locations also tend to display larger ranges of seasonal variation.

4. Materials and methods

4.1 Sample descriptions

In total, four culturally modified tooth 'pendants' of non-Antillean animals (two jaguar canines, one peccary canine, and one tapir molar) were analyzed for strontium and oxygen isotope composition. A single jaguar canine was sampled from the settlement site of Punta Candelero on the eastern coast of Puerto Rico. The other three teeth were sampled from the site of La Hueca-Sorcé, on the island of Vieques. The La Hueca-Sorcé jaguar tooth has multiple biconical perforations and although this may indicate that the tooth was worn (as a pendant) it is also possible that the multiple perforations indicate other modes of display on the body or even the possibility that it formed part of a larger composite artifact. The Punta Candelero jaguar tooth and the peccary and tapir teeth from La Hueca-Sorcé all possess single biconical

perforations through the root, the latter also having multiple parallel and rectilinear incisions carved into the surface of the enamel (Fig. 4).

4.2 Site descriptions and context

The La Hueca-Sorcé site lies on the southwestern part of the island of Vieques, which is located 14 km east of Puerto Rico (Fig. 1). This site is situated over a series of coastal terraces that project toward the Caribbean Sea, which cover a total area of approximately 2 km^2. This site represents the first locus where the Huecoid tradition was identified as an isolated cultural component, being characterized by the presence of zone-incised crosshatched designs and a highly elaborate lapidary tradition for which a vast array of semi-precious stones were imported. In addition, this tradition includes the production of a myriad of artifacts made of mother of pearl and other shell material and an iconography whose most conspicuous element is the production of pendants depicting raptorial birds that have been primarily identified as either king vultures (Boomert, 2001) or Andean condors (Chanlatte Baik and Narganes Storde, 1983; Rodríguez Ramos, 2011), neither of which is present in the insular Caribbean. The Huecoid mounded middens are spatially separated from several Saladoid deposits, whose pottery is primarily characterized by white on red negative designs and complex vessel forms. The earliest sample is the jaguar pendant obtained from the Huecoid component of the site (unit Z-15; 2.6 m BS), with an associated charcoal date of 1800 ± 80 BP (I-11139; AD 60-410 cal. 2 sigma). The peccary specimen was also unearthed from a Huecoid deposit (unit Z-20; 1.20 m BS) and has an associated shell date of 1670 ± 80 BP (I-18661; AD 570-900 cal. 2 sigma). The tapir adornment was recovered from a Saladoid context (unit YTA—3; 80 cm BS). A charcoal date from a neighboring unit went back to 1575 ± 85 (I-10547; AD 260-650 cal. 2 sigma).

Punta Candelero is located on the eastern coast of Puerto Rico, in the Municipality of Humacao. This site lies on an embayed beach peninsula that is surrounded by thalassia prairies and mangrove strands. The archaeological deposits nestle on the ridges of a chain of elongated dunes that rise up to 2 m above sea level. This is also a multicomponent site, containing in its earliest phase the remains of the Huecoid tradition, being overlain by contexts associated to the Cuevas style, the latest manifestation of the Saladoid series in

Fig. 4. Composite photo of analyzed animal teeth: (a) jaguar – Punta Candelero; (b) jaguar – La Hueca-Sorcé; (c) tapir – La Hueca-Sorcé; and (d) peccary – La Hueca-Sorcé.

Puerto Rico. The jaguar tooth pendant was collected from unit A-7, at a depth between 20 and 30 cm. A burial recovered from contiguous unit A-6 dated to 1350 ± 46 (AD 610-770, cal. 2 sigma; AA-75809), in association to the Cuevas (Late Saladoid) context of the site (Pestle, 2010), thus this tooth purportedly is the youngest of the analyzed specimens.

4.3 Isotope analyses

Details of sample treatment protocols and procedures for strontium isotope (Booden et al., 2008) and oxygen isotope (Laffoon et al., 2013b) analyses are reported elsewhere. Briefly, teeth were mechanically cleaned to remove any encrustations, calculus, staining, and the outer layer of surface enamel and to expose the inner core enamel. Approximately 2–4 mg of core enamel was extracted using a hand-held drill equipped with a pre-cleaned, diamond-tipped rotary burr. The drill bit was cleaned with ethanol, 1% HNO_3, and ultra-pure H_2O and blown dry with filtered, compressed air before and between each sample extraction. For strontium isotope analysis, extracted enamel samples were: (1) leached briefly with 0.1 N acetic acid (CH_3CO_2H); (2) washed in demineralized, deionized water (H_2O); and (3) dissolved in 3 N nitric acid (HNO_3). All samples were loaded onto cation exchange columns comprising Sr-specific crown ether resin (Eichrom©) for separation of strontium ions from the sample matrix. After separation, strontium samples were loaded onto pre-cleaned, degassed rhenium filaments and $^{87}Sr/^{86}Sr$ was measured with a ThermoFinnigan MAT 262 RPQ plus, thermal ionization mass spectrometer (TIMS) at the Faculty of Earth and Life Sciences, VU University Amsterdam. Long term measurements of the standard reference material (NBS-987) produced a mean $^{87}Sr/^{86}Sr$ of 0.71026 ± 0.00003 (1σ) and the typical analytical error for all samples reported here is ~0.00001. The strontium yield of blanks are consistently low (<100 pg) and negligible relative to the overall amount of strontium in the samples. A correction was applied to each $^{87}Sr/^{86}Sr$ measurement equaling the difference between the in-run measurement of the standard reference material and the generally accepted value of 0.710240.

Oxygen isotope compositions were measured on a Finnigan DeltaPlus Isotope Ratio Mass Spectrometer, following reaction of the carbonate sample with orthophosphoric acid (H_3PO_4) [100%] and isolation of the produced carbon dioxide (CO_2), with a Gasbench II universal automated interface (Faculty of Earth and Life Sciences, VU University Amsterdam). The long term reproducibility of the standard reference material (NBS-19) for $\delta^{18}O$ is <0.2‰. All $\delta^{18}O$ values referenced herein are reported in the delta (δ) notation, in parts per thousand (‰) relative to the international VSMOW (Vienna Standard Mean Ocean Water) standard, unless noted otherwise. Samples measured for oxygen isotope composition were mechanically cleaned but not chemically pretreated as enamel is generally considered relatively resistant to diagenic alteration and several recent studies have shown insignificant differences in isotope results between enamel samples subjected to chemical pretreatment and those that were not (Chenery et al., 2012; Passey et al., 2002; Pellegrini et al., 2011; Warinner, 2010).

5. Results

In this section we present first the strontium isotope results followed by the oxygen isotope results. The isotope data and relevant sample information are listed in Table 1 and displayed in Fig. 5.

5.1 Strontium isotope results

Although two modified jaguar tooth pendants have been recovered from archaeological deposits at Punta Candelero, only one had

sufficient intact enamel for isotopic analysis. The $^{87}Sr/^{86}Sr$ ratio of the analyzed jaguar tooth from this site is very radiogenic (0.73687) and exceeds almost all reported strontium isotope values of humans and animals from the Neotropics reported to date (cf. Price et al., 2012). Such an extreme $^{87}Sr/^{86}Sr$ ratio is relatively rare in the Circum-Caribbean and one of the only places in the tropical Americas with such high $^{87}Sr/^{86}Sr$ ratios is the Guiana Shield Region of northeastern South America. The Guiana Shield, a Precambrian craton dating to more than 1.7 Ga, is one of only three cratons in South America and one of the only places in the Circum-Caribbean area where the geological substrate is old enough to produce such a radiogenic $^{87}Sr/^{86}Sr$ ratio (Kroonenberg and de Roever, 2009). In addition to the Guiana Shield, radiogenic $^{87}Sr/^{86}Sr$ ratios have also been reported from the Maya Mountains and Metamorphic Province in Mesoamerica, although these generally do not exceed ~0.715 for the former and ~0.720 for the latter. However, Thornton (2011) also reports a very high $^{87}Sr/^{86}Sr$ ratio (0.7316) from a nonlocal collared peccary (Pecari tajacu) at the site of Tipu, Belize but this value is still substantially lower than that obtained from the Punta Candelero jaguar. Although additional research is required to fully map the range of bioavailable $^{87}Sr/^{86}Sr$ variation in the Neotropics, based on the currently available evidence, the Guiana Shield Region appears the most likely provenance for the jaguar tooth pendant recovered from Punta Candelero.

Animal tooth samples from the site of La Hueca-Sorcé on Vieques consist of three 'pendants' including two perforated canines- one jaguar and one peccary (both from Huecoid deposits)- and one incised and perforated tapir molar (from a Saladoid context). The La Hueca-Sorcé jaguar sample possesses an $^{87}Sr/^{86}Sr$ ratio of 0.70757. It is interesting to note that the very large difference in $^{87}Sr/^{86}Sr$ ratios between the Punta Candelero and La Hueca-Sorcé jaguar teeth rules out a similar provenance. In fact, the $^{87}Sr/^{86}Sr$ ratio of the La Hueca-Sorcé sample is far too low to have originated in the Guiana Shield Region or in northeastern South America more generally. The La Hueca-Sorcé jaguar's $^{87}Sr/^{86}Sr$ ratio is within the range of measured $^{87}Sr/^{86}Sr$ variation for many sites in the Southern Lowlands of Mesoamerica including much of Belize and the Petén Basin of northern Guatemala, in addition to some sites in the Metamorphic Province such as Copán, Honduras (Hodell et al., 2004; Price et al., 2010; Thornton, 2011; Wright, 2005). As previously mentioned, very few empirical biosphere $^{87}Sr/^{86}Sr$ data are available for Central America or northern South America. Thus, comparative analysis is based on the predictive model of Bataille et al. (2012), which has been shown to be relatively accurate when tested against large empirical datasets in the Circum-Caribbean. Comparison with a modified version of Bataille and colleagues' (2012) multi-source modeling map (Fig. 2) of bioavailable $^{87}Sr/^{86}Sr$ variation indicates the presence of many areas with similar biosphere $^{87}Sr/^{86}Sr$ values occurring in discontinuous pockets extending from roughly southeastern Mexico to northwestern Venezuela, mostly represented by areas underlain by older (Late Cretaceous to Paleocene) marine carbonates. Thus, although it is possible to eliminate many areas as possible sources for this specimen, this $^{87}Sr/^{86}Sr$ value is also
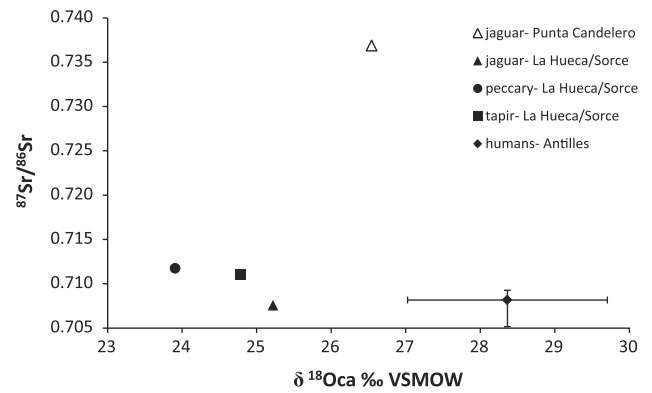
Fig. 5. Chart of strontium and oxygen isotope values of animal tooth samples (this study) compared to the range of human enamel isotope values reported for the Antilles. For the Antillean isotope data, the symbol represents the mean value ($^{87}Sr/^{86}Sr$, n = 272; $\delta^{18}O_c$, n = 46) and the error bars contain the maximum and minimum values reported for indigenous populations from different time periods and islands. Isotope data from: (Laffoon, 2012; Laffoon et al., 2013b).

consistent with origins from many different regions within the study area that range from northwestern Venezuela to southern Mexico.

The La Hueca-Sorcé peccary tooth has an $^{87}Sr/^{86}Sr$ ratio of 0.71175 and the tapir tooth has an $^{87}Sr/^{86}Sr$ ratio of 0.71099. These values are comparable in the context of local variation in bioavailable $^{87}Sr/^{86}Sr$ at individual sites, and fall outside the range of biosphere $^{87}Sr/^{86}Sr$ variation (ca. 0.7050-0.7095) for the Antilles (sensu stricto). $^{87}Sr/^{86}Sr$ values above ca. 0.7095 are generally more consistent with areas underlain by 'continental' bedrock, particularly certain types of metamorphic and granitic deposits, as opposed to volcanic or marine carbonate geologies (Faure and Mensing, 2005). In Mesoamerica, similar elevated $^{87}Sr/^{86}Sr$ ratios have been reported for a local collared peccary (Pecari tajacu) at Tipu, Belize and for a nonlocal peccary (Tayassuidae) at Caracol, Belize and a nonlocal white-tailed deer (Odocoileus virginianus) at Copan, Honduras (Thornton, 2011). The Maya Mountains of Belize or the Metamorphic Province of southern Mesoamerica have been proposed as possible places of origin for these nonlocal animals (Thornton, 2011) and the $^{87}Sr/^{86}Sr$ ratio of the La Hueca-Sorcé peccary and tapir samples are both consistent with an origin from these two areas. Other areas with similar bioavailable $^{87}Sr/^{86}Sr$ ratios also occur in dispersed pockets in Central America, especially in Honduras, and across much of northern coastal South America from approximately eastern Colombia to the lower Orinoco River.

5.2 Oxygen isotope results

Currently there is insufficient research into the exact effects of diet, physiology, climate, and possible other factors on $\delta^{18}O$ in skeletal bioapatites of the three taxa analyzed for this study (jaguar, tapir, and peccary). Moreover, the regression formulae for estimating $\delta^{18}O_{dw}$ or $\delta^{18}O_{prec}$ from $\delta^{18}O_{ap}$ have fairly substantial (compounded) associated errors (Pollard et al., 2011). In this study

Table 1

Sample information and isotope results for animal dental enamel samples. The $\delta^{18}O_c$ values were converted to the SMOW scale using the conversion equation of Coplen (1988) and then $\delta^{18}O_{dw}$ estimates were subsequently derived by applying the conversion equation of Chenery and colleagues (2012).

Lab #	Location	Taxa	Name	Element	$^{87}Sr/^{86}Sr$	$\delta^{18}O_c$ ‰ VPDB	$\delta^{18}O_c$ ‰ VSMOW	$\delta^{18}O_{dw}$ ‰ VSMOW
S776	Punta Candelero	Panthera onca	Jaguar	Canine	0.73687	−4.2	26.5	−6.4
S767	La Hueca-Sorcé	Panthera onca	Jaguar	Canine	0.70757	−5.5	25.2	−8.5
S370	La Hueca-Sorcé	Tayassu pecari	Peccary	Canine	0.71175	−6.7	23.9	−10.6
T477	La Hueca-Sorcé	Tapirus terrestris	Tapir	Molar	0.71099	−5.9	24.8	−9.2

we also have to question the comparability of $\delta^{18}O_{ap}$ from different taxa (Martin et al., 2008). Consequently, compared to the conservative behavior of strontium isotope ratios in the biosphere more caution is required in using oxygen isotope data in terms assessing possible geographic origins.

There are various formulae reported in the literature for conversion between carbonate ($\delta^{18}O_c$) and phosphate ($\delta^{18}O_p$) oxygen isotope values (Bryant et al., 1996; Chenery et al., 2012; Iacumin et al., 1996; Martin et al., 2008; Pellegrini et al., 2011; Wright et al., 2010; Zazzo et al., 2004) and for subsequently estimating $\delta^{18}O_{dw}$ from $\delta^{18}O_p$ (e.g. Daux et al., 2008; Levinson et al., 1987; Longinelli, 1984; Luz et al., 1984; Pollard et al., 2011). However, there are relatively few formulae reported for estimating drinking water isotope values ($\delta^{18}O_{dw}$) directly from $\delta^{18}O_c$ obtained from either (archaeological) human (Chenery et al., 2012) or (modern) mammalian (Iacumin et al., 1996) oxygen isotope data. We applied these last two conversions to archaeological (local) human $\delta^{18}O_c$ datasets from the Antilles (Laffoon et al., 2013b). Applying the formula of Chenery et al. (2012) for the conversion of carbonate oxygen isotope values ($\delta^{18}O_c$ VSMOW) to $\delta^{18}O_{dw}$ [$\delta^{18}O_{dw} = 1.590 \times \delta^{18}O_c - 48.634$] to the $\delta^{18}O_c$ data from local Antillean archaeological samples generated predicted $\delta^{18}O_{dw}$ values ranging from −5.1‰ to −1.3‰ and the formula derived from that of Iacumin and colleagues (1996) [$\delta^{18}O_{dw} = (\delta^{18}O_c - 33.63) \times 1.002$] (recalculated from original) produced $\delta^{18}O_{dw}$ estimates ranging from −6.3‰ to −3.9‰. These values correspond well with modern $\delta^{18}O_{prec}$ ranges (ca. −5‰ to +1‰) from four regional monitoring stations (Havana, Cuba; Santana, Dominican Republic; San Juan, Puerto Rico; and Seawall Airport, Barbados) in the insular Caribbean (IAEA/WMO, 2013).

We recognize that the formula for estimating drinking water values from carbonate values: (1) may not be accurate or applicable to all regions, (2) may vary between different geographic contexts, and (3) may vary between or even amongst different species. Clearly much more research on this topic is required, and we are currently in the process of investigating the relationship between these variables for the Circum-Caribbean region. However, we argue that the generally high degree of correspondence between the measured $\delta^{18}O_{prec}$ ranges in the Antilles and the $\delta^{18}O_{dw}$ estimates justifies an exploratory application of the drinking water estimates (with the aforementioned caveats in mind).

As the conversion formula of Chenery and colleagues (2012) produced $\delta^{18}O_{dw}$ estimates that correspond better with modern $\delta^{18}O_{prec}$ data we use this conversion formula for our exploratory comparative analysis. The $\delta^{18}O_c$ results and the corresponding $\delta^{18}O_{dw}$ estimates are listed in Table 1. The $\delta^{18}O_c$ values of the four analyzed samples range from 23.9‰ to 26.5‰. The highest $\delta^{18}O_c$ in this study was obtained from the Punta Candelero jaguar tooth (26.5‰) and this value is consistent with the inferred origin from the Guiana Shield region based on $^{87}Sr/^{86}Sr$ but a more precise estimation of origins cannot be determined, owing in part to a lack of directly comparable oxygen isotope ($\delta^{18}O_c$) data from this area. The $\delta^{18}O_{dw}$ estimate from this sample is fairly low (−6.4‰) and such a value is distinct from mean $\delta^{18}O_{prec}$ at most coastal locations within the study area but is comparable to mean $\delta^{18}O_{prec}$ obtained from more inland and moderate-elevation locations. For example, the long-term weighted mean $\delta^{18}O_{prec}$ at the near-coastal location of Cayenne, French Guiana (−1.8‰), is significantly higher than that recorded at the inland measuring station on the Caroni River, Venezuela (−4.9‰). Thus, with the previous caveats in mind, we can tentatively propose that this sample's $\delta^{18}O$ value is more consistent with an inland (as opposed to a coastal) origin within the Guiana Shield region.

The La Hueca-Sorcé jaguar tooth's $\delta^{18}O_c$ value of 25.2‰ is lower than the range defined by human and faunal $\delta^{18}O_c$ data from Antillean sites and from coastal Caribbean sites in Mesoamerica but is higher than similar data from the Oaxaca Valley and Pacific Coast regions of Mesoamerica (Price et al., 2010; White et al., 2007; Wright et al., 2010). In Mesoamerica, this $\delta^{18}O_c$ value is most similar to the range of $\delta^{18}O_c$ reported for several inland sites in the Central Highlands of Mexico (Price et al., 2010) while the inferred $\delta^{18}O_{dw}$ value is −8.5‰. Comparing this estimate with $\delta^{18}O_{prec}$ data, indicates that a coastal location is even more unlikely for this specimen, as the value falls outside the range (mean ± 1σ) of variation for coastal locations within the study area (IAEA/WMO, 2013) but within the range of $\delta^{18}O_{prec}$ variation at higher elevation/inland locations. The $\delta^{18}O$ isotope result from this sample is consistent with the proposed origins for this sample based on the $^{87}Sr/^{86}Sr$ data. However (and once again keeping the previously noted caveats in mind), compared to sites in the Southern Maya Lowlands the combined isotope results from this sample are somewhat less consistent with an origin from this region. For example, this sample's $^{87}Sr/^{86}Sr$ ratio is much higher than those reported for Kaminaljuyu and Pacific Coast sites and its $\delta^{18}O_c$ is lower than those from Copan, Honduras. As such we suggest that the isotope results are somewhat more consistent with a Lower Central American/Isthmo-Columbian (for example in Costa Rica and western Panama or the northern Andean regions of Columbia and Venezuela), where small yet dispersed areas where this combination of strontium and oxygen isotope values can be found (see Figs. 2 and 3).

The $\delta^{18}O_c$ value (23.9‰) of the peccary tooth sample is the lowest of the four samples and it also falls outside of the ranges of both human and animal $\delta^{18}O_c$ variation for the Antilles and most Mesoamerican sites studied to date. For example, this $\delta^{18}O_c$ value is at the edge of the range of measured $\delta^{18}O_c$ variation for Kaminaljuyu, Guatemala (Wright et al., 2010) and falls within the range of variation for Teotihuacan (Price et al., 2010). However, as noted previously, this sample's $^{87}Sr/^{86}Sr$ ratio is far too high to have originated from Central Mexico. Although a Southern Highland location (within the Metamorphic Province of Mesoamerica) cannot be ruled out, the derived $\delta^{18}O_{dw}$ estimate of −10.6‰ for this sample is very low and is comparable to reported $\delta^{18}O_{prec}$ ranges from high elevation locations in the Isthmo-Columbian area. For example, this value lies within the range (at 1σ) of $\delta^{18}O_{prec}$ for only a few locations (namely in the highlands of Colombia and Costa Rica) in the larger study area.

The tapir tooth's $\delta^{18}O_c$ value of 24.8‰ is slightly higher than that obtained from the La Hueca/Sorcé peccary tooth, which also has a comparable $^{87}Sr/^{86}Sr$ ratio. The similarity of the combined isotope measurements may indicate shared origins or simply origins from regions with similar factors influencing both strontium and oxygen isotope variation. The estimated $\delta^{18}O_{dw}$ of this sample (−9.2‰) is slightly more common than that of the peccary sample and falls within the range of reported $\delta^{18}O_{dw}$ variation (at 1σ) for a wider array of locations (including in the highlands of Colombia, Costa Rica, and Nicaragua). Thus the combined strontium and oxygen isotope results from both the peccary and tapir samples permit us to narrow down their possible origins to a small number of possibilities within the study region. We tentatively interpret the combined isotope results as deriving from a higher elevation area underlain by metamorphic or continental bedrock. Within the study area, the most likely candidates for such a combination include higher altitude locations within: (1) the Metamorphic Province (of southern Mesoamerica/northern Central America), or (2) in the Isthmo-Columbian Region (of southern Central America/northeast South America).

6. Discussion

The combined strontium and isotope results are consistent with at least three distinct source regions for the four analyzed exotic

animal tooth artifacts. Although it is not possible to identify a specific origin for these samples, the isotope results from the Punta Candelero jaguar tooth pendant are most consistent with an origin in the Guiana Shield region of northeastern South America. Such an origin is also consistent with a large body of evidence indicating that this area has had enduring contacts and relationships of exchange with Antillean peoples dating back at least two millennia and may have been one of the primary regions of origin for the Ceramic Age societies of the Antilles, particularly those associated to the Cedrosan Saladoid subseries (Rouse, 1948, 1964, 1983, 1992; Rouse and Cruxent, 1963). This area has also been deemed to contain some of the potential sources of the semi-precious stones and other lithic raw materials that were employed by indigenous societies of the insular Caribbean (Boomert, 1987; Boomert and Rogers, 2007; Rodríguez López, 1991, 1993).

Areas with baseline isotope ranges consistent with those obtained from the La Hueca-Sorcé jaguar tooth pendant can be found in a wide range of geographic settings from northwestern South America throughout much of Central America and parts of Mesoamerica. These potential places of origin are consistent with those proposed for Huecoid populations and their associated material remains and the large body of evidence indicating the presence of precolonial indigenous interactions between the peoples of the northern Antilles and the Isthmo-Columbian area (Chanlatte Baik, 2013; Chanlatte Baik and Narganes Storde, 1980; Rodríguez Ramos, 2010, 2011, 2013). In contrast, a Mesoamerican origin, specifically from the Metamorphic Province, would also concur with the proposed origin of jadeite axes from Puerto Rico, Antigua and St. Eustatius (also found on a multitude of other Antillean islands), which have been tentatively sourced to the Motagua Valley of Guatemala (García-Casco et al., 2013; Harlow et al., 2006). Thus, despite the difficulties of identifying a specific source based on isotope data alone, clearly these two jaguar teeth derived from very distinct and distant origins. The peccary and tapir tooth pendants appear to have a distinct origin to both of the jaguar teeth and the closest regions with similar expected and measured strontium isotope values are northern coastal Venezuela, the Metamorphic Province of northern Central America, and the Maya Mountains in Belize. The combined isotope results from these two samples are consistent with a number of different and widely dispersed places of origin.

Clearly, as is generally the case, the isotope results are equivocal in reference to determining a precise origin for the analyzed specimens. However it is apparent that despite the fact that these four pendants were ultimately deposited at Puerto Rican locations during the Early Ceramic Age, they must have originated from at least three different source areas on the mainland and possibly by different mechanisms as well. The widespread circulation of animal tooth ornaments and pendants has been reported for a variety of mainland communities during the early contact period (reviewed in Boomert, 2000), indicating that such social valuables may have been trade commodities for an extended period of time. However, the extreme rarity of pendants made from the teeth of mainland fauna in precolonial insular Caribbean contexts may indicate that such items were difficult to acquire and/or were not readily disposed of in an archaeologically visible manner. One possibility is that the animal tooth pendants were items that were transported directly by first-generation migrants to the Antilles (as opposed to trade items *per se*). In this sense, it is interesting that the earliest of these pendants, the jaguar specimen obtained from the bottom level of the early Huecoid context of La Hueca-Sorcé, was likely obtained from the Isthmo-Colombian area, which fits with the purported importance of this region for the articulation of this cultural manifestation (Rodríguez Ramos, 2010; Rodríguez Ramos and Pagán Jimenez, 2006).

The long-term circulation of social valuables in networks of exchange, for example in the context of feasting (Hofman and Hoogland, 2011), may also have contributed to the relative scarcity and unusual distribution of certain classes of artifacts, including exotic teeth pendants. It is doubtful that a lack of contact or interaction between mainland and island communities can wholly account for the scarcity of these types of social valuables amongst the latter, as other objects, raw materials and traditions continued to be negotiated between them throughout the Ceramic Age. This, in fact, could account for the presence of the late jaguar tooth pendant from Punta Candelero whose origins are most likely located in the Guiana Shield region, which could indicate the articulation of an additional vector of interaction through which this material moved into the island in later contexts. Although the Late Ceramic Age in the Caribbean is *generally* characterized by a process of nucleation whereby local or micro-regional variants of previously widespread cultural traits become increasingly common and a general decrease in the quantity and diversity of long-distance trade goods, particularly personal adornments, occurs, there are indicators that relationships with the surrounding continents continued to take place as is noted by the import of extraneous fauna such as guinea pig (*Cavia porcellus*) (Curet and Pestle, 2010; Newsom and Wing, 2004) and of *guanín* (gold-copper alloy) specimens (Valcárcel Rojas and Martinón Torres, 2013), among others.

Rodríguez Ramos (2011) has also noted the widespread presence of personal adornments made from shiny materials (greenstones, semiprecious stones, shell) with similar iconographic themes and production sequences in Ceramic Age contexts of both the Antilles and the Isthmo-Columbian area. Although teeth pendants were not explicitly noted in this category of artifacts, they would certainly fit into this categorization based on the 'shininess' of dental enamel and the likelihood that the decorated teeth were displayed (worn) on the body and thus were highly visible symbols of the wearers' access to larger networks of interaction (Helms, 1979, 1988, 1992; see also Hofman and Hoogland, 2011). Additionally, a number of sites in the Antilles have been identified as possible 'gem centers' or micro-lapidary workshops (Boomert, 1987; Chanlatte Baik, 1981; Chanlatte Baik and Narganes Storde, 1983; Cody, 1991; Harrington, 1924; Haviser, 1999; Rodríguez López, 1991, 1993; Watters and Scaglion, 1994). The presence of a wide variety of local and exotic semi-precious stones (including amethyst, carnelian, jadeite, nephrite serpentinite, turquoise, and others) in various phases of production in addition to thousands of finished beads and amulets, support the interpretation of these locations as centers of lapidary production (and presumably distribution) (Hofman and Hoogland, 2011).

In the Early Ceramic Age, these micro-lapidary workshops are associated with both Saladoid and Huecoid deposits, and differ from later Ceramic Age ones primarily owing to the preponderance of exotic materials in the former relative to the latter. The possible implications of the highly variable sources of the stone materials (within the Antilles and on the mainland) utilized at these sites for elucidating early trade networks in the Caribbean have been explored previously (Boomert, 2000; Cody, 1993; Rodríguez López, 1993). It is perhaps not coincidental, that of the small number of reported Early Ceramic Age 'gem centers', three of them (namely Punta Candelero, La Hueca-Sorcé, and Pearls) are also the only known locations in the Antilles where jaguar tooth pendants have been recovered (and some of the few locations where peccary and tapir tooth pendants have also been obtained). This does not mean that the exotic lithic raw materials and the exotic animals used to make the teeth pendants analyzed herein have the same origins but that they were likely circulating within the same large-scale networks of exchange and interaction that connected pre-Columbian communities of the islands and the mainland. Their relative rarity and co-occurrence at a small number of sites may indicate that these specific locations were important nodes within these networks.

7. Conclusions

Multi-faceted isotope analyses offer much promise for human and animal provenance studies in the Circum-Caribbean region and elsewhere. This study has confirmed that certain modified tooth pendants were exchanged and/or transported over vast distances across the Caribbean. Origins of the exotic animals from which the teeth pendants were manufactured could be proposed based on comparative analysis of multiple isotope data sets and spatial models. Further explorations of the origins of these artifacts are the focus of ongoing research by the Caribbean Research Group at Leiden University and these will greatly benefit from the expansion of baseline strontium and oxygen isotope datasets from the surrounding mainland regions, especially of northern South America and Central America. It should also be kept in mind that the identification of the origins of these artifacts reveals little of the mechanisms by which they arrived in the Antilles, how they were used and why they were eventually deposited at settlement sites in the islands. Although the available evidence supports a multi-scalar, reticulate model of inter-community articulations and interactions amongst the precolonial societies of the Circum-Caribbean region (Hofman et al., 2010; Rodríguez Ramos, 2010), much more work is required to disentangle how these were manifested in different ways over space and time. Lastly, renewed emphasis on sourcing the different semi-precious stones and other materials utilized in the production of objects of personal adornment in conjunction with further isotope analysis of these types of artifacts should contribute to a better understanding of the changing dynamics of precolonial Amerindian relations within larger-scale networks of interaction in the Circum-Caribbean.

Acknowledgments

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