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RESEARCH ARTICLE

Food Has No Borders: Methodological Insights from the Forensic Isotopic Profile of a New York City Immigrant

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ABSTRACT: Isotopic analyses of human remains augment the biological profile with geolocation and dietary information, furthering efforts to identify unknown individuals from a forensic context. Here we test the methodological resolution of geolocation (δ^{18}O, ^{87}Sr/^{86}Sr) and dietary (δ^{13}C, δ^{15}N) isotopes of one identified individual who immigrated to New York City from St. Vincent and the Grenadines (SVG), Lesser Antilles. Isotope-based geolocation estimates did not identify the childhood residency on SVG, but did point to New York City as a possible residence during early adulthood. The individual's C_3-based diet did not significantly change from childhood to early adulthood, illustrating the maintenance of food traditions after the immigration event. This study illustrates that further development of tissue-specific isoscapes incorporating bioavailable foods, drinking water, and cultural traditions is warranted to refine methodological resolution of isotopic applications in forensic anthropology.

KEYWORDS: geolocation isotopes, dietary isotopes, Caribbean isoscapes, US isoscapes, food traditions

1. Introduction

Forensic investigators employ multiple layers of data (e.g., biological profile, dental charting, unique features, recovery context, and personal effects) to propose matches of unidentified human remains to missing individuals. A proposed match can then be confirmed or excluded using accepted forensic identification methodologies, such as DNA, fingerprints, or comparative dental or medical radiography. Due to a variety of reasons, some unknown individuals are not identified with established techniques and may require additional investigative tools to aid identification efforts. Isotopic analyses of human remains, long established in bioarchaeology (e.g., Schoeninger 1981; Vogel & van der Merwe 1977) and paleoanthropology (e.g., Sillen et al. 1995; Sponheimer & Lee-Thorp 1999), are now being applied to unidentified human remains to aid in investigative efforts (Bartelink et al. 2016; Kamenov et al. 2014; Meier-Augenstein & Fraser 2008; Remien et al. 2014). Ingested, imbibed, or inhaled chemicals recorded in human tissues and measured as isotopic values are patterned geographically. Depending on the specific isotopic system used and tissue measured, different aspects of lifeways, including location of residence ("geolocation") and diet during specific windows of time in the individual's life, are inferred and incorporated into the biological profile.

In forensic contexts, isotopic values measured in unidentified remains provide a means to infer geographic location of residence ("geolocation") during tissue formation. Isotopic systems such as carbon (δ^{13}C), nitrogen (δ^{15}N), oxygen (δ^{18}O), and strontium (^{87}Sr/^{86}Sr) utilized in this study have been applied to differentiate immigrants from local residents especially within the context of the humanitarian crisis at the southern US border (Bartelink & Chesson 2019; Juarez 2008). Other isotopic systems such as hydrogen, sulfur, and lead, although not used in this study, are also used to assess geolocation in forensic contexts (Gulson et al. 1997; Keller et al. 2016; Lehn et al. 2011; Mant et al. 2016; Richards et al. 2001). For all of these isotopic systems, efficacy to detect the geolocation depends on the accurate measurement of the geographic distribution of isotopic ratios ("isoscapes") (West et al. 2010) through access to baseline samples relevant to patterns of ingestion and the biologically available ("bioavailable") values in a particular cultural context (Sillen 1992; Price et al. 2002; Bataille et al., 2020). We provide a brief overview of isotopic methods used in this study (See section 2 Forensic Isotopes, below); for detailed explanations as applied to forensic anthropology,

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see Meier-Augenstein (2010), Cerling et al. (2016), and Bartelink and Chesson (2019).

Studies involving the mapping of human isoscapes for forensic purposes (e.g., Bataille & Bowen 2012; Ehleringer et al. 2008; Keller et al. 2016; Laffoon et al. 2012) focus on bioavailable isotopic values, which are typically measured via local plants, animals, and drinking water. With respect to $^{87}Sr/^{86}Sr$ isoscapes, Sillen (1992) and Price et al. (2002) aptly recognized that geologic bedrock and surface waters do not fully characterize the $^{87}Sr/^{86}Sr$ values in bioavailable sources. Likewise, the systematic offset of US tap water-based $\delta^{18}O$ isoscapes (Ehleringer et al. 2008) compared to the US and global rainfall-based $\delta^{18}O$ isoscapes (e.g., Dutton et al. 2005; Waterisotopes.org) illustrates the necessity of measuring $\delta^{18}O$ values of the water that people are actually drinking in order to construct accurate isoscapes for forensic purposes (e.g., Ammer et al. 2020, Kramer et al. 2020).

Numerous combinations of $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values are found across the US and around the world. Thus, dietary isotopes ($\delta^{13}C$, $\delta^{15}N$) from unidentified individuals are used to gauge general food inputs and point investigations to plausible regions of residence in order to triangulate $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values measured from the same tissue samples (e.g., Bartelink & Chesson 2019; Meier-Augenstein 2010). Culturally and geographically based identities from global communities have distinct food traditions. For example, the (pre) historical and industrial use of corn, a C_4 plant, in the Americas resulted in significantly higher $\delta^{13}C$ values across populations geographically (Hutchinson 1998; Valenzuela et al. 2011, 2012; Vogel & van der Merwe 1977), and thus can narrow the general region to then apply $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values. But for immigrants, it is quite possible for an individual to live in one geographic area and maintain the dietary habits of the ancestral home in part as a consequence of access and cultural tradition maintenance specific to family and community. Moreover, the incorporation of non-local foods and beverages from various US states or imported from other countries is a main concern in locations with extensive food trade networks, referred to as the "supermarket effect," (e.g., Chesson et al. 2010) which can potentially incorporate non-local residency signals within the human tissue. Human diets are shaped by numerous influences in addition to food traditions, such as food availability, economic security, personal tastes, and food allergies, among others. Corn and sugar, also a C_4 plant, are differentially utilized in low-cost foodstuffs (Chesson et al. 2008). Consequently, an abundance of processed, corn-based food items are found in poor neighborhoods, and a large diversity of food items are available in more affluent ones (Ehleringer et al. 2020). Thus, an individual's tissue $\delta^{13}C$ value can potentially reflect aspects of socioeconomic status and residence in so-called "food deserts."

Testing forensic isotopic methods with individuals of known residential histories, socioeconomic status, and cultural traditions is critical to gauging resolution and identifying avenues for future research (e.g., Kramer et al. 2020; Marcuso & Ehleringer, 2019). To this aim, we analyzed enamel $\delta^{18}O$, $\delta^{13}C$, and $^{87}Sr/^{86}Sr$ values; bone carbonate $\delta^{13}C$ and $\delta^{18}O$ values; and bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of one individual with a known immigration history to New York City. The resection of all bone and tooth samples and isotopic analyses were originally conducted in an effort to identify the individual. Subsequent to these analyses, an unrelated investigative lead resulted in a DNA identification. To maintain confidentiality of the decedent and family, no identifying information will be shared.

2. Forensic Isotopes

Isotopic systems measured in a human tissue reflect dietary, imbibed, and inhaled inputs derived from bedrock, soil, aerosols, beverages, and foods where an individual lived during the time that particular tissue was formed. For example, strontium isotopic ($^{87}Sr/^{86}Sr$) values of bedrock, soils and aerosols are incorporated into local food and water without significant fractionation (see review of Bentley 2006). Because $^{87}Sr/^{86}Sr$ values vary geographically, human tissues, in turn, record $^{87}Sr/^{86}Sr$ values of ingested foods and beverages reflecting the measured individual's geolocation during tissue formation (Beard and Johnson 2000; Price et al. 1994; Sealy et al. 1991). Human tissues incorporate both internal (e.g., ingested food, imbibed beverages, inhaled particulates) and external (e.g., burial sediment, aerosols) $^{87}Sr/^{86}Sr$ sources to varying degrees and have different susceptibilities to chemical alteration or diagenesis. For example, hair $^{87}Sr/^{86}Sr$ ratios represent those from food and other ingested components; however, hair quickly incorporates $^{87}Sr/^{86}Sr$ ratios from the environment of deposition and/or contact such as sediment, aerosols, or water (Hu et al. 2020a, b; Tipple et al. 2018). Bone and enamel mineral phases primarily record $^{87}Sr/^{86}Sr$ values from ingested foods and beverages (Keller et al. 2016) and are less susceptible to diagenesis (e.g., Koch et al. 1997) especially in modern forensic contexts.

Oxygen isotopic ($\delta^{18}O$) values in human tissues incorporate $\delta^{18}O$ values from drinking water, water in food, and atmospheric O_2 (Kennedy et al. 2011; Knudson & Price 2007; Kohn & Cerling 2002; Stuart-Williams et al. 1996; White et al. 1998). Both the phosphate (subscript PHOS) and carbonate (subscript CARB) phases of bone and enamel mineral reflect body water $\delta^{18}O$ values and demonstrate a strong correlative relationship with one another (Bryant et al. 1996; Iacumin et al. 1996). $\delta^{18}O_{CARB}$ values are analyzed more easily via mass spectrometry and also yield $\delta^{13}C_{CARB}$ values from the same analysis; however $\delta^{18}O_{CARB}$ values have been shown to be more susceptible to diagenesis than $\delta^{18}O_{PHOS}$ in archaeological and paleontological contexts (Iacumin et al. 1996; Sharp et al. 2000; Wang & Cerling 1994).

It is common for studies to compare meteoric water (e.g., local rainfall and tap water) $\delta^{18}O$ values to bone and enamel $\delta^{18}O_{CARB}$ for inferring geolocation from human remains (Ammer et al. 2020; Laffoon et al. 2017; Quinn et al. 2008; Turner 2013; Vanderpool & Turner 2013). Conversion equations are necessary to make the comparison, however, and are thus sources of error due to variation in the correlative relationships (Pollard et al. 2011). Typically, three equations are used to convert the $\delta^{18}O_{CARB}$ value measured from human enamel and bone to those of meteoric water. The first equation converts the measured tissue $\delta^{18}O$ value reported in V-PBD (Vienna-Pee Dee Belemnite) to those reported in V-SMOW (Vienna-Standard Mean Ocean Water) (Coplen et al. 1983). Then $\delta^{18}O_{CARB}$ must be converted into $\delta^{18}O_{PHOS}$ (Iacumin et al. 1996). Finally, $\delta^{18}O_{PHOS}$ is converted into imbibed water $\delta^{18}O$ subscript IW; Daux et al. 2008). Different combinations of equations produce slightly different $\delta^{18}O_{IW}$ estimations (Chenery et al. 2012; Pollard et al. 2011). Notably, prior to ingestion, imbibed water $\delta^{18}O$ values can be modified through cultural practices such as heating, cooking, boiling, and stewing (Brettell et al. 2012; Gagnon et al. 2015).

Diet is inferred through the analysis of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic values measured in human tissues (see review of Katzenberg 2000). General diet groups can be delineated by plotting human tissue $\delta^{13}C$ and $\delta^{15}N$ values in concert (e.g., Ambrose et al. 1997; Müldner & Richards 2007; Nardoto et al.2006). Dietary $\delta^{13}C$ values are incorporated into both the organic (e.g., bone collagen, hair keratin) and inorganic phases (e.g., enamel and bone bioapatite) of human tissues with fractionation effects (Crowley et al. 2010; Lee-Thorp 1989; O'Connell et al. 2012). $\delta^{13}C$ values are used to differentiate diets composed of C_3 (Calvin-Benson photosynthesis), C_4 (Hatch-Slack photosynthesis) and CAM (Crassulacean acid metabolism) plants (Ehleringer 1989; Tieszen 1991), or the animals that feed on those plant types. Several studies, however, have shown that dietary isotopic values from macronutrients (e.g., proteins, carbohydrates) can be routed in various ways to different human tissues (Jim et al. 2004; Kellner et al. 2007). For example, $\delta^{13}C_{CARB}$ values available from human bone and enamel reflect whole diet $\delta^{13}C$ values, whereas collagen and keratin $\delta^{13}C$ values in bone/dentin and hair, respectively, record dietary protein $\delta^{13}C$ values (Ambrose & Norr 1993). $\delta^{15}N$ values are preserved in organic components of tissues (e.g., keratin, bone collagen, muscle), and represent the protein component of diet (Ambrose & Norr 1993). $\delta^{15}N$ values fractionate with increasing trophic level and therefore tend to be higher in individuals who consume animal protein compared to vegetarians (Ambrose 2000; Petzke et al. 2005). Moreover, freshwater and marine systems typically have more trophic spaces than those in terrestrial food webs; thus, humans who regularly consume pelagic fish have elevated $\delta^{15}N$ values compared to those who consume reef fish, shellfish, or terrestrial animal protein (Ambrose et al. 1997; Jones & Quinn 2009; Schoeninger & DeNiro 1984). $\delta^{15}N$ values measured in human tissues have also been useful in detecting nutritional deficits and can mimic high protein diets (Fuller et al. 2005; see review of Reitsema 2013).

3. Materials and Methods

3.1. Tissue formation and isotopic time averaging

Time of tissue formation must be considered when applying isotopic systems to forensic contexts. For example, hair provides an incremental record of months to years prior to death depending on the length of the hair sample (Loussouarn et al. 2005). Bone records various intervals of time depending on the specific skeletal element formation and turnover rates. For instance, ribs, commonly used for forensic isotopic analyses, are thought to represent the last ~2–5 years prior to death; the femur, alternatively, records 15+ years prior to death (Hedges et al. 2007). Enamel formation time ranges from in-utero/birth to late childhood (~9–12 years of age; Hillson 1996); thus, enamel provides an indication of childhood diet and geolocation.

To date, most isotopic studies of human remains have analyzed bulk samples. Bulk tissue samples can average years of isotopic inputs and, as a result, pose the issue of isotopic equifinality (Quinn 2019), which is when two or more isotopic inputs contribute to an erroneous interpretation of diet or geolocation from an averaged isotopic value. There is potential for measuring incremental isotopic data transversely along long bone diaphyses (e.g., Meier-Augenstein & Fraser 2008). Laser ablation mass spectrometry measurements combined with high-resolution imaging of daily enamel growth increments suggest that enamel records isotopic inputs during enamel secretion with little time averaging (Austin et al. 2013; Green et al. 2018; Smith et al. 2018). Thus, mobility and dietary information on short time scales (~days–weeks) during childhood can be inferred from enamel sampling via laser techniques.

3.2. Known New York City Immigrant

The individual analyzed in this study lived on the islands of St. Vincent and the Grenadines (SVG) in the Lesser Antilles (Caribbean) during childhood and subsequently immigrated to New York City. Two tissue types were analyzed, the right mandibular second premolar and the right 9th rib, which represent the individual's childhood (1–8 years of age; Hillson 1996) and early adulthood (last 2–5 years of life) periods, respectively. Based on the known residence during childhood, the enamel isotopic values reflect the geolocation on SVG. The early adulthood period recorded in the bone sample represents geolocation in New York City. A total of four isotopic ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$) systems were used to test the accuracy of current isoscapes of the two known geolocations. Enamel and bone carbonate were measured for $\delta^{18}O$ and $\delta^{13}C$ values, representing imbibed water $\delta^{18}O$ and whole diet $\delta^{13}C$ values, respectively. Enamel $^{87}Sr/^{86}Sr$ ratios were measured to infer consumed food and water $^{87}Sr/^{86}Sr$ ratios. Bone collagen was measured for $\delta^{13}C$ and $\delta^{15}N$ to infer dietary protein $\delta^{13}C$ and $\delta^{15}N$ values.

The enamel bulk sample averages geolocation and dietary information for the total duration of enamel formation (1–8 years of age) when the individual lived on SVG. The bulk bone sample averages isotopic inputs during the last ~2–5 years of life during early adulthood when the individual resided in New York City. We utilized laser ablation techniques to measure $^{87}Sr/^{86}Sr$ ratios along enamel growth increments to detect variations in $^{87}Sr/^{86}Sr$ inputs and the potential for isotopic equifinality. Daily enamel growth thicknesses range from ~2 to ~7 mm (Smith 2008); thus, laser ablation lines spanning 1800 mm represent an internal between 8.5 months and 2.5 years within the childhood period (1–8 years of age).

3.3. Sample Preparation and Mass Spectrometry

Bulk enamel and bone $\delta^{18}O_{CARB}$ and $\delta^{13}C_{CARB}$ analyses were first commissioned by the NYC-OCME from IsoForensics, Inc., as part of a grant-funded project to use new technology to identify the missing (NIJ-2015-4055). IsoForensics, Inc. reported the following methodology: Enamel and bone powders were collected using a handheld rotary tool (Dremel®) and carbide bit. Powdered samples were treated with 3% hydrogen peroxide to remove organic material and 0.1 M acetic acid solution to remove labile carbonates. Bone samples were defatted with a methanol-chloroform solution. Between each step, samples were washed with deionized water. Dried, treated sample material was weighed (1.7–2.5 mg) into Exetainer® screw capped glass vials with rubber septa. Helium-flushed vials containing weighed samples and reference materials were placed in a heating block held at 26°C and five to eight drops of phosphoric acid were manually injected into each vial. Samples and reference materials were allowed to react for a minimum of 24 hours before measurement. The CO_2 gas evolved from carbonates reacting with the acid in the vials was collected via an autosampler and swept in a continuous helium stream to the isotope ratio mass spectrometer for simultaneous carbon and oxygen isotope ratio measurement. All reported $\delta^{18}O$ and $\delta^{13}C$ values are relative to Vienna-Pee Dee Belemnite (V-PDB) in delta notation (parts per thousand, per mil, ‰). Analytical error for both values is < 0.05‰.

For the second phase of analysis, sample pretreatment was conducted at Anthropological Isotope Lab at Seton Hall University, and mass spectrometry was conducted at the Geochemistry Laboratory in the Department of Earth and Planetary Sciences at Rutgers University. Bone collagen was extracted following the methods reported by IsoForensics, Inc. to compare with other cases in the future. Bone samples were decalcified using a solution of 0.5N HCl. Humic acids were removed with 0.1N NaOH. Defatting was achieved with a methanol and chloroform mixture. After each step, samples were washed with deionized water until pH neutral. Treated samples were freeze-dried and approximately 200–300 mg was loaded into tins. Bulk collagen was analyzed on a GV Instruments Isoprime stable isotope mass spectrometer combined with a Eurovector elemental analyzer (continuous flow). Bone $\delta^{13}C_{COLL}$ and $\delta^{15}N_{COLL}$ values were standardized against reference materials: NBS-22 (oil) for $\delta^{13}C$ and IAEA-N-1 ($(NH_4)_2SO_4$) for $\delta^{15}N$, additional certified C and N standards were included with each analysis (IAEA-CH6, IAEA-N-3). Analytical error for both isotopic values is < 0.05‰. Bone collagen fidelity was gauged with C:N ratio of 2.9–3.6 (Ambrose 1990).

The remaining outer enamel surface of the mandibular second premolar was smoothed from tooth cusp to cervico-enamel junction (cej) with a rotary drill (Foredom®) affixed with a diamond-tipped bit. $^{87}Sr/^{86}Sr$ ratios were measured incrementally oriented from cusp to cej with a Thermo Scientific Neptune Plus MC-ICP-MS coupled to a Teledyne CETAC Photon Machines laser ablation (LA) system with a HelEx II volume cell. An in-house carbonate standard, calibrated against NBS 987 thermal ionization mass spectrometry (TIMS), was ablated throughout to assure accuracy. In-house enamel samples of humans and mammals measured previously with column chemistry and TIMS techniques for $^{87}Sr/^{86}Sr$ were also used to gauge accuracy. Each measured area consisted of a 0.6 mm line with a 110 mm spot moving at 5 mm/s. A fluence of 6.5 J/cm^2 was used for $^{87}Sr/^{86}Sr$ ratios via laser ablation. Strontium concentrations as gauged with ^{88}Sr signals during analyses were sufficiently high (0.7 V) to minimize interfering isotopes (Horstwood et al. 2008).

3.4. Conversion Equations and Isoscape Comparisons

IsoForensics, Inc. utilized three equations to convert the enamel and bone $\delta^{18}O_{CARB}$ values to US tap water and global precipitation $\delta^{18}O$ values. Measurements via mass spectrometry reported relative to the Vienna-Pee Dee Belemnite (V-PDB) standard were converted to Vienna-Standard Mean Ocean Water (V-SMOW) with the equation of Coplen et al. (1983): $\delta^{18}O_{V\text{-}SMOW} = 1.03092 * \delta^{18}O_{V\text{-}PDB} + 30.92$. The equation of Iacumin et al. (1996): $\delta^{18}O_{PHOS} = 0.998 * \delta^{18}O_{CARB} - 8.5$ (‰, V-SMOW) was utilized to convert $\delta^{18}O_{CARB}$ to $\delta^{18}O_{PHOS}$. In order to estimate the $\delta^{18}O_{IW}$ value from the $\delta^{18}O_{PHOS}$ value, the equation of Daux et al. (2008): $\delta^{18}O_{IW} = 1.54\ (+/-0.09) * \delta^{18}O_{PHOS} - 33.72\ (+/-1.51)$ was used. Calculated $\delta^{18}O_{IW}$ values from enamel and bone were mapped onto the World and US isoscapes by IsoForensics, Inc. These maps utilize the Interval Approach based on measured US tap-water $\delta^{18}O$ values (Bowen et al. 2007; Ehleringer et al. 2008) and global precipitation $\delta^{18}O$ values (Waterisotopes.org; West et al. 2010). We compared the calculated $\delta^{18}O_{IW}$ value and incremental $^{87}Sr/^{86}Sr$ ratios of enamel to the established isoscapes of known residence from childhood in SVG (Laffoon et al. 2017).

We estimated the percentage of C_4 resources (%C_4) in whole diet across the migration event by comparing enamel and bone $\delta^{13}C_{CARB}$ values. We calculated the percentage of consumed C_4 foods from the $\delta^{13}C_{CARB}$ values using the linear mixing model as reviewed by Quinn (2019:405): $\%C_4 = (\delta^{13}C_{DIET} - \delta^{13}C_{C3}) \times 100/(\delta^{13}C_{C3} - \delta^{13}C_{C4})$, where %$C_4$ diet represents the estimation of C_4 food contribution as a percentage of total diet, $\delta^{13}C_{DIET}$ is the estimation of the dietary $\delta^{13}C$ value, $\delta^{13}C_{C3}$ is the average ingested C_3 food $\delta^{13}C$ value, and $\delta^{13}C_{C4}$ is average ingested C_4 food $\delta^{13}C$ value. $\delta^{13}C_{C3}$ and $\delta^{13}C_{C4}$ endmember values used to calculate percent C_4 diet are −27‰ and −13‰, respectively (Kohn 2010). The offset between the measured $\delta^{13}C_{CARB}$ value and dietary $\delta^{13}C$ value ($\varepsilon^*_{CARB\text{-}DIET}$) is assumed as 12‰ (Crowley et al. 2010; Lee-Thorp 1989). Given the childhood location on SVG, we predicted that the enamel $\delta^{13}C_{CARB}$ value would be similar to those in South America but lower than those in the US (data compiled from Lehn et al. 2015) due to the Caribbean region's access to corn and pineapple, a CAM plant that yields $\delta^{13}C$ values near those of C_4 plants (Ambrose et al. 1997; Martinelli et al. 2020). We predicted that the individual's bone $\delta^{13}C_{CARB}$ value would be higher than the enamel $\delta^{13}C_{CARB}$ value, matching those found in the US, due to differential access to industrialized foods.

Bone $\delta^{13}C_{COLL}$ and $\delta^{15}N_{COLL}$ values were compared modern hair $\delta^{13}C$ and $\delta^{15}N$ values compiled in Lehn et al. (2015) to test if the geographic patterning in diet agreed with the known geolocation in New York City during early adulthood. In order to compare $\delta^{13}C_{COLL}$ and $\delta^{15}N_{COLL}$ to those of modern hair samples, we used the following tissue-spacings: $\delta^{13}C$ values: $\varepsilon^*_{HAIR\text{-}COLL}$= 1‰ (Crowley et al. 2010); $\delta^{15}N$ values: $\varepsilon^*_{HAIR\text{-}COLL}$ = 1‰ (O'Connell et al. 2012). We also utilized the model of Kellner and Schoeninger (2007), which plots bone $\delta^{13}C_{CARB}$ and $\delta^{13}C_{COLL}$ values to gauge if dietary protein in early adulthood was derived from C_3, C_4 or mixed C_3-C_4 sources.

4. Results

The incrementally measured enamel $^{87}Sr/^{86}Sr$ values of the mandibular second premolar show a range of 0.70800–0.70943, averaging 0.70869 (Table 1). The measured enamel $\delta^{18}O_{CARB}$ value, −3.11‰, equates to the $\delta^{18}O_{IW}$ estimate of −4.22‰. The individual's enamel $\delta^{13}C_{CARB}$ value, −11.05‰, calculates to 23% of C_4 resources in the whole diet. The mandibular second premolar should reflect the individual's childhood years in the SVG, however, the maps based on enamel $\delta^{18}O_{IW}$ values provided by IsoForensics, Inc. did not include SVG or the Lesser Antilles (Figure 1). The individual's estimated childhood $\delta^{18}O_{IW}$ value is lower than that predicted by the precipitation-based $\delta^{18}O$ global isoscapes (Waterisotopes.org; West et al. 2010). Based on bone $\delta^{18}O_{CARB}$ values of human remains from across the Caribbean (Laffoon et al. 2013), there appears to be a high degree of overlap across the island groups. The individual measured here yielded an enamel $\delta^{18}O_{CARB}$ value that falls within the range of those identified as local to St. Lucia (−3.4 to −2.0 ‰), the island nearest to SVG of those reported in Laffoon et al. (2013).

TABLE 1—*NYC-OCME individual's isotopic ($\delta^{13}C_{CARB}$, $\delta^{18}O_{CARB}$) values of bulk enamel and bone carbonate, isotopic ($\delta^{13}C_{COLL}$, $\delta^{15}N_{COLL}$) values of bulk collagen, incremental $^{87}Sr/^{86}Sr$ values of enamel by laser ablation, converted $\delta^{18}O$ values of imbibed water (IW), and calculated percentage of C_4 foods in whole diet.*

Bulk enamel carbonate	$\delta^{13}C_{CARB}$	−11.05‰
	whole diet %C_4	23%
	$\delta^{18}O_{CARB}$	−3.11‰
	$\delta^{18}O_{IW}$	−4.22‰
Bulk bone carbonate	$\delta^{13}C_{CARB}$	−12.01‰
	whole diet %C_4	17%
	$\delta^{18}O_{CARB}$	−4.67‰
	$\delta^{18}O_{IW}$	−6.72‰
Bulk bone collagen	$\delta^{13}C_{COLL}$	−18.67‰
	$\delta^{15}N_{COLL}$	9.92‰
Incremental enamel	$^{87}Sr/^{86}Sr$ mean ± 1σ	0.70869 ± 0.00032
	$^{87}Sr/^{86}Sr$ range (n)	0.70800–0.70943 (69)

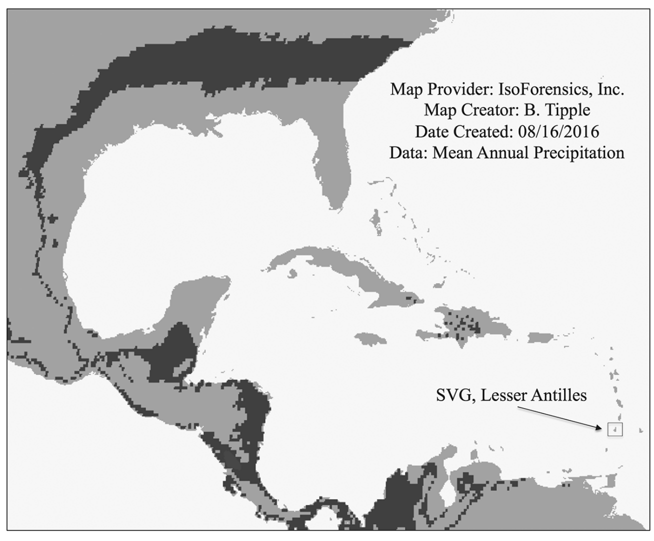

FIG. 1—*NYC-OCME individual's enamel carbonate $\delta^{18}O_{IW}$-based geolocation estimation during childhood commissioned by IsoForensics, Inc.; area of known residence is boxed.*

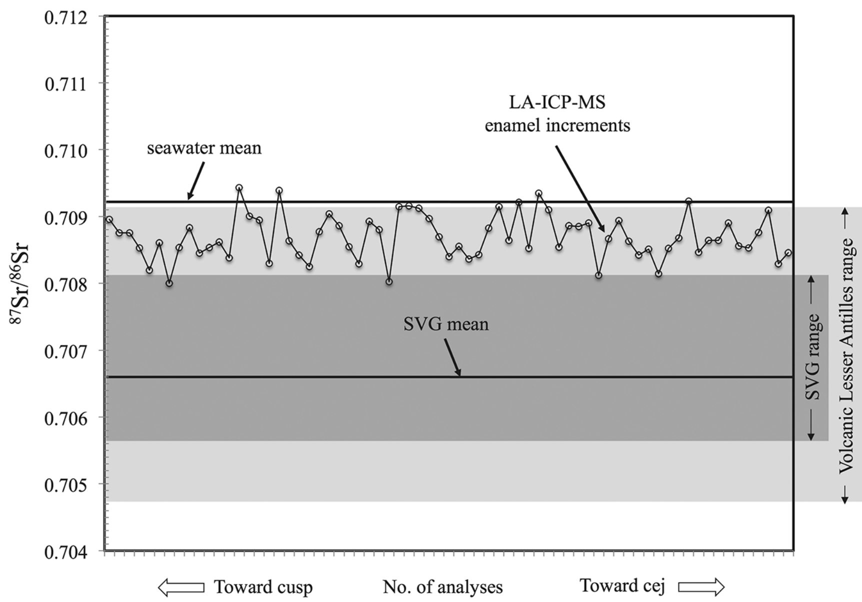

FIG. 2—*NYC-OCME individual's incremental $^{87}Sr/^{86}Sr$ ratios along enamel growth layers. Color bands denote predicted $^{87}Sr/^{86}Sr$ ranges of SVG and all volcanic/intrusive islands of Lesser Antilles based on bioavailable (plant and animal) sources (data from Laffoon et al. 2012, 2017).*

The individual's enamel $^{87}Sr/^{86}Sr$ ratios do not point to SVG as a possible geolocation when compared against the $^{87}Sr/^{86}Sr$ isoscape constructed by Laffoon et al. (2017) (Figure 2) based on SVG data reported in Laffoon et al. (2012). The individual's $^{87}Sr/^{86}Sr$ ratios are significantly higher (*t test*, $p < 0.05$) than the bioavailable $^{87}Sr/^{86}Sr$ ratios measured from eight plant and animal samples for SVG (average = 0.70659, range = 0.70566–0.70812; Laffoon et al. 2012), but fall within the higher end of the range of compiled bioavailable $^{87}Sr/^{86}Sr$ ratios measured from volcanic and intrusive islands in the Lesser Antilles (average = 0.70774, range = 0.70475–0.70920; Laffoon et al. 2012).

The bone $\delta^{18}O_{CARB}$ value, −4.67‰, equates to a $\delta^{18}O_{IW}$ estimate of −6.72‰ (Table 1), which according to the isoscape map provided by IsoForensics, Inc., identifies New York City as a possible geolocation during the individual's early adulthood period (Figure 3). The individual's bone $\delta^{13}C_{CARB}$ value, –12.01‰, calculates to 17% of C_4 resources in the whole diet (Table 1). Bone $\delta^{13}C_{COLL}$ and $\delta^{15}N_{COLL}$ values are –18.67‰ and 9.92‰, respectively, and plot nearest to modern residents of Australia-New Zealand, Asia, and Europe (Figure 4, compiled dataset of Lehn et al. 2015). The bone $\delta^{13}C_{CARB}$ and $\delta^{13}C_{COLL}$ values fall near the C_3 protein diet line (Figure 5, model of Kellner and Schoeninger 2007).

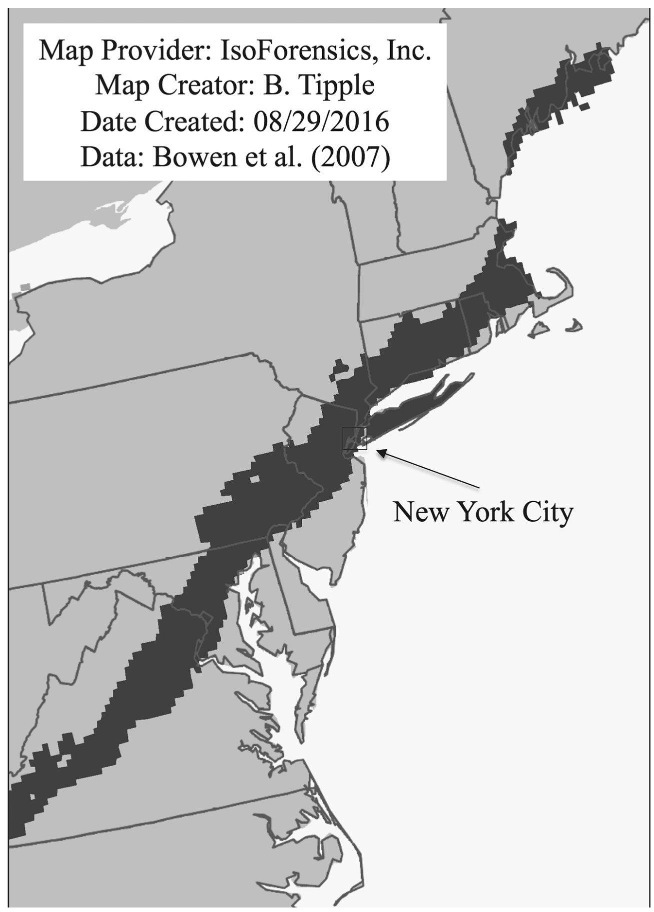

FIG. 3—*NYC-OCME individual's bone carbonate $\delta^{18}O_{IW}$-based geolocation estimation during early adulthood commissioned by IsoForensics, Inc.; area of known residence is boxed.*

5. Discussion

The reliability of isoscapes for matching unidentified human remains to place(s) of residence heavily depends on access

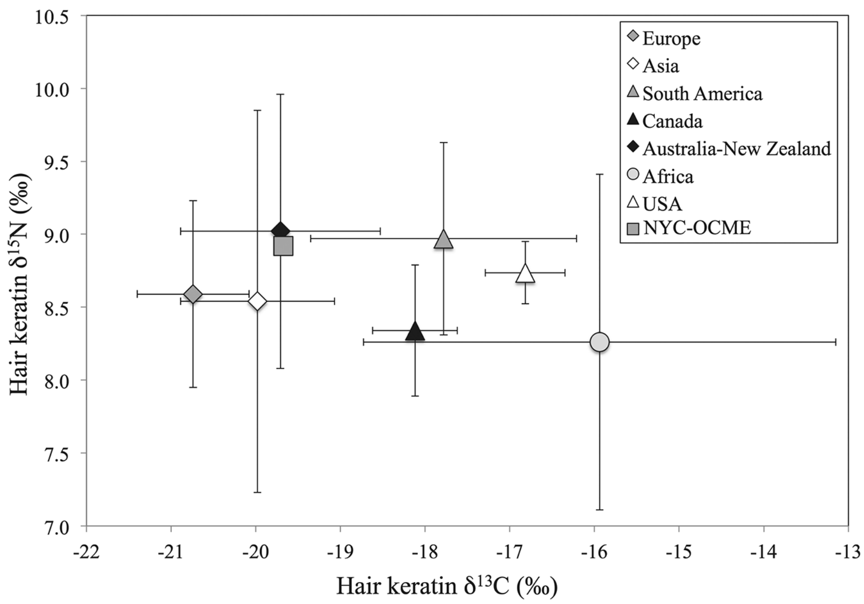

FIG. 4—*NYC-OCME individual's corrected bone collagen* $\delta^{13}C$ *and* $\delta^{15}N$ *bivariate plot compared to those of modern hair keratin* $\delta^{13}C$ *and* $\delta^{15}N$ *values patterned geographically (data from compilation of Lehn et al. 2015).*

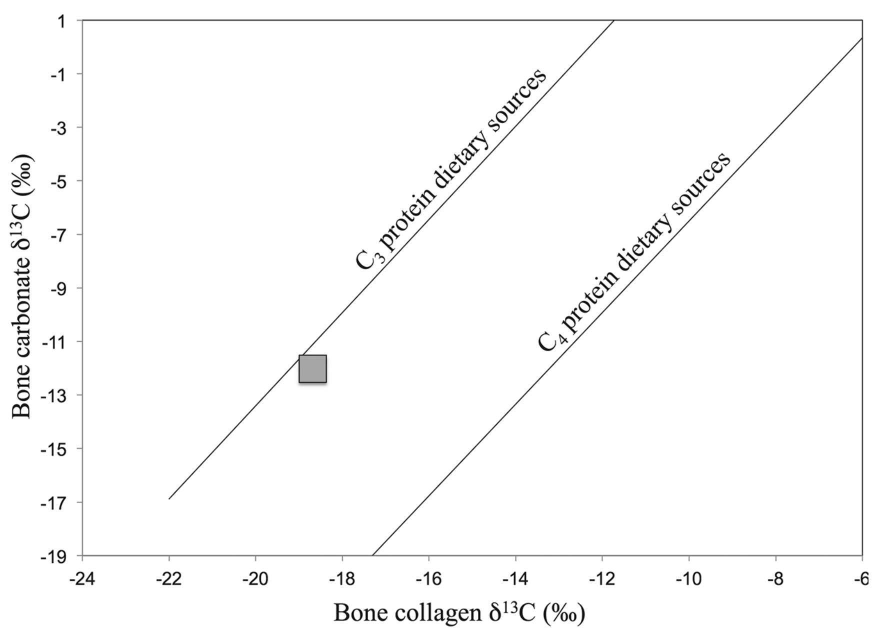

FIG. 5—*NYC-OCME individual's bone carbonate and collagen* $\delta^{13}C$ *plot within protein model of Kellner and Schoeninger (2007).*

to baseline samples relevant to food and water consumption. For example, the accurate geolocation estimate of the known immigrant's $\delta^{18}O_{IW}$ values presented in this study during early adulthood, and the lack of correspondence during childhood, reveals the contrast between the US tap-based $\delta^{18}O$ isoscape (Bowen et al. 2007; Ehleringer et al. 2008) and the global precipitation-based $\delta^{18}O$ isoscape (Waterisotopes.org; West et al. 2010). Our results emphasize the necessity of measuring $\delta^{18}O$ values of actual drinking water to construct isoscapes for forensic purposes (e.g., Ammer et al. 2020, Kramer et al. 2020). The known individual yielded a lower childhood $\delta^{18}O_{IW}$ value compared to precipitation $\delta^{18}O$ values on SVG, which may reflect the relatively lower $\delta^{18}O$ values of SVG tap water and/or other water treatment practices. Drinking water in the Lesser Antilles is primarily delivered by tap, but is also harvested via rain collection and other surface sources (St. Vincent National Report 2001). Variable evaporative conditions and temperature changes alter surface water δ^{18}O values (Craig 1961; Gat 1996) and thus may not necessarily match δ^{18}O values of imbibed tap water. Other factors, such as heating and boiling during cooking, which have an ^{18}O-depletion effect on water δ^{18}O values (e.g., Brettell et al. 2012; Gagnon et al. 2015), as well as the error propagation of the various conversion equations, may have contributed to the individual's lower than expected childhood $\delta^{18}O_{IW}$ value.

In the forensic isotopic study in the Caribbean by Laffoon et al. (2017), the authors assert that the Likelihood Approach (e.g., Veen et al. 2014) provides more accurate geolocation estimations than the Interval Approach (Ehleringer et al. 2008, 2010) utilized in the commissioned work by IsoForensics, Inc. reported here. The childhood $\delta^{18}O_{CARB}$ value of the individual measured here falls between the $\delta^{18}O_{CARB}$ values of two individuals measured by Laffoon et al. (2017), and both indicate SVG as one of several probable geolocations in the Caribbean. Overlapping $\delta^{18}O_{CARB}$ values of the individual during childhood and those from comparable human tissues from nearby St. Lucia (data from Laffoon et al. 2013) also suggests a Caribbean residence likely including SVG. Both approaches, the Likelihood Approach and a comparable tissue comparison, identify SVG as a potential geolocation and therefore appear more accurate than the Interval Approach with regional precipitation δ^{18}O data. However, these methods point to many Caribbean locations, and consequently are not highly specific tools in the Caribbean region for forensic purposes. Clearly additional samples of drinking water are needed across the Caribbean and Central/South America to increase the resolution and gauge the utility of the method suggested by test cases of Kramer et al. (2020).

Our study also suggests that bioavailable $^{87}Sr/^{86}Sr$ ratios incorporating food traditions are needed for constructing accurate isoscapes for forensic purposes in the Caribbean. Laffoon and others (2012) showed that sea spray substantially impacted terrestrial plant and animal $^{87}Sr/^{86}Sr$ ratios in the Lesser Antilles causing a shift away from volcanic and intrusive bedrock $^{87}Sr/^{86}Sr$ ratios (< 0.70600) and toward those of seawater (0.70922). Although Laffoon et al.'s (2017) $^{87}Sr/^{86}Sr$ isoscape of the Caribbean incorporates a large number of bioavailable samples and represents one of the best resolved isoscapes globally to date, the known resident presented here demonstrates that human diets are not adequately characterized with existing local plant and animal $^{87}Sr/^{86}Sr$ ratios. Three issues are identified below that may have contributed individually or in concert to produce offsets from current baseline $^{87}Sr/^{86}Sr$ data.

Residents of SVG consume substantial amounts of fish and shellfish (Adams 1980, 1992; FAO Report 2010); for example, the national dish of SVG is roasted breadfruit and fried jack fish. Marine foods, which have $^{87}Sr/^{86}Sr$ ratios of or near that of seawater (0.70922; Hodell et al. 2004), were not incorporated into the bioavailable $^{87}Sr/^{86}Sr$ dataset of plants, rodent, and snail samples reported by Laffoon et al. (2012). Additionally, the concentration of strontium in fish and shellfish is relatively high compared to terrestrial domestics (e.g., chicken, goat) and some vegetables (e.g., corn) (Balter 2004; Burton & Price 1999; Burton & Wright 1995) and thus may bias an individual's $^{87}Sr/^{86}Sr$ ratio toward that of seawater even if all foods are consumed in comparable amounts. That is, there is a concentration-dependent effect on $^{87}Sr/^{86}Sr$ ratios from dietary sources. SVG has had a reduction in local food production for a few decades and relies heavily on imported foods (Grossman 1993; Thomas-Hope 2017), potentially increasing the impact of the "supermarket effect." Thus, the individual may have achieved higher $^{87}Sr/^{86}Sr$ ratios than locally available with the ingestion of imported foods from areas with $^{87}Sr/^{86}Sr$ ratios > 0.70900, which are available in numerous locations around the Caribbean (Laffoon et al. 2012).

Our finding of comparable childhood and early adulthood $\delta^{13}C_{CARB}$ values suggests that the individual's food tradition practiced while on SVG was largely maintained after immigration to New York City. The individual's early adulthood $\delta^{13}C_{COLL}$ and $\delta^{13}C_{CARB}$ values indicate a protein diet dominated by C_3 resources (Figure 4; Table 1), which are not typical for corn-based and high-sugar diets in the US (Valenzuela et al. 2011). Moreover, the individual's whole diet %C_4 consumption decreased slightly from childhood to early adulthood, which is in the opposite of what we predicted by the immigration event to the US. This case study illustrates that some Caribbean food traditions utilize significantly higher amounts of C_3 vegetables and proteins than neighboring regions with a considerable reliance on corn (e.g., Yucatan Peninsula; Laffoon et al. 2013).

As previously emphasized, numerous combinations of $^{87}Sr/^{86}Sr$ and δ^{18}O values are found globally and span the US border (Ammer et al. 2020; Kramer et al. 2020), and dietary isotopes from unidentified individuals are used to gauge general food inputs and point investigations to plausible regions of focus (e.g., Bartelink & Chesson 2019; Meier-Augenstein, 2010). Our initial blind test of the individual's childhood geolocation based solely on the multi-isotopic data erroneously placed the individual in an Asian/European low-latitude, coastal location. Specifically, the individual's enamel $\delta^{18}O_{CARB}$ values are typical of low-latitude regions across the globe (e.g., Waterisotopes.org). The individual's enamel $^{87}Sr/^{86}Sr$ values overlap those of recent marine limestone bedrocks and/or marine foods aligned with modern seawater (~0.708–0.709; Hodell et al. 2004). The individual's reconstructed childhood whole diet composed of primarily C_3 resources is consistent with European and Asian diets rather than those found in the Americas and Africa, which are more reliant on C_4 foods (Chesson et al. 2010; Lehn et al. 2015; Valenzuela et al. 2011). This case study demonstrates the need for increasing resolution of current isoscapes with bioavailable sources, the importance of considering geographic variations in food traditions within regions, and the potential for maintaining food traditions with migration events especially in multi-cultural metropolitan areas of the US such as New York City.

6. Conclusion

Forensic isotopic analysis holds promise for aiding in the investigation of unidentified human remains in a forensic context; however, accurate isoscape construction is critical to the methodological resolution. The individual presented here with a known residential history demonstrates that culturally influenced bioavailable food and water sources are not accurately mapped with non-food items and precipitation of the childhood residence of SVG. The accurate residency estimate of New York City during early adulthood attests to the importance of tap-based δ^{18}O isoscapes rather than those based on precipitation δ^{18}O values. The maintenance of food traditions may mask immigration events, especially in large metropolitan areas, like New York City, where a variety of food items are accessible and hundreds of cultural communities maintain food traditions that may not be similar to current dietary isoscapes of the US. Additional research of culturally distinct dietary and drinking practices must be incorporated into tissue-specific isoscape construction and isotope-based interpretations of geolocation of unidentified individuals in order to increase methodological utility and accuracy of forensic isotopes.

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