Chemical signatures of salt sources in the Maya world: implications for isotopic signals in ancient consumers

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1. Introduction

Salt is an essential nutrient, as well as a spice and a food preservative. Inland sources are rare, making it one of the most precious commodities in the world. In the Maya region, salt production sites are located in multiple places on the Pacific and Caribbean coasts and the Gulf of Mexico, but there are multiple salt sources in the interior in both Guatemala and Mexico. However, while there is archaeological evidence of salt production on a scale to suggest that salt was a major export at each of these sources, it is difficult to reconstruct the movement of salt before the Spanish conquest. This is a critical question for isotopic studies of migration, which are based on the premise that Maya communities relied on local foods, even as evidence for marketplaces emerges. Salt was a non-local food consumed by most Mayas not living in proximity to saltworks.

The purpose of this paper is twofold: to explore the effect that non-local salt may have on isotopic identification of migration and to provide data that can be used to source salt to a particular saltworks. We interpret strontium isotopic and elemental data from salt production sites in Mexico and Guatemala: Celestun and Xtampu on the Yucatan, Mexico Gulf coast; Salinas de los Nueve Cerros in the Guatemalan lowlands; Ixtapa in highland Chiapas, Mexico; Sacapulas, El Salitre/Lake Amatitlan, and San Mateo Ixtatan in the Guatemalan highlands; and Sipacate, Guatemala on the Pacific coast. A potential salt source in lowland Chiapas, San Isidrio, was also sampled. Our findings show that salt sources have distinct strontium isotopic values that may not mirror the underlying bedrock and may increase, decrease, or have no effect on human strontium isotopic values depending on the source used and how the salt was treated or consumed.

2. Background

Radiogenic strontium isotope ratios ($^{87}Sr/^{86}Sr$) allow archaeologists to identify migration because average isotopic values in human populations reflect those in the catchment(s) they use. That is, the combination of aerial and fluvial inputs and bedrock geology provides a foundation for human isotopic values, which reflect the biologically available $^{87}Sr/^{86}Sr$ of the animals and plants they eat (Price et al., 1994, 2002, 2008; Price and Gestsdóttir, 2006; also see Hobson, 1999). A key assumption is that people consumed local food, and that imports like salt, marine fish, or cacao did not significantly affect human isotopic compositions.

Wright (2005) was the first to identify a potential problem with this assumption at Tikal, where average strontium isotopic values in the human population were higher than those of the faunal baseline near the site and surrounding region (also see Hodell et al., 2004). Wright (2005) proposed that salt, which had to be imported, may have contributed to human $^{87}Sr/^{86}Sr$ values that were higher than expected. Fenner and Wright (2014) then noted that sea salt has expected $^{87}Sr/^{86}Sr$ values that are higher than those at Tikal and has high levels of strontium that might be amplified if added to lime-treated maize (also see Burton and Wright, 1995). A number of sites have average human values that differ from the faunal baseline values, such as Uxbenka in southern Belize, which Trask et al. (2012) interpret as the use of non-local foods. Most studies, however, show close correspondence between human and plant, animal, and geologic $^{87}Sr/^{86}Sr$ values despite variability in sample size, local geologic heterogeneity, catchment use, and the type of baseline sample collected (Freiwald, 2011; Patterson and Freiwald, 2016; Price et al., 2008). We focus on further exploring the potential effects of salt from different sources with distinct strontium isotope ratios on migration studies of different Maya populations.

The salt samples included in this study come from different cultural and geologic areas in the Maya region (Fig. 1). Andrews (1980) described salt production in three main areas in his inventory of modern and ancient production localities, including the Pacific coast, the northern Gulf coast, and inland Guatemala and Chiapas. He also described Caribbean coastal production sites that likely were important salt sources for Maya lowland populations, including sites that are now submerged along the Belize coast (Sills and McKillop, 2018).

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Fig. 1. Saltworks referenced in the text, including a potential salt source at San Isidro.

2.1. Celestun and Xtampu, Yucatan, Mexico

Celestun saltworks consist of more than two dozen production sites reported by Andrews (1980) along the Gulf Coast. Salt is still produced on the peninsula where Celestun is located. It is evaporated from salt beds, then scraped and stored in open air storage facilities where Freiwald acquired sample UM341. Xtampu is a salt production site located on the Dzemul–Xtampu road near the Laguna Rosada and the Xcambo archaeological site approximately 2 km from the modern coastline. Many coastal municipalities' saltworks were not in production in 2018 when Freiwald purchased Xtampu salt (sample UM342).

2.2. Salinas de los Nueve Cerros, Guatemala

Salinas de los Nueve Cerros is the only inland saltworks in the Maya lowlands associated with a Classic Maya city (sample UM291). It covers an area of over 40 km north of the Guatemalan highlands stretching along both banks of the Chixoy-Salinas River and surrounding a 3 km^2 salt dome from which flows a perennial brine stream. The city was occupied by the Early Middle Preclassic period (ca. 1000 BCE) through the Classic period collapse (ca. 900 CE). Even after its abandonment, the salt was exploited through the Spanish conquest and into the 20th century (Woodfill, in press).

Research conducted by Dillon et al. (1988) in the 1970s documented heavy investment in “industrial” infrastructure at the base of the salt dome. An artificial platform that was over 9.5 m tall and spanned both sides of the brine stream was built up over at least 2000 years. Platform excavations revealed multiple saltmaking workshops on the surface and on buried earlier floors. At least during the better-understood Classic period, brine was collected from the stream in giant bowls with diameters approaching 2 m before being boiled down in round, single-use ceramic molds placed atop long ovens.

Much of the salt was likely exported in cake form, but the presence of specialized salt grinders in every neighborhood investigated to date indicates that salt was used in the production of secondary commodities. Along the river, for example, salted fish was produced on a massive scale; other neighborhoods could have produced jerky, leather, or dyed fabrics (also see Andrews, 1980). While city elite may have controlled the saltworks, which were adjacent to administrative structures, secondary workshops show production at the household level.

The scale of salt production at the site is unknown (Dillon, 1979, 1990; Dillon et al., 1988; Woodfill et al., 2015, in review; Woodfill, in press). One early twentieth century salt producer suggested a potential yield of a quarter of a million metric tons of salt (Andrews, 1983:99)—an amount 28 times the entire output of the Republic of Guatemala at that time (United States Department of Commerce, 1912:712). Scraping the salt flats downstream from the dome could have produced 6000 metric tons of salt annually without modifying the terrain to increase the evaporation zone. However, the extent to which solar evaporation was used is not clear. Most of the salt, from the Preclassic period through Guatemalan independence, was produced by boiling the brine in ovens near the brine stream. Dillon et al. (1988) suggested a total annual yield of up to 24,000 metric tons based on experiments done onsite in the 1970s, and a later paper (Woodfill et al., 2015) suggested a more conservative 14,500 metric tons based on available firewood.

2.3. *Ixtapa, Chiapas*

Ixtapa consists of a Precolumbian brine well carved out of bedrock at the edge of a small stream. The well is surrounded by modern, colonial, and ancient ceramics from as early as 200 BCE (McVicker, 1969:276), and at least one Precolumbian oven for boiling the brine. A Late Classic center with multiple ritual and administrative structures and public monuments is located on the ridge behind it. Two families currently produce salt (UM331) by boiling the brine in ovens attached to their households that are nearly identical to ones excavated by Dillon in the 1970s (Dillon et al., 1988; Woodfill et al., 2015). The only significant difference is that they are topped with permanent receptacles for heating the brine made out of corrugated tin, wooden planks, and concrete; at Nueve Cerros, molds were placed on open shelving on the ovens.

Cerro de la Tortuga has evidence of use spanning the Late Classic through Late Postclassic periods (650–1520 CE), although it may have fallen into disuse before the Spanish conquest (McVicker, 1974:548). While mountaintop sites are typically assumed to be defensive settlements after the Classic collapse, McVicker (1974:547-548) noted that most ceremonial construction was located on the ridge above the salt source and that the population likely occupied a series of sites located in the open valley along a major trail. Woodfill observed plazas and religious structures on the mountaintop with no room for residences, suggesting that it was a ritual center for ceremonies related to salt production.

A second salt source located 40 km upstream, Atzam (salt in most Maya languages), is not yet included in this study. The salt source was historically used by the Tzotzil of Zinacantan, and they continue to control it. There has been almost no archaeology done in Zinacantan beyond a few test pits excavated by McVicker (1974), who recorded the Postclassic site of Ch'ivit Krus (1050–1520 CE) < 1 km from the saltworks. The site is on a hill overlooking the Salinas valley 5 km from Zinacantan and had an abundance of obsidian, snail shells (a trade item from the lowlands), and sherds, but no evidence of architecture (McVicker, 1974:549). It continues to be an important ritual site for visiting saints from Ixtapa and Zinacantan, and even its name, which means "Market Cross," ties it to both ritual and commerce (McVicker, 1974).

2.4. *San Mateo Ixtatan and Sacapulas, Guatemala*

San Mateo Ixtatan and Sacapulas are both found in the highlands of western Guatemala. The former consists of several excavated wells that reach the salty water table, each located inside locked houses that limit access to a few official saltworkers. Like Ixtapa, the wells are located below a Late Classic ceremonial center. The brine is brought back to people's houses and boiled into round salt cakes that are sold in local markets. The Ixtatan samples consist of brine (UM337) and salt cakes (UM338) that are black because they are processed with *masa,* maize (corn or *Zea mays*) that is treated with white lime to form a dough. As the brine boils off, the masa is carbonized, giving the final product its black color. One saltworker from Sacapulas informed Woodfill that she added approximately 2.5 kg worth of maize for every 50 kg of salt, a process identical to that described by Tovilla (2000:105) after his visit to the same saltworks in the early 17th century.

Unlike Ixtapa and Ixtatan, the Sacapulas brine (UM369) is less salty, due largely to the fact that it originates in several hot springs near the banks of the Chixoy River. Today salt is extracted from a large evaporation pool that is regularly scraped, but most local salt producers dig up soil below the hot springs, which have a higher concentration of salt than the brine itself, and bring it to a household workshop. They place the soil on a large stone table with a drain in the center and leach the salt out of the soil by pouring water through it. The leachate is caught in a large basin and the salt is then boiled down in an open fire in thin, single-use molds. Salt production is largely limited to the dry season because the river periodically floods the source of the brine.

At the time of the Spanish conquest, the Sacapulas saltworks were controlled by the K'iche' empire and worked by enslaved Kaqchikel captives. Salt was obtained by pouring the hot brine onto piles of soil that were leached in a manner identical to modern production (Reina and Monaghan, 1981; Tovilla, 2000). Although the indigenous *Titulo de los señores de Sacapulas* states that these workers lived in a nearby cave, it is more likely that they occupied one of the four Late Postclassic archaeological sites described by Fox (1978). One of them, Chuitinamit, is located across the river from the salt springs and atop a ridge. In addition to ceremonial architecture, the site contains several long council houses and a ballcourt. The presence of a jaguar sculpture and corbelled vaulted edifices suggests links to the lowlands.

2.5. *San Isidrio, Chiapas*

The San Isidrio hot springs may be a second lowland salt source that has not been discussed in the archaeological literature. Woodfill visited the headwaters of the Arroyo Salado (salty stream) in the Lacandon Forest near the Late Classic site San Isidro, Chiapas. The site contains a hieroglyphic staircase fronting a low-lying palace and at least one monument, a circular altar with an eroded glyphic text (Woodfill et al. 2019). There was no evidence of production around the hot springs, but brine from the source was sampled (UM336).

2.6. *El Salitre, Guatemala*

The saltworks at El Salitre were located on the banks of Lake Amatitlan on the outskirts of Guatemala City. The saltworks are no longer active, and unfortunately, any evidence of Precolumbian or Colonial saltworking has been overlain by luxury houses and spas. Woodfill found one hot spring that might have had high salt content near a public beach and collected a sample (UM339), which was boiled down in the project lab in Guatemala City. Like Sacapulas, the thermal springs have a much lower mineral content than their cooler peers at most saltworks.

2.7. *Sipacate, Guatemala*

Sipacate is one of a number of saltworks that spanned the Pacific

Table 1
Strontium isotopic values and elemental concentrations in the Maya region, arranged by geographic proximity.

Sample	Sample number	^{87}Sr/^{86}Sr	% SE	Sr ppm	Location
Celestun, Yucatan, Mexico	UM341	0.708836	0.0009	27 ± 1	21.859275 −90.3971912
Charcas saltworks, Xtampu, Yucatan, Mexico	UM342	0.709080	0.0008	31 ± 1	21.330675 −89.348697
Salinas de los Nueve Cerros, Guatemala	UM291	0.708066 0.708066	0.0008 0.0008	76 ± 1	15.99205 −90.597978
San Isidrio, Chiapas, Mexico	UM336	0.707546	0.0007	510 ± 3	16.263575 −90.755198
San Mateo Ixtatan, Guatemala salt brine	UM337	0.708137	0.0007	95 ± 1	15.831092 −91.475625
San Mateo Ixtatan, Guatemala salt cake	UM338	0.709023	0.0008	72 ± 1	15.831092 −91.475625
Sacapulas, Guatemala	UM369	0.707969	0.0007	254 ± 2	15.289641 −91.088698
Ixtapa, Chiapas	UM331	0.710686 0.710638	0.0008 0.0008	2300 ± 40 193 ± 2	16.802153 −92.902403
Playa Salitre, Lake Amatitlan, Guatemala	UM339	0.704099	0.0007	38 ± 1	14.473256 −90.602523
Sipacate, Pacific Coast of Guatemala	UM340	0.709172	0.0007	920 ± 10	13.932114 −91.150711

Coast from El Salvador to Chiapas. Salt sample UM340 came from saltworks on the Pacific Coast located between the beach and a brackish channel that runs parallel to it. The salt is created by pumping water from the channel into a series of long, flat evaporation pools lined with black nylon, which is then left to dry. The saltmaker produced salted fish as well, since he was also a fisherman. Woodfill did not observe any Precolumbian material, but the location of this particular saltworks may relate to its proximity to modern fishing and tourism.

2.8. *Strontium isotope geochemistry*

Strontium isotopic values in the Maya region generally reflect differences in bedrock geology, although there are not clear boundaries between places with different values (Freiwald, 2011; Hodell et al., 2004; Miller Wolf and Freiwald, 2018; Price et al., 2008; Suzuki et al., 2015). The lowest ^{87}Sr/^{86}Sr values (0.704–0.705) are found in volcanic derived soils of the Guatemalan highlands and the Pacific coastal plain that extends from Chiapas, Mexico to El Salvador. Metamorphic bedrock formations are found along the Guatemala-Honduras border and result in ^{87}Sr/^{86}Sr values in the range of 0.706–0.707 near Copan, Honduras. Most Maya lowland centers are located on limestone bedrock that once formed an ancient sea floor and reflect the value of the ocean water when it was formed. Strontium isotope ratios increase gradually from the southern lowlands to the coast of the Yucatan peninsula (0.707–0.709 ^{87}Sr/^{86}Sr). The highest ^{87}Sr/^{86}Sr values in the Maya region are associated with the Maya Mountains and range from 0.710 to > 0.730 (Freiwald, 2011; Thornton et al., 2012; Wrobel et al., 2017). West of the Maya region, ^{87}Sr/^{86}Sr values decrease from east to west in the Sierra Madres of Chiapas (0.7079 to 0.7071), with little isotopic information for the metamorphic region that abuts the coastal alluvium (Freiwald 2011, 2019; Price et al., 2008).

Isotopic variability in human populations does not always reflect the full range of regional geologic values. For example, average human and faunal baseline values shift over short distances from the Belize Valley into the foothills of the Maya Mountains, where sites located just 5 km apart have distinct average ^{87}Sr/^{86}Sr values (Freiwald, 2011; Wrobel et al., 2017). Yaxchilan and Bonampak, approximately 25 km apart, have distinct strontium isotopic faunal values likely resulting from alternating Tertiary and Cretaceous period bedrock limestones. Palenque's population may have used catchments in the immediate vicinity of the site with distinct strontium isotopic values, resulting in two 'local' ranges. In contrast, El Perú and Calakmul, central lowland sites > 100 km apart, have similar strontium isotopic values (Patterson and Freiwald, 2016; Price et al., 2018). Salt values should reflect a combination of geologic and cultural influences, with different values for inland and coastal sources that in places are distinct from those found locally.

3. Method

We measured Sr isotopic compositions and Sr elemental concentrations [Sr] of salt samples to understand the potential dietary contribution and potential effects in migration studies. Strontium isotopic compositions and [Sr] of salt samples were obtained through isotope dilution thermal ionization mass spectrometry (ID-TIMS) at the University of North Carolina at Chapel Hill. Samples were dissolved in 3.5M HNO_3 and an isotopically enriched tracer (dominantly ^{84}Sr) was added, then heated in a sealed teflon beaker to ensure sample-tracer equilibrium. Strontium was then purified using Eichrom Sr-Spec resin. Strontium was analyzed on a VG Sector 54 as a metal in dynamic multicollector mode with $^{88}\mathrm{Sr} = 3\,\mathrm{V}$. Strontium isotopic ratios were corrected for mass fractionation using an exponential law correction and normalized to $^{86}\mathrm{Sr}/^{88}\mathrm{Sr} = 0.1194$. Replicate analyses of the NBS 987 Sr standard yielded $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.710250 \pm 0.000015$ (2σ, $n = 20$). Internal precision of each sample was better than the reproducibility of the standard, and thus the uncertainty of the standard is the uncertainty ascribed to each unknown. Post analysis data reduction using the mass of sample, mass of tracer, and the isotopic ratios measured via mass spectrometry recovers the sample ^{87}Sr/^{86}Sr values as well as the [Sr] of each sample.

4. Results

Table 1 shows strontium isotopic and concentration results. Salt samples collected at coastal production sites (Celestun, Xtampu) on the north and northwest coast of the Yucatan Peninsula have ^{87}Sr/^{86}Sr values that are similar to those expected for modern seawater (Hodell et al., 1991, 2007) and that are found at nearby archaeological sites (Price et al., 2008; Sierra Sosa et al., 2014). The Pacific coast sample (Sipacate) has a ^{87}Sr/^{86}Sr value that is strikingly different than those associated with the volcanic bedrock geology in the region. Samples from inland salt works have values that reflect a combination of the expected value for the location and additives to some of the processed salt (Table 1, Fig. 2). Sample UM291 was analyzed with and without the tracer, and the ^{87}Sr/^{86}Sr values for the two runs are within uncertainty. Sample UM331 was run twice with the tracer because the original [Sr]

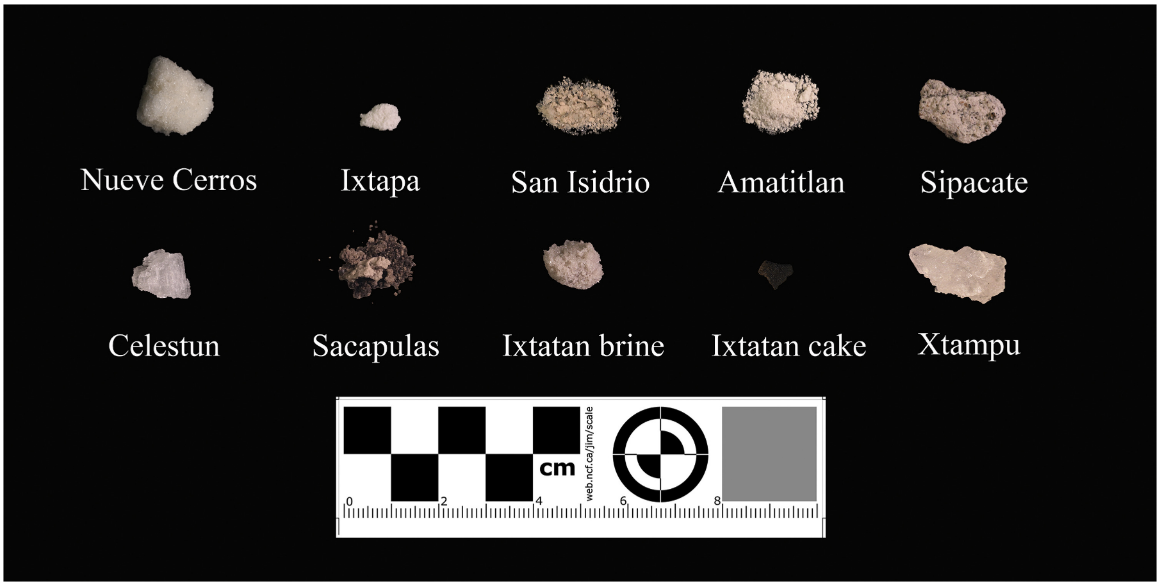

Fig. 2. Mesoamerican salts reflect both environmental and cultural factors with different colors, textures, and intentional or unintentional additives. Image by Benjamin Davis.

result is quite high (2300 ppm); the second [Sr] analysis is lower (193 ppm). The $^{87}Sr/^{86}Sr$ of the two analyses for UM331 are similar (Table 1), but not quite the same within uncertainty.

5. Discussion

The $^{87}Sr/^{86}Sr$ values of salt from the evaporation beds at Celestun (0.708836) and Xtampu (0.709080) on the Gulf coast are similar to those reported in Yucatecan bedrock geology and in human migration studies. For example, Sierra Sosa et al. (2014) reported an average $^{87}Sr/^{86}Sr$ value of 0.7088 in the Xcambo archaeological population, which is adjacent to the Xtampu salt flats < 2 km to the north (Fig. 3). Similar $^{87}Sr/^{86}Sr$ values are reported for human populations at Chac (0.7088) and Oxkintok (0.7088), and sites located on the eastern coast of the Yucatan Peninsula (Ortega-Muñoz et al., 2019; Price et al., 2008).

Woodfill suggests that potential markets for the salt, which leaves very few traces in the archaeological record (Woodfill, in press) due to its propensity to dissolve into the water table and flow away, might be reconstructed using topography and the location of other known saltworks. According to Hutson (2017:23), salt from the northwestern Yucatan may have been traded into the central lowlands, potentially encroaching on the Nueve Cerros salt trade during the Early Classic period (250–600 CE). However, this finding was based on the relative paucity of Early Classic material at Nueve Cerros initially reported by Woodfill et al. (2015). Later investigations show that this period was well represented (Woodfill, 2019a).

The salt from Salinas de Nueve Cerros has a $^{87}Sr/^{86}Sr$ value (0.708066) that likely reflects strontium isotope values of the ancient sea when the bedrock formed (Hodell et al., 2004) and is similar to values at archaeological sites (human and fauna) found along the Usumacinta River (Fig. 3). The hypothetical market for Salinas salt may have included the southwestern lowlands and much of the central Petén, due to its potential to be transported along the Chixoy-Pasión-Lacantun-Usumacinta river network (also see Fenner and Wright, 2014). Nueve Cerros has strong connections with multiple sites in this drainage system that are visible in figurines and ceramics, including Chama, Cancuen, and the Petexbatun region.

Other inland salt sources have variable strontium isotopic compositions. San Isidrio's salt sample $^{87}Sr/^{86}Sr$ value (0.707546) matches expected values for its Chiapas location, as does the value from Sacapulas (0.707969 $^{87}Sr/^{86}Sr$). However, two samples from San Mateo Ixtatan show more specifically how salt preparation may affect the strontium isotopic composition of the salt itself. Expected values for this part of the Maya region are not known, but maize added during preparation of the salt cakes may have affected the $^{87}Sr/^{86}Sr$ values because the brine (0.708137) differs from the salt cake (0.709023), showing that variable signatures may come from salt produced in a single location.

Less work has been done to reconstruct the history of production at the other inland salt sources in Guatemala and Chiapas. Sacapulas was likely the most important highland source during the years leading up to the Spanish conquest based on K'iche' interest, while San Mateo Ixtatan's Late Classic ceremonial center might indicate earlier reliance on its salt. San Mateo Ixtatan maintained close ties with the Colonial period Lakandon living near the base of the highlands in eastern Chiapas (Pons Sáez, 1997:154), and a splinter faction of Ixtatecos moved into the Comitan region in the early 20th century, many of whom conduct a yearly pilgrimage back to Ixtatan (Chavarochette, 2003). All of this could indicate long-standing ties between the two areas rooted in an ease of access based on topographic factors as much as cultural ones.

There are several additional salt sources located nearby—Barrillas, San Miguel Acatan, Las Victorias, and Magdalena—although Andrews (1983:79-81, 88-9, 93-5) points out that these were all relatively minor sources used for local consumption by humans and cattle in the 19th and 20th centuries before roads were built. Only two, Magdalena and San Miguel Acatan, are associated with registered archaeological sites. In highland Chiapas, producers in both Ixtapa and Atzam would likely have distributed salt to a large geographical area, only competing with the pink salt from La Concordia (see Andrews, 1983:51–6). Unfortunately, it is not possible to acquire salt samples because the source was flooded by a hydroelectric dam.

Salt from Ixtapa is distributed across a wide area and is regularly found in regional markets such as San Cristóbal de las Casas. Its $^{87}Sr/^{86}Sr$ values (0.710686, 0.710638) are higher than expected for the marine carbonate geology, and Woodfill noted no inclusions in the sample. Further investigation is needed both of the salt value and the potential for the local environ to have a strontium isotope value higher than modern seawater. In addition to the archaeological site above it, Woodfill noted the presence of Classic, Postclassic, and Colonial period sherds—including several massive sherds similar to the Atzam Red bowls at Nueve Cerros that were in use as makeshift bricks for an old

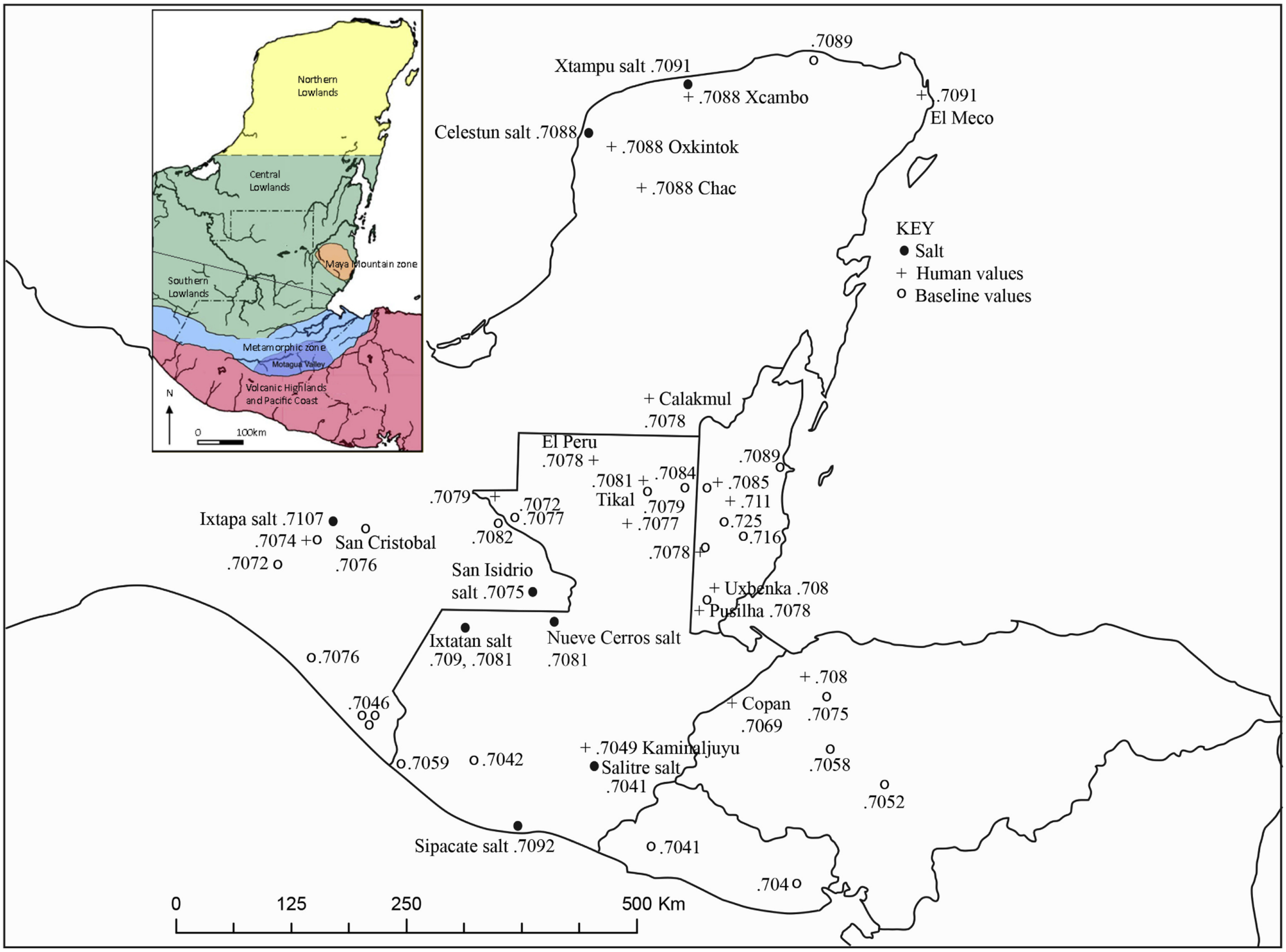

Fig. 3. Strontium isotope values of salt samples and isotope values in the Maya and neighboring regions. Includes values from Freiwald, 2011, 2019; Freiwald and Pugh, 2018; Freiwald et al., 2014; Ortega-Muñoz et al., 2019; Patterson and Freiwald, 2016; Price et al., 2008, 2018; Somerville et al., 2016; Trask et al., 2012; Wright, 2012; Wright et al., 2010; Wrobel et al., 2017; Miller Wolf and Freiwald, 2018; Suzuki et al., 2015. Inset showing cultural areas and proposed ^{87}Sr/^{86}Sr isotopic divisions modified from Wright, 2005:557, Fig. 1.

wall—in the area surrounding the brine well.

El Salitre could have provided a local salt source for Kaminaljuyu and other parts of the central Guatemalan highlands. There are records of Salitre salt as tribute during the Colonial period, and four archaeological sites are located near Lake Amatitlan (Andrews, 1983:78). The Lake Amatitlan salt source has a ^{87}Sr/^{86}Sr value that reflects the volcanic soils of the region (0.704099), and is similar to human values from Kaminaljuyu (0.7049) and faunal values at Izapa (0.7047). A salt production center also was reported at Sabalpop, a source on the shores of Lake Atitlan with an unknown strontium isotopic composition. Sabalpop produced “a few hundred kilograms a year” for local consumption during the Colonial period and into the 20th century (Andrews, 1983:79).

However, coastal salt was easier to acquire because of a relatively straightforward 100 km uphill hike from the source to the site. The Sipacate salt sample has a ^{87}Sr/^{86}Sr value (0.709172) that is distinct from sites on the coastal plain and the highlands, and coastal salts could have had a greater impact on human strontium isotopic compositions because the strontium content is significantly higher than that of El Salitre (Table 1). Neither of these samples have intentional additives, although unintentional ones such as sand are visible in Fig. 2 images.

The Sr concentration data [Sr] for the salt span a range of one to two orders of magnitude. Sample UM331 was run twice, and the [Sr] data are different by an order of magnitude. We hypothesize that the first analyses may have contained an inclusion in the salt that had a higher [Sr] than the salt. Interestingly, the ^{87}Sr/^{86}Sr values for the two analyses are very similar (0.710686 and 0.710638), but not the same within uncertainty. Thus it is possible that the fluid inclusion was not in complete isotopic equilibrium with the salt. Future work analyzing multiple salt fragments per sample will help in understanding the variability in [Sr] in the salt and the associated isotopic variability.

6. Conclusions

Strontium isotopic compositions are variable among Mesoamerican salt sources in and around the Maya region. Coastal salt ^{87}Sr/^{86}Sr values appear to be higher than those of most non-coastal Maya human populations. Salt ^{87}Sr/^{86}Sr values along the Pacific coast may be significantly higher than local and regional human and non-human values (0.703–0.705). Inland ^{87}Sr/^{86}Sr values are highly variable (0.704099 to 0.710686), especially when production of salt includes additives as the cakes are produced and exported, which may affect the ^{87}Sr/^{86}Sr values of the salt itself. In fact, production techniques may differ at the same source, and may even change over time. Strontium in salt could have had variable effects—or none at all—on isotope ratios in Maya populations.

Salt production sites were likely not monopolies, so multiple sources might have reached the same market, at the same time or in different seasons, offering alternative desired attributes, uses, or statuses. It is difficult to assess the full reach of any salt source because of its inherent impermanence and volatility. Salt simply does not survive in any meaningful quantities in the archaeological record, especially in humid, rainy lowland environments. To date, most of the energy devoted to understanding the salt trade has been restricted to salt in its raw form. Dried fish and other secondary products may have had very different distribution patterns, which also could affect the isotopic compositions of ancient Maya consumers (see McKillop and Aoyama, 2018; Woodfill, in press; Woodfill et al., 2017).

Salt was a critical non-local food in the Maya region, but it was not the only one. Isotopic mixing models that consider only salt are useful (i.e., Fenner and Wright, 2014), but other non-local $^{87}Sr/^{86}Sr$ values may have come from marine fish, wild and domestic game, cacao, and even water, as well as medicinal or other products that have not yet been considered. Water, for example, may contribute to distinct strontium isotopic values (Frei and Frei, 2011:339; Killgrove and Montgomery, 2016), derived from weathering of limestones and silicates with different strontium concentrations and isotopic levels (Graustein, 1989; Palmer and Edmond, 1992:2099). Strontium isotope values of wild game sampled from 18 sites across the Maya region include non-local deer and peccary species at 13 of them (Thornton, 2011:3258–3259; Yaeger and Freiwald, 2009), and non-local turkey and domesticated dog were exchanged as well (Sharpe et al., 2018; Thornton et al., 2012). The potential mix of local and non-local resources will differ for each site and possibly each individual, and the overall *isotopic* impact of non-local foods may be smaller than the economic and social impacts of the foods and other products. Even in areas such as the Belize Valley where non-local game and salt likely were consumed by all or part of the population, the $^{87}Sr/^{86}Sr$ values illustrate the close fit between average human (0.7086 $^{87}Sr/^{86}Sr$) and baseline faunal (0.7085 $^{87}Sr/^{86}Sr$) samples (Freiwald, 2011; also see Green, 2016; Novotny, 2015; Spotts, 2013).

Non-local foods are just one of a number of factors that affect isotope migration studies, and possibly not the most important one. The size and composition of the sample population, local and regional geologic variability, and the catchments people chose to use are all important factors that differ for every site, highlighting the interpretive nature of scholarship on mobility and migration. Overall, the salt strontium isotope data may allow more refined interpretations of the effects of inland and sea salt and other variables in future migration studies.

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