Isotopic Taphonomy of Human Remains

2014-DN-BX-K002

PI: Dr. Gwyneth W. Gordon, PhD (School of Earth and Space Exploration, Arizona State University)

Co-Investigators: Tiffany Saul (University of Tennessee, Knoxville)

Dr. Dawnie Steadman, PhD (University of Tennessee, Knoxville)

Dr. Kelly Knudson, PhD (School of Human Evolution and Social Change, Arizona State University)

Dr. Ariel D. Anbar, PhD (School of Earth and Space Exploration and School of Molecular Sciences, Arizona State University)

with the assistance of Dr. Daniel Wescott, PhD (Texas State University, San Marcos)

ABSTRACT

The primary purpose of this research was: 1) to analyze hair, bone, and teeth samples of recently deceased human donors and compare to samples after environmental exposure during decomposition and 2) to validate the geolocation and dietary predictions of isotopes with the known origins, travel and lifestyle of individuals. The goal was to determine if taphonomic processes altered pre-mortem signatures, and if both pre-mortem and post-mortem isotope signatures gave accurate inferences about where the individuals were from. Within the limitations of the sample size, limited environments, and exposure time studied, teeth, bone and hair $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ inferences about region of origin and diet are similar between post-mortem and pre-mortem measurements; $\delta^{2}H$ measurements have more variability but generally preserve original values. Elemental concentrations, Sr, and Pb isotopes are preserved through decomposition in teeth and bone. However, elemental concentrations, Sr, and Pb isotopes are *not* well preserved in hair, despite best practices in cleaning and sample preparation. Improvements in leaching and sample preparation are unlikely to recover endogenous values. Rare earth elements may be developed as a useful postmortem modification indicator for hair. While endogenous values may be preserved in some cases and environments, it will be difficult to have confidence in the region of origin interpretation for bodies that have been exposed to the elements for more than a few days.

Despite concerns developed here about the accuracy and interpretation of Sr and Pb isotopes in hair, teeth and bone are robust indicators for geolocation prediction of unknown individuals. This study strongly supports the continued implementation of isotopic signature implementation in forensic case work on a broader and more consistent basis. Costs for this type of analysis are quite modest compared to the total cost of investigation, and additional federal funding earmarked for such work has the potential to provide many scientifically solid leads for identification.

TABLE OF CONTENTS

Tables.

Figures.

1 EXECUTIVE SUMMARY

1.1 Problem As of 2017, there are 11,479 open cases of unidentified human remains in the United States.[1] Although DNA, fingerprints, and forensic anthropological profiles are available in many of these cases, the identity of these individuals remain unknown. Additional investigational leads are required in order to solve these cases, provide closure to their families and loved ones, and bring perpetrators to justice. One such lead is to find out where the individual lived, and what type of life he or she led. Isotopic analysis holds the promise of revealing just such information and has led to identifications in important forensic cases.

However, life history through isotopic analysis emerged out of the fields of anthropology and geology, and has been primarily validated in only two contexts: ancient peoples and currently living individuals. In the former, there is frequently no good way to authenticate the isotopic interpretations. In the latter, samples are typically pristine and free from environmental exposure, so measurements directly reflect those in the living individual. Forensic cases occur in the gap between these two areas of inquiry – recent deaths, but exposed to decomposition. Our research addresses this knowledge gap by analyzing hair, bone, and teeth samples from known individuals as they decompose naturally over a year of environmental exposure to evaluate if pre-mortem isotope signatures are preserved through decomposition, and if the isotopic interpretations of geolocation and diet are accurate.

1.2 Purpose of Research The primary purpose of this research was: 1) to analyze hair, bone, and teeth samples of recently deceased human donors and compare to samples after environmental exposure during decomposition and 2) to validate the geolocation and dietary

[1] https://www.identifyus.org/en, NamUs website information, downloaded on July 19, 2017.

predictions of isotopes with the known origins, travel and lifestyle of individuals. The goal was to determine if taphonomic processes altered pre-mortem signatures, and if both pre-mortem and post-mortem isotope signatures gave accurate inferences about where the individuals were from.

1.3 Research Design We evaluated human cadavers at two geologically and climatologically disparate locations (six at Anthropological Research Facility (ARF), University of Tennessee, and five at Forensic Anthropological Research Facility (FARF), Texas State, San Marcos), and in both surface (n=7) and shallow burial (n=4) placements. Bone, teeth, and hair samples, as different tissues record different time periods in a person's life and experience different degrees of taphonomic change as the tissues vary substantially in structure and composition. We analyzed cadaver samples over a year of exposure, with hair sampled most frequently and at high resolution during early taphonomy (Accumulated Degree Hours, ADH <2000).

To evaluate parameters controlling any observed isotopic or elemental deviations from pre-mortem values, we analyzed environmental samples (soil, soil bioavailable leaches, precipitation, groundwater). We also determined multi-element concentrations for most samples in order to begin to understand the fluxes of elements from the bodies to the soil, and vice versa.

We measured $\delta^{13}C$ and $\delta^{18}O$ in carbonate, elemental concentrations, strontium, and lead isotope compositions in tooth enamel and bone during intake and after about a year of environmental exposure. In order to evaluate the impact of potential complicating factors, we conducted five studies on hair:

1. a laboratory comparison validation from an isotope consumer perspective *to judge the accuracy and precision of isotopic data from external laboratories and to calibrate two in-house hair standards*;

2. an evaluation of the preservation of hair $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ isotopes during freezing following law enforcement (L.E.) protocols and materials *to evaluate the impact of evidence storage on samples*;
3. a comparison of intake and recovery samples of $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ isotopes from hair mats at FARF (Texas) *to measure any isotopic offsets for a larger number of samples at more advanced stages of decomposition and environmental exposure*;
4. a time series analysis of $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$, $\delta^{88}Sr$, Pb isotopes, and elemental concentrations in cleaned bulk digested hair, as well as both the solid residual digests and the leachate solutions of hair following the procedure of Tipple et al (2013) *to examine systematics of isotope variation in hair over time*; and
5. a pilot aqueous exposure experiment of hair soaked in deionized water and seawater spiked with lead *to measure isotopic offsets and exchange with a known aqueous endmember*.

1.4 Results

1.4.1 Teeth The skeletal collections at ARF and FARF – the eventual destination of our donors – are irreplaceable, so we minimized destructive skeletal and dental analyses. Ideally, we would have measured right and left molars at intake and recovery, but donors were frequently missing dental elements, molars in particular. We sampled predominantly incisors and canines, as these were the most common dental elements, and their removal was less likely to damage the underlying jaw bone.

Because we were typically unable to sample identical dental elements at intake and recovery, we were unable to minimize intra-individual variation. There can be significant differences in $\delta^{13}C$, $\delta^{18}O$, strontium isotopes, and lead isotopes if an individual has changed diet or locale or during the developmental process (Moorrees et al 1963; Scott and Turner, 2000; Ubeleker 1987). Given these limitations, however, we see no indication that there is systematic variation in $\Delta^{13}C_{VPDB}$ in carbonate in tooth enamel between intake and recovery; the median difference is -0.24‰, while the range in offset is from ±0.69‰ to -2.75‰. The $\Delta^{18}O_{VPDB}$ in tooth enamel carbonate has a systematic bias, with a median difference of -1.32‰. While this could indicate a taphonomic change, we suspect it more likely indicates a systematic difference in tooth elements sampled; the intake samples were more likely to be canine or incisors, while the recovery samples were more likely to be premolars or molars. There were no systematic differences for the strontium or lead isotopes between intake and recovery teeth. The Ca/P ratio for all samples was very close to the ideal ratio for hydroxyapatite, and uranium and rare earth element concentrations showed no evidence for hydrologic alteration. $^{87}Sr/^{86}Sr$, $\delta^{88}Sr$ and Pb isotopes showed some variability, but the variation between individuals was much larger than that between intake and recovery samples.

1.4.2 Bone To minimize destructive analyses, we utilized a new technique for collecting small bone cores, and sampled the sixth ribs; this rib is not used in forensic anthropology for creating biological profiles. A ¼" diamond-tipped hole drill bit was used to drill a core from the center of the rib. However, in many cases this produced very little cortical bone. Our initial plan was to analyze $\delta^{13}C$ and $\delta^{18}O$ in the carbonate fraction, $\delta^{13}C$ and $\delta^{15}N$ in the collagen fraction, and elemental concentrations, strontium and lead isotopes in the mineral fraction. Our standard sample preparation procedures required more initial material than our sampling provided in most

cases. We are optimizing our protocols for sample sizes, including validating using the discarded solution from collagen preparation for strontium isotope analysis. Study is continuing on this aspect of the project. Initial evidence is inconclusive due to limited samples, but does not appear to indicate significant taphonomic effects on this time scale.

1.4.3 Hair To estimate the impact of potentially complicating parameters on our analyses, we completed five sub-projects on the topic of isotopic preservation of hair: a laboratory validation study, a freezing study, a hair mat study, a time series study, and a preliminary aqueous exposure study. We will address each set of results in sequence.

A good estimate of the accuracy and any systematic bias, as well as the precision, of the isotopic measurements is essential to determine the investigative weight to give geolocation predictions. Previous studies have had difficulties because of systematic differences between laboratory measurements (Herrmann, Li, & Warner, 2015). We compared isotopic measurements for $\delta^{13}C$, $\delta^{15}N$ (n=4 laboratories), $\delta^{18}O$ (n=2 labs), $\delta^{2}H$ (n=3 labs), and $\delta^{34}S$ (n=3 labs). We submitted USGS 42 (Hydrogen and Oxygen isotopes in Tibetan Human Hair, n=1) and USGS 43 (Hydrogen and Oxygen isotopes in Indian Human Hair, n=1) and two in-house U.S. human hair standards (n=3, each) as unknowns. This was *not* designed as a full inter-laboratory calibration study, but simply as validation for a consumer of isotopic measurements. Laboratories were not notified prior to sample submission as we initially anticipated that results would be comparable between labs. All samples passed internal QA/QC at the reporting laboratories.

$\delta^{13}C$, $\delta^{15}N$ values were accurate for USGS 42 and 43, and precise for the two in-house hair standards (H Std 1, 2) at all four labs. $\delta^{34}S$ values were within 2σ of the certified values of USGS 42 and 43 of two of the laboratories, and just outside it for the third laboratory, although all three laboratories reported values systematically enriched in ^{34}S by amounts varying from

0.16 to 0.76‰. H Std-1 and -2 δ^{34}Sr values were reasonably precise (median $\sigma = 0.29$) for all three laboratories. It is important to note that the dietary interpretations of these measurements are consistent between all the laboratories. For δ^{18}O, one laboratory was within 2 σ (~0.2‰) of the certified value, while the other was systematically biased 1.39‰ and 1.56‰ enriched in ^{18}O. Both labs gave reasonably precise values for H Std 1 and 2. While larger than ideal, this is within the local range of intake values for the Tennessee donors. However, the originally reported $\delta^{2}H_{VSMOW\text{-}SLAP}$ values had a range of 37.8‰ (USGS 42) and 24.9‰ (USGS 43), and would cause substantial inaccuracies in the prediction of recent region of origin – an Arizona resident was predicted to be from a small region in central Texas using the Ehleringer et al. (2008) model for region of origin estimation. As discussed in detail in the technical report, this discrepancy is related to issues with normalization, an area often ignored by isotope data consumers; but which has the potential to fundamentally misdirect a forensic investigation.

Because several of our donors were frozen prior to placement, and some samples had to be frozen for preservation, we needed to evaluate the impact of freezing on stable isotope preservation of hair. We selected 20 hair samples designed to simulate the range of possible forensic samples, including exemplars from multiple ancestries, cosmetic treatments (dyes, relaxers), and condition (salon, hair from decomposed remains). Each had five storage conditions: a) control and frozen at -20°C for b) two weeks in a plastic clamshell c) two weeks in butcher paper d) six months in a plastic clamshell and e) six months in butcher paper. Storage materials were obtained with the cooperation of the Mesa Police Department, and packaged in accordance with Mesa Police Department evidence packaging policy and guidelines. In addition, 10 paired samples (room temperature in a coin envelope and frozen) from intake hair samples at

the ARF at the University of Tennessee were also analyzed, where samples had been stored for up to 4.1 years.

No significant differences from control materials were found for $\delta^{13}C$, $\delta^{15}N$, or $\delta^{18}O$ in either the experimentally stored samples or the samples stored at ARF. In the $\delta^{2}H$ values, there was a small but systematic bias toward enrichment in ^{2}H, accompanied by a small loss in hydrogen content consistent with evaporation during freezing that was not compensated for during sample processing prior to measurement. In all cases, the forensic interpretation of the samples is the same, irrespective of these storage conditions.

In order to increase the number and diversity of donors and the length of exposure time in our study, we collected 10 hair mats associated with known donors in surface placements at FARF in Texas and compared the $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ values to intake samples from the same individuals. Although there was some variation, there were no systematic differences in hair samples exposed for up to 312 days.

Sequential time series sampling was the main analysis used for the hair portion of this study. In addition to $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $\delta^{2}H$ measurements, we analyzed elemental concentrations, and Sr and Pb isotopic compositions. As in the studies discussed above, we observed no systematic differences for $\delta^{13}C$ in hair over a year of decomposition. For $\delta^{15}N$, there was a general increase over time of up to 1‰; this is smaller than the trophic level division, but substantially larger than the analytical error. While this would not introduce any interpretational differences of diet or trophic level, it could potentially continue increasing. Additional research will be needed to clarify the controlling parameters and the potential extent of change.

For $\delta^{18}O$ measurements, there was a spread of values over time from +2 to -1.5‰, larger than the external reproducibility of samples, with a slight bias toward isotopically heavier values. For $\delta^{2}H$, there was a spread of values over time from about +8 to -8‰, again larger than the external reproducibility of samples. These variations may be related to inherent heterogeneity of hair; no attempt to homogenize material was made during sample collection, so if individuals traveled prior to death, they may have had some heterogeneity in $\delta^{18}O$. Travel would not introduce a similar variability in $\delta^{13}C$ or $\delta^{15}N$ if the traveler maintained a consistent diet to the diet when not traveling. These variations introduce some inaccuracy (scale of 50-400 miles) in forensic geolocation interpretation, but are still accurate for the general region.

In order to accommodate the best practices of hair analysis, we expanded our study to include not only bulk hair, but also the Tipple, Chau, Chesson, Fernandez, and Ehleringer (2013) leaching process, including both solid digested residual hair as well as the leachate solution; the solid digested residual is proposed as the most likely to represent endogenous strontium. Although initial metal concentrations varied among the individuals, all three components – bulk, leachate solution ("leachate"), and solid residual digests ("residue") – were typically enriched in Al, Ti, Cr, Mn, Fe, Co, Ni, As, Cd, Ba, REE, Pb, and U with increasing exposure time. The bulk and leachate components were enriched in V and Pd, while bulk and residual digests were enriched in Mo and Re. We propose that REE and U may be good indicators of soil exposure of hair samples.

Shower water is suggested to add strontium and exogenous elements to hair (Tipple, 2016). In order to evaluate the magnitude of these exogenous additions, we measured elemental concentrations, strontium and lead isotopes in sequential samples along an oriented length of hair from one of the donors who was exposed outdoors for two days. The strontium and lead isotopic

results were of particular concern, as these have been proposed to provide an independent line of evidence for geolocation. Unfortunately, this study demonstrated that strontium exchanges with the bioavailable metals pool in the soil, and the variation in bulk, leachate solution and solid residual are unable to recover the intake values within a few days of exposure. The residual solid digest was often more radiogenic than that of the bulk or leachate, but was typically a less accurate representation of the intake value for residual fraction, compared to the bulk and leachate solution. The variation in strontium isotope composition in the residual fraction for a single donor over one year was frequently larger than the entire estimated range of strontium for the United States. Additional leaching seems unlikely to improve upon this technique, as the residual digest at later time points frequently had similar strontium concentrations to the intake residual digests. Similarly, lead isotopes in residual digests, bulk digests and leachate solutions also appear to rapidly equilibrate with environmental sources.

In order to evaluate the change with known endmembers, we soaked hair in two different solutions, deionized water and IAPSO seawater spiked to 24 ppb lead. After three days of exposure, the hair samples were drained, cleaned, and processed as if they were forensic samples. The $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ results were comparable between the two solutions, although the solutions were very different in elemental and isotopic composition. This strongly suggests these signatures are robust over this time period, although additional studies over longer time periods, in more realistic forensic solutions including bacteria, and in a wider range of pH and Eh conditions are needed.

However, the strontium and lead isotopes equilibrated with the local solutions, even for the residual digested portion of hair after leaching. The strontium concentration of the residual hair in the seawater experiment was similar to that in the deionized water experiment,

suggesting that the leaching process was highly efficient at removing excess strontium. The $^{87}Sr/^{86}Sr$ isotope composition (0.70925) was very similar to seawater (0.70920), and very different the sample in deionized water (0.71390). The residual digest was less effective at removing the lead associated with the seawater exposure, and the lead isotope composition was again very similar to the seawater value, and dissimilar to the deionized water value.

Unfortunately, we must recommend Sr and Pb isotopes in hair not be utilized in geolocation predictions, unless the individual is recovered immediately after death. While it is certainly the case that the Sr and Pb isotopic compositions may be preserved for some individuals, we can have no confidence that these values have not been reset. Additional work may evaluate under what conditions these isotope signatures are reliable. However, poor preservation of these systems in hair should *not* be taken as an indication that isotopic signatures are poorly preserved in all tissues; bone and teeth appear quite robust over the observed time scale.

1.5 Conclusion: Implications for Policy and Practice Within the limitations of the sample size, limited environments, and exposure time studied, teeth, bone and hair $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ inferences about region of origin and diet are similar between post-mortem and pre-mortem measurements; $\delta^{2}H$ measurements have more variability but generally preserve original values. Elemental concentrations, Sr, and Pb isotopes are preserved through decomposition in teeth and bone. However, elemental concentrations, Sr, and Pb isotopes are *not* well preserved in hair, despite best practices in cleaning and sample preparation. Improvements in leaching and sample preparation are unlikely to recover endogenous values. Rare earth elements may be developed as a useful postmortem modification indicator for hair. While endogenous values may be preserved in some cases and environments, it will be difficult to have confidence in the region

of origin interpretation for bodies that have been exposed to the elements for more than a few days.

We strongly recommend that any laboratories doing isotopic analyses of unknown modern human remains be involved with regular blind testing of a variety of matrix-matched standards, and that reporting the results of recent testing and details of QA/QC should be required prior to publication. Membership in accrediting bodies such as FIRMS[2] should be strongly encouraged to have an external validation of laboratory protocols. Continuing development and frequent use of additional certified matrix-matched standards for measurement validation such as USGS 42 and 43 for hair is critical for elucidation of matrix-specific issues. Additional studies of the isotopic variability both within individuals of a local population, as well as intra-individual skeletal and dental elements of known individuals is clearly needed to place accurate error estimates on geolocation and dietary inferences.

Despite concerns developed here about the accuracy and interpretation of Sr and Pb isotopes in hair, teeth and bone are robust indicators for geolocation prediction of unknown individuals. This study strongly supports the continued implementation of isotopic signature implementation in forensic case work on a broader and more consistent basis. Costs for this type of analysis are quite modest compared to the total cost of investigation, and additional federal funding earmarked for such work has the potential to provide many scientifically solid leads for identification.

[2] Forensic Isotope Ratio Mass Spectrometry Network (http://www.forensic-isotopes.org/)

2 INTRODUCTION

2.1 Statement of the Problem

As of 2017, there are 11,479 open cases of unidentified human remains in the United States.[3] Although DNA, fingerprints, and forensic anthropological profiles are available in many of these cases, these individuals continue to remain unknown. Additional investigational leads are required in order to solve these cases, provide closure to their families and loved ones, and bring perpetrators to justice. One such lead is to find out where the individual lived, and what type of life he or she led. Isotopic analysis holds the promise of revealing just such information and has led to identifications in important forensic cases.

However, life history through isotopic analysis emerged out of the fields of anthropology and geology, and has been primarily studied in two specific contexts: ancient peoples and currently living individuals. In the former, it is typically not possible to validate the isotopic interpretations. In the latter, samples are typically pristine and free from environmental exposure or decomposition, so the measurements directly reflect the isotope signatures in the living individual. Forensic identification cases occur in the gap between these two areas of research – deaths of modern individuals, but frequently exposed to the outdoor environment and subject to decay processes. Our research addresses this knowledge gap by analyzing hair, bone, and teeth samples from known deceased human individuals as they decompose naturally over a year of environmental exposure.

In addition, while there has been some research in validating the accuracy of isotopic predictions of known individuals (Herrmann, Li, & Soto, 2010; IsoForensics, Inc., 2016), additional work has been needed to evaluate the relative robustness and accuracy of multiple isotope systems (C, N, O, H, Sr, Pb) in multiple tissues. In particular, if some isotope systems are poor predictors of geographic residence, a forensic investigation could be focused in a wrong direction. Interpretations of data always have an associated error rate; while determining a general error rate for isotopic analysis is outside the scope of the current research, the current study provides important guidance for future research to approach such error rates.

The project was designed to answer two specific questions:

[3] https://www.identifyus.org/en, NamUs website information, downloaded on July 19, 2017.

GOAL 1) Are pre-mortem isotopic compositions in different tissues retained during decomposition?

GOAL 2) How reliable are the correlations between isotope ratios of remains and geography that underlie the use of isoscapes?

The project monitored the isotopic and elemental composition of different tissues over prolonged periods of time at two facilities (Anthropological Research Facility at the University of Tennessee and Forensic Anthropological Research Facility at Texas State University) in human bodies with surficial emplacement and shallow burial. Both male and female donors were studied. Although every effort was made to obtain as much diversity of ancestry as possible, the constraints of donor demographics for the two institutions dictated that all analyzed donors were Caucasian. The age range of the donors was 38 to 97, with an average age of 63.9 ±18.8 (1σ, n=11). There were six men and five women enrolled in the study.

Multiple tissue types (hair, bone, and tooth enamel) were collected during the processes of natural decay, and compared to environmental samples (groundwater, precipitation, and soil). The types of tissues analyzed have a) a strong background in anthropological and ecosystem research, b) are likely to be preserved in forensic contexts longer than soft tissue such as muscle or blood, and c) can contain information about both birthplace and travel history. These samples allowed us to compare the measured isotope values to existing models of geographic origin (*e.g.,* Ehleringer et al., 2008).

Sex is included as a variable because females tend to be smaller in mass than those of males; differential surface area-to-volume ratios are well known to affect rates of modification. In addition, post-menopausal females tend to have more osteoporotic bones that may show increased rates of diagenetic alteration due to increased porosity.

The number of donors at the two sites was limited, and this significantly constrains how broad the conclusions concerning the agreement of the measured values with isoscape models can be. However, because analysis of donor cadavers most closely resembles forensic cases, even the limited insights that can be gained from n=11 are useful. In addition, combining these detailed studies with broader surveys (Herrmann et al., 2015; IsoForensics, Inc., 2016; Regan, 2006) can bridge the intra-individual scale to the intra-population scale.

3 LITERATURE CITATIONS AND REVIEW

3.1 Isotopic analysis This study utilized multiple isotope systems as well as trace elements to maximize the information obtained from samples of human remains. The isotope systems studied can broadly be divided into two groups: mass-dependent stable isotopes ($\delta^{18}O$, δD, $\delta^{13}C$, $\delta^{15}N$, and $\delta^{88}Sr$) and radiogenic isotopes ($^{87}Sr/^{86}Sr$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{206}Pb$). The mass-dependent stable isotope variations are caused by mass-dependent differences in reaction rates and equilibrium constants, which result in changes in the isotope ratios between product and reactant, or products when reactions do not go to completion. The radiogenic isotope variations are caused by radioactive decay of one element to another.

One critical factor is that multiple isotope systems can provide *independent* sources of information:

Isotope system	Primary controlling variable(s)
$\delta^{18}O$, δD	Hydrologic cycle
$\delta^{13}C$	Ratio of C_3/C_4 plants in diet
$\delta^{15}N$	Amount and type of protein in diet
$^{87}Sr/^{86}Sr$	Underlying lithology
$\delta^{88/86}Sr$	Trophic level, diagenesis indicator
Pb isotopes	Lithology, anthropogenic pollution

Table 1. Isotope systems examined in this study, with the primary parameters controlling variability.

The causes of variation of these isotope systems are quite different, and using them in concert is far more powerful than a single system alone. However, just as the causes of the isotope variations differ, the preservation fidelity of one isotopic system will not be controlled by the same parameters as another isotope system. Hence, careful sampling design and strategic analyses are critical to achieve our scientific objectives. A very brief discussion of the causes of variation for each isotope system follows, along with the most relevant scientific literature for application to forensic identification of human remains.

3.1.1. Oxygen (O) and hydrogen (H) isotopes Oxygen ($\delta^{18}O$) and hydrogen (δD) isotope variations in biological materials are controlled by the hydrologic cycle and biochemical

processes. The isotopic composition of precipitation is controlled by latitude and elevation. Water vapor is always isotopically lighter than co-existing liquid water due to an isotopic fractionation during the phase transition. Globally, evaporation occurs the most at the Earth's equator, and at higher latitudes – or elevations – precipitation is isotopically heavier than cloud water vapor. Hence, $\delta^{18}O$ and δD vary with increasing distance from bodies of water, at higher latitudes and at higher elevations (Bowen & Wilkinson, 2002; Craig, 1961; Dansgaard, 1964; Gat, 1996).

Organisms also significantly fractionate body water, and a great deal of research has gone into understanding and predicting these variations (Bowen et al., 2007; Ehleringer et al., 2008; Epstein & Zeiri, 1988; Lane & Dole, 1956; Levinson, Luz, & Kolodny, 1987; Longinelli, 1984; Luz, Kolodny, & Horowitz, 1984; Luz & Kolodny, 1985; Podlesak, Bowen, O'Grady, Cerling, & Ehleringer, 2012). Additional water is contributed by food, and accurate isotope models of organismal water are complicated by metabolic reactions (Ehleringer et al., 2008; Podlesak et al., 2008). As a result, the $\delta^{18}O$ and δD values of people will differ substantially from local tap water or groundwater.

For example, the $\delta^{18}O$ of precipitation at ARF estimated from the Online Isotopes in Precipitation Calculator (OIPC; waterisotopes.org) is -5.8 ±0.0‰ (V-SMOW, 95% C.I.) and the δD is -34 ±0‰ (V-SMOW, 95% C.I.) (Bowen, 2017; Bowen & Revenaugh 2003). In contrast, the $\delta^{18}O$ and δD of hair for people living in eastern Tennessee is estimated to be between +12.1 to +13‰ and -89 to -94‰, respectively (Ehleringer et al., 2008).

The $\delta^{18}O$ of precipitation at FARF estimated from the Online Isotopes in Precipitation Calculator (OIPC; waterisotopes.org) is -3.9 ±0.1‰ (V-SMOW, 95% C.I.) and the δD is -22 ±1‰ (V-SMOW, 95% C.I.) (Bowen and Revenaugh 2003; Bowen 2017). In contrast, the $\delta^{18}O$ and δD of hair for people living around San Marcos, TX is estimated to be between +14.1 to +15‰ and -80 to -84‰, respectively (Ehleringer et al 2008).

In addition, there may be significant variation due to anthropogenic control of water resource utilization and distribution. Different municipal water sources including runoff, groundwater, and imported water will have different isotopic compositions, which can cause isotopic variation in local populations (Ehleringer, Barnette, Jameel, Tipple, & Bowen, 2016; Good et al., 2014; Jameel et al., 2016; Tipple, 2016).

δ^2H may not be preserved with the same fidelity as $\delta^{18}O$ so it is important to analyze both isotope systems, even though $\delta^{18}O$ and δD are typically related by the meteoric water line (Chenery, Pashley, Lamb, Sloane, & Evans, 2012; Longinelli, 1984; Luz et al., 1984; Luz & Kolodny, 1985; Pollard, Pellegrini, & Lee-Thorp, 2011). This is related to the single, weaker bonding of hydrogen in biological materials including the keratin protein compared to that of oxygen. As well as food and water, another oxygen source to human tissue is atmospheric oxygen (O_2), which does not contribute hydrogen. Finally, the amount of *de novo* proteins synthesized for keratin can change, depending on the amount of dietary protein; such changes will subtly decouple the hydrogen and oxygen isotope cycles in hair (Ehleringer et al., 2008).

3.1.2 Carbon (C) and nitrogen (N) isotopes The variations in carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes in humans are related to diet. The C_3 and C_4 photosynthetic pathways isotopically fractionate CO_2 from the atmosphere by different amounts (Calvin, 1962; Hatch & Slack, 1966; Hatch, Slack, & Jackson, 1967; Kortshack, Hartt, & Burr, 1965). In brief, C_4 grasses (which produce a four-carbon compound in the first photosynthetic step) adapted to arid climates such as corn do not fractionate atmospheric CO_2 as much as other common C_3 (which produce a three-carbon compound in the first photosynthetic step) plants in the human diet, such as fruits, vegetables, and sugar beets (Jahren et al., 2006; among many others).

People from the Americas consume significantly more corn in their diet, both directly and through fattening of industrially-farmed animals in corn feed lots (Jahren & Kraft, 2008). Hence, North Americans and Europeans differ significantly in their $\delta^{13}C$ values (Bol & Pfleiger, 2002; Kraft, Jahren, & Saudek, 2008; Nash et al., 2013; O'Connell, Kneale, Tasevska, & Kuhnle, 2012; Valenzuela, Chesson, Bowen, Cerling, & Ehleringer, 2012). Valenzuela et al. (2012) presents a large database on hair in the United States and Western Europe, and there are systematic differences between the two regions. In the United States, $\delta^{13}C$ values average -17.2 ±0.8‰ (1σ, n=234), while western Europe $\delta^{13}C$ values average -20.3 ±0.8‰ (1σ, n=126). However, $\delta^{13}C$ and $\delta^{15}N$ cannot be uniquely related to geographic origin within the central United States (Valenzuela, Chesson, O'Grady, Cerling, & Ehleringer, 2011). Valenzuela et al., (2011) suggest that there may be regional differences if databases were expanded to the northeastern United States. Kraft et al. (2008) analyzed blood from individuals from the Boston area, and found serum had a value of -19.1 ±0.8‰ (1σ, n=406) and clot had a value of -19.3

±0.8‰ (1σ, n=406). Using the correlation of $\delta^{13}C$ in red blood cells and hair from the same individuals studied in Nash et al. (2009) suggest the Boston area residents should have hair values of ~-17.0‰, very similar to (and well within 1 σ) the hair values found in Valenzuela et al. (2012) and Valenzuela et al. (2011). However, differences are likely to appear if socioeconomic status is included (Bender et al., 2015).

$\delta^{15}N$ values increase as an organism moves up trophic level, factors that have caused it to be widely used in ecosystem research and anthropology (Loudon, Sponheimer, Sauther, & Cuozzo, 2007; White, Nelson, Longstaffe, Grupe, & Jung, 2009). Both $\delta^{13}C$ and $\delta^{15}N$ are related to the amount and type of protein ingested (McMahon, Fogel, Elsdon, & Thorrold, 2010; Petzke, Boeing, & Metges, 2005), with both isotope values positively correlated with an increase in trophic level (Nash et al., 2012). Nitrogen isotopes are also known to vary significantly, particularly in periods of nutritional stress, deprivation (Fuller et al., 2005; Mekota, Grupe, Ufer, & Cuntz, 2006; Petzke, Fuller, & Metges, 2010), and pregnancy (Fuller et al., 2004).

$\delta^{15}N$ values for fish and shellfish, however, are high relative to terrestrial sources of protein, and variable (Huelsemann, Koehler, Braun, Schaenzer, & Flenker, 2013, Nash et al., 2012). Because of the high $\delta^{15}N$ values for marine foods, we might expect to find an increase in $\delta^{15}N$ for those with easy access to fresh fish, which are less expensive than in more remote regions.

Valenzuela et al., (2011) found no systematic variation of $\delta^{15}N$ in the central United States (8.8 ±0.4‰, 1σ, n=206). $\delta^{15}N$ of U.S. residents (8.9 ±0.4‰, 1s, n=234) are similar to the $\delta^{15}N$ of western European residents (9.2 ±0.5‰, 1σ, n=129), with significant overlap in the ranges. The $\delta^{15}N$ range for patients at Johns Hopkins University, in Baltimore, Maryland, was 8.9 ±0.4‰ (1σ, n=206), after conversion of red blood cell $\delta^{15}N$ to hair $\delta^{15}N$ using the correlation in Nash et al. (2009).

This suggests that $\delta^{15}N$ values are not as indicative of geographic region as $\delta^{13}C$ values, although additional research may well demonstrate that $\delta^{15}N$ is useful in distinguishing socioeconomic status or food preferences as there is significant range within the United States (3.2‰ in Valenzuela et al., 2011).

3.1.3 Strontium (Sr) isotopes Radiogenic strontium isotopes vary because ^{87}Rb decays at a constant rate to ^{87}Sr. The amount of decay is negligible during a human lifespan due to the long decay constant of ^{87}Rb (1.419×10^{-11} yr^{-1}; Davis, Gray, Cumming, & Baadsgard, 1977). However, differences in Rb/Sr ratio and age of bedrock lithology cause different geological domains to have significantly different isotopic compositions. Regions with older cratonic bedrock, particularly differentiated bedrock such as granites, will have substantially more "radiogenic" strontium isotope signatures. Because Rb and Sr have different geochemical cycles and behavior, specific minerals can have very different Rb/Sr ratios, even among co-existing minerals in a single rock type. These isotopic variations are transmitted to organisms through dissolved Sr in drinking water and trace elements from soil incorporated into edible plants (Hodell, Quinn, Brenner, & Kamenov, 2004; Price, Manzanilla, & Middleton, 2000; Price, Tiesler, & Burton, 2006). Significant progress has been made in creating a predictive isoscape for Sr isotopes in plants and people in the United States (Beard & Johnson, 2000; Chesson et al., 2012; Tipple 2016; West, Hurley, Dudás, & Ehleringer, 2009), although improvements are still required. Sr behaves similarly to Ca, and tissues such as teeth and bone high in Ca also have relatively high Sr concentrations.

The nature of radiogenic isotope variations is fundamentally different than those of the stable isotope variations of carbon, nitrogen, oxygen, and hydrogen. **Radiogenic isotope signatures do not vary during chemical reactions.** While $\delta^{13}C$ and $\delta^{15}N$ in tissues vary depending on the biological processes during uptake and incorporation, $^{87}Sr/^{86}Sr$ ratios do not. Hence, red blood cells, serum, hair, and bone will all have different $\delta^{13}C$ and $\delta^{15}N$ ratios. $\delta^{13}C$ values in the carbonate and collagen in the same bone will be different, even if the individual has lived in the same place all his or her life. However, if an individual has always lived in the same place, the $^{87}Sr/^{86}Sr$ value in all of these tissues will be identical. This point needs strong emphasis, as there is widespread confusion in some sectors of the forensic community about the fundamentally different mechanisms of variation between stable, mass-dependent isotope ratios and radiogenic isotope ratios (e.g., Juarez, 2008; Santamaria-Fernandez & Wolff, 2010), despite significant publications in the geological literature about these two systems (Boehm et al., 2012; Fietzke & Eisenhauer 2006; Halicz, Segal, Fruchter, Stein, & Lazar, 2008; Knudson et al., 2010; Krabbenhöft et al., 2009; Krabbenhöft et al., 2010; Ma et al., 2013; Wakaki, Obata, Tazoe, & Ishikawa, 2017; among many others).

Although outside the scope of the original grant, our laboratory also has been developing mass-dependent strontium isotopes as a trophic level indicator (Knudson et al., 2010). There is much confusion in the archaeological and forensic literature about nomenclature and application of these two aspects of the same isotope system (*e.g.*, Juarez, 2008). Sr isotopes have four isotopes, ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr. All of these isotopes are stable, in that they do not decay over time. ^{87}Sr is a radiogenic daughter product of ^{87}Rb. Radiogenic strontium isotope signatures vary because there can be an excess of ^{87}Sr over time. However, when undergoing chemical reactions, the relative abundance of Sr isotopes can vary due to changes in bond strength in different chemical product pools. The variation due to chemical reactions is *mass-dependent* isotope fractionation. Frequently, the term "stable isotopes" is used when mass-dependent isotope fractionation is meant. "Stable isotopes" is a confusing term, as all the isotopes of Sr are stable, even when considering radiogenic isotope variation. In order to clarify the usage and interpretation of these two aspects of the strontium isotope system, which can be measured simultaneously, the differences are summarized in Table 2.

	Radiogenic Sr	Mass-dependent Sr
Nomenclature	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$
Units	Absolute value	Relative to a standard
Typical range	0.704-0.722	~ -0.9‰ to +0.8‰
Typical sample error	<0.00003 (2 σ, replicate chemical preparation)	<0.07‰
Standards used	Secondary standards (SRM 987, NIST 1400, BCR-2…)	Reference standard: SRM 987=0.00‰ by definition
Cause of variation	Ingrowth of radiogenic ^{87}Sr	Variable bond strength between reactants and products during chemical reactions
Controls on variation	Geology, age	Trophic level
Typical applications	Rock dating, source attribution, human mobility	Ecosystem food webs, dietary strategies

Table 2. A comparison of the similarities and differences between the mass-dependent and radiogenic aspects of the strontium isotope system.

When measuring radiogenic strontium isotopes, the assumption is made that the $^{88}Sr/^{86}Sr$ ratio is constant. Any change in the measured $^{88}Sr/^{86}Sr$ is assumed to be due to variations in

instrumental mass fractionation. Thus, the mass-dependent strontium isotope variation is corrected away when analyzing for radiogenic strontium isotopes. Both of these isotope signatures can be measured simultaneously, but it requires substantial modification to the analytical protocols to complete these measurements, as detailed in Table 3.

	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$
Sample preparation considerations: yield or chemical recovery	Low yield still gives acceptable values	Dependent on chemical purification protocol used, generally >90% required in order to have accurate data
Samples preparation: purity requirements	Highly efficient removal of Rb prior to analysis critical. Significant matrix may remain	Removal of matrix elements important; removal of Rb does not need to be highly efficient
Analytical throughput	High; for optimized MC-ICPMS, can be >100 samples per day	Moderate: for optimized MC-ICPMS, ~25 samples per day
Analytical considerations	• Frequent blanks • standards run every 5-10 samples, • accurate and precise isotopic composition can be measured even if samples and standards are mismatched within range of ~5% to 350%	• Frequent blanks • standards bracket each sample, • frequent secondary standards, • ideally match sample and standard concentrations within 20% • dope sample with Zr for instrumental mass fractionation correction
instrumental mass fractionation correction	Correct measured $^{87}Sr/^{86}Sr$ values to a constant $^{86}Sr/^{88}Sr$ of 0.1194	Correct samples to a constant $^{90}Zr/^{91}Zr$ value
Sample introduction system: laser ablation	Laser ablation of low Rb samples such as teeth, bones and carbonate can give accurate and precise measurements.	Laser ablation analysis of any sample matrix has never been reported in the literature.

Table 3. Considerations when making measurements of mass-dependent and radiogenic isotopes differ substantially. Archived data cannot be re-analyzed to derive mass-dependent values. The substantial increase in rigor required for mass-dependent Sr measurements means the analytical cost is significantly

higher, although published rates for mass-dependent Sr do not exist with the exception of our lab. Most labs do not routinely measure mass-dependent Sr isotopes.

3.1.4 Lead (Pb) isotopes Lead isotopes are produced through several radioactive decay chains; ^{204}Pb is primordial, and is often used as the denominator ratio for other Pb isotopes (Faure, 1986). They include ^{206}Pb (from ^{238}U), ^{207}Pb (from ^{235}U), and ^{208}Pb (from ^{232}Th). Like Sr isotopes, Pb isotopes can source a geologic terrain of a given age; because the parent elements of U and Th have different geochemical behavior, Pb isotope ratios can vary widely.

However, Pb is also a common indicator of anthropogenic activity. While leaded gasoline has been phased out in the United States, Pb contamination is still a common pollutant originating from smelting or mining operations and residual left from previous leaded gasoline usage, and was a common additive to house paint for decades. Unlike the light stable isotopes, or Sr substituting for Ca, there is no known biological use for Pb. Contamination is common and easily measurable due to lead's lower general concentration. In addition, it is not incorporated into mineral or protein structures such as hydroxyapatite or keratin (Baxter, Beardah, & Westwood, 2000; Bower, Getty, Smith, Simpson, & Hoffman, 2005; Faure, 1986). Pb isotopes have frequently been used to determine migration and origins of anthropological populations (Aufderheide, Wittmers, Rapp, & Wallgren, 1988; Carlson, 1996; Thibodeau, Chesley, & Ruiz, 2012; among many others), as well as being used as an indicator of specific occupations, such as mining (Durali-Mueller, Brey, Wigg-Wolf, & Layahe, 2007), or problems in local water systems (Hanna-Attisha, LaChance, Sadler, & Schnepp, 2016; Laidlaw et al., 2016).

Lead in the context of forensic investigations of human remains has been increasing. Recent research evaluated if soil lead could lead to false positives when testing for GSR residue in buried bodies (Boracchi et al., 2017). There has also been recent interest in using Pb isotope ratios for provenancing unidentified human remains (Aufderheide et al., 1988; Font et al., 2012; Kamenov, Kimmerle, Curtis, & Norris, 2014; Keller, Regan, Lundstrom, & Bower, 2016; Shrag, Ulden, Mangin, & Froidevaux, 2012; Vautour, Poirier, & Widory, 2015). Lead isoscapes have been examined, although not as extensively as strontium isotopes (Keller et al., 2016; Reimann et al., 2012).

3.2 Trace elements and element ratios

Trace element signatures can be used as indicators of occupation or geographic origins (Basu et al., 2015; Esteban & Castaño; 2009). In

addition, trace element profiles are commonly used to monitor for diagenetic modification of tissues such as bone. Elevated concentrations of rare earth elements (REE) or uranium in bone typically indicate diagenetic alteration by groundwater flow (Knudson & Price, 2007; Kohn, Schoeninger, & Barker, 1999). Element ratios, such as Ca/P for bone or teeth or C/N for biological tissues, can also indicate diagenetic change. Samples for this study were measured for major elements (Na, K, Al, Ca, P, Mg by Q-ICP-MS; C, N, O and H by IRMS) and trace elements (V, Cr, Mn, Co, Fe, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Ag, Sn, Sb, Ba, Nd, W, REE, Pb, and U) by Q-ICP-MS. These elements were selected as important either because of biological requirements, toxicity to humans, sourced from anthropogenic contamination, or as monitors of diagenesis.

3.3 Isoscapes Isoscapes ("isotopic landscapes") is the term for maps generated for isotopic variation across a region. Typically, they arise from a database of measured values, and these values are interpolated across space and sometimes time (Beard & Johnson, 2000; Bowen, West, & Hoogerwerff, 2009; Chesson et al., 2012; Ehleringer et al., 2008; Juarez, 2008). The sample types used for generating such maps are critical because the measured isotope values in one sample, such as precipitation or groundwater (West, Sobek, & Ehleringer, 2008; Wassenaar, Van Wilgenburg, Larson, & Hobson, 2009), will be different for a different sample type, such as bird feathers or human hair (Ehleringer et al., 2008; Hobson et al 2009; Hobson et al 2010; Kennedy et al 2011). These differences arise because organisms can fractionate isotopes mass-dependently, and do not necessarily absorb or retain the bedrock or water values for an area. The elements that are bioavailable are typically only one component of the total. In addition, diet may incorporate food or water from a variable area. This is of particular concern for modern humans, who have a very different diet than hunter-gatherers typically studied in anthropology (Knudson 2009; Knudson et al 2009). Databases of samples such as precipitation and groundwater are more robust and richer because they have many more samples in them. Frequently, they were developed for other purposes such as climate change prediction, and have been repurposed for geolocating unidentified human remains.

Conversion of one parameter (such as precipitation) to another (such as hair or bone) requires a number of assumptions and a detailed understanding of the biological mechanisms of fractionation and incorporation. Additional parameters that can cause variability in the

incorporation fractionation, including lifestyle parameters such as diet or amount of exercise, or climatic parameters such as temperature or local humidity, means that a 1:1 conversion from water to hair or bone is not possible without introducing additional error. In addition, there are still many parameters that are not well enough constrained to provide absolute errors on the estimates generated by these methods, although this is a very active area of research (West et al 2008; Kennedy et al 2011). While radiogenic isotopes such as Sr and Pb have less impact from this type of issue because they are measuring non-mass-dependent effects, other issues such as dietary choice can still have a dramatic impact. In addition, there can be considerable variability depending on municipal water usage and patterns (Tipple 2016).

As noted earlier, we intend to use two anthropological research facilities for our studies, one at the University of Tennessee, Knoxville, and one at Texas State, San Marcos. These two locations have contrasting climatic conditions, with the former temperate and moist, with high amounts of precipitation, and the Texas site more arid and hotter. We will analyze hair, tooth enamel, and bone samples from human cadavers at both sites over time to evaluate the amount of isotopic alteration.

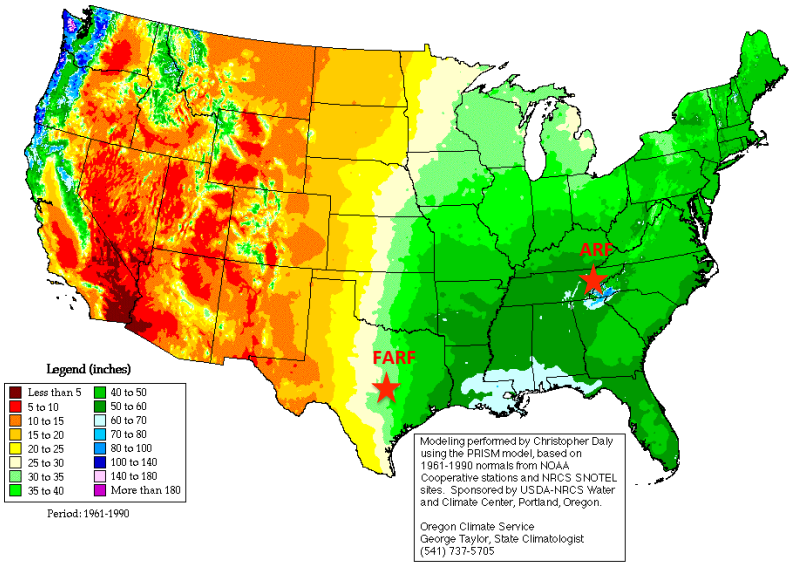

Figure 1. Locations of study sites, with average annual precipitation (from NOAA website).

3.4 University of Tennessee at Knoxville's Anthropological Research Facility (ARF)

University of Tennessee at Knoxville's Anthropological Research Facility (ARF) is the world's oldest research facility for studying the active processes of decomposition and taphonomy. Knoxville has a temperate climate with average monthly rainfall of 3 to 5 inches for

the year, and an annual precipitation of 48.2 inches. Monthly temperatures reach 88°F in July and August. (www.usclimatedata.com). Use of this facility will allow comparison with the largest existing database of decomposition processes in human remains.

ARF is located on 2.5 acres on a meander of the Tennessee River. It is built on Lower Ordovician clays and silty clay soils developed on limestone, although there are also subordinate shales in the area. (Cattermole, 1958). The Lower Ordovician marine $^{87}Sr/^{86}Sr$ value was between 0.7088 and 0.7092 (McArthur et al, 2001).

ARF is located on 2.5 acres of the University of Tennessee's Knoxville campus, behind the Medical Center. The Medical Center is on the Newala Formation of the Lower Ordovician Knox group, while upslope from the facility is Middle Ordovician Chapman Ridge sandstone (Cattermole, 1958; see Figure 1). The Medical Center has clay to silty clay soil developed on limestone, while further upslope the soil profile is dominantly clay loam developed on calcareous sandstone with subordinate shale.

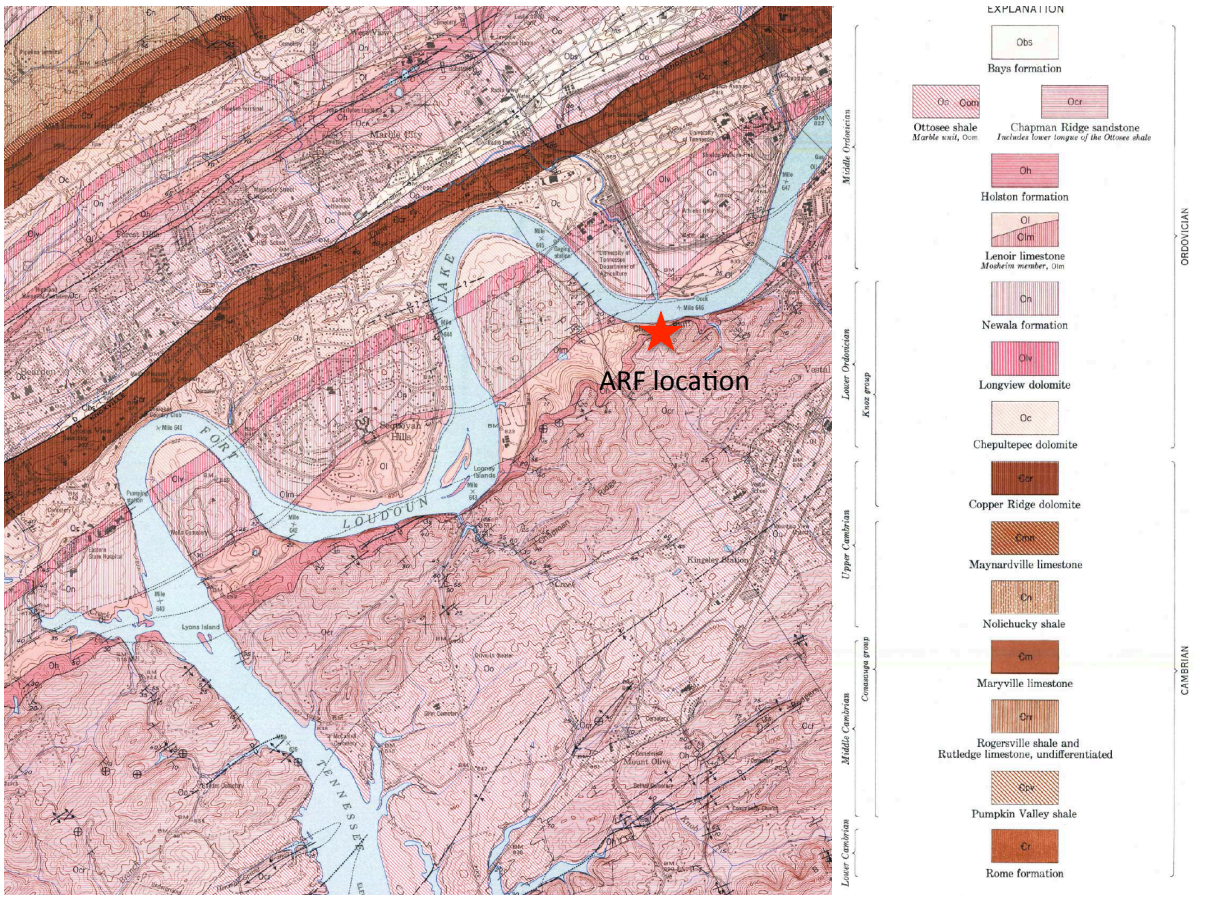

Figure 2. Geological map of the area around the Anthropological Research Facility at the University of Tennessee, Knoxville. Adapted from Cattermole (1958).

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

The average high temperature in Knoxville is 88° F in July and August, with high temperatures falling to 47° F in January and the average temperature is 59.4° (www.usclimatedata.com).

The $\delta^{18}O$ of precipitation at ARF is estimated to be -6.3 ±0.5‰ (V-SMOW, 95% C.I.) and the $\delta^{2}H$ is -39 ±6‰ (V-SMOW, 95% C.I.) (Bowen, 2013; Bowen & Revenaugh, 2003).

3.5 Texas State University at San Marcos' Forensic Anthropological Research Facility (FARF)

Texas State University at San Marcos houses a research facility for studying active processes of decomposition in a much more arid, warmer climate than that of University of Tennessee. Annual rainfall is much lower at 37.2 inches per year, with average temperatures of 68.5°F, while monthly temperatures reach 96°F in August (www.usclimatedata.com). The average high temperature in San Marcos is 95° F in July and August, with high temperatures falling to 61° F in January. The maximum monthly rainfall is typically in May, at 5.3 inches, while the periods December-April and July-August have average rainfall less than 3 inches. The patterns of decomposition in these hotter, drier conditions are different than that of Tennessee.

In particular, one of the largest groups of unidentified human remains in the US are illegal immigrants across the United States' southern border (Aggarwal et al., 2008; Juarez, 2008). FARF's environmental conditions are similar to the environment in which many of these remains are found.

Texas State University at San Marcos' research facility is located on 26 acres of Freeman Ranch, six miles northwest of San Marcos, Texas. The underlying bedrock is mudstones, limestones, and minor cherts from the Lower Cretaceous period. During the Lower Cretaceous, the marine $^{87}Sr/^{86}Sr$ value was between 0.7072 and 0.7074 (McArthur et al, 2001).

The Mustang Branch fault cuts through Freeman Ranch, trending northeast-southwest (Blome et al, 2005; see Figure 2). The grainstone member of the Lower Cretaceous Kainer Formation and the lower two members of the Person Formation lie to the northwest of the center of the facility. Lithologies range from fossiliferous mudstone and wackestone to crystalline limestone. The Kirschberg Evaporite and grainstone members of the Kainer Formation lie to the southeast of the Mustang Branch fault.

The topography is gentle, and there are many faults trending northeast-southwest throughout the region. The groundwater flow is controlled by the regional fabric of the faults.

The groundwater is generally very hard (96% has >200 ppm TDS), with significant concentrations of calcium, magnesium, and fluoride. Nearly 10% of the wells measured in the Edwards Limestone had more than 2000 ppm TDS (DeCook, 1963).

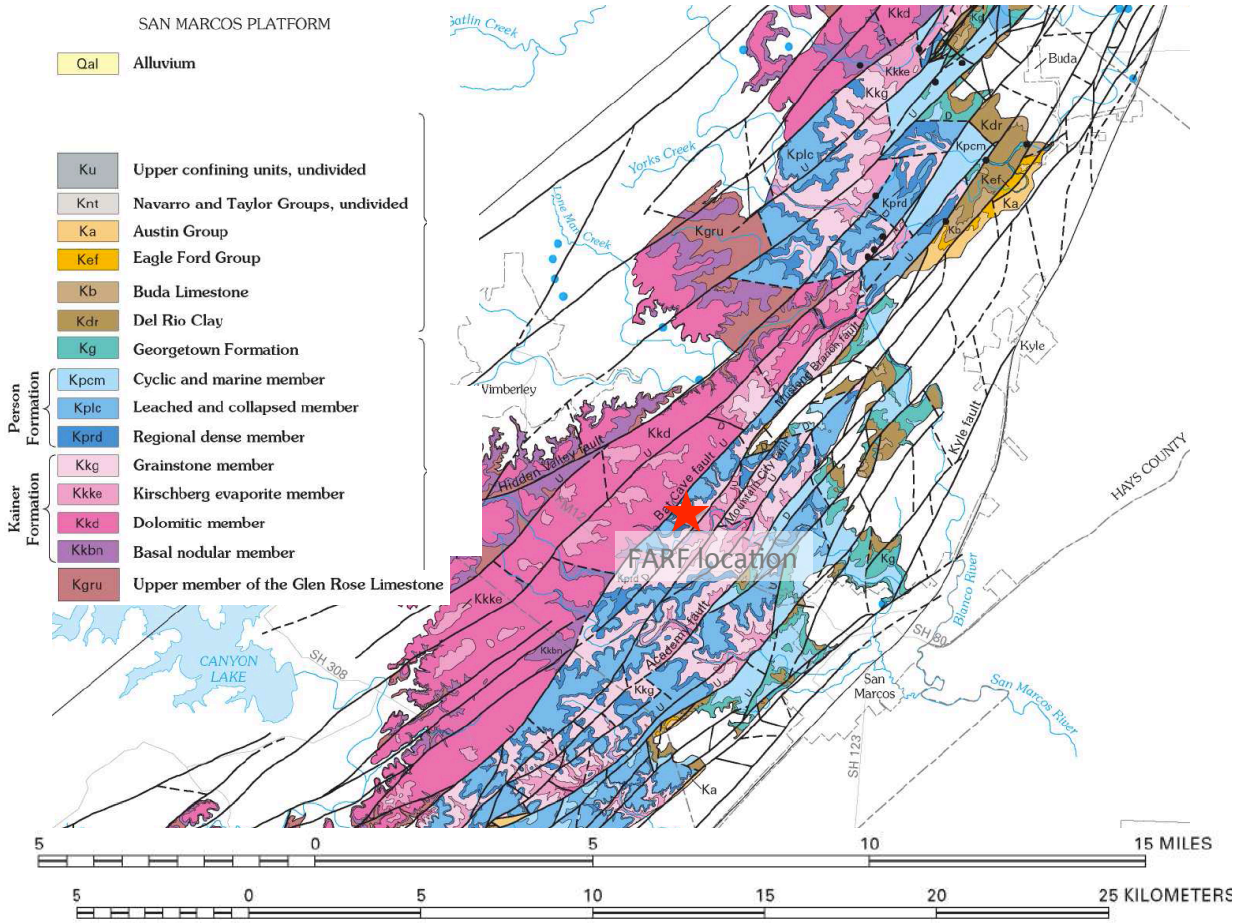

Figure 3. Geological map of the area around the Forensic Anthropological Research Facility at Texas State, San Marcos. Adapted from Blome et al (2005).

The $\delta^{18}O$ of precipitation at FARF is estimated to be -3.9 ±0.1‰ (V-SMOW, 95% C.I.) and the $\delta^{2}H$ is -22 ±1‰ (V-SMOW, 95% C.I.) (Bowen, 2017; Bowen and Revenaugh, 2003).

3.6 Taphonomic stages The stages of decomposition are well documented visually (*cf* Marks et al, 2009), but the rate of change during decay depends on many factors including body composition, size, wrapping or clothing, temperature, humidity, pH of the soil environment, depth of burial, soil moisture, precipitation, availability of oxygen, and exposure to insects. Temperature is the most important contributor to decomposition, as it influences both the rate of

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

chemical reactions and the rates of infestation and life cycle of cold-blooded arthropods that break down bodies. Hence, stages of decay are described in accumulated degree hours (ADH) or accumulated degree days (ADD), which are calculated average hourly and daily temperatures (Byrd & Castner, 2010; Vass et al., 1992; Vass, 2011; Megyesi et al., 2005). Research conducted at the ARF demonstrates that ADH 125-2000 captures the major stages of decomposition. ADH 2000 translates to approximately 80 spring or fall days and 45 summer days. Although temperature may prove to not be the primary control on isotopic change, we will use ADH as a monitor of taphonomic change to allow other researchers to compare their results with our own.

Isotopic change can occur through several processes, but essentially requires either partial loss of elements (light stable isotopes) or gain of elements from the environment (all systems). For tissues such as hair, tooth enamel, and bone, the most critical factor in isotopic change is often water, although hydrological factors are not the only ones. In dry environments, bodies mummify, and the isotopic composition of tissues has successfully been used to approximate premortem isotopic compositions even thousands of years after death (Cartmell et al, 1999; Knudson et al., 2007; Knudson & Buikstra, 2007; White, 1993; White & Schwarz, 1994). The decision to utilize both ARF in East Tennessee and FARF in Texas is designed to explicitly evaluate the role of aridity in isotopic preservation.

Multiple tissue and environmental sample types will be monitored through the project. Various studies have demonstrated the variable turnover rate of different tissues (refs). For example, tooth enamel begins to form *in utero* for the first molar, and the isotopic and elemental composition of enamel does not generally change after enamel forms in the first few years of life. In contrast, bone remodeling rates vary widely, based on skeletal element, age, sex and activity levels, although bone isotopic and elemental values reflect the last years or decades of life (Mulhern & van Gerven 1997; Branca et al., 1992; Dibba et al., 1999; Hedges et al., 2007; Stout & Lueck, 1995; Cho et al., 2006).

Hair, by contrast, grows at a rate of about a centimeter per month (Lehn et al., 2011; Lubeck et al., 1987; Randall & Ebling, 1991; O'Connell & Hedges, 1999a, b; O'Connell et al., 2001; Roy et al., 2005). Combining the isotopic signatures of these different tissues can provide a travel and dietary history of an individual. Hence, using multiple tissues is often helpful in forensic case studies.

However, the chemical structure, the concentrations of different elements, and the manner of their incorporation in tissues differ drastically. Consequently, some tissues record isotopic signatures with more fidelity to premortem values than others. Tooth enamel is known from anthropology to be quite robust to diagenetic modification, while more porous bone is more susceptible to alteration. Bones with lower proportions of compact to spongy bone, and higher surface area to volume ratios are more likely to be altered. Bone in ribs tends to turn over more quickly than weight-bearing limbs.

Hair, composed dominantly of keratin protein, does not have the inorganic matrix of hydroxyapatite to protect it from alteration. Since this was expected to alter first among the sampled tissues, the frequency of sampling was highest. Hair still shows resistance to alteration, making it an important potential forensic tissue type (Knudson et al., 2007; Lubec et al., 1987; White, 1993; Macko et al., 1999; O'Connell & Hedges, 1999a, b; O'Connell et al., 2001; Sharp et al., 2003; McCullagh et al., 2005; Roy et al., 2005; Loudon et al., 2007; Ehleringer et al., 2008; Sponheimer et al., 2009; White et al., 2009; Webb et al., 2010; Williams et al., 2011; Williams & Katzenberg, 2012; Webb et al., 2013). Based on anthropological research, tooth enamel should be robust and so the sampling frequency is lowest in these samples. In addition, hair is typically much more abundant than teeth, so destructive analyses of hair do not compromise the skeletal collections in the same way that teeth and bone collection do. The wetter environment of ARF were expected to facilitate isotopic change, so more subjects are selected for that site, and are sampled earlier. Element ratios (Ca/P ratios for bone and tooth enamel; C/N for hair) as well as U and REE abundances in bone and tooth were utilized to screen for diagenesis.

3.7 Environmental samples: Precipitation, groundwater, and soil To evaluate the amount of alteration of tissues, we need the environmental solutions or solids modifying them. The microenvironment of body emplacement is critical, so data loggers will monitor temperature and humidity at the emplacement sites. This will also allow accurate measurement of ADH. The composition of precipitation is modified by throughfall from vegetation, so collection and measurement of water samples adjacent to the bodies is important. Groundwater is an important transport mechanism of elements to and from the body, so we will use steel probes and syringes to collect groundwater at each site. We will measure pH, major and trace element composition,

and both light stable and radiogenic isotope profile of both the precipitation and groundwater samples. Groundwater will be collected prior to body emplacement, while three rainfall events at each body site will be collected.

The bioavailable component, rather than a bulk analysis, of soil mostly closely samples potential exchange with biological tissues. We will use a 1 molar ammonium acetate overnight leach (Blum et al, 2000; Appendix) to sample the bioavailable cation pool. Due to the overwhelming amount of oxygen and hydrogen in precipitation and groundwater, we will neglect the potential contributions of those elements from the soil pool. Prior to body emplacement, we will sample the soil to a depth of at least 18 inches, and measure a bioavailable cation profile. Other measurements will include $\delta^{13}C$ and $\delta^{15}N$ as indicators of the type of biological activity and Sr and Pb isotopes (Komárek et al, 2006).

4 STATEMENT OF HYPOTHESIS

We predicted that tooth enamel and bone would preserve pre-mortem isotopic values during the one year environmental exposure in taphonomic conditions. Although bone is more subject to diagenetic modification than teeth, we predicted that one year would be insufficient to substantially alter the pre-mortem isotope compositions. This expectation was developed from previous study results in anthropology (*e.g.,* Nielsen-Marsh & Hedges 2000a, 2000b; Budd et al., 2000; Dauphin, Massard & Quantin, 2008; Hedges, 2002; Kohn, Schoeninger, & Barker, 1999; Lee-Thorp & Sealy, 2008; Nelson et al., 1986; Price et al., 1992; Sillen, 1989; Sillen & Sealy, 1995; Tütken, Vennemann, & Pfretzschner, 2008; Wright & Schwartz, 1996). Hair has been studied in modern individuals, as well as archaeological populations (Ehleringer et al., 2008; Tipple, 2016; Valenzuela et al., 2011; 2012), but isotope studies of taphonomic change in keratin suggested that hair would be the least well preserved (O'Connell & Hedges, 1999; von Holstein et al., 2014; von Holstein et al., 2015). In addition, we predicted that if tissues were modified, they would change in the direction of the bioavailable leach in soils for C, N, Sr, and Pb, or local precipitation for O and H. We also predicted that peri-mortem isotopic compositions would be broadly consistent with values predicted from isoscapes.

5 METHODS

5.1 Initial experimental design

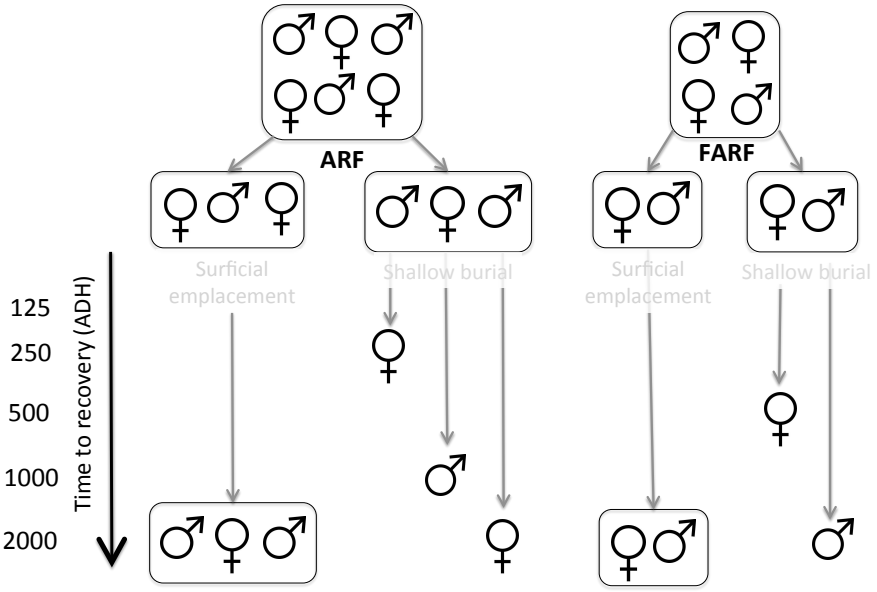

Figure 4. Sampling design of emplacement and recovery of bodies at ARF and FARF

	ARF (n=6)			FARF (n=4)		
	Hair	Enamel	Bone	Hair	Enamel	Bone
Surface (n=5)						
Receipt	3	3	3	2	2	2
ADH 125	3	-	-	2	-	-
ADH 250	3	-	3	2	-	-
ADH 500	3	-	-	2	-	2
ADH 1000	3	-	3	2	-	2
ADH 2000	3	3	3	2	2	2
Shallow burial (n=5)						
Receipt	3	3	3	2	2	2
ADH 125	-	-	-	-	-	-
ADH 250	1	1	1	-	-	-
ADH 500	-	-	-	1	1	1
ADH 1000	1	1	1	-	-	-
ADH 2000	1	1	1	1	1	1
Subtotal by sample type	24	12	18	16	8	12

Table 5. Sampling design of number of individuals (n) by tissue type, emplacement and time. Each number may include multiple skeletal elements (in the case of bone) or multiple replicates to evaluate homogeneity.

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

	ARF (n=6)				FARF (n=4)			
	Soil		Groundwater	Precipitation	Soil		Groundwater	Precipitation
	Leach	bulk			Leach	bulk		
Surface (n=5)								
Emplacement	3	2	3	-	2	1	2	-
ADH 125	-	-	-	-	-	-	-	-
ADH 250	-	-	-	3	-	-	-	1
ADH 500	-	-	-	-	-	-	-	-
ADH 1000	-	-	-	3	-	-	-	1
ADH 2000	-	-	-	3	-	-	-	1
Shallow burial (n=5)								
Emplacement	3	2	3	-	2	1	2	-
ADH 125	-	-	-	-	-	-	-	-
ADH 250	-	-	-	3	-	-	-	1
ADH 500	-	-	-	-	-	-	-	-
ADH 1000	-	-	-	3	-	-	-	1
ADH 2000	-	-	-	3	-	-	-	1
Subtotal by sample type	6	4	6	18	4	2	4	6

Table 6. Sampling design of number of environmental samples by sample type, emplacement and time. Each number may include multiple samples at different depths (in the case of soil for burials) or multiple replicates to evaluate homogeneity.

5.2 Sample collection protocols

5.2.1 Water The precipitation samplers were modified from assemblies developed and described by Scholl (2006) from the United States Geological Survey. Precipitation samples were collected in collapsible 4 L trace metal clean containers. The sampling containers were attached to an acid-cleaned Tygon tubing with luer-lock fittings. The top of the tube was attached to an acid-cleaned funnel seated in a custom-cut hole in a large plastic bucket. The funnel had a fitted plastic cap that could be closed when the assembly was being transported, or when sample was not being collected. The funnel had an acid-cleaned ping-pong ball blocking the neck, which effectively closed the sample container when no water was entering the assembly. When water entered the funnel, the ball floated and allowed water to enter the storage container. The funnel was covered in netting, secured by a size 117 elastic band (7" x 1/8") to prevent large debris from falling into the funnel and potentially blocking the movement of the ping-pong ball. The ball, along with the small diameter tubing, minimized evaporation during sample collection and storage. Sample evaporation would be expected to increase the apparent concentration of dissolved material and could radically change the $\delta^{18}O$ and $\delta^{2}H$ values measured, so this was of particular concern.

The precipitation sampling containers were carried in the field as the bucket, lid, a pre-assembled funnel assembly, and a pre-assembled receiving container assembly. Sections were

pre-assembled in a clean lab environment to minimize potential contamination during field assembly of the entire unit. The funnel assembly consisted of the following items, all acid-cleaned prior to use: 2" PVC coupling, 2" to ¾" PVC reducer, ½" x ¾" TxT reducer, ¼" OD x ½" MIP quick connector adapter, and 18" of ¼" OD Tygon tubing. The MIP quick connector adapter was only rinsed three times in 18 MΩ water instead of acid-cleaned, because it contains a metal clip. The receiving container assembly included a one-gallon cubitainer (Thermo catalog #314-0001), a screw top closure, an extra screw top closure adapted by insertion of a female luer thread-style panel mount ¼" UNF to barb (1/8" ID; Cole Parmer 45502-34), 3" of 1/8" Tygon tubing, and a male luer lock plug. During water collection, the screw top with luer lock was in place. For shipment of unfiltered water samples, the luer lock screw top was replaced with a solid screw top to prevent leakage.

For field deployment, sand was poured into the bottom of the bucket for stability. The receiving container assembly was placed in the bucket on top of the sand, the funnel assembly was inserted through the hole in the bucket lid and attached to the top of the receiving container assembly. The bucket lid was tightened onto the bucket, and the funnel fixed into the top of the bucket lid with silicone caulk and duct tape.

To monitor field blanks, we conducted two types of controls: one was a complete water sampling assembly, in which the funnel cap remained in place. Eighteen MΩ water was then poured into the top of the funnel in the field after deployment to monitor the complete field blank. To evaluate the potential evaporation of water during extended deployment, 18 MΩ water was added to the sampler during initial deployment; this water was collected and processed in parallel with samples. Because the 18 MΩ water was brought from Phoenix, Arizona, it was independently measured and isotopically distinct from that of local precipitation, ground water, or well water. The water was below detection limits for all measured ions.

Ground water presented difficulties for collection. Initial sampling equipment was a Soil Measurement System stainless steel suction lysimeter (catalog #SW-074-4) and motorized pump for extracting solutions. However, both sites were in unsaturated zones, with the water table far below the depth of the lysimeter. Despite purchase of a stronger pump, we were unable to collect sufficient groundwater for routine analysis. We were able to collect some stationary surface water downslope from donor placement area at ARF after particularly heavy rains, but this was unlikely to be representative of groundwater at the site.

For well water samples at the FARF site in Texas, a well close to the site pumped water from the local aquifer. Water was allowed to flow for at least five minutes to flush all pipes in case stagnant water had leached metals out of the pipes.

Water samples, including precipitation, ground and well water, was separated into aliquots for different analyses in the field. The pH was measured with disposable strips prior to filtration. Gloves were worn during any manipulation of the sampling assembly to minimize contamination.

Each water sample was divided into six prepared pre-labelled containers, color-coded according to future analysis type. Samples were refrigerated after collection and shipped to ASU within 48 hours. Water was filtered to 0.25 um using a closed 250 mL bottle-top filtration unit with a hand-held vacuum pump. To decrease the potential for contamination of the filtration equipment, containers were then filled in the following order: 1) 250 mL bottle-top filter, 2) $\delta^{18}O$ and $\delta^{2}H$ (white label), 3) DOC/DIC (Dissolved Organic Carbon / Dissolved Inorganic Carbon) concentrations (yellow label), 4) $\delta^{13}C$ of DOC (blue label), 5) $\delta^{13}C$ of DIC (red label), and 6) trace elements, Sr and Pb isotopes (green label).

Approximately 30 mLs of water was filtered into the 250 mL screw-top bottle, swirled, and discarded. An additional 250 mLs was filtered, topping off from the 1 gallon cubitainer as needed. Vacuum for filtration was provided with a hand pump. This provided the source water for the next set of samples. Ten mLs of water from the filter unit was taken up in a syringe, rinsed, and discarded. An additional 60 mLs of filtered water was added to the syringe, and a 0.2 μm luer-lock filter was attached. Approximately 1 mL of water was pushed through the 0.2 μm filter and discarded. An additional 2 mLs of water was filtered into a 2 mL glass screw top container and discarded. It was refilled completely full and sealed for $\delta^{18}O$ and $\delta^{2}H$ analysis (white label).

For DOC/DIC concentrations, several mLs were filtered at 0.2 μm into a 40 mL trace metal clean amber borosilicate vial with silicon septa with Teflon lining (VWR Catalog# 15900-024). The container was rinsed with the filtered water, and the water was discarded. The container was completely filled (yellow label).

For $\delta^{13}C$ of DOC, the 40 mL trace metal clean amber borosilicate vial with silicon septa with Teflon lining was pre-acidifed with 0.2 mLs of 85% H_3PO_4. The blue labelled container was filled to the top with the 0.2 μm filtered water.

For $\delta^{13}C$ of DIC, the 40 mL trace metal clean amber borosilicate vial had a black butyl septa. The blue labelled container was filled to the top. The butyl septa prevents loss of inorganic carbon as the silicon septa with Teflon lining is permeable. The butyl septum was made from a sheet of black butyl rubber (McMaster Carr Catalog #8609K67; Air-Tight Butyl Rubber Plain Back, 1/8" thick, 36" width, 60A Durometer). Septa were punched out using a 7/8" hole diameter arch punch (McMaster Carr Catalog #3427A22), rinsed three times in 18 MΩ water, and dried under ULPA filtered air.

For trace elements, Sr and Pb isotopes, a 60 mL acid-cleaned LDPE screw top container was pre-acidified with 2 mLs of trace metal grade hydrochloric acid. Water filtered to 0.2 μm was used for this analysis.

5.2.2 Soil Two types of soil were collected: grab samples and core samples. Samples were collected prior to emplacement and during recovery. Grab samples were surface samples collected in a trace metal clean container, typically a 50 mL centrifuge tube.

Core samples were collected with a 2" diameter, stainless steel soil corer with a 12" sampling depth (AMS, Inc., Catalog #404.67). Soil cores were collected in plastic retaining cores (AMS, Inc., Catalog #405.10) capped by 2" plastic end caps (AMS, Inc., Catalog #418.10). Both the retaining cylinders and end caps were acid-cleaned prior to use. Cores were marked as to vertical directionality in the field. Cores and grab samples were refrigerated upon collection and shipped to ASU labs within 48 hours on ice.

5.2.3 Donor placement and recovery Donors were placed nude on either the ground surface or in a shallow grave. Scavengers differ between the two facilities, with raccoons the primary large animal scavengers at ARF and vultures at FARF. To maintain consistency, at both facilities, a wooden cage constructed from 2' x 4' structural support with chicken wire was placed over the bodies. The cage was set over the bodies, but was not embedded in the ground. On a daily basis, the donors had the cages removed and were photographed to record the visual indications of decomposition. As decomposition continued, photographs were made less frequently as visual changes decreased. To prevent loss of the small bones of the hands and feet, a plastic mesh was secured to the extremities with a plastic tie. Each donor was marked with a stake, and had two metal markers with the donor number attached. In order to preserve donor anonymity, donors in

this current work are referred to as Surface 1, Burial 1, etc., numbered sequentially from time of placement. Burials 1-3 were at ARF, and Burial 4 was at FARF. Surface donors 1-3 were at ARF and Surface donors 4-7 were placed at FARF.

Due to the unpredictable timing of donor arrival at the two facilities, Surface donors 1 and 2 were frozen prior to placement. All other donors were recovered and placed within 48 hours of death, and were stored in a cooler until placement.

After approximately a year of decomposition, donors were recovered and processed via maceration for final addition to the local skeletal collections. Recovery followed standard protocols at the respective facilities.

5.2.4 Teeth Teeth were removed in the field using a dental extraction kit with forceps and elevators. During the immediate post-mortem period, teeth were firmly fixed within the jawbone and required significant effort to remove teeth. Because of concerns of damaging the jaw during removal, care was taken to minimize scraping or contact between the dental tools and the jaw. Many of the donors had relatively few remaining teeth, with premolars and molars particularly absent. By necessity, frequently canines and incisors were sampled rather than premolars or molars. Every effort was made to take tooth pairs: if a right incisor was sampled at intake, we tried to sample left incisors at recovery. Teeth emerge at different times during development, and variations in different dental elements are interpreted to represent lifestyle or mobility changes. Because the dental condition of many of the donors is poor, it was frequently not possible to match the same tooth during intake and recovery – e.g., to remove the left lateral incisor at intake and the right lateral incisor during recovery. In order to minimize damage to the jaw during tooth removal, incisors were frequently used in our analysis. These were the most frequently remaining dental elements, as many donors had few to no molars remaining. A high frequency of dental caries meant that the condition of some teeth was quite poor.

5.2.5 Bone To minimize destructive analyses, we utilized a new technique for collecting small bone cores, and sampled the sixth ribs; this rib is not used in forensic anthropology for creating biological profiles. A ¼” diamond-tipped hole drill bit was used to drill a core from the center of the rib. However, in many cases this produced very little cortical bone. If donors had previously

been autopsied, larger samples of the sixth rib were sampled using gardening shears since significant destruction had already rendered the bones unsuitable for creation of forensic anthropology profiles. Samples were then frozen and sent to the Arizona State Laboratories for additional cleaning soon after collection.

5.2.6 Hair Samples were collected by gently pulling from the root out of the scalp. When possible, hair orientation was maintained by folding the hair in aluminum foil immediately after collection. During advanced decomposition, frequently hair had sloughed off and was no longer connected to the scalp. In such cases, the best estimate from physical positioning was used for orientation. During intake, samples from several areas of the scalp were combined. When possible, multiple samples were also taken. Donor 1 from ARF had died from a self-inflicted gunshot wound to the head, and samples from this donor were kept separate and oriented as to the relationship to the gunshot wound. Initially, samples were air-dried. However, as discussed below, due to logistical needs, later samples were frozen to maintain sample integrity.

5.3 Sample preparation and measurement protocols

5.3.1 Laboratory facilities at Arizona State University Sample cleaning and preparation procedures were completed in a trace-metal clean lab, with all chemical procedures performed in ULPA-filtered Class 10 laminar-air flow exhaust hoods. The hoods are housed in a positively-pressurized clean laboratory with ULPA-filtered air supply routinely maintained at Class 10,000 conditions. This lab was built with minimal metal; all workstations, cabinetry and wall coverings are polypropylene and other corrosion-resistant materials. An adjacent laboratory space maintained at Class 100,000 conditions provides space for acid-cleaning of all reagent vessels and laboratory consumables.

All water used in cleaning is campus deionized water (typically ~3 MΩ resistance) that is further purified through a four-stage ion exchange filtration system to 18 MΩ and piped throughout the laboratory. All chemistry is conducted with water that goes through an additional Millipore brand Milli-Q® Gradient point-of-use filtration unit (hereafter referred to as "18 MΩ water").

All chemical reagents used in chemical processing is at least trace metal grade or better. Nitric acid was either BDH Aristar High-Purity Plus (VWR catalog #87003-261) or 70% ACS

grade nitric acid additionally purified through a dedicated Savillex DST-1000 Acid Purification System (Savillex Corp., Eden Prairie, MN). Hydrochloric acid was either 36.5-38% ACS grade nitric acid additionally purified through a dedicated Savillex DST-1000 Acid Purification System (Savillex Corp., Eden Prairie, MN). Hydrofluoric acid was Fisher Chemical TraceMetal™ Grade (Fisher catalog #A513-500). Hydrogen peroxide was VWR brand BDH Aristar® Ultra 30% hydrogen peroxide (Catalog #87003-224).

Centrifuge tubes are trace metal grade (VWR cat. 89049-170). All other plastic consumables are cleaned by overnight soaking in a ~1% solution of Micro-90 detergent (Fisher brand cat. NC0233367) in 18 MΩ water. They are then thoroughly rinsed with 18 MΩ water and soaked for at least three days in 20% by volume reagent grade nitric acid. They are rinsed with 18 MΩ water and soaked for at least three days in 20% by volume reagent grade hydrochloric acid. They are rinsed at least 3 times in 18 MΩ water and dried under ULPA-filtered air in a specially designated hood before being stored in closed plastic bins. Teflon vials (Savillex Corporation, Eden Prairie, MN) are reused after cleaning. After use, vials are rinsed with 18 MΩ water and labels and any organic material is removed with acetone and a kimwipe. They are soaked at least overnight in a ~1% solution of Micro-90 detergent (Fisher brand cat. NC0233367) in 18 MΩ water. They are then heated to sub-boiling in 8 M reagent grade nitric acid for 24 hours, rinsed three times in 18 MΩ water, heated to sub-boiling in 6 M reagent grade hydrochloric acid for 24 hours, rinsed three times in 18 MΩ water and heated overnight in 18 MΩ water. They are rinsed three times in 18 MW water and dried under ULPA-filtered air in a specially-designated hood. In addition, for sensitive blank analyses of low-level lead or small samples, vials had an additional stage of heating with 6 M trace metal grade hydrochloric acid on a hot plate for at least an hour before rinsing 3 times with 18 MΩ water. Teflon vial usage is logged as to user name, date, and previous sample type using engraved letter and number combinations. Any vial which had previous usage incompatible (carbonates, synthetic metal components) with the current study were not used. Vertical and horizontal dry-down laminar air flow hoods reserved for low-level analysis were used to reduce potential cross-contamination from other contemporaneous laboratory projects.

5.3.2 Water

5.3.2.1 $\delta^{18}O$ and $\delta^{2}H$ Water samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$ using a Los Gatos Research liquid water isotope analyzer with a modification of the post-run optimization method in van Geldern and Barth (2012) with the assistance of Randall (Vince) Debes, using the instrument managed by Professor John Sabo in the School of Life Sciences at Arizona State University. The regression line for connection to the SMOW scale was made up with four standards: MSW (Mean Sea Water), 5C, 1C, and either 3A, 2A, or 2C. Five injections of 18 MW water rinses were run between each sample or standard. Sample and standard injections were increased by five, and the first five injections were removed from the analysis to reduce memory effects. Each sample or standard averaged five injections. Drift over the course of a run was generally minimal, but was corrected for by analysis of MSW every 4-5 samples. Samples were run in three analytical sessions. Quality control for certified standards is included in Table 7.

$\delta^{18}O$

	measured	σ	n	certified value	σ
MSW	-14.40	0.19	15	-14.54	0.06
5C	-2.69	0.00	3	-2.69	0.05
1C	-19.49	0.00	3	-19.49	0.05
2A	-15.93	0.10	1	-16.14	0.3
2C	-15.84	0.06	1	-16.24	0.3
3A	-13.26	0.09	1	-13.1	0.3

$\delta^{2}H$

	measured	σ	n	certified value	σ
MSW	-107.48	0.83	15	-107.70	0.42
5C	-9.21	0.01	3	-9.2	0.5
1C	-153.99	0.01	3	-154.3	0.43
2A	-123.41	0.62	1	-123.6	1
2C	-123.24	0.47	1	-123.7	1
3A	-97.16	0.35	1	-96.4	1

Table 7. Reproducibility and accuracy of standards used during analysis of liquid water samples.

5.3.2.2 Carbon concentrations and $\delta^{13}C$ for dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) Carbon and nitrogen concentrations were measured for concentrations by fluorescence using a Shimadzu TOC analyzer (Columbia, MD). The organic carbon concentration was determined by the addition of acid to the sample prior to injection, volatilizing

the inorganic carbon component. The inorganic carbon concentration was determined by the difference between acidified and un-acidified aliquots of the same sample. Carbon concentrations were determined by Joshua Nye under the supervision of Professor Hilairy Hartnett in the School of Earth & Space Exploration at Arizona State University.

Samples with more than 2 mg C/L were measured for isotopic composition using IRMS (Isotope Ratio Mass Spectrometry) on a Thermo Delta Plus Advantage using an OI Analytical TOC Analyzer with an interface to allow isotope ratio analysis of the effluent gases from the TOC Analyzer. Samples with 2-10 mg C/L were measured using a 10 mL sample loop injection, and well water samples that had >50 mg C/L were measured with a 1 mL sample loop injection. Samples with <2 mg C/L were not analyzed for isotopic composition since they were close to the field blanks for the method.

The concentration of dissolved inorganic carbon in the IRMS configuration was quantified by infrared detection of the CO_2 gas produced upon addition of 10% phosphoric acid. The concentration of dissolved organic carbon was quantified by infrared detection of the CO_2 gas produced upon addition of the strongly oxidizing reagent sodium persulfate to the solution. The effluent CO_2 gases were then fed into the Delta Plus Advantage for isotopic measurement. There was good agreement between the fluorescence and infrared determination of carbon concentration by the two methods, with the median difference between the two methods being <0.25 mg C/L for samples <10 mg C/L, with no apparent systematic bias between the two methods. For two samples with >50 mg C/L, the fluorescence method gave 4 to 12% lower concentrations; it should be noted that these samples were above the standard calibration curve for the fluorescence method.

5.3.3 Soil Upon receipt, cores and grab samples were photographed. Initial cores were extruded using a plunger and vise system. However, due to the high caliche and clay content of cores, the heavy plastic liners had difficulty retaining physical integrity due to the high stress. Subsequently, cores were cut using a tile saw with a modified stand that allowed the saw blade to heavily score the core along the long axis of the liner in two cuts 180° apart from each other, but prevented it from completely cutting through it. The final break in integrity of the core liner was completed with an Exacto blade to minimize contamination and allow maximal control of cutting depth. The core was divided into sections and re-photographed. Each core section was then

weighed, placed in a plastic weigh boat, and dried at 90°C in an oven until the boats reached constant weight. Samples were photographed again and sieved to separate >2 and <2 mm size fractions. A portion of the fine fraction was ground, and a second portion was leached for the bioavailable metals.

Including all size fractions of soil in analysis was inappropriate because a few large cobbles can dilute and skew the concentration of other elements as well as the isotope composition (Bong et al., 2012; Dawson & Hillier, 2010; Uitdehaag et al., 2017; Pye 2007; Pye et al., 2006; Pye & Croft, 2007; Croft & Pye, 2003, 2004). In addition, large cobbles are much less likely to exchange or interact with the cadaver samples. According to the Wentworth scale, 2 mm is the standard cutoff for separating fine gravel from smaller grain sizes.

Because of concerns about metal contamination, we designed and built an all-plastic sieve system consisting of a 4" PVC pipe with a coupling. Acid-cleaned plastic mesh with 2-mm-hole diameters was cut to size and used as the sieve. This allowed frequent replacement of the sieve material to reduce cross-contamination. In between samples, the assembly was cleaned with 18 MΩ water, kimwipes, and 100% ethanol and then dried in a laminar air flow hood.

The proportion of fine and coarse fractions was determined by weight. Between 15 to 50 g of the fine fraction was then ground in a ball mill (SPEX® SamplePREP 8000D Mixer/Mill High-Energy Ball Mill) using a set of silicon nitride vial and ball set (SPEX SamplePrep Catalog #8008 with Catalog #8008A ½" balls). This fraction was used for carbon and nitrogen concentration and isotopic composition; because relatively small amounts of material is used in the measurement, it is critical to ensure homogeneity prior to analysis (Pye et al 2006).

Soil samples were analyzed by EA-IRMS at the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University, with the assistance of Natasha Zolotova. The analytical sequence was an acetanilide, followed by a blank capsule and then a pair of glycine low (value of -39.64‰ for $\delta^{13}C$, 31.58 weight percent C, +1.35‰ for $\delta^{15}N$ and 18.42 weight percent N) and glycine high (value of +15.67‰ for $\delta^{13}C$, 31.58 weight percent C, +51.8‰ for $\delta^{15}N$ and 18.42 weight percent N). There was a series of seven NIST 2710 Montana soil samples (value of -24.74‰ for $\delta^{13}C$, 3.01 weight percent C, +5.14‰ for $\delta^{15}N$, and 0.30 weight percent N) from 1 to 50 mg to evaluate linearity over the probable range of signals. Every six samples, there was another glycine low/glycine high pair for isotope scale normalization and a glycine mid (value of -8.36‰ for $\delta^{13}C$, 31.58 weight percent C, +27.9‰ for $\delta^{15}N$, and 18.42

weight percent N) as a check standard. During the course of this study, the glycine mid measured values were in good agreement with the known values (value of -8.38 ±018‰ for $\delta^{13}C$, 31.55 ±0.74 weight percent C, +27.73 ±0.14‰ for $\delta^{15}N$ and 19.32 ±0.65 weight percent N, n=23). The NIST 2710 values measured during the analysis of samples also had good agreement with known values (value of -24.83 ±0.38‰ for $\delta^{13}C$, 3.01 ±0.05 weight percent C, +4.84 ±0.57‰ for $\delta^{15}N$, and 0.29 ±0.01 weight percent N, n=24). Initial soil sample weights were 15 mg, which was later increased up to a maximum of 50 mg due to low nitrogen concentrations.

Because the underlying lithology for the FARF site is limestone, there was concern that the contribution of inorganic carbon could be high and might alter interpretations of variations due to cadaver presence or absence. The standard protocol for inorganic carbon removal involves acidification of the sample that will volatilize any carbonate content, removing the associated carbon as CO_2 gas (Harris et al, 2001). In addition, the potentially high concentration of inorganic carbon required verification that complete removal of inorganic carbon was achieved by comparing protocols using increasing aggressiveness of removal. The three protocols were: a) fuming, b) addition of 1 N HCl, and c) fuming + 1 N HCl. For fuming samples, a tray containing the open silver capsules was placed above an open container of 12 M trace metal grade hydrochloric acid for at least 12 hours. For samples with acid addition, after pre-weighing the soil powders (1-5 mg, designed to be between 60-160 μg C) into silver capsules, trace metal grade 1 N hydrochloric acid was added dropwise to each capsule until effervescence ceased. For the third treatment, samples had 1 N hydrochloric acid added, and then were fumed. Subsequently, the silver capsules were closed and samples were placed in a tin capsule as the acidification process substantially degrades the integrity of the silver capsule. All three protocols were done on a representative subset of soil samples, as well as NIST 2710 (Montana Soil). Unfortunately, no certified standards for carbon or nitrogen isotopes of acidified soils are available. The results of these experiments are discussed in the results section.

When evaluating the amount of elemental and isotopic exchange between the donor cadavers and soil, it is important to examine only what fraction is likely to participate in the exchange. Blum et al (2000) demonstrated that leaching soil with a 1 M ammonium acetate solution buffered to pH 7 gave similar $^{87}Sr/^{86}Sr$ values as plants and fauna living above. This bioavailable leach approximates the easily exchangeable ion pools. We used one gram of an unground fine fraction of the soil and ten mLs of a 1 M ammonium acetate solution buffered to

pH 7 at room temperature overnight in 15 mL trace metal grade centrifuge tubes on a rocker table at 10 rpm. These fractions were not ground because of concerns that the increased mineral surface area during grinding would produce a leach fraction that over-extracted metals from the sample. However, because the soils were not homogenized, we took additional efforts to make sure the samples were representative. As a simple example, if aliquots are scooped from the top of the sample, size sorting as samples settled might make such aliquots have a larger proportion of larger grain sizes. Hence, samples were poured into weigh boats and then subdivided into quadrants or eighths, depending on the amount of sample. The entire quadrant was then sampled. In addition, we conducted triplicate leaches of 10% of the samples to evaluate how effective our sampling protocol was.

After leaching, samples were centrifuged at 3000 rpm for 5 minutes. The supernatant was filtered through a 0.45 μm syringe filter, discarding the first mL of sample and collecting the rest in a 15-mL trace metal grade centrifuge tube. Solutions were acidified to 0.32 M trace metal grade nitric acid, and 100 μLs was diluted gravimetrically to 10 mLs for ICP-MS analysis. After concentration determination, appropriately sized aliquots were used for strontium and lead measurement (see sections below for method description).

5.3.4 Tooth enamel and bone Upon receipt, samples were assigned an Archaeological Chemistry Laboratory specimen number. They were cleaned by sonicating with water and soft tissue removed. They were then weighed, photographed and two casts made using standard laboratory protocols. One cast was to be retained at Arizona State University, and the other was intended for return to the respective skeletal collections.

Using a Dremel and either a carbide or diamond bur, visible dirt or contamination was removed. Tooth enamel was then removed with the Dremel and bur, using a light microscope to remove any cream-colored dentin.

Approximately 15 mg of powdered tooth enamel or bone powder was cleaned as outlined above and weighed into a tube. To remove organics from the sample, it was treated with 2% (v/v) NaOCl (bleach) at a ratio of 0.04 mL of bleach solution per mg of enamel or bone powder. The bleach solution was vortexed for 60 seconds, allowed to sit for 24 hours, and rinsed with 18 MΩ water three times. Subsequently, to remove diagenetic carbonate, samples were treated with 0.1 M CH_3COOH (acetic acid) at a ratio of 0.04 mL of acetic acid solution per mg of enamel or

bone powder. The acetic acid solution was vortexed for 60 seconds, allowed to sit for 24 hours, and rinsed with 18 MΩ water three times. The water was removed and the sample was dried at 50°C for 24 hours.

Between 3.6 and 3.9 mg of cleaned enamel or bone powder was weighed into Exetainers for IRMS analysis. Bone and enamel samples for $\delta^{13}C$ and $\delta^{18}O$ of carbonate were run at the Colorado Plateau Stable Isotope Laboratory (CPSIL) at Northern Arizona University. The drift standard used during analysis was Joplin CC with measured values of $\delta^{13}C_{VPDB}$ of -5.07 ±0.16 and $\delta^{18}O_{VPDB}$ of -23.46 ±0.22 (1σ, n=34). Isotope standards for scale correction included NBS 18, NBS 19, LSVEC, while Calcium Carb 3 was used for linearity correction. The accuracy and reproducibility of these standards during the samples processed for this project is listed in the Table 8.

	$\delta^{13}C_{VPDB}$	σ	$\delta^{18}O_{VPDB}$	σ	N
Isotope scale normalization standards					
NBS-18	-4.99	0.17	-23.01	0.22	23
Certificate value	*-5.014*	*0.035*	*-23.2*	*0.1*	
NBS-19	1.93	0.19	-2.20	0.18	24
Expected value	*1.95*		*-2.2*		
LSVEC	-46.60	0.18	-26.22	0.38	18
Expected value	*-46.6*		*-26.41*		
Drift standard					
Joplin CC	-5.07	0.16	-23.46	0.22	34
Linearity standard					
Calcium Carb 3	-9.68	0.17	-13.02	0.21	21

Table 8. Reproducibility and accuracy of standards for $\delta^{13}C$ and $\delta^{18}O$ for carbonates analyzed during this study.

For trace elements, Sr, and Pb isotopes, tooth enamel or bone was ashed at 800°C for at least 10 hours. Approximately 10 mg of ashed powdered tooth enamel or bone powder was digested using 0.5 mLs of 5 M nitric acid at room temperature. It was then dried down and reconstituted in 4 mLs of 2 M HNO_3 in a screw-top beaker by gravimetry. Gravimetrically-determined 50 µLs of this stock was diluted to 10 mLs with 0.32 M HNO_3 for ICP-MS analysis.

5.3.5 Hair

5.3.5.1 Mechanical and chemical cleaning Each hair sample from the ten serial donors (*n*=6 ARF, *n*=4 FARF) of approximately 100 strands was mechanically cleaned to remove any debris from the surface. Hair was gently washed by sonicating for 10 minutes in 50 mL beakers of Milli-Q water. The water was discarded after sonication. Hair was then sonicated for 10 minutes in a 2:1 chloroform:methanol solution to remove surficial contaminants, particularly lipids. The supernatant was discarded and the chloroform: methanol procedure was repeated until the solution appeared relatively free of dirt and lipids. Cleaned hair was allowed to dry in a laminar flow hood. Clean, dry hair was stored in paper coin envelopes until additional analysis-specific preparation was performed.

5.4.5.2 Carbon and Nitrogen Analyses Hair was milled into a fine powder using a liquid nitrogen ball mill (6775 Freezer/Mill, SPEX Sample Prep; Metuchen, NJ). The powder was weighed and encapsulated for bulk analysis. Carbon and nitrogen samples (0.50mg±0.10) were loaded into 3.5 x 5 mm tin capsules and were analyzed on a Costech elemental analyzer, and were introduced to the instrument via an attached zero-blank autosampler. These analyses were completed at the Stable Isotope Facility for Environmental Research (SIRFER) at the University of Utah in Salt Lake City, Utah for the majority of the samples included in this study, including the sequential time series during decomposition. Other samples were processed at several other laboratories as outlined in the comparison of laboratory data from an isotope consumer's perspective.

5.4.5.3 Oxygen and Hydrogen Analyses Hair was milled into a fine powder using a liquid nitrogen ball mill (6775 Freezer/Mill, SPEX Sample Prep; Metuchen, NJ). The powder was weighed and shipped in small glass vials to SIRFER at the University of Utah in Salt Lake City, Utah. Prior to encapsulation, samples were allowed to equilibrate with ambient laboratory atmosphere for 48 hours. After equilibration, hair was weighed and encapsulated for bulk analysis. Oxygen and hydrogen samples (0.15mg±10) were loaded into 3.5 x 5 mm silver capsules (Costech Analytical Technologies, Inc.; Valencia, CA, USA). Laboratory reference materials (keratin: DS, ORX, and POW) and USGS 42 and USGS43 were weighed into silver

capsules at similar masses to the hair samples. Samples and reference materials were stored in 96-well plastic trays under vacuum for a minimum of 5 days prior to analysis. All samples were analyzed on a ThermoFinnigan MAT 253 isotope ratio mass spectrometer. Samples were introduced to the instrument via a zero-blank autosampler attached to a high temperature conversion elemental analyzer (TC/EA). Reference materials DS and ORX were used for normalization (assigned $\delta^{18}O$ = 6.02 ‰ and 25.09 ‰, respectively) while POW was used for quality assurance (long-term mean $\delta^{18}O$ = 12.44 ‰, 2σ = 0.54 ‰, n = 335). Other samples were processed at several other laboratories as outlined in the comparison of laboratory data from an isotope consumer's perspective.

5.4 Additional hair studies This study analyzed a much larger number of hair samples than originally proposed. Hair samples for identifying recent travels can potentially provide critical investigative leads that are difficult to replicate with other techniques. There is a body of literature on preservation of isotopes in teeth and bone from the anthropological literature, but isotope preservation in hair has received less scientific study, with important exceptions (von Holstein et al 2014; Tipple et al 2013; Fraser, Meier-Augenstein and Kalin 2008). There have been important studies of morphological degradation of hair in association with burial, but much of the work has not explicitly examined isotopic preservation (Wilson et al 2007a, Wilson et al 2007b, Wilson 2008, Wilson et al 2010; Tridico et al 2014; Kintz 2012; Ji et al 2013; Chang et al 2005; Lubec et al 1987).

Destructive analyses of hair do not compromise other researcher's use of irreplaceable skeletal collections, such as the W.M. Bass Collection. Hence, much higher time resolution analyses are possible through the decomposition time period.

Hence, we ended up completing a number of small hair studies in order to achieve the original goals of this project: to determine if hair isotope values are preserved through decomposition, and if they are accurate indicators of region-of-origin. The studies are listed in Table 9.

	Individuals, samples	goal	Time scale
Data comparison from an isotopic data consumer perspective	4 standards, up to 4 labs	Accuracy and precision of measured data	n/a
Freezer study	20 individuals	Preservation during freezing	Up to 3 months
Time series	10 individuals	Preservation during decomposition	High resolution, ~1 year
Hair mats	10 individuals, 2-4 samples per individual	Increase n, longer time period than originally proposed	~1 year
Aqueous exposure (pilot)	One hair sample, two endmember water samples	Measure isotopic offsets and exchange with known aqueous endmember	3 days

Table 9. List of hair studies completed with number of samples, study goal and time scale evaluated.

These studies are not always independent; for instance, some of the hair mat samples and time series samples also were used in the freezing study. These additional analyses were required in order for us to have confidence in the data. Each project is outlined below.

5.4.1 An isotopic consumer's view of isotope data: comparison of data from multiple laboratories Our lab does not currently have validated methods for $\delta^{18}O$ and $\delta^{2}H$ of hair. Because of concerns about quality control related in particular to $\delta^{2}H$ measured values of hair, we sent out certified standards USGS 42 and 43 (Indian and Tibetan hair) for blind analysis by three external laboratories. Keratin (the protein which makes up hair) has many exchangeable hydrogen sites that typically equilibrate with local humidity. This means that if proper precautions are not taken, the measured values can reflect a mixture of the isotopic composition of the hydrogen endogenous to the hair as well as of the humidity of the laboratory in which they were analyzed. Particularly when multiple laboratories are used during the course of the study, inter-laboratory differences in accuracy or precision could seriously compromise the conclusions resulting from the analysis (Carter and Fry, 2013; Meier-Augenstein et al., 2011; Pestle, Crowley, & Weirauch, 2014).

In addition, we wanted to develop two in-house hair standards that would a) provide sufficient material to run frequent check standards and b) be more similar in isotopic

composition to our target subject pool of modern Americans. Americans are well known to be substantially different in $\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$, and $\delta^{18}O$ from Europeans and Asians (O'Connell & Hedges, 1999; Ehleringer et al., 2008; Thompson et al., 2010; Valenzuela et al., 2012; Bartelink et al., 2014). Hence, hair from two anonymous donors from local hair salons was collected, cleaned, and powdered following normal protocols. The two salons were selected with different demographics of clientele. One was a SuperCuts, and the clientele at the time of collection was dominantly Caucasian males. The other ("Transformations by Michelle") was a salon catering to African-American women. No other information is available about the donors. Samples were cleaned and powdered by with a liquid nitrogen ball mill for sufficient material to run replicates at all laboratories, as well as used as blind standards for the period of the project.

Samples were prepared and submitted according to each laboratory's preferences and analyzed according to the methods developed and validated at each laboratory. Results and details of sample preparation are listed in Section 6.4.3.

5.4.2 ***Isotopic impact of freezing and law enforcement evidence packaging protocols*** Because several of our donors were frozen prior to placement, and some samples had to be frozen for preservation, we needed to evaluate the impact of freezing on stable isotope preservation of hair. We selected 20 hair samples designed to simulate the range of possible forensic samples, including exemplars from multiple ancestries, cosmetic treatments (dyes, relaxers), and condition (salon, hair from decomposed remains). Each had five storage conditions: a) control and frozen at -20°C for b) two weeks in a plastic clamshell c) two weeks in butcher paper d) six months in a plastic clamshell and e) six months in butcher paper. Storage materials were obtained with the cooperation of the Mesa Police Department, and packaged in accordance with Mesa Police Department evidence packaging policy and guidelines. In addition, 10 paired samples (room temperature in a coin envelope and frozen) from intake hair samples at the ARF at the University of Tennessee were also analyzed, where samples had been stored for up to 4.1 years.

All samples were cleaned, powdered, processed and analyzed as unknown samples.

5.4.3 Intake and recovery hair samples at FARF To increase the number and diversity of donors and the length of exposure time in our study, we collected 10 hair mats associated with known donors in surface placements at FARF in Texas and compared the $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ values to intake samples from the same individuals.

5.4.4 Time Series Sequential time series sampling was the main analysis used for the hair portion of this study. In addition to $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $\delta^{2}H$ measurements, we analyzed elemental concentrations, and Sr and Pb isotopic compositions. Following the protocol of Tipple et al (2013), for elemental concentrations, and Sr and Pb isotopic compositions, we analyzed both bulk, a leachate and the solid residual fraction. The leach solution was a 0.1 M HCl leach, sonicated for ten minutes and repeated three times. All three leach solutions were combined to give the "leach" value. The "residue" was the solid material left after the leach solution was pipetted away. 50mg samples of hair were weighed and placed in acid-leached round-interior Teflon vials.

Samples were submerged in 3mL of concentrated HNO_3, capped, and heated on a hot plate overnight. The leachates were uncapped and dried the following day. After drying, 1mL of concentrated HNO_3 and 100uL H_2O_2 were added to each sample. The vials were capped and heated on a hot plate overnight. The samples were uncapped and dried the following day. This process was completed a total of four times, or until the organics were sufficiently digested, as indicated by visual inspection of the surface tension of sample. Samples requiring additional purification were treated with a solution of 250uL HNO_3 and 750uL 0.1M HCl; a 1:3 ratio of nitric to hydrochloric acid, also known as *aqua regia*, is particularly effective at degrading organic matter. Once digestion was completed, samples were dried down and then reconstituted in 1 mL of 2M HNO_3. A 100uL (~10%, gravimetrically determined precisely) aliquot of each sample stock solution was diluted by mass to 3.5mL using 0.32M HNO_3 for Q-ICP-MS analysis

5.4.5 ***Aqueous Exposure Pilot Study*** Results from both the hair mat study at FARF and the time series raised concerns about the preservation of strontium and lead in particular in relation to hair samples. As a preliminary method to address these concerns, we took a sample of modern hair from a single donor and submerged it into two different aqueous environments. The first was

deionized water, and the second was IAPSO seawater doped with small amounts of lead. This allowed us to evaluate any elemental and isotopic exchange with well-constrained endmembers. The endmembers were intended to span a large range in elemental composition and isotopic composition, as well as ionic strength. While neither hair nor water samples were sterilized, there was no intentional introduction of bacterial activity into the experiment. Samples were kept sealed in lighted conditions at room temperature for three days. Solutions were decanted, and the leaching procedure of Tipple et al. (2013) was followed. One modification from the time series was that leach solutions for all three sequential leaches were kept and analyzed independently.

5.5 Quadrupole inductively-coupled plasma mass mass spectrometry (Q-ICP-MS)

Aliquots of all samples were analyzed for elemental concentrations on the Thermo Fisher Scientific iCAP Q quadrupole inductively-couple plasma mass spectrometry (Q-ICP-MS) with Collision Cell Technology (CCT) option. Each measurement session the tuning parameters were optimized to maximize sensitivity, signal stability and minimize oxide and doubly charged ion production; this included tuning, mass calibration, cross-calibration and performance reports using the instrument manufacturer specified multi-element solutions. Due to the iCAP Q's improved sensitivity combined with low oxide production ratio compared to previous instrument models, all analytes were run in Kinetic Energy Discrimination (KED) mode. Typical instrument tuning parameters are listed below in Table 10.

Instrument settings	
RF power 1550 W	1550 W
Cool gas flow 14.0 L/min	14.0 L/min
Auxiliary gas flow 0.8 L/min	0.8 L/min
Sample gas flow 1.01 L/min	1.01 L/min
Mode	Kinetic Energy Discrimination (KED)
CCT gas flow 4.34 mL/min	4.34 mL/min
CCT gas 99.999% He	99.999% He
Nebulizer	400 uL/min PFA-ST nebulizer (Elemental Scientific Incorporated, Omaha, NE)
Peltier cooler temperature	2.7°C
Peristaltic pump speed	10 rpm

Table 10. Instrument parameters used for Q-ICP-MS analysis with a ThermoFinnegan iCAP Q-ICP-MS.

An internal standard solution of 200 ppb Sc, Ge, Y, In and Bi was introduced to all blanks, standards and samples by a Y-connection prior to the nebulizer. Corrections for instrumental drift in sensitivity during the course of the run was made by interpolating between internal standard elements. Standard solutions were multi-element solutions that were custom designed to have similar element ratios to natural samples such as soils. Samples were diluted to fall within the linear calibration curve; if an important element was more than 20% outside of the calibrated range, the sample was re-diluted and reanalyzed. Check standards, designed to be similar in concentration to samples, and blanks were analyzed every six samples; typical precision of check standards was better than 2% over the course of a run, and long-term reproducibility of check standards was better than 5% for most elements. When possible, multiple isotopes for elements were measured to look for potential interferences; the concentration for the isotope with the best detection limit and reproducibility and accuracy for the check standard was used in reporting. Elements analyzed included Na, Mg, Al, P, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Pd, Ag, Cd, Sn, Sb, Te, Ba, REEs, Hf, W, Re, Pt, Pb and U.

Each batch of samples analyzed also had certified reference materials processed in parallel. Occasionally, there is no certified element or isotope abundances for some elements presented, but the materials are internationally available and are included for reference for other laboratories wishing to repeat our procedures. For hair residue and leachates, we used an in-house standard from a Phoenix area salon that appeared to be from a single individual based on appearance; no additional information was available. The leaching process requires hair that is not powdered, and there is no internationally available material to our knowledge. For bulk hair, we analyzed IAEA 086, a powdered hair standard with recommended values for Hg, Fe, Zn and methylmercury; information values for Ca, Cu, Mg, Mn, Sc and Se are also listed, but Sr, Pb and other elements analyzed are not listed. Four aliquots of IAEA 086 were analyzed, and the concentrations for Mg, Ca, Mn and Fe were within the 95% confidence limit of the certified values. Scandium was not measured, as it was used in the internal standard. Se and Hg are known to be lost at variable efficiency with the digestion method used, and so are not reported. Cu and Zn were 14 and 35% lower, respectively, than the information value provided.

For soil bioavailable leaches, no international standard materials exist. However, 10% of samples were leached, processed and analyzed in triplicate to verify reproducibility. Water

samples were analyzed in parallel with SLEW-3, SLRS-4 and SRM 1640a to cover the range of ionic strengths of samples. For teeth and bones, we processed NIST 1400 (bone ash) and CUE-001 (an in-house standard of llama bone in use by Professor Kelly Knudson's lab for more than ten years).

5.5 Strontium (Sr) purification and isotopic analysis by multiple-collector inductively-coupled plasma mass spectrometry (MC-ICP-MS) Concentration data from Q-ICP-MS analysis was used to calculate the required volume of stock solution containing a maximum of 100 μg of Ca for each sample. 100 μg of Ca is the maximum amount of solute that can be added to a 1 mL ion exchange column prior to non-quantitative recovery (Romaniello et al 2015). Samples with <0.5 ng of lead were processed through manual ion exchange chromatography micro-columns to purify and separate lead for isotopic measurement. If samples had sufficient lead and strontium, separate aliquots were processed for each isotopic measurement. If the amount of sample was minimal (Pb < 0.5 ng and Sr < 5 ng), then the sample was processed first for Pb, and then for Sr. Lead isotopes are highly sensitive to potential contamination; samples varied widely in their Sr/Pb ratios, so there was concern that processing for strontium first could introduce cross-contamination, particularly as soil samples would be orders of magnitude concentration higher than hair or teeth samples.

The desired stock solution was increased to the final volume of 1mL with titrated 2M HNO_3. The automated Prepfast-MC ion exchange chromatography system (Elemental Scientific, Incorporated, Omaha, NE) was utilized in the purification, with only slight modifications in sample volumes from Romaniello et al (2015). While other laboratories use this system in-line with a MC-ICP-MS for measurement of strontium isotopes, the sample purification time exceeds that of the instrumental measurement time. In addition, this requires the use of significant molarity gradients between samples, standards, and rinse acids which often degrades the stability of the plasma temperature. Since we were also analyzing for mass-dependent strontium, a consistent matrix and well-matched sample and standard concentrations is required for good accuracy and reproducibility in $\delta^{88/86}Sr$.

Step	Purpose	Volume	Reagent
1	Condition column	10 mLs	2 M HNO_3 + 1% (v/v) H_2O_2

2	Load sample	1 mL	2 M HNO_3 + 1% (v/v) H_2O_2
3	Elute matrix elements	10 mLs	2 M HNO_3 + 1% (v/v) H_2O_2
4	Elute Sr and Pb	8-10 mLs	6 M HNO_3
5	Elute Ca	10 mLs	12 M HNO_3
6	Elute REEs, Hf, Cd, U	10 mLs	1 M HF

Table 11. Ion exchange purification of strontium and calcium (1 mL Eichrom Sr-Ca resin column); modified from Romaniello et al (2015).

The nitric acid molarities for this chemistry were titrated to within 0.2 M units, due to a steep slope in the distribution coefficients with nitric molarity. Unlike traditional manual chromatography, the column is reused for subsequent samples. In order to prevent memory effects from impacting later samples, safeguards included A) analysis of at least four method blanks per rack of sixty samples, B) analysis of at least three standards with very different isotopic compositions per rack of sixty samples, C) triplicate purification and analysis of 5-10% of samples, and D) replacement of ion exchange resin at least every 200 samples. This protocol uses a resin from Elemental Scientific, Inc. Despite extensive testing, we were unable to reduce the memory effects and blanks to acceptable levels using the traditional Eichrom Sr Spec resin. Method blanks were always less than 110 pg Sr; due to the very low amount of blank material, we were unable to properly characterize the blank isotopically. Hence, we decided to not analyze samples with <2 ng Sr because we could not accurately assess any potential blank contribution.

Strontium eluates from the Prepfast were in 10 mL of 6M HNO_3, later reduced to 8 mLs to reduce calcium peak creep forward into the strontium fraction. The matrix (steps 2 + 3 in table above), strontium (step 4) and calcium (step 5) elutions had a 10% post-chemistry aliquot was reserved from each sample to be analyzed for elemental concentrations by Q-ICP-MS. The postchemistry measurements were made in order to determine a) yield and b) sample purity from matrix. Yields were particularly important because mass-dependent strontium and calcium isotopes, in addition to radiogenic strontium isotopes, were measured for a subset of samples. Ion exchange processing is well known to produce significant mass-dependent fractionation if recovery is non-quantitative. Poor yield will not impact the accuracy or precision of the radiogenic Sr isotopes, but could bias the mass-dependent isotope values. All Sr yields were

determined to be > 88%, which has been demonstrated to give accurate mass-dependent and radiogenic Sr isotopes (Romaniello et al, 2015). Mass-dependent Ca data from a selection of subsamples were measured, and will be discussed elsewhere as interpretation is ongoing.

The remaining 9 mLs of each sample Sr eluate were dried down completely and digested overnight in 500 μL concentrated HNO_3 and 200 μL 30% H_2O_2. This process was repeated until the desired surface tension was established, for a minimum of twice and a maximum of five times. Once digestion was complete, samples were reconstituted in 0.32M HNO_3 for MC-ICP-MS analysis.

Using concentrations measured on the Q-ICP-MS, samples were diluted to 50ppb strontium, with a minimum 0.5 mL required for analysis. To monitor instrument stability and compensate for instrumental fractionation over the course of analysis, 25ppb of Zr was added to each sample measured for mass-dependent Sr as well as radiogenic Sr. Zr was not added if only radiogenic Sr was being measured. A portion of the samples (10%) were run in triplicate in order to calculate instrumental standard deviation and external reproducibility. Measurements of $^{87}Sr/^{86}Sr$ were made using a static multi-collector routine that consisted of 1 block of 60 cycles with an integration time of 4.194 sec $cycle^{-1}$ and the same cup configuration as described above. The measured $^{87}Sr/^{86}Sr$ ratios were blank-corrected, interference-corrected, and normalized for instrumental mass discrimination using a defined $^{86}Sr/^{88}Sr$ value of 0.1194. Solutions of SRM 987 (National Institute of Standards and Technology; Gaithersburg, MD, USA) of 10 or 50 μg kg^{-1}, with certified $^{87}Sr/^{86}Sr$ value of 0.71034 ± 0.00026, were analyzed before and after each set of five samples when measuring radiogenic Sr only to verify measurement accuracy and precision. To verify detector linearity, gain calibration was run prior to each measurement session, and a series of standards of varying concentration were measured. If only radiogenic Sr was being measured, the linearity standards were 1, 3, 5, 10 and 20 μg kg^{-1}; if mass-dependent Sr was also being measured, the linearity standards were 10, 20, 35, 50 and 65 μg kg^{-1}.

The reproducibility of the SRM 987 measurements through the life cycle of the study was 0.710262 ± 0.000026 (2σ, n = 598). The ^{88}Sr signal intensity and $^{87}Sr/^{86}Sr$ ranges were 0.35 – 40 volts (V) and 0.70764 – 0.73544, respectively. Samples with <1 V of signal are indicated in the table as they have an expanded error associated with them.

Additional standards run in parallel during this project are included in Table 12.

Standard	Measured value	Purpose
GravSRM	0.709910 ±0.000023 (2σ, n = 70)	gravimetrically spiked standard to determine accuracy when measuring mass-dependent Sr isotopes
SRM-987 Ca/Sr series	SRM-987 doped at increasing Ca/Sr ratios of 10, 100, 200, 350 and 500; values were always within error of the standard	Testing matrix effects for samples with variable purification
SRM-987 50%, Ca/Sr 500	0.710254 ±0.000032 (2σ, n=27)	verify if poorly concentration matched samples with residual matrix will be reproducible and accurate
BCR-2 (USGS basalt)	0.705025 ±0.000063 (2σ, n=3; three replicate chemical purifications). Literature value is 0.705015 ±0.00005 Ma et al (2013) and Fantle (2015).	Accuracy and reproducibility of external standards (rock standard)
IAPSO (seawater salinity standard, from OSIL Environmental Instruments and Systems, UK)	0.709184 ±0.000046 (2σ, n=15) for 11 separate chemical purification aliquots and 0.709182 ±0.000025 (2σ, n=18) for replicate analyses of a single chemical purification aliquot. Literature value is 0.709182 ±0.000004 (Ma et al, 2013).	Accuracy and reproducibility of external standards (seawater standard)
CUE-001 (llama bone)	0.704445 ±0.000004 (2σ, n=3, one chemical purification, three replicate analytical measurements). The literature value is 0.704455 ±0.000009 (Romaniello et al, 2015).	Accuracy and reproducibility of external standards (bone standard)
NIST 1400 (bone ash)	0.713118 ±0.000024 (2σ, n=10) for 10 independent chemically purified aliquots. Literature value is 0.713150 ±0.000160 (Galler et al, 2007).	Accuracy and reproducibility of external standards (bone standard)

Table 12. Secondary standards for $^{87}Sr/^{86}Sr$ and $\delta^{88/86}Sr$ analyzed during the course of this study.

We processed a number of matrix-matched standards through chemistry in parallel with samples to evaluate the external error. For bulk hair, these included an internationally available standard, IAEA 086, and for the leaching protocol, they included an in-house standard since no appropriate unpowdered hair standard is available. The elemental concentrations, strontium and lead isotope compositions or measured during the course of this study are discussed in Sections 6.4.1 and 6.4.2. They illustrate that the powdered standard, IAEA 086, shows better reproducibility than that of our in-house hair standard. The 5-mg sample size for the in-house standard shows poorer reproducibility for the isotope composition compared to the larger sample sizes, but is still relatively accurate. Again, the average sample size for bulk study samples was 40 mg, so we anticipate that this is in the range where the isotope composition may be reasonably reproducible.

5.7 Lead (Pb) purification and isotopic methods For good accuracy and precision, it is necessary to purify samples from the large amount of matrix that could interfere analysis, either from direct isobaric or polyatomic interferences, or from high ionic strength causing instability or non-linearity in the mass bias. In addition, because detection limits for lead are quite low, it is essential to avoid contamination at every step of sample processing, from sample collection to preparation. In addition, because we knew we had one donor with a gunshot wound to the head, we anticipated that the lead concentrations of hair samples might vary over a number of orders of magnitude. Because samples were processed with anonymized LIMS numbers, we took great care in minimizing any potential cross-contamination. This included engineering controls, such as thoroughly cleaning any work surfaces in between samples and only working with a single sample exposed at a time. Gloves were worn during all sample collection, and hair collection avoided the use of metal scissors by pulling samples from the scalp. In addition, each individual beaker went through an additional round of 6 M TM HCl heating and rinsing, after the lab cleaning using Micro90 detergent ±acetone, followed by 24 hours in heated 50% (v/v) HNO_3, 50% (v/v) HCl and 18 MΩ H_2O. Complete process blanks were run through all procedures in parallel with all batches of samples, and a significant number of samples were run in duplicate or triplicate, as well as analyzing certified and matrix-matched in-house standards when possible.

The resin used was Biorad AG1X-8 200-400 mesh resin, and was precleaned in a 250 mL glass column by passing a series of reagents through it to strip the residual matrix contributed by

the manufacturing process. This included 5 column volumes (CV) of 18 MΩ H_2O, 5 CV 0.5 N reagent (RG) HNO_3, 2 CV 18 MΩ H_2O, 5 CV 6 M RG HCl, 2 CV 18 MΩ H_2O, 2 CV ethanol, 2 CV 18 MΩ H_2O after resuspension of the resin, 1 CV 0.5 N TM HNO3, 2 CV 6M TM HCl and 3 CV 18 MΩ H_2O. The resin is then stored in 18 MΩ H_2O for use.

Custom columns were made from shrinkable Teflon tubing with a resin reservoir volume of 50 μL, 1.3 mm in height and 0.35 mm in diameter. All samples had their lead concentrations measured prior to processing, and an aliquot equivalent to 6 ng of lead or less was loaded to prevent cross-contamination between samples during column re-use. Each sample was run through columns twice to minimize any residual matrix, with fresh resin used for each column.

Samples were purified using either a custom-built metal-free "lazy Susan" column holder design or plastic column stands; both prevented needing to reach over samples to add reagents and all processes were done in Class 10 laminar air flow exhaust hoods. The column holder was designed and built by Trevor Martin. The chemistry protocol is shown in Table BB. Resin was used once and discarded. Columns were re-used after discarding the resin, and passing water, ethanol, and water through the column and fret. Columns were heated overnight in 50% v/v TM HNO_3, rinsed, and stored in 6 M TM HCl until needed. Columns were loaded with 50 uL resin, and then chemistry proceed as shown below in Table 13.

Step	Purpose	Volume	Reagent
1	Clean columns	1 mL	6 M HCl
2		500 μL	H_2O
3		1 mL	0.5 M HNO_3
4		500 μL	H_2O
5		1 mL	6 M HCl
6	Rinse out HCl	500 μL	H_2O
7	Condition column	600 μL	1.5 M HBr
8	Load sample	500 μL	1.5 M HBr
9	Remove matrix	500 μL	1.5 M HBr
10		500 μL	1.5 M HBr

11	Rinse out HBr, convert resin to chloride form	500 µL	1 M HCl
12	Collect Pb (uses 500 µL aliquots)	2 mL	6 M HCl
Dry down steps 11 and 12, and reconstitute in 500 µL 1.5 M HBr.			
13	Repeat steps 1-7 with new resin		
14	Load sample	500 µL	1.5 M HBr
15	Remove matrix	500 µL	1.5 M HBr
16		500 µL	1.5 M HBr
17	Rinse out HBr, convert resin to chloride form	500 µL	1 M HCl
18	Collect Pb (uses 500 µL aliuqots)	2.5 mLs	6 M HCl
Dry down steps 17 and 18, digest twice in 250 µLs 16 M HNO_3 and 100 mLs 30% H_2O_2 to degrade organics. Reconstitute in 500 µL 0.32 M HNO_3 for MC-ICPMS analysis.			
Dry down steps 8-10 and 14-16, digest once in 16 M HNO_3 and 100 mLs 30% H_2O_2 to degrade organics. Reconstitute in 1 mL 2 M HNO_3 for Prepfast automated purification of Sr.			

Table 13. Ion exchange purification scheme for lead isotope analysis using manual chromatography

The maximum lead blank recorded for the digests was 130 pg of Pb, with all other blank amounts <40 pg.

6 RESULTS

6.1 Water samples

6.1.1 $\delta^{18}O$ and $\delta^{2}H$ Oxygen and hydrogen isotope results for precipitation, well water land tap water samples are listed in Table 14. As discussed in the methods section for water, difficulties prevented obtaining sufficient sample to measure soil water in the unsaturated zone of both the surficial and burial sites.

	Collection date	$\delta^{18}O_{SMOW}$ ‰	σ	OIPC $\delta^{18}O_{SMOW}$ ‰	$\delta^{2}H_{SMOW}$ ‰	σ	OIPC $\delta^{2}H_{SMOW}$ ‰
Texas State							
Blanks							
Filtration blank	6/7/15	-5.87	0.13		-52.91	1.21	
Field Blank 1	6/7/15	-5.93	0.04		-56.02	0.48	
Field Blank 2	6/7/15	-5.27	0.06		-52.20	0.23	
Collector 1	6/7/15	-6.95	0.04		-48.95	0.19	
Collector 2	6/7/15	-6.94	0.06		-48.82	0.11	
Collector 3	6/7/15	-6.97	0.10		-48.58	0.24	
	6/7/15 average	-6.95	0.01	-0.7	-48.78	0.19	1
Collector 1	9/22/15	-2.20	0.15		-13.31	1.46	
Collector 2	9/22/15	-1.21	0.09		-7.22	0.74	
	9/22/15 average	-1.70	0.70	-2.5	-10.26	4.31	-11
well water	7/6/15	-3.52	0.06	annual	-23.26	0.13	annual
well water	9/22/15	-3.34	0.11	-3.9	-20.07	1.11	-22
University of Tennessee, Knoxville							
Blanks							
Field Blank 1	7/14/15	-4.09	0.08		-51.27	0.76	
Field Blank 2	7/14/15	-5.29	0.14		-55.19	1.15	
Field Blank 1	6/9/16	-5.10	0.24		-31.76	1.66	
Collector 1	7/14/15	-1.51	0.12		-4.11	0.37	
Collector 2	7/14/15	-1.48	0.10		-3.44	0.34	
Collector 3	7/14/15	-1.37	0.13		-4.08	1.31	
	7/14/15 average	-1.45	0.08	-1.8	-3.88	0.38	-3
Collector 1	8/3/15	-1.53	0.08		-4.24	0.28	
Collector 2	8/3/15	-0.59	0.11		-0.04	1.42	
Collector 3	8/3/15	-1.10	0.19		-5.30	1.57	
	8/3/15 average	-1.07	0.47	-2.8	-3.19	2.78	-11
Collector 1	*10/23/15*	*4.57*	*0.08*		*-5.32*	*0.50*	
Collector 2	*10/23/15*	*7.75*	*0.15*		*-4.79*	*0.56*	
Collector 3	*10/23/15*	*0.27*	*0.14*		*-18.78*	*0.42*	
	10/23/15 average	4.19	3.75	-5.5	-9.63	7.93	-33
Collector 1	*12/30/15*	*7.03*	*0.17*		*-16.42*	*0.63*	
Collector 2	*12/30/15*	*0.36*	*0.29*		*-24.40*	*1.59*	
Collector 3	12/30/15	-8.59	0.16		-59.99	0.37	
	12/30/15 average	-0.40	7.84	-8.3	-33.60	23.20	-55
Collector 1	6/9/16	-8.14	0.05		-50.30	1.06	
Collector 2	6/9/16	-4.87	0.21		-46.10	1.59	
Collector 3	6/9/16	-6.93	0.15		-54.77	0.51	
	6/9/16 average	-6.65	1.65	-2.8	-50.39	4.34	-10
tap water (unfiltered)	7/20/15	-4.08	0.11		-33.75	0.56	
tap water (filtered)	7/20/15	-4.78	0.08	annual	-35.14	0.52	annual
tap water (filtered)	3/9/16	-2.72	0.24	-5.8	-33.63	0.45	-34
ground water	12/30/15	-9.28	0.10		-66.40	0.65	

Table 14. Precipitation, tap water and well water samples for $\delta^{18}O$ and $\delta^{2}H$ at the two sites. For comparison, values from the OIPC for those sampling dates are also listed.

6.1.2 $\delta^{13}C$, [DIC], [DOC], total nitrogen Dissolved organic and inorganic carbon concentrations, total nitrogen, and carbon isotopes for precipitation and well water samples are listed in Table 15. As discussed in the methods, carbon isotopes were only determined on samples with >2 mg C/L due to blank considerations. None of the listed water samples were in contact with the donor bodies.

	Collection date	DOC (mg C/L)	DOC - δ^{13C}_{VPDB} ‰	σ	DIC (mg C/L)	DIC - δ^{13C}_{VPDB} ‰	σ	TN (mg N/L)
instrumental blank		0.4			-0.1			0.02
Texas State								
Blanks								
Field Blank 1	6/7/15	2.2	-31.3	0.2	0.1	n.d.		0.57
Field Blank 2	6/7/15	1.3	n.d.		bdl	n.d.		0.34
Collector 1	6/7/15	2.2	-28.0	0.2	bdl	n.d.		1.42
Collector 2	6/7/15	7.8	-26.1	0.2	0.5	n.d.		1.45
Collector 3	6/7/15	1.7	n.d.		bdl	n.d.		0.83
	6/7/15 average	3.9	-27.0	1.3				
Collector 1	9/22/15	3.7	-27.9	0.2	0.8	n.d.		0.50
Collector 2	9/22/15	8.1	-26.8	0.2	0.1	n.d.		0.47
	9/22/15 average	5.9	-27.4	0.8				
well water	7/6/15	0.5	n.d.		57.8	-6.2	0.3	1.03
well water	9/22/15	0.6	n.d.		57.6	-6.4	0.3	1.35
University of Tennessee, Knoxville								
Blanks								
Field Blank 1	7/14/15	0.6	n.d.		bdl	n.d.		0.04
Field Blank 2	7/14/15	0.7	n.d.		bdl	n.d.		0.06
Collector 1	7/14/15	7.3	-27.7	0.2	bdl	n.d.		1.36
Collector 2	7/14/15	5.7	-27.6	0.2	bdl	n.d.		0.80
Collector 3	7/14/15	6.5	-27.8	0.2	0.4	n.d.		1.01
	7/14/15 average	6.5	-27.7	0.1				
Collector 1	8/3/15	3.8	-28.0	0.2	0.6	n.d.		2.03
Collector 2	8/3/15	3.0	-27.0	0.2	1.3	n.d.		0.81
Collector 3	8/3/15	2.8	-27.2	0.2	0.5	n.d.		0.68
	8/3/15 average	3.2	-27.4	0.6	0.8			

Table 15. Concentrations and isotopic composition of carbon and nitrogen in water samples. The DOC and DIC concentrations are those measured by fluorescence, although they are in good agreement with concentrations measured by an infrared sensor. For samples with less than 2 mg C/L, isotopic compositions were not measured. Error on DOC concentrations was 0.2 mg/L, while the error for DIC concentrations was less than 0.5 mg/L for field blanks and precipitation samples. The error on DIC concentrations for the two well samples is 1.0 and 1.3 mg C/L, respectively.

6.1.3 Major and trace element concentrations Major and trace element concentrations of water samples as determined by Q-ICP-MS are listed in Table 16. Samples were filtered and acidified in the field, as outlined in the Section 5.2.1. The groundwater sample for the ARF site was collected as ponded water at the base of the slope, and should not be taken as representative of groundwater at the site.

	Collection date	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
		ppm	ppm	ppb	ppb	ppm	ppm	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
Texas State															
Blanks															
Field Blank 1	6/7/15	0.08	0.15	201.3	8.69	<LOD	2.67	0.42	0.72	0.88	2.51	79.0	0.62	0.24	1.07
Field Blank 2	6/7/15	0.02	0.27	6.06	<LOD	<LOD	0.57	0.15	0.60	0.20	13.70	17.6	0.46	0.11	0.33
Collector 1	6/7/15	0.72	0.86	22.7	20.48	<LOD	2.09	0.35	0.24	0.79	4.18	64.0	1.80	0.35	1.15
Collector 2	6/7/15	0.92	0.33	108.4	54.87	0.96	2.69	0.64	0.37	0.48	6.20	47.2	0.31	0.35	7.32
Collector 3	6/7/15	0.62	0.13	67.0	33.34	<LOD	1.28	0.29	0.21	0.38	2.56	35.4	0.29	0.29	2.37
Collector 1	9/22/15	0.98	0.59	7.35	<LOD	0.15	3.08	0.50	0.73	0.67	9.38	5.6	1.12	0.31	0.08
Collector 2	9/22/15	1.15	0.62	66.4	<LOD	1.86	6.72	0.54	1.20	0.94	18.30	34.4	0.86	0.82	18.15
well water	6/7/15	4.03	28.37	<LOD	5.79	1.17	111.80	0.35	0.68	0.08	0.25	38.1	0.01	0.17	0.77
well water	9/22/15	3.71	27.75	<LOD	17.57	1.01	100.94	0.33	1.37	0.53	0.50	1.5	0.01	0.25	0.68
University of Tennessee, Knoxville															
Blanks															
Field Blank 1	7/14/15	<LOD	0.00	<LOD	<LOD	<LOD	0.02	0.14	0.54	0.15	0.05	0.1	0.00	0.03	<LOD
Field Blank 2	7/14/15	0.03	0.01	<LOD	<LOD	<LOD	0.15	0.22	0.68	0.40	0.86	0.7	0.04	0.16	0.53
Collector 1	7/14/15	0.24	0.18	10.71	33.19	1.41	1.03	0.43	0.64	0.51	53.24	9.0	0.06	0.18	1.94
Collector 2	7/14/15	0.18	0.15	7.97	<LOD	1.03	0.86	0.30	0.67	0.28	25.28	6.5	0.05	0.13	1.13
Collector 3	7/14/15	0.15	0.20	9.59	9.92	1.56	1.04	0.37	0.68	0.42	40.38	8.3	0.10	0.23	1.57
Collector 1	8/3/15	0.39	0.23	6.48	140.33	1.31	1.25	0.55	0.64	1.26	3.46	12.8	0.06	0.40	1.34
Collector 2	8/3/15	0.18	0.23	7.85	43.30	1.43	1.26	0.53	0.63	3.43	16.74	8.6	0.04	0.33	2.80
Collector 3	8/3/15	0.18	0.18	6.15	18.85	1.15	0.90	0.35	0.62	0.27	30.01	5.1	0.04	0.09	0.87
Collector 1	12/30/15	0.31	0.65	30.90	27.28	10.28	2.54	0.66	0.76	0.80	5.13	30.3	0.03	0.70	4.02
Collector 2	12/30/15	0.34	0.69	15.01	16.04	5.77	2.66	0.51	0.82	5.20	1.00	18.3	0.02	0.36	6.24
Collector 3	12/30/15	0.19	0.44	100.33	27.30	7.47	1.56	0.68	0.56	0.26	119.7	100.7	0.10	0.28	2.26
tap water (filtered)	3/9/16	8.20	6.30	bdl	225.47	1.72	24.92	0.22	0.39	0.23	0.12	bdl	0.13	0.84	26.31
ground water	12/30/15	4316.48	22.99	34.52	86.16	10.72	225.37	1.42	0.84	1.29	6530	973.2	10.50	1.64	1.76

Table 16. Elemental concentrations of precipitation, well water and tap water, measured by Q-ICP-MS. Samples are corrected for field blanks, using the field blank collected from the site closest in time to the samples.

Table 16. Elemental concentrations of water samples continued

	Collection date	Zn ppb	As ppb	Se ppb	Rb ppb	Sr ppb	Mo ppb	Cd ppb	Sn ppb	Sb ppb	Ba ppb	La ppb	Ce ppb	Pr ppb	Nd ppb
Texas State															
Blanks															
Field Blank 1	6/7/15	190.0	0.77	0.22	0.08	2.79	<LOD	0.294	1.31	0.18	3.00	0.73	2.12	0.139	0.18
Field Blank 2	6/7/15	33.3	0.07	<LOD	0.01	0.65	<LOD	0.014	0.57	0.15	1.20	0.01	0.02	0.002	0.01
Collector 1	6/7/15	124.5	0.14	<LOD	0.12	2.40	0.13	0.055	0.95	0.87	1.81	0.05	0.08	0.009	0.05
Collector 2	6/7/15	145.0	0.59	<LOD	1.09	3.11	0.04	0.303	0.55	0.17	3.13	0.37	1.14	0.076	0.11
Collector 3	6/7/15	143.0	0.42	<LOD	0.10	1.61	<LOD	0.298	0.48	0.47	1.94	0.24	0.77	0.047	0.06
Collector 1	9/22/15	98.6	0.53	0.46	0.36	4.40	0.04	0.039	0.37	0.39	7.08	0.01	0.08	0.011	0.05
Collector 2	9/22/15	220.0	1.93	0.59	2.32	7.40	<LOD	0.373	0.27	0.20	6.96	0.22	0.70	0.057	0.11
well water	6/7/15	27.0	0.20	0.42	2.45	10188	4.90	0.006	0.34	0.02	106.4	0.00	<LOD	<LOD	<LOD
well water	9/22/15	28.0	0.22	0.51	2.09	8544	5.45	0.004	4.39	0.05	98.0	0.00	<LOD	<LOD	<LOD
University of Tennessee, Knoxville															
Blanks															
Field Blank 1	7/14/15	7.7	0.02	<LOD	<LOD	0.04	<LOD	0.004	0.15	0.02	0.82	<LOD	<LOD	<LOD	<LOD
Field Blank 2	7/14/15	13.9	0.05	0.23	0.03	0.54	<LOD	0.012	0.20	0.03	1.52	<LOD	0.00	0.000	0.00
Collector 1	7/14/15	10.9	2.13	<LOD	0.62	1.78	<LOD	0.011	0.22	0.18	3.20	0.04	0.09	0.012	0.06
Collector 2	7/14/15	65.6	0.37	<LOD	0.47	1.56	<LOD	0.009	0.18	0.16	2.78	0.03	0.07	0.009	0.04
Collector 3	7/14/15	16.7	0.36	<LOD	0.73	1.71	<LOD	0.023	0.26	0.13	3.42	0.05	0.12	0.015	0.07
Collector 1	8/3/15	8.4	2.26	<LOD	0.59	1.82	0.04	0.013	0.17	0.41	3.37	0.02	0.05	0.006	0.03
Collector 2	8/3/15	12.8	4.65	<LOD	0.66	1.59	0.03	0.007	0.14	0.30	3.23	0.03	0.07	0.009	0.04
Collector 3	8/3/15	32.7	0.91	<LOD	0.56	1.20	<LOD	0.010	0.07	0.28	2.51	0.02	0.04	0.005	0.02
Collector 1	12/30/15	17.4	2.54	bdl	3.48	2.78	0.88	bdl	0.34	0.67	2.82	0.03	0.08	0.018	0.08
Collector 2	12/30/15	11.0	6.95	0.65	1.67	2.93	0.77	bdl	0.18	0.65	3.07	0.03	0.03	0.015	0.07
Collector 3	12/30/15	15.9	1.18	bdl	2.40	1.75	0.39	bdl	0.04	0.29	bdl	0.04	0.18	0.025	0.11
tap water (filtered)	3/9/16	50.6	0.20	bdl	1.23	87.6	0.65	0.004	0.03	0.06	24.56	0.00	bdl	bdl	bdl
ground water	12/30/15	43.09	2.72	1.98	1.69	707.30	0.67	0.03	0.09	0.28	625	0.15	0.74	0.064	0.28

	Collection date	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pb	U
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
Texas State																
Blanks																
Field Blank 1	6/7/15	0.029	0.004	0.020	0.002	0.013	0.003	0.008	0.001	0.008	0.001	0.001	0.006	0.0003	2.15	0.0011
Field Blank 2	6/7/15	0.002	0.000	0.002	0.000	0.003	0.000	0.001	0.000	0.001	0.000	<LOD	0.003	0.0002	0.46	0.0289
Collector 1	6/7/15	0.007	0.001	0.008	0.001	0.007	0.001	0.003	0.000	0.004	0.000	0.000	0.004	<LOD	2.08	0.0088
Collector 2	6/7/15	0.020	0.003	0.016	0.002	0.011	0.002	0.006	0.001	0.005	0.001	0.000	0.072	0.0002	1.76	0.0111
Collector 3	6/7/15	0.011	0.002	0.008	0.001	0.006	0.001	0.003	0.000	0.003	0.000	0.001	0.005	<LOD	1.36	0.0037
Collector 1	9/22/15	0.012	0.003	0.011	0.001	0.009	0.002	0.005	0.001	0.004	0.001	0.001	0.003	0.0006	0.46	0.0129
Collector 2	9/22/15	0.022	0.004	0.018	0.003	0.014	0.003	0.009	0.001	0.010	0.002	0.001	0.011	0.0004	1.18	0.0081
well water	6/7/15	<LOD	0.003	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.0104	0.22	0.48
well water	9/22/15	<LOD	0.003	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.000	<LOD	0.004	0.0164	0.14	0.61
University of Tennessee, Knoxville																
Blanks																
Field Blank 1	7/14/15	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.004	0.0007	0.05	<LOD
Field Blank 2	7/14/15	<LOD	0.000	0.000	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.000	0.024	0.0006	0.84	0.0004
Collector 1	7/14/15	0.014	0.003	0.013	0.002	0.010	0.002	0.007	0.001	0.006	0.001	0.001	0.009	0.0005	0.55	0.0049
Collector 2	7/14/15	0.008	0.002	0.009	0.001	0.008	0.002	0.004	0.001	0.004	0.001	0.000	0.009	0.0005	0.59	0.0040
Collector 3	7/14/15	0.014	0.003	0.015	0.002	0.012	0.003	0.007	0.001	0.005	0.001	0.001	0.008	0.0005	0.55	0.0045
Collector 1	8/3/15	0.006	0.001	0.007	0.001	0.006	0.001	0.004	0.000	0.003	0.000	0.001	0.021	0.0011	1.00	0.0072
Collector 2	8/3/15	0.008	0.002	0.010	0.001	0.008	0.002	0.005	0.001	0.004	0.001	0.001	0.015	0.0010	0.81	0.0042
Collector 3	8/3/15	0.007	0.001	0.005	0.001	0.005	0.001	0.003	0.000	0.003	0.000	<LOD	0.004	0.0005	0.48	0.0019
Collector 1	12/30/15	0.162	0.004	0.019	0.033	0.018	0.004	0.012	0.019	0.010	0.002	bdl	bdl	0.0015	0.03	bdl
Collector 2	12/30/15	0.168	0.004	0.021	0.030	0.019	0.005	0.012	0.014	0.007	0.001	bdl	bdl	0.0012	0.01	bdl
Collector 3	12/30/15	0.254	0.005	0.030	0.050	0.036	0.009	0.027	0.041	0.025	0.004	bdl	bdl	0.0008	0.11	bdl
tap water (filtered)	3/9/16	bdl	0.001	0.003	bdl	0.001	bdl	0.001	0.003	0.001	0.000	bdl	bdl	0.0009	0.20	0.0191
ground water	12/30/15	0.658	0.027	0.067	0.100	0.059	0.013	0.036	0.048	0.030	0.005	0.007	bdl	0.0026	0.48	0.60

Table 16 Elemental concentrations of water samples continued.

6.1.4 Strontium and lead isotope compositions Strontium and lead isotope compositions of water samples are listed in Table 17. Strontium and lead concentrations in precipitation was negligible compared to concentrations in bioavailable soil leaches. Lead isotope compositions were only analyzed in the earlier samples. Strontium concentrations in the well water samples at FARF (10,188 and 8,544 ppm Sr) were far higher than the precipitation samples (<8 ppm Sr).

	Collection date	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Texas State								
Blanks								
Field Blank 1	6/7/15	0.70840	0.26	*18.291*	*15.591*	*38.000*	*2.078*	*0.852*
Field Blank 2	6/7/15			18.069	15.590	38.164	2.112	0.863
Collector 1	9/22/15	0.71040	n.d.	18.195	15.597	38.198	2.099	0.857
Collector 2	9/22/15	0.70924	0.57	18.084	15.605	38.120	2.108	0.863
well water	6/7/15	0.70751	0.15					
	repeat	0.70753	0.22					
well water	9/22/15	0.70752	0.14					
	repeat	0.70750	0.16					
	repeat	0.70751	0.19					
University of Tennessee, Knoxville								
Blanks								
Field Blank 1	7/14/15			bdl	bdl	bdl	bdl	bdl
Field Blank 2	7/14/15	0.70902	0.35	18.007	15.593	38.078	2.115	0.866
Collector 1	7/14/15			18.598	15.625	38.299	2.059	0.840
Collector 2	7/14/15			18.448	15.610	38.199	2.071	0.846
Collector 3	7/14/15	0.71095	0.34					
Collector 1	8/3/15	0.71203	0.29	18.716	15.643	38.333	2.048	0.836
Collector 2	8/3/15	0.71113	0.27	18.604	15.629	38.292	2.058	0.840
Collector 3	8/3/15			18.548	15.627	38.293	2.064	0.843
Collector 1	12/30/15	0.71150	0.50					
Collector 2	12/30/15							
Collector 3	12/30/15	0.71143	0.24					
tap water (filtered)	3/9/16	0.71119	0.30	18.357	15.613	38.067	2.074	0.850
	repeat	0.71117	0.28					
ground water	12/30/15	0.71150	0.31	18.790	15.631	38.413	2.044	0.832
	repeat	0.71151	0.31					
	repeat	0.71151	0.19					

Table 17. Strontium and lead isotopic composition of waters analyzed during the course of this study. Repeat means a repeat chemical purification of the same sample collection.

6.2 Soil samples Samples were taken as "grab" samples, or core samples. "Grab" samples were taken from close to the site of the head immediately prior to placement of the donor cadaver. Hence, "grab" sample for burials were taken from the bottom of the grave immediately prior to cadaver placement. A core sample was taken from the site of Burial 2 at ARF, immediately prior to digging the grave. Two soil core samples were taken from each of the two facilities. At ARF, the two cores were taken from the general area of the donor placements, and tried to avoid previous placements which may have altered the element cycling (Damman, Tanittaisong, & O'Carter, 2012). FARF has far less historical occupation of the area by cadavers, and is not expected to be as modified by previous placements. The two cores at FARF were designed to include both open grassland and forested grove. Most of the placements were within the forested grove.

6.2.1 $\delta^{13}C$ and $\delta^{15}N$ The carbon and nitrogen concentrations and isotopic composition of the soils was determined on the <2 mm fraction after homogenization by grinding as outlined in Section 5.3.3. The sieving process excluded large leaf litter, but smaller plant organic material was included.

	depth (inches)	$\delta^{13}C_{VPDB}$	wt% C	$\delta^{15}N_{AIR}$	wt% N
University of Tennessee, Knoxville					
Surface 1	grab	-26.96	4.73	4.75	0.32
	replicate	-28.04	4.52	4.37	0.32
	replicate	-26.38	4.64	4.62	0.32
	mean	-27.13	4.63	4.58	0.32
	σ	0.84	0.10	0.19	0.00
Surface 2	grab	-27.37	7.84	2.38	0.51
Surface 3	grab	-27.29	9.54	2.76	0.61
Burial 1	grab	-25.92	2.55	4.36	0.19
Burial 2	grab	-24.35	0.81	7.16	0.089
	replicate	-23.76	0.70	6.43	0.085
	replicate	-23.46	0.69	7.12	0.085
	mean	-23.86	0.73	6.90	0.087
	σ	0.46	0.06	0.41	0.003
Burial 2 - core prior to placement	0-1	-25.65	2.34	6.69	0.19
	replicate	-26.07	2.36	6.39	0.19
	1-2	-26.08	2.30	6.29	0.19
	2-4	-25.91	1.93	7.03	0.17
	4-6	-25.37	1.23	7.39	0.12
	6-8 1/2	-23.19	0.36	6.26	0.05
Core 1	0-1	-26.96	4.78	5.52	0.35
	1-2	-26.19	4.24	5.00	0.32
	replicate	-26.86	4.31	4.87	0.32
	2-4	-26.08	3.05	4.32	0.24
	4-6	-25.91	2.51	5.00	0.20
	replicate	-25.40	2.50	4.77	0.20
	6-9	-25.29	1.72	5.41	0.14
	9-12	-25.16	1.10	6.18	0.09
Core 2	0-1	-26.19	5.73	3.26	0.45
	1-2	-25.83	4.57	3.77	0.38
	2-4	-25.23	3.80	4.21	0.32
	4-6	-25.26	2.37	5.96	0.21
	6-9	-25.09	1.47	7.70	0.12
	9-12	-24.64	1.08	7.96	0.09
Texas State, San Marcos					
Surface 4	grab	-17.20	3.35	4.66	0.29
Surface 5	grab	-19.42	3.99	4.36	0.33
Surface 6	grab	-15.33	3.11	3.82	0.25
	replicate	-15.63	3.13	3.70	0.24
Burial 4	grab	-15.67	2.34	8.17	0.21
Core 1 (open grassland)	0-1	-18.38	2.66	4.41	0.25
	1-2	-17.03	1.95	5.71	0.18
	replicate	-17.32	1.93	5.61	0.18
	2-4	-15.87	1.65	6.93	0.15
	4-6	-14.63	1.30	8.21	0.11
	6-9	-14.07	1.13	8.96	0.09
	9-12	-12.84	1.11	9.26	0.10
	replicate	-13.05	1.10	9.47	0.10
Core 2 (forested)	0-4 1/2	-23.00	3.71	3.94	0.29
	4 1/2-8	-15.90	2.04	7.85	0.16
	8-12	-19.86	2.28	7.74	0.13

Table 18. Carbon and nitrogen contents and isotopic composition of soil samples at both ARF and FARF.

6.2.2 Major and trace element concentrations of bioavailable soil leaches Soils were leached with 1 M ammonium acetate as described in Section 5.3.3 in order to determine the components most likely to be bioavailable and reactive with the donor bodies. Aliquots of the resulting leach stocks were measured for major and trace element composition, as listed in Table BN for the FARF site and Table BO for the ARF site.

		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppb	ppm
	LOD	0.20	0.012	0.046	0.35	0.13	0.09	0.011	0.32	0.67	0.0005
	LOQ	0.66	0.039	0.153	1.15	0.42	0.30	0.038	1.08	2.23	0.0017
Process leach blank		<LOD	<LOQ	<LOD	<LOQ	<LOQ	0.3	<LOD	<LOD	<LOQ	<LOD
Texas State, San Marcos											
Grab samples (surface material, <2 inches depth)											
Surface 4	grab	<LOQ	24.98	<LOD	<LOQ	15.2	186	<LOD	<LOQ	<LOQ	5.09
Surface 5	grab	0.69	23.99	<LOD	<LOQ	15.0	199	<LOD	<LOQ	<LOQ	5.22
Surface 6	grab	<LOD	24.22	<LOD	<LOQ	33.2	239	<LOD	<LOQ	<LOQ	3.45
	replicate	<LOQ	24.81	<LOD	<LOQ	26.5	301	<LOD	<LOQ	<LOQ	15.98
Surface 7	grab	<LOD	20.69	<LOD	<LOQ	21.7	427	<LOD	1.52	<LOQ	1.78
Soil cores (depth in inches)											
Core 1 (open grassland)	0-1	<LOD	20.33	<LOD	<LOQ	26.7	199	<LOD	<LOQ	<LOQ	5.10
	1-2	<LOQ	17.22	<LOD	<LOQ	23.1	169	<LOD	<LOQ	<LOQ	3.92
	2-4	<LOD	15.41	<LOD	<LOQ	21.6	166	<LOD	<LOD	<LOQ	4.71
	4-6	<LOQ	12.21	<LOD	<LOQ	16.3	169	<LOD	<LOD	<LOQ	2.67
	6-9	<LOQ	10.86	<LOD	<LOQ	14.0	203	<LOD	<LOD	<LOQ	2.16
	replicate	<LOQ	10.56	<LOD	<LOQ	13.7	196	<LOD	<LOD	<LOQ	2.13
	replicate 2	<LOQ	10.86	<LOD	<LOD	13.4	197	<LOD	<LOD	<LOD	2.17
	mean	<LOQ	10.76	<LOD	<LOQ	13.7	198.6	<LOD	<LOQ	<LOQ	2.16
	σ		0.18			0.3	4.1				0.02
	σ (%)		2%			2%	2%				1%
	9-12	0.72	11.31	<LOD	<LOQ	15.4	272	<LOD	<LOD	<LOQ	1.90
Core 2 (forested)	0-4 1/2	<LOD	24.75	<LOD	<LOQ	16.4	212	<LOD	<LOQ	<LOQ	7.01
	4 1/2-8	<LOQ	21.66	<LOD	<LOQ	12.8	177	<LOD	<LOD	<LOQ	4.45
	8-12	1.15	23.65	<LOD	<LOQ	15.5	210	<LOD	<LOD	<LOQ	6.29

Table 19. Soil leach elemental concentrations in ppm for the Texas FARF site. Samples denoted with Surface 4 indicate that soil was taken from the site immediately before placement of the corresponding donor near the cranial region. Samples are corrected for the leach process blank. The limit of detection (LOD) and limit of quantitation (LOQ) are the instrumental limits, multiplied by the typical dilution factor. This is to allow interpretation of what LOD and LOQ are in the context of these samples.

		Fe	Co	Ni	Cu	As	Se	Rb	Sr	Mo	Cd
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	4.35	0.14	0.90	5.84	2.72	23.03	0.41	0.31	0.12	0.11
	LOQ	14.49	0.46	3.00	19.47	9.06	76.77	1.37	1.02	0.40	0.37
Process leach blank		<LOQ	<LOD	<LOD	<LOD	<LOD	<LOD	13.37	<LOQ	0.46	<LOD
Texas State, San Marcos											
Grab samples (surface material, <2 inches depth)											
Surface 4	grab	12.22	5.21	5.24	<LOD	<LOQ	<LOD	201.7	266	0.07	4.77
Surface 5	grab	38.77	5.76	4.98	<LOD	<LOQ	<LOQ	193.9	275	0.29	3.81
Surface 6	grab	<LOQ	5.14	3.93	<LOD	<LOQ	<LOD	135.2	257	0.07	2.75
	replicate	<LOQ	37.06	9.60	<LOQ	<LOQ	<LOD	165.9	301	<LOQ	4.54
Surface 7	grab	<LOQ	2.18	<LOQ	<LOD	<LOD	<LOD	192.4	268	<LOQ	1.44
Soil cores (depth in inches)											
Core 1 (open grassland)	0-1	<LOQ	5.62	4.67	<LOD	<LOQ	<LOD	179.6	239	0.33	4.67
	1-2	<LOQ	3.57	6.82	<LOD	<LOQ	<LOD	134.6	203	0.20	3.38
	2-4	<LOQ	4.01	9.55	<LOD	<LOQ	<LOD	115.3	200	0.37	3.58
	4-6	<LOD	2.00	9.91	<LOD	<LOQ	<LOD	110.2	179	0.09	2.77
	6-9	<LOD	2.10	8.68	<LOD	<LOQ	<LOQ	134.8	169	0.06	2.25
	replicate	<LOQ	2.25	8.66	<LOD	<LOQ	<LOD	132.4	166	0.07	1.85
	replicate 2	<LOD	2.42	9.15	<LOD	<LOQ	<LOQ	140.0	176	0.28	1.62
	mean	<LOD	2.26	<LOQ	<LOQ	<LOQ	<LOD	135.8	170	0.14	1.91
	σ		0.16					3.9	5	0.13	0.32
	σ (%)		7%					3%	3%	91%	17%
	9-12	22.48	2.11	7.31	<LOQ	9.46	<LOD	182.5	189	0.40	2.06
Core 2 (forested)	0-4 1/2	<LOQ	7.50	5.46	<LOD	<LOQ	<LOQ	105.5	226	<LOQ	3.81
	4 1/2-8	<LOQ	9.47	9.88	<LOD	9.18	<LOQ	109.5	203	<LOQ	2.88
	8-12	<LOQ	34.88	8.17	<LOD	11.76	<LOQ	113.1	231	0.06	2.26

Table 19. Soil leach elemental concentrations at FARF continued.

		Sn	Sb	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.45	0.11	0.06	0.06	0.15	0.024	0.11	0.031	0.020	0.11
	LOQ	1.49	0.35	0.20	0.19	0.50	0.079	0.38	0.105	0.068	0.36
Process leach blank		<LOD	<LOQ	<LOQ	0.76	<LOD	0.47	<LOQ	<LOD	<LOD	<LOD
Texas State, San Marcos											
Grab samples (surface material, <2 inches depth)											
Surface 4	grab	<LOD	<LOQ	292.4	17.65	29.20	4.00	21.67	4.85	1.02	4.17
Surface 5	grab	<LOD	<LOQ	335.1	18.57	31.92	4.34	22.60	4.82	1.01	4.57
Surface 6	grab	<LOD	<LOD	290.1	9.97	15.45	2.18	13.23	2.72	0.64	2.61
	replicate	<LOD	<LOQ	325.8	28.74	41.44	6.82	34.44	7.55	1.48	6.56
Surface 7	grab	<LOD	<LOQ	247.7	8.42	10.47	1.58	9.71	2.04	0.36	1.84
Soil cores (depth in inches)											
Core 1 (open grassland)	0-1	<LOD	<LOD	273.0	13.91	19.90	3.20	16.91	3.41	0.80	3.36
	1-2	<LOD	<LOD	240.3	20.02	30.18	4.97	26.05	5.50	1.25	5.09
	2-4	<LOD	<LOQ	262.9	23.03	34.37	5.96	30.18	6.97	1.44	6.74
	4-6	<LOD	<LOD	261.9	25.75	30.75	6.79	35.69	8.38	1.69	7.23
	6-9	<LOD	<LOD	284.9	36.34	27.32	9.86	49.14	11.01	2.23	10.31
	replicate	<LOD	<LOD	268.8	34.18	26.44	9.02	46.22	10.43	2.22	10.05
	replicate 2	<LOD	<LOD	286.1	36.67	28.31	9.65	50.28	11.34	2.20	10.83
	mean	<LOD	<LOQ	280.0	35.73	27.36	9.51	48.55	10.93	2.22	10.40
	σ			9.7	1.35	0.93	0.44	2.10	0.46	0.01	0.40
	σ (%)			3%	4%	3%	5%	4%	4%	1%	4%
	9-12	<LOD	<LOD	355.4	49.99	26.24	13.12	65.29	14.72	2.89	13.09
Core 2 (forested)	0-4 1/2	<LOD	<LOQ	295.4	19.53	34.17	4.62	24.50	5.89	1.16	4.84
	4 1/2-8	<LOD	<LOQ	332.1	33.11	59.84	9.21	47.49	11.41	2.11	10.24
	8-12	<LOD	<LOQ	377.6	44.18	87.46	11.85	60.36	13.91	2.83	12.20

Table 19. Soil leach elemental concentrations at FARF continued.

		Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pb	U
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.042	0.10	0.04	0.12	0.03	0.09	0.02	0.02	0.25	0.02	0.05	0.014
	LOQ	0.142	0.32	0.13	0.40	0.09	0.29	0.07	0.06	0.84	0.05	0.15	0.048
Process leach blank		<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOQ	<LOQ
Texas State, San Marcos													
Grab samples (surface material, <2 inches depth)													
Surface 4	grab	0.45	2.22	0.41	0.93	0.09	0.50	0.08	<LOD	<LOD	<LOD	1.26	0.30
Surface 5	grab	0.48	2.24	0.40	0.90	0.09	0.54	0.08	<LOD	<LOD	<LOD	2.10	0.35
Surface 6	grab	0.23	1.15	0.21	0.46	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	1.06	0.26
	replicate	0.68	3.19	0.55	1.16	0.11	0.54	<LOQ	<LOD	<LOD	<LOD	1.63	0.56
Surface 7	grab	0.17	0.92	0.16	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	<LOD	0.77	0.19
Soil cores (depth in inches)													
Core 1 (open grassland)	0-1	0.37	1.81	0.29	0.65	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	1.10	0.21
	1-2	0.55	2.62	0.45	1.08	0.11	0.41	0.07	<LOD	<LOD	<LOD	1.29	0.29
	2-4	0.68	3.13	0.60	1.43	0.13	0.69	0.08	<LOD	<LOD	<LOD	1.32	0.39
	4-6	0.78	3.62	0.70	1.64	0.15	0.72	0.11	<LOD	<LOD	<LOD	0.99	0.47
	6-9	1.07	5.24	0.92	2.40	0.24	0.98	0.15	<LOD	<LOD	<LOD	0.87	0.61
	replicate	1.08	5.07	0.97	2.08	0.22	1.06	0.13	<LOD	<LOD	<LOD	0.74	0.54
	replicate 2	1.06	5.78	1.00	2.38	0.20	1.14	0.18	<LOD	<LOD	<LOD	0.86	0.60
	mean	1.07	5.36	0.97	2.29	0.22	1.06	0.16	<LOD	<LOD	<LOD	0.82	0.59
	σ	0.01	0.37	0.04	0.18	0.02	0.08	0.02				0.07	0.04
	σ (%)	1%	7%	4%	8%	8%	7%	15%				9%	6%
	9-12	1.41	6.86	1.23	2.62	0.26	1.19	0.18	<LOD	<LOD	<LOD	0.90	0.58
Core 2 (forested)	0-4 1/2	0.55	2.76	0.51	1.21	0.12	0.66	0.10	<LOD	<LOD	<LOD	3.03	0.46
	4 1/2-8	1.07	5.49	1.01	2.47	0.24	1.27	0.19	<LOD	<LOD	<LOD	1.89	1.03
	8-12	1.31	6.18	1.18	2.64	0.28	1.49	0.24	<LOD	<LOD	<LOD	3.01	0.95

Table 19. Soil leach elemental concentrations at FARF continued.

		Na	Mg	Al	P	K	Ca	Ti	V
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb
	LOD	0.20	0.012	0.046	0.35	0.13	0.09	0.011	0.32
	LOQ	0.66	0.039	0.153	1.15	0.42	0.30	0.038	1.08
University of Tennessee, Knoxville									
Grab samples (surface material, <2 inches depth)									
Surface 1	grab	<LOQ	14.61	<LOQ	<LOQ	14.2	179	<LOD	<LOQ
	replicate	<LOQ	13.87	<LOD	<LOQ	14.0	172	<LOD	<LOQ
	replicate 2	<LOQ	14.12	<LOD	<LOQ	14.3	172	<LOD	<LOQ
mean		<LOQ	14.20	<LOD	<LOQ	14.17	174.4	<LOD	<LOQ
σ			0.38			0.14	4.4		
σ (%)			3%			1%	2%		
Surface 1 (3 months)	grab	38.82	22.87	0.22	4.68	109.1	57	<LOD	9.66
Surface 2	grab	0.68	25.12	<LOD	<LOQ	22.0	234	<LOD	<LOQ
Surface 2 (3 months)	grab	30.97	15.44	0.26	1.79	67.3	149	<LOD	6.60
Surface 3	grab	1.27	39.03	<LOQ	1.37	37.5	398	<LOD	<LOQ
Surface 3 (3 months)	grab	3.51	8.48	0.16	<LOQ	24.2	78	<LOD	<LOQ
Burial 1	grab	<LOQ	9.78	<LOD	<LOQ	12.6	127	<LOD	<LOD
Burial 2	grab	0.84	19.45	<LOD	<LOQ	11.0	161	<LOD	<LOD
Soil cores (depth in inches)									
Core 1	0-1	<LOD	17.95	<LOD	<LOQ	14.9	190	<LOD	<LOQ
	replicate	<LOD	23.19	<LOD	<LOQ	16.6	309	<LOD	<LOQ
	1-2	<LOD	17.17	<LOD	<LOQ	13.0	202	<LOD	<LOQ
	2-4	<LOD	12.84	<LOD	<LOQ	8.6	142	<LOD	<LOQ
	4-6	<LOD	10.22	<LOD	<LOQ	7.7	113	<LOD	<LOD
	6-9	<LOD	5.24	<LOD	<LOQ	6.1	56	<LOD	<LOD
	9-12	<LOD	6.22	<LOD	<LOQ	6.8	65	<LOD	<LOD
Core 2	1-2	<LOD	19.06	<LOD	<LOQ	13.4	280	<LOD	<LOQ
	2-4	<LOD	15.58	<LOD	<LOQ	11.8	254	<LOD	<LOQ
	4-6	<LOD	13.34	<LOD	<LOQ	9.7	204	<LOD	<LOQ
	6-9	<LOD	12.22	<LOD	<LOQ	6.8	160	<LOD	<LOD
	9-12	<LOD	12.43	<LOD	<LOQ	7.3	152	<LOD	<LOD
Burial 2	0-1	<LOD	12.38	<LOD	<LOQ	12.8	130	<LOD	<LOD
	replicate	<LOD	12.18	<LOD	<LOQ	12.6	129	<LOD	<LOD
	replicate 2	<LOD	12.19	<LOD	<LOQ	12.6	132	<LOD	<LOD
mean		<LOD	12.25	<LOD	<LOQ	12.64	130.30	<LOD	<LOD
σ			0.11			0.11	1.37		
σ (%)			1%			1%	1%		
	1-2	<LOD	12.12	<LOD	<LOQ	12.7	122	<LOD	<LOD
	2-4	<LOD	11.00	<LOD	<LOQ	12.2	104	<LOD	<LOD
	4-6	<LOD	14.38	<LOD	<LOQ	13.0	125	<LOD	<LOD
	6-8 1/2	<LOD	20.42	<LOD	<LOQ	11.9	166	<LOD	<LOD

Table 20. Soil leach elemental concentrations in ppm for the Tennessee ARF site. Samples denoted with Surface 4 indicate that soil was taken from the site immediately before placement of the corresponding donor near the cranial region. Samples are corrected for the leach process blank. The limit of detection (LOD) and limit of quantitation (LOQ) are the instrumental limits, multiplied by the typical dilution factor. This is to allow interpretation of what LOD and LOQ are in the context of these samples. Replicate indicates that it was a replicate leach and chemical purification.

		Cr	Mn	Fe	Co	Ni	Cu	As	Se
		ppb	ppm	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.67	0.0005	4.35	0.14	0.90	5.84	2.72	23.03
	LOQ	2.23	0.0017	14.49	0.46	3.00	19.47	9.06	76.77
University of Tennessee, Knoxville									
Grab samples (surface material, <2 inches depth)									
Surface 1	grab	2.47	6.90	23.39	6.36	<LOQ	<LOQ	<LOQ	<LOD
	replicate	<LOQ	6.64	22.12	6.08	<LOQ	<LOQ	<LOQ	<LOD
	replicate 2	<LOQ	6.72	19.69	6.12	<LOQ	<LOQ	<LOQ	<LOD
mean		2.31	6.75	21.73	6.18	<LOQ	<LOQ	<LOQ	<LOD
σ			0.13	1.88	0.15				
σ (%)			2%	9%	2%				
Surface 1 (3 months)	grab	4.47	<LOD	1171.61	36.82	12.63	<LOD	26.20	<LOQ
Surface 2	grab	3.86	9.90	45.58	7.09	<LOQ	50.45	20.18	<LOD
Surface 2 (3 months)	grab	12.83	<LOD	1070.94	124.47	23.44	138.26	79.13	<LOD
Surface 3	grab	2.40	14.80	65.78	6.34	3.67	<LOQ	15.27	<LOD
Surface 3 (3 months)	grab	3.23	24.26	242.95	65.64	9.51	19.20	<LOQ	<LOD
Burial 1	grab	<LOQ	3.51	<LOQ	2.96	<LOQ	<LOQ	<LOQ	<LOD
Burial 2	grab	<LOQ	2.82	<LOQ	45.80	3.91	<LOD	34.19	<LOQ
Soil cores (depth in inches)									
Core 1	0-1	2.52	6.73	42.66	6.90	<LOQ	21.59	<LOQ	<LOD
	replicate	<LOQ	4.47	18.37	1.93	<LOQ	<LOQ	<LOQ	<LOD
	1-2	3.05	5.85	30.79	5.63	<LOQ	23.61	<LOQ	<LOD
	2-4	<LOQ	3.13	<LOQ	2.90	<LOQ	<LOQ	<LOQ	<LOD
	4-6	<LOQ	2.46	<LOQ	2.36	<LOQ	<LOQ	<LOQ	<LOD
	6-9	2.28	3.75	<LOQ	3.81	<LOQ	<LOD	<LOQ	<LOQ
	9-12	<LOQ	5.44	<LOQ	11.71	<LOQ	<LOD	<LOQ	<LOQ
Core 2	1-2	<LOQ	2.74	18.07	1.20	<LOQ	<LOQ	<LOQ	<LOD
	2-4	<LOQ	1.53	15.41	0.69	<LOQ	<LOD	<LOQ	<LOD
	4-6	<LOQ	0.59	<LOQ	<LOQ	<LOQ	<LOD	<LOQ	<LOD
	6-9	<LOQ	0.70	<LOQ	<LOQ	<LOQ	<LOD	<LOQ	<LOD
	9-12	<LOQ	0.24	<LOQ	<LOQ	<LOQ	<LOD	<LOQ	<LOD
Burial 2	0-1	<LOQ	4.87	14.22	10.73	<LOQ	<LOQ	<LOQ	<LOD
	replicate	<LOQ	4.88	<LOQ	10.04	<LOQ	<LOQ	10.55	<LOD
	replicate 2	2.20	4.88	17.80	9.61	4.52	<LOQ	<LOQ	<LOQ
mean		<LOQ	4.88	15.50	10.13		<LOQ	9.56	<LOD
σ			0.01		0.57				
σ (%)			0.1%		6%				
	1-2	<LOQ	5.20	<LOQ	10.02	<LOQ	<LOQ	7.98	<LOQ
	2-4	<LOQ	5.29	<LOQ	12.50	3.17	<LOQ	<LOQ	<LOQ
	4-6	<LOQ	3.53	<LOQ	17.33	<LOQ	<LOD	11.51	<LOQ
	6-8 1/2	<LOQ	0.46	<LOQ	13.01	3.53	<LOD	35.94	<LOQ

Table 20. Soil leach elemental concentrations at ARF continued.

		Rb	Sr	Mo	Cd	Sn	Sb	Ba	La
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.41	0.31	0.12	0.11	0.45	0.11	0.06	0.06
	LOQ	1.37	1.02	0.40	0.37	1.49	0.35	0.20	0.19
University of Tennessee, Knoxville									
Grab samples (surface material, <2 inches depth)									
Surface 1	grab	5.1	247	0.54	2.68	<LOD	<LOQ	178.0	9.27
	replicate	6.5	248	0.94	2.76	<LOD	<LOQ	185.1	8.87
	replicate 2	5.7	239	0.66	3.52	<LOD	<LOQ	177.3	9.04
mean		5.8	244	0.71	2.99	<LOD	<LOQ	180.1	9.06
σ		0.7	5	0.21	0.47			4.3	0.20
σ (%)		12%	2%	29%	16%			2%	2%
Surface 1 (3 months)	grab	112.8	205	2.83	0.85	<LOD	0.63	95.2	4.57
Surface 2	grab	18.1	315	0.69	2.97	<LOD	0.63	183.1	5.71
Surface 2 (3 months)	grab	55.3	203	5.42	3.10	<LOD	2.90	150.9	6.38
Surface 3	grab	30.2	489	0.16	2.63	<LOD	<LOQ	247.2	8.66
Surface 3 (3 months)	grab	29.6	122	0.85	2.83	<LOD	0.47	162.9	16.48
Burial 1	grab	9.1	236	0.66	2.59	<LOD	0.34	237.0	12.02
Burial 2	grab	125.6	257	<LOQ	<LOQ	<LOD	<LOQ	543.0	231.07
Soil cores (depth in inches)									
Core 1	0-1	16.8	258	0.51	2.78	<LOD	0.37	183.3	10.13
	replicate	22.8	411	0.48	2.86	<LOD	<LOD	350.9	9.95
	1-2	19.1	282	0.49	2.33	<LOD	0.48	196.1	8.98
	2-4	10.7	218	0.65	3.13	<LOD	0.32	235.0	10.02
	4-6	19.0	190	0.84	2.70	<LOD	<LOQ	227.1	12.90
	6-9	21.9	111	0.69	1.80	<LOD	0.38	174.3	20.42
	9-12	50.5	124	0.28	1.45	<LOD	<LOQ	238.6	23.93
Core 2	1-2	28.4	410	0.36	2.46	<LOD	<LOQ	433.9	12.41
	2-4	32.6	388	0.17	2.30	<LOD	<LOD	463.1	13.44
	4-6	34.8	342	<LOQ	0.76	<LOD	<LOD	484.5	17.22
	6-9	55.6	285	0.11	0.73	<LOD	<LOQ	555.9	28.43
	9-12	44.9	235	<LOD	0.59	<LOD	<LOQ	604.9	32.24
Burial 2	0-1	33.5	192	<LOQ	2.16	<LOD	<LOQ	294.5	30.58
	replicate	35.0	193	0.08	2.15	<LOD	<LOQ	290.5	31.34
	replicate 2	30.1	193	<LOD	1.72	<LOD	<LOQ	280.4	28.97
mean		32.85	192.91	<LOQ	2.01	<LOD	<LOQ	288.45	30.30
σ		2.51	0.61		0.25			7.25	1.21
σ (%)		8%	0.3%		12%			3%	4%
	1-2	32.2	182	<LOQ	1.93	<LOD	0.36	279.1	30.48
	2-4	36.1	157	0.01	2.14	<LOD	<LOQ	275.1	33.38
	4-6	91.1	215	<LOQ	1.20	<LOD	<LOQ	402.0	73.51
	6-8 1/2	200.2	292	<LOQ	<LOD	<LOD	<LOQ	569.2	307.02

Table 20. Soil leach elemental concentrations at ARF continued.

		Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.15	0.024	0.11	0.031	0.020	0.11	0.042	0.10
	LOQ	0.50	0.079	0.38	0.105	0.068	0.36	0.142	0.32
University of Tennessee, Knoxville									
Grab samples (surface material, <2 inches depth)									
Surface 1	grab	15.33	1.84	9.91	2.08	0.43	2.57	0.25	1.56
	replicate	15.29	1.79	10.42	1.96	0.57	2.44	0.25	1.56
	replicate 2	15.15	1.70	11.00	2.07	0.42	2.20	0.26	1.50
mean		15.26	1.78	10.45	2.04	0.47	2.40	0.25	1.54
σ		0.09	0.07	0.54	0.06	0.08	0.19	0.01	0.03
σ (%)		1%	4%	5%	3%	18%	8%	3%	2%
Surface 1 (3 months)	grab	16.26	1.37	9.07	2.46	0.57	3.00	0.37	2.36
Surface 2	grab	8.40	0.98	6.93	1.45	0.36	1.37	0.16	0.79
Surface 2 (3 months)	grab	24.05	1.60	9.81	2.33	0.55	7.42	0.41	2.19
Surface 3	grab	12.15	1.55	8.75	1.90	0.45	1.99	0.24	1.19
Surface 3 (3 months)	grab	56.10	4.18	21.33	5.00	1.11	5.48	0.63	3.88
Burial 1	grab	14.45	2.52	14.11	3.07	0.62	3.36	0.35	2.01
Burial 2	grab	399.78	50.22	228.76	40.45	7.29	33.13	3.22	16.06
Soil cores (depth in inches)									
Core 1	0-1	19.02	2.06	11.21	2.71	0.58	2.95	0.32	1.70
	replicate	9.96	1.71	10.53	1.96	0.41	2.41	0.24	1.17
	1-2	15.07	1.90	10.31	2.23	0.51	2.19	0.28	1.38
	2-4	11.30	2.08	12.04	2.70	0.57	2.56	0.29	1.63
	4-6	12.86	2.75	14.89	3.10	0.78	3.16	0.40	2.18
	6-9	28.75	5.07	27.76	5.83	1.27	6.59	0.79	4.35
	9-12	42.89	5.83	30.44	6.79	1.40	7.06	0.78	4.22
Core 2	1-2	10.99	2.46	13.16	2.56	0.60	2.91	0.30	1.39
	2-4	10.77	2.66	14.14	3.08	0.63	3.13	0.31	1.63
	4-6	10.04	3.50	18.14	4.00	0.80	3.88	0.41	2.19
	6-9	13.82	6.26	30.84	7.04	1.48	7.09	0.76	3.73
	9-12	11.49	7.07	34.97	7.60	1.70	8.41	0.89	4.27
Burial 2	0-1	64.38	7.19	35.33	7.61	1.45	7.79	0.82	4.32
	replicate	65.21	7.51	36.84	8.16	1.81	8.14	0.85	4.41
	replicate 2	59.56	6.78	34.06	7.79	1.58	6.99	0.80	3.96
mean		63.05	7.16	35.41	7.86	1.62	7.64	0.82	4.23
σ		3.05	0.37	1.39	0.28	0.18	0.59	0.02	0.24
σ (%)		5%	5%	4%	4%	11%	8%	3%	6%
	1-2	63.79	6.98	35.81	7.36	1.54	7.40	0.80	4.26
	2-4	76.49	7.97	40.36	8.28	1.79	8.43	0.95	5.10
	4-6	148.63	16.41	78.71	15.37	2.88	13.63	1.41	6.99
	6-8 1/2	499.96	60.47	261.26	42.55	7.53	34.35	3.08	14.75

Table 20. Soil leach elemental concentrations at ARF continued.

		Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pb	U
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	LOD	0.04	0.12	0.03	0.09	0.02	0.02	0.25	0.02	0.05	0.014
	LOQ	0.13	0.40	0.09	0.29	0.07	0.06	0.84	0.05	0.15	0.048
University of Tennessee, Knoxville											
Grab samples (surface material, <2 inches depth)											
Surface 1	grab	0.23	0.58	<LOQ	0.34	<LOQ	<LOD	<LOD	<LOD	1.92	0.43
	replicate	0.30	0.61	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	2.06	0.45
	replicate 2	0.28	0.55	<LOQ	0.36	<LOQ	<LOD	<LOD	<LOD	1.98	0.35
mean		0.27	0.58	<LOQ	0.33	<LOQ	<LOD	<LOD	<LOD	1.99	0.41
σ		0.04	0.03							0.07	0.05
σ (%)		14%	5%							3%	13%
Surface 1 (3 months)	grab	0.51	1.44	0.15	1.06	0.15	0.07	<LOD	<LOD	12.80	0.70
Surface 2	grab	0.16	<LOQ	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	2.69	0.30
Surface 2 (3 months)	grab	0.46	1.22	0.15	0.78	0.09	0.10	<LOD	<LOD	14.50	0.79
Surface 3	grab	0.25	0.60	0.09	0.44	<LOQ	<LOD	<LOD	<LOD	1.63	0.22
Surface 3 (3 months)	grab	0.72	1.89	0.20	1.08	0.18	0.08	<LOD	<LOD	9.37	1.40
Burial 1	grab	0.36	0.80	<LOQ	0.43	<LOQ	<LOD	<LOD	<LOD	2.44	0.58
Burial 2	grab	3.17	7.08	0.67	3.29	0.52	<LOD	<LOD	<LOD	10.91	2.36
Soil cores (depth in inches)											
Core 1	0-1	0.33	0.74	0.09	0.43	0.07	<LOQ	<LOD	<LOD	1.86	0.44
	replicate	0.22	0.57	<LOQ	0.29	<LOQ	<LOD	<LOD	<LOD	1.50	0.20
	1-2	0.27	0.67	<LOQ	0.29	0.07	<LOD	<LOD	<LOD	1.91	0.38
	2-4	0.31	0.68	<LOQ	0.34	<LOQ	<LOD	<LOD	<LOD	2.93	0.56
	4-6	0.45	0.96	0.10	0.46	<LOQ	<LOD	<LOD	<LOD	2.90	0.77
	6-9	0.81	1.88	0.19	0.94	0.16	<LOQ	<LOD	<LOD	1.73	1.59
	9-12	0.86	2.03	0.20	0.98	0.15	<LOD	<LOD	<LOD	1.12	1.61
Core 2	1-2	0.32	0.62	<LOQ	0.29	<LOQ	<LOD	<LOD	<LOD	1.54	0.25
	2-4	0.31	0.53	<LOQ	0.34	<LOQ	<LOD	<LOD	<LOD	1.23	0.23
	4-6	0.44	0.89	<LOQ	0.34	<LOQ	<LOD	<LOD	<LOD	0.43	0.25
	6-9	0.65	1.38	0.11	0.84	0.09	<LOD	<LOD	<LOQ	0.28	0.44
	9-12	0.86	1.74	0.18	0.76	0.12	<LOD	<LOD	<LOD	0.16	0.52
Burial 2	0-1	0.84	1.95	0.17	0.95	0.12	<LOD	<LOD	<LOD	4.46	1.14
	replicate	0.85	2.16	0.18	1.06	0.17	<LOD	<LOD	<LOD	4.41	1.10
	replicate 2	0.81	1.78	0.20	0.93	0.15	<LOD	<LOD	<LOD	4.22	1.05
mean		0.83	1.96	0.18	0.98	0.15	<LOD	<LOD	<LOD	4.36	1.09
σ		0.02	0.19	0.01	0.07	0.02				0.13	0.04
σ (%)		2%	10%	7%	7%	15%				3%	4%
	1-2	0.78	1.95	0.17	0.91	0.14	<LOD	<LOD	<LOD	3.74	1.10
	2-4	0.98	2.19	0.21	1.26	0.17	<LOQ	<LOD	<LOD	4.67	1.36
	4-6	1.28	3.20	0.31	1.55	0.22	<LOD	<LOD	<LOD	6.89	1.72
	6-8 1/2	2.85	6.53	0.61	2.97	0.45	<LOD	<LOD	<LOD	11.81	2.85

Table 20. Soil leach elemental concentrations at ARF continued.

6.2.3 Strontium and lead isotope compositions After elemental determination by Q-ICP-MS, aliquots were purified and analyzed for $^{87}Sr/^{86}Sr$, $\delta^{88/86}Sr$, and Pb isotopes. Results are listed in Table 21 for the FARF site and Table 22 for the ARF site.

	depth (inches)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Texas State, San Marcos								
Surface 4	grab	0.70906	0.28					
Surface 5	grab	0.70942	0.46	19.204	15.664	38.655	2.013	0.816
Surface 6	grab	0.70933	0.24					
	replicate	0.70910	0.15	19.467	15.699	38.814	1.994	0.806
Surface 7	grab	0.70906	0.28	19.039	15.627	38.481	2.021	0.821
Core 1 (open grassland)	0-1	0.70888	0.35	19.126	15.640	38.553	2.016	0.818
	1-2	0.70894	0.31	19.205	15.654	38.627	2.011	0.815
	2-4	0.70899	0.22					
	4-6	0.70923	0.20	19.312	15.664	38.699	2.004	0.811
	6-9	0.70952	0.17	19.512	15.679	38.776	1.987	0.804
	replicate	0.70952	0.21	19.452	15.689	38.789	1.994	0.807
	replicate	0.70953	0.20	19.474	15.663	38.740	1.989	0.804
	mean	0.70952	0.19	19.479	15.677	38.768	1.990	0.805
	2 σ	0.00001	0.05	0.061	0.027	0.050	0.007	0.003
				0.31%	0.17%	0.13%	0.36%	0.40%
	9-12			19.472	15.692	38.791	1.992	0.806
Core 2 (forested)	0-4 1/2	0.70971	0.33	19.239	15.669	38.695	2.011	0.814
	4 1/2-8	0.70997	0.28	19.327	15.670	38.728	2.004	0.811
	8-12	0.71011	0.27	19.479	15.683	38.823	1.993	0.805

Table 21. Sr and Pb isotope composition of bioavailable soil leaches at FARF in Texas.

	depth (inches)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
University of Tennessee, Knoxville								
Surface 1	grab	0.71291	0.14	18.974	15.665	38.610	2.035	0.826
	replicate	0.71292	0.17	18.965	15.652	38.571	2.034	0.825
	replicate	0.71295	0.39	18.914	15.651	38.555	2.038	0.828
	mean	0.71292	0.24	18.951	15.656	38.579	2.036	0.826
	2 σ	0.00004	0.27	0.064	0.015	0.056	0.005	0.002
				0.34%	0.10%	0.15%	0.23%	0.29%
Surface 1 (3 months)	grab	0.71238	-0.04					
Surface 2	grab	0.71276	0.13	18.897	15.647	38.532	2.039	0.828
Surface 2 (3 months)	grab	0.71286	0.28	18.916	15.646	38.571	2.039	0.827
Surface 3	grab	0.71241	0.11	18.911	15.647	38.520	2.037	0.827
Surface 3 (3 months)	grab	0.71325	0.19	18.959	15.649	38.607	2.036	0.825
Burial 1	grab	0.71231	0.20					
Burial 2	grab	0.71511	0.29	19.162	15.657	38.749	2.022	0.817
Core 1	0-1	0.71324	0.14	18.954	15.649	38.565	2.035	0.826
	replicate	0.71233	0.19	18.930	15.649	38.538	2.036	0.827
	1-2	0.71331	0.13	18.947	15.649	38.565	2.035	0.826
	2-4	0.71343	0.10					
	4-6	0.71362	0.29	18.926	15.648	38.542	2.037	0.827
	6-9	0.71387	0.17	18.970	15.656	38.624	2.036	0.825
	9-12	0.71413	0.19	19.032	15.662	38.708	2.034	0.823
Core 2	1-2	0.71235	0.13	18.911	15.636	38.490	2.035	0.827
	2-4	0.71237	0.14	18.985	15.666	38.582	2.032	0.825
	4-6	0.71256	0.16	18.954	15.638	38.559	2.034	0.825
	6-9	0.71262	0.20					
	9-12	0.71264	0.26	19.080	15.636	38.587	2.022	0.819
Burial 2	0-1	0.71352	0.19	18.998	15.652	38.628	2.033	0.824
	replicate	0.71354	0.25	19.006	15.654	38.631	2.033	0.824
	replicate	0.71331	0.07	19.014	15.654	38.640	2.032	0.823
	mean	0.71346	0.17	19.006	15.653	38.633	2.033	0.824
	2 σ	0.00025	0.18	0.016	0.002	0.012	0.001	0.001
				0.08%	0.02%	0.03%	0.05%	0.07%
	1-2	0.71355	0.38	19.006	15.650	38.632	2.033	0.823
	2-4	0.71362	0.25					
	4-6	0.71437	0.34	19.093	15.658	38.709	2.027	0.820
	6-8 1/2	0.71556	0.37	19.079	15.517	38.328	2.007	0.813

Table 22. Sr and Pb isotope composition of bioavailable soil leaches at ARF in Tennessee.

6.3 Teeth and bone samples As discussed in the introduction and methodology sections, due to our technique to minimize destructive sampling, many bone samples had very limited amounts of material for collagen preparation. Work is continuing to optimize protocols to give accurate and precise isotopic compositions for these precious samples.

6.3.1 $\delta^{13}C$ and $\delta^{18}O$ of carbonate The carbonate fractions of teeth and bone were analyzed, as described in Section 5.3.4. Results are presented in Table 23, listing both intake and recovery samples, and the offset between the two samples.

		$\delta^{13}C_{VPDB}$ (‰)	σ	$\Delta^{13}C$	$\delta^{18}O_{VPDB}$ (‰)	σ	$\Delta^{18}O$
Teeth							
Burial 1 - ARF	intake	-9.01	0.01		-2.54	0.03	
	recovery	-9.79	0.01	-0.78	-4.30	0.04	-1.77
Burial 2 - ARF	intake	-9.62	0.01		-4.38	0.02	
	recovery	-8.95	0.01	0.66	-5.92	0.01	-1.54
Burial 3 - ARF	intake	-10.88	0.02		-5.75	0.02	
	recovery	-10.44	0.01	0.45	-5.75	0.02	0.01
Burial 4 - FARF	intake	-8.75	0.06		-6.38	0.04	
Surface 1 - ARF	intake	-9.59	0.03		-4.95	0.03	
	recovery	-10.37	0.05	-0.78	-6.80	0.05	-1.85
Surface 2 - ARF	intake	-8.83	0.03		-4.41	0.02	
	recovery	-8.14	0.03	0.69	-5.50	0.03	-1.09
Surface 3 - ARF	intake	-8.09	0.05		-3.24	0.03	
	recovery	-10.84	0.01	-2.75	-6.01	0.01	-2.77
Surface 4 - FARF	intake	-8.63	0.03		-3.24	0.06	
	recovery	-9.16	0.02	-0.53	-2.53	0.03	0.71
Surface 5 - FARF	intake	-7.66	0.02		-3.21	0.02	
	recovery	-7.62	0.02	0.04	-3.65	0.01	-0.44
Surface 6 - FARF	intake	-12.41	0.01		-4.75	0.03	
Surface 7 - FARF	intake	-9.27	0.04		-5.58	0.04	
Bone							
Burial 1 - ARF	intake	-11.79	0.02		-6.24	0.02	
Surface 3 - ARF	intake	-13.04	0.01		-4.41	0.08	
	recovery	-11.69	0.03	1.35	-0.86	0.02	3.55

Table 23. $\delta^{13}C$ and $\delta^{18}O$ of carbonate in tooth enamel and bone. Offsets between intake and recovery samples are also shown.

6.3.2 Major and trace element concentrations Major and trace element concentrations of bone and teeth samples are presented in Table G. Elements listed are major constituents (Ca, P, Sr), trace elements (Na, K, Ti, Fe, Cu, Pb) or diagenetic indicators (U, Ca/P). All samples passed typical quality criteria indicating little to no diagenesis.

		Na	P	K	Ca	Ti	Fe	Cu	Sr	Pb	U	Ca/P	Ca/Sr
Teeth		ppm	wt%	ppm	wt%	ppm	ppm	ppm	ppm	ppm	ppm		
LOD		53	0.013	63	0.003	3.3	1.3	1.09	0.045	0.024	0.002		
LOQ		177	0.043	211	0.011	11.1	4.2	3.63	0.149	0.080	0.007		
Burial 1 - ARF	intake	6282	19.1	494	39.6	21	14.4	bdl	116	8.22	<LOQ	2.07	3410
	recovery	4470	16.1	233	33.7	12	15.4	bdl	86	6.88	<LOQ	2.10	3902
Burial 2 - ARF	intake	5711	17.1	530	35.2	35	31.3	bdl	49	3.78	bdl	2.06	7151
	recovery	5126	16.8	291	34.6	22	36.2	bdl	48	2.46	<LOQ	2.06	7260
Burial 3 - ARF	intake	5049	13.5	497	28.1	<LOQ	20.7	<LOQ	76	2.67	<LOQ	2.08	3721
	recovery	5127	15.3	284	31.6	13	41.8	<LOQ	96	2.48	0.05	2.06	3274
Burial 4 - FARF	intake	5677	15.0	670	31.3	174	22.5	<LOQ	61	10.24	0.03	2.09	5146
Surface 1 - ARF	intake	5307	16.5	515	34.4	48	20.8	<LOQ	62	4.69	bdl	2.08	5519
	recovery	4554	17.0	221	35.5	15	23.9	bdl	49	2.30	bdl	2.09	7299
Surface 2 - ARF	intake	5462	16.5	451	34.4	102	19.8	<LOQ	95	2.48	bdl	2.08	3627
	recovery	5137	16.7	232	34.9	15	12.9	bdl	92	1.59	bdl	2.09	3783
Surface 3 - ARF	intake	4909	16.7	554	35.0	118	33.3	7.40	51	7.83	<LOQ	2.10	6833
	recovery	5377	17.6	292	36.7	21	25.0	bdl	46	2.71	bdl	2.08	7975
Surface 4 - FAR	intake	4976	17.4	499	36.5	24	9.7	bdl	92	13.51	bdl	2.10	3962
	recovery	5390	16.1	384	33.3	15	6.9	<LOQ	79	6.82	0.01	2.07	4204
Surface 5 - FAR	intake	5787	18.1	487	38.0	56	15.7	bdl	119	28.34	<LOQ	2.11	3197
	recovery	5161	15.7	310	32.4	<LOQ	12.8	<LOQ	105	24.80	<LOQ	2.06	3085
Surface 6 - FAR	intake	8061	25.2	652	52.6	75	12.2	bdl	61	13.06	bdl	2.09	8647
Surface 7 - FAR	intake	5525	17.9	502	37.1	32	90.6	<LOQ	66	4.55	<LOQ	2.07	5603
hydroxyapatite: $Ca_5(PO_4)_3(OH)$			19.0		39.6							2.08	
Bone													
Burial 1 - ARF	intake	2129	17.2	<LOQ	36.9	<LOQ	214.7	9.86	78	3.88	0.03	2.15	4713
Surface 3 - ARF	intake	2902	18.3	<LOQ	39.5	14	295.0	3.79	131	3.88	0.06	2.16	3002
	recovery	2801	18.1	<LOQ	38.8	<LOQ	314.6	15.92	89	6.22	0.06	2.15	4375
NIST 1400 bone ash (certified values			17.91 ±0.19	186 ±8	38.18 ±0.13		660 ±27		249 ±7	9.07 ±0.12		2.13	1533

Table 24. Elemental concentrations of teeth and bone from this project. LOD and LOQ are instrumental detection limits, multiplied by the median dilution factor for the samples, for convenience of estimating maximum possible concentrations of samples. All samples were below detection limit for arsenic (0.85), selenium (8.31) and molybdenum (0.13 ppm). Samples were below detection limit (0.13) or the limit of quantitation (LOQ, 0.44 ppm) for rubidium. Because most samples were below detection limit (2.2 ppb) or LOQ (7.4 ppb) for U, Ca/U ratios are not presented; all measured Ca/U ratios were >6 x 10^6. NIST 1400 certified elemental composition is shown, as is theoretical ideal hydroxyapatite.

6.3.3 Strontium and lead isotope compositions Results from the Sr and Pb isotope ratio determinations are listed in Table 25.

		$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Teeth								
Burial 1 - ARF	intake	0.71095	-0.59	19.022	15.662	38.652	2.032	0.823
	replicate			19.009	15.654	38.637	2.033	0.824
	recovery	0.71030	-0.47	19.044	15.654	38.662	2.030	0.822
Burial 2 - ARF	intake	0.71091	-0.62	18.540	15.613	38.236	2.062	0.842
	replicate			18.531	15.609	38.226	2.063	0.842
	recovery	0.71127	-0.57	18.495	15.608	38.201	2.065	0.844
Burial 3 - ARF	intake	0.70931	-0.37	18.977	15.650	38.457	2.027	0.825
	replicate			18.974	15.652	38.465	2.027	0.825
	recovery	0.70953	-0.33	18.973	15.652	38.476	2.028	0.825
Burial 4 - FARF	intake	0.71088	-0.70	18.606	15.625	38.290	2.058	0.840
	replicate			18.598	15.614	38.271	2.058	0.840
Surface 1 - ARF	intake	0.70940	-0.48	18.310	15.592	37.977	2.074	0.852
	replicate			18.305	15.589	37.971	2.074	0.852
	recovery	0.70969	-0.47	18.535	15.610	38.154	2.059	0.842
Surface 2 - ARF	intake	0.70925	-0.22	18.904	15.644	38.440	2.033	0.828
	replicate			18.899	15.643	38.440	2.034	0.828
	recovery	0.70925	-0.29	18.894	15.640	38.414	2.033	0.828
Surface 3 - ARF	intake	0.71052	-0.33	18.415	15.606	38.148	2.072	0.847
	replicate			18.416	15.602	38.147	2.071	0.847
	recovery	0.71032	-0.65	18.432	15.603	38.111	2.068	0.847
Surface 4 - FARF	intake	0.71050	-0.41	18.952	15.646	38.545	2.034	0.826
	replicate			18.944	15.643	38.536	2.034	0.826
	recovery	0.70947	-0.25	18.904	15.640	38.527	2.038	0.827
Surface 5 - FARF	intake	0.70917	-0.56	19.188	15.671	38.629	2.013	0.817
	replicate			19.182	15.669	38.626	2.014	0.817
	recovery	0.70922	-0.60	19.163	15.665	38.611	2.015	0.818
Surface 6 - FARF	intake	0.70987	-0.58	18.998	15.649	38.572	2.030	0.824
	replicate			18.988	15.647	38.569	2.031	0.824
Surface 7 - FARF	intake	0.70955	-0.52	18.489	15.607	38.215	2.067	0.844
				18.481	15.605	38.212	2.068	0.844
Bone								
Burial 1 - ARF	intake	0.71060	-0.61	18.504	15.582	38.078	2.058	0.842
Surface 3 - ARF	intake	0.70973	-0.19	18.541	15.611	38.231	2.062	0.842
	recovery			18.475	15.582	37.902	2.052	0.843

Table 25. Sr and Pb isotope composition of teeth and bone from this project. "Replicates" are replicate chemical purification and instrumental measurement.

6.4 Hair samples

6.4.1 Sample size testing Varying amounts of hair for study samples were available, and we wanted to evaluate the homogeneity of hair sampled at varying initial sample mass. If smaller samples had significantly poorer reproducibility, or a systematic bias, this could be a confounding factor in interpreting study results. Although it is beyond the scope of this study to do a complete evaluation of elemental and isotopic heterogeneity in hair, we did want to have an initial validation, which we are unaware of in the literature. It is also important to note that throughout this study, we did not sample hair longitudinally. If donors had traveled significantly or changed their diet prior to death, this may not be revealed in the donor questionnaires. If there is a systematic bias in sampling later samples to include more (or less) hair nearest the scalp, this could induce a signal that would be interpreted as changes during preservation – but might actually represent real changes due to recent travel or dietary modification.

Triplicates of samples at 5, 15, 30, 50 and 75 mg of an in-house standard and triplicates of IAEA-086 were processed to evaluate the accuracy and precision of samples at these different sample sizes. The elemental concentrations are presented in Table 26, and the Sr and Pb isotope compositions are presented in Table 27.

	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Blanks in µg																
Bulk blank	bdl	0.024	0.027	0.42	bdl	bdl	0.003	bdl	0.0008	0.0055	0.004	0.000	0.0004	bdl	0.016	bdl
replicate	bdl	0.007	0.016	0.30	bdl	bdl	0.003	bdl	0.0004	bdl	0.002	bdl	bdl	bdl	0.003	bdl
replicate 2	bdl	0.007	0.020	0.32	bdl	bdl	0.004	bdl	bdl	0.0001	0.004	bdl	bdl	bdl	0.003	bdl
replicate 3	0.28	0.015	0.017	0.23	0.06	0.15	bdl	0.000	0.0003	bdl	0.003	bdl	bdl	bdl	0.007	bdl
In-house standard, bulk digests (ppm)																
5 mg A	72.5	1729.2	57.98	82.4	117.94	13497	3.68	0.057	0.309	2.51	61.06	0.020	1.14	28.9	3242	bdl
5 mg B	337.1	1886.7	43.22	90.5	221.40	13221	2.32	0.037	0.122	2.04	35.15	0.033	1.27	26.6	3369	bdl
5 mg C	269.9	2089.6	56.28	95.2	186.61	15189	2.83	0.051	0.229	2.55	52.42	0.028	1.34	30.8	3630	bdl
average	226.5	1901.8	52.49	89.4	175.32	13969	2.94	0.048	0.220	2.37	49.54	0.027	1.25	28.8	3414	bdl
st dev (ppm)	137.5	180.7	8.07	6.5	52.65	1065	0.69	0.010	0.094	0.29	13.19	0.006	0.10	2.1	197	
15 mg A	10.2	188.1	13.50	136.5	7.41	1400	bdl	0.039	0.055	0.24	11.92	0.010	0.23	18.2	394	bdl
15 mg B	26.8	165.2	11.16	139.9	15.86	1147	bdl	0.018	0.075	0.25	13.06	0.012	0.20	16.3	304	bdl
15 mg C	5.7	140.1	10.19	131.5	6.22	1056	bdl	0.024	0.048	0.27	10.16	0.013	0.15	17.9	288	bdl
average	14.2	164.4	11.62	136.0	9.83	1201	bdl	0.027	0.059	0.25	11.71	0.012	0.19	17.5	329	bdl
st dev (ppm)	11.1	24.0	1.70	4.2	5.26	178		0.011	0.014	0.01	1.46	0.002	0.04	1.0	57	
30 mg A	33.8	148.6	10.55	138.7	21.64	1087	0.07	0.029	0.066	0.26	10.79	0.014	0.27	16.1	299	0.023
30 mg B	50.0	182.5	12.37	145.3	25.02	1397	0.21	0.031	0.141	0.33	14.76	0.015	0.39	19.2	339	0.025
30 mg C	43.0	254.6	14.28	134.0	18.70	1770	0.64	0.035	0.061	0.33	13.52	0.012	0.29	20.4	437	bdl
average	42.3	195.2	12.40	139.3	21.78	1418	0.31	0.032	0.089	0.31	13.02	0.014	0.32	18.6	358	0.024
st dev (ppm)	8.1	54.1	1.87	5.6	3.16	342	0.29	0.003	0.045	0.04	2.03	0.002	0.06	2.3	71	0.001
50 mg A	51.0	242.4	9.30	125.8	27.00	1610	0.36	0.019	0.038	0.27	10.32	0.012	0.26	19.2	367	0.019
50 mg B	17.6	114.2	12.52	138.4	19.25	849	0.54	0.031	0.055	0.19	13.06	0.008	0.16	13.5	255	0.034
50 mg C	39.8	228.2	15.45	132.3	23.33	1672	1.58	0.043	0.071	0.36	15.22	0.014	0.42	21.5	424	0.013
average	36.2	194.9	12.42	132.2	23.19	1377	0.82	0.031	0.055	0.27	12.86	0.011	0.28	18.1	348	0.022
st dev (ppm)	17.0	70.3	3.07	6.3	3.87	458	0.66	0.012	0.016	0.08	2.46	0.003	0.13	4.1	86	0.011
75 mg A	18.7	188.1	9.66	126.3	14.37	1376	0.83	0.030	0.051	0.26	13.05	0.009	0.44	18.2	367	0.016
75 mg B	28.2	160.7	9.53	132.2	19.35	1103	0.72	0.025	0.048	0.23	11.31	0.008	0.58	16.0	296	0.022
75 mg C	21.2	169.9	9.07	126.9	16.73	1203	1.04	0.019	0.084	0.20	11.93	0.008	0.21	15.6	335	0.020
average	22.7	172.9	9.42	128.5	16.82	1227	0.86	0.025	0.061	0.23	12.10	0.008	0.41	16.6	333	0.019
st dev (ppm)	5.0	13.9	0.31	3.2	2.49	138	0.16	0.006	0.020	0.03	0.88	0.001	0.19	1.4	36	0.003
Certified standard, IAEA 086, ppm																
IAEA-086	64	157	59.6	125	40.3	938	3.42	0.35	5.09	8.57	109.3	0.106	3.32	16.04	111.1	0.128
replicate	61	148	54.3	120	39.3	869	2.94	0.32	4.05	8.55	103.2	0.090	2.63	13.98	106.2	0.097
replicate 2	69	158	59.2	125	43.1	994	3.76	0.36	4.47	9.02	110.8	0.096	2.81	15.36	109.7	0.094
replicate 3	68	163	59.4	124	42.4	1243	3.66	0.34	4.73	9.01	111.3	0.101	2.97	15.06	109.1	0.092
average	66	156	57.6	123	41.6	1035	3.45	0.34	4.42	8.86	108.4	0.096	2.80	14.80	108.3	0.095
st dev (ppm)	4	7	2.9	2	2.0	190	0.45	0.02	0.34	0.27	4.5	0.006	0.17	0.73	1.9	0.003
recommended value		177.0				1120.0				9.6	123.0			17.600	167.0	
95% confidence interval		156-197				1000-1240				8.9-10.3	110-136			16.6-18.5	159-174	

Table 26. Concentration measurements in ppm of in-house hair standard at varying sample size, testing for homogeneity. Samples are corrected for process blank, prepared in parallel with the samples. The effective detection limit varies by sample, as smaller original samples had higher dilution factors.

	Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Blanks in µg															
Bulk blank	bdl	0.0006	bdl	bdl	bdl	0.00003	0.068	0.001	bdl	0.0013	bdl	bdl	bdl	bdl	bdl
replicate	bdl	0.0002	bdl	bdl	bdl	bdl	0.023	0.002	bdl	bdl	bdl	bdl	bdl	bdl	bdl
replicate 2	bdl	0.0002	bdl	bdl	bdl	bdl	0.001	0.002	bdl	0.0001	bdl	bdl	bdl	bdl	bdl
replicate 3	bdl	0.0003	bdl	bdl	0.0002	bdl	0.001	0.001	0.0000	0.0001	bdl	bdl	bdl	bdl	bdl
In-house standard, bulk digests (ppm)															
5 mg A	bdl	134.8	0.025	0.0113	0.3833	0.4128	1.69	0.06	bdl	45.8	0.000062	0.140	0.0119	0.0526	0.0623
5 mg B	bdl	129.3	0.053	bdl	0.2715	0.2311	1.59	0.24	bdl	42.2	0.000050	0.126	0.0083	0.0348	0.0520
5 mg C	0.317	149.7	0.043	0.0111	0.3472	0.3661	1.68	0.14	bdl	49.6	0.000063	0.142	0.0114	0.0493	0.0713
average	bdl	137.9	0.040	bdl	0.3340	0.3367	1.65	0.15	bdl	45.9	0.000058	0.136	0.0105	0.0456	0.0618
st dev (ppm)	bdl	10.6	0.014	bdl	0.0571	0.0943	0.06	0.09		3.7	0.000007	0.009	0.0019	0.0095	0.0097
15 mg A	0.136	13.42	0.053	0.0050	0.0362	0.0263	1.44	0.02	bdl	4.9	0.000028	0.065	0.0015	0.0074	0.0084
15 mg B	0.042	10.88	0.071	0.0037	0.0345	0.0179	0.91	0.06	bdl	3.7	0.000007	0.016	0.0010	0.0058	0.0049
15 mg C	0.009	10.37	0.063	0.0034	0.0335	0.0187	0.83	0.02	bdl	3.7	0.000007	0.019	0.0005	0.0048	bdl
average	0.062	11.56	0.063	0.0041	0.0347	0.0210	1.06	0.04	bdl	4.1	0.000014	0.033	0.0010	0.0060	0.0066
st dev (ppm)	0.066	1.63	0.009	0.0008	0.0013	0.0046	0.33	0.02		0.7	0.000012	0.027	0.0005	0.0013	0.0025
30 mg A	0.019	10.12	0.093	0.0026	0.0382	0.0194	1.01	0.04	bdl	3.6	0.000008	0.016	0.0012	0.0058	bdl
30 mg B	0.026	12.95	0.096	0.0036	0.0427	0.0328	1.25	0.10	bdl	4.5	0.000010	0.021	0.0020	0.0095	0.0104
30 mg C	0.019	17.44	0.073	0.0027	0.0406	0.0381	1.42	0.04	bdl	6.1	0.000024	0.053	0.0019	0.0085	0.0099
average	0.021	13.50	0.087	0.0030	0.0405	0.0301	1.23	0.06	bdl	4.8	0.000014	0.030	0.0017	0.0079	0.0102
st dev (ppm)	0.004	3.69	0.012	0.0006	0.0022	0.0096	0.21	0.03		1.3	0.000009	0.020	0.0004	0.0019	0.0003
50 mg A	0.079	15.17	0.052	0.0022	0.0383	0.0323	1.30	0.02	bdl	5.2	0.000012	0.031	0.0013	0.0051	0.0075
50 mg B	0.011	7.20	0.099	0.0029	0.0470	0.0251	1.18	0.04	bdl	2.5	0.000010	0.022	0.0014	0.0056	0.0079
50 mg C	bdl	16.13	0.094	0.0034	0.0538	0.0385	1.63	0.05	bdl	5.7	0.000011	0.023	0.0023	0.0090	0.0156
average	0.045	12.84	0.082	0.0029	0.0464	0.0320	1.37	0.04	bdl	4.5	0.000011	0.025	0.0017	0.0066	0.0103
st dev (ppm)	0.048	4.90	0.025	0.0006	0.0078	0.0067	0.23	0.02		1.7	0.000001	0.005	0.0005	0.0021	0.0046
75 mg A	bdl	13.34	0.067	0.0026	0.0353	0.0229	1.30	0.02	bdl	4.8	0.000008	0.018	0.0013	0.0061	0.0110
75 mg B	0.004	10.08	0.092	0.0026	0.0338	0.0173	1.10	0.11	bdl	3.5	0.000011	0.021	0.0013	0.0051	0.0088
75 mg C	0.007	11.34	0.124	0.0022	0.0377	0.0210	1.18	0.02	bdl	3.9	0.000007	0.016	0.0013	0.0053	0.0083
average	0.006	11.58	0.094	0.0024	0.0356	0.0204	1.19	0.05	bdl	4.1	0.000009	0.018	0.0013	0.0055	0.0094
st dev (ppm)	0.002	1.65	0.029	0.0003	0.0019	0.0029	0.10	0.05		0.6	0.000002	0.002	0.0000	0.0005	0.0014
Certified standard, IAEA 086, ppm															
IAEA-086	0.117	7.73	0.115	0.003	0.26	0.15	0.23	0.08	0.0025	4.99	0.058	0.123	0.013	0.049	0.009
replicate	0.110	7.07	0.090	0.001	1.08	0.13	0.21	0.10	bdl	4.87	0.054	0.112	0.012	0.043	0.090
replicate 2	0.095	7.80	0.113	0.001	1.05	0.16	0.23	0.11	bdl	5.16	0.062	0.130	0.014	0.051	0.100
replicate 3	0.108	8.80	0.119	0.001	1.02	0.16	0.17	0.11	bdl	5.17	0.069	0.152	0.016	0.060	0.117
average	0.104	7.89	0.107	0.001	1.05	0.15	0.20	0.10	bdl	5.07	0.062	0.131	0.014	0.051	0.102
st dev (ppm)	0.008	0.87	0.015	0.000	0.03	0.02	0.03	0.01		0.17	0.008	0.020	0.002	0.008	0.014
recommended value															
95% confidence interval															

Table 26. Concentration measurements in ppm of in-house hair standard continued.

	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Blanks in µg															
Bulk blank	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.00013	bdl
replicate	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0001	bdl	bdl	bdl	bdl	0.00000
replicate 2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	bdl	bdl	bdl	bdl
replicate 3	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	0.0000	bdl	bdl	0.00002
In-house standard, bulk digests (ppm)															
5 mg A	0.00156	0.0046	bdl	0.00550	bdl	0.00262	bdl	0.0026	bdl	0.020	bdl	0.00060	bdl	4.83	0.29
5 mg B	0.00105	0.0047	bdl	0.00298	bdl	bdl	bdl	bdl	bdl	0.013	bdl	0.00091	bdl	2.50	0.37
5 mg C	0.00167	0.0055	bdl	0.00518	bdl	0.00303	bdl	0.0031	bdl	0.018	0.47	0.00095	bdl	3.76	0.33
average	0.00142	0.0049	bdl	0.00455	bdl	bdl	bdl	bdl	bdl	0.017	bdl	0.00082	bdl	3.70	0.33
st dev (ppm)	0.00033	0.0005		0.00137						0.003		0.00019		1.17	0.04
15 mg A	bdl	0.0013	bdl	0.00136	bdl	bdl	bdl	bdl	bdl	0.023	2.17	0.00032	0.0038	0.37	0.08
15 mg B	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.013	bdl	0.00050	0.0033	0.37	0.11
15 mg C	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.014	0.54	0.00031	0.0033	0.28	0.16
average	bdl	bdl	bdl	0.00136	bdl	bdl	bdl	bdl	bdl	0.017	1.35	0.00037	0.0034	0.34	0.11
st dev (ppm)				#DIV/0!						0.005	1.16	0.00011	0.0003	0.05	0.04
30 mg A	bdl	bdl	bdl	0.00041	bdl	bdl	bdl	bdl	bdl	0.015	0.79	0.00049	0.0036	0.36	0.11
30 mg B	bdl	0.0012	bdl	0.00142	bdl	0.00067	bdl	bdl	bdl	0.016	0.32	0.00032	0.0104	0.41	0.09
30 mg C	bdl	0.0011	bdl	0.00097	bdl	0.00047	bdl	bdl	bdl	0.024	1.42	0.00024	0.0034	0.37	0.07
average	bdl	0.0011	bdl	0.00093	bdl	0.00057	bdl	bdl	bdl	0.018	0.84	0.00035	0.0058	0.38	0.09
st dev (ppm)		0.0000		0.00050		0.00014				0.005	0.55	0.00013	0.0040	0.03	0.02
50 mg A	0.00026	0.0009	bdl	0.00078	0.00016	0.00042	0.00005	0.0004	0.00005	0.015	bdl	0.00045	0.0022	0.35	0.06
50 mg B	0.00011	0.0012	bdl	0.00079	bdl	0.00060	bdl	0.0005	bdl	0.025	0.45	0.00056	0.0021	0.51	0.12
50 mg C	0.00051	0.0016	bdl	0.00145	0.00018	0.00062	bdl	0.0007	bdl	0.025	1.77	0.00024	0.0059	0.42	0.06
average	0.00030	0.0012	bdl	0.00100	0.00017	0.00054	bdl	0.0005	bdl	0.022	1.11	0.00042	0.0034	0.43	0.08
st dev (ppm)	0.00020	0.0004		0.00039	0.00002	0.00011		0.0001		0.006	0.94	0.00017	0.0022	0.08	0.04
75 mg A	0.00022	0.0011	0.00017	0.00093	0.00011	0.00047	bdl	0.0005	bdl	0.020	1.57	0.00030	0.0036	0.33	0.09
75 mg B	0.00012	0.0008	0.00021	0.00069	0.00008	0.00048	bdl	0.0003	bdl	0.017	1.03	0.00033	0.0030	0.34	0.10
75 mg C	0.00019	0.0009	bdl	0.00075	0.00010	0.00039	bdl	0.0004	bdl	0.014	0.07	0.00034	0.0029	0.38	0.10
average	0.00018	0.0009	0.00019	0.00079	0.00010	0.00045	bdl	0.0004	bdl	0.017	0.89	0.00032	0.0032	0.35	0.10
st dev (ppm)	0.00005	0.0002	0.00003	0.00012	0.00002	0.00005		0.0001		0.003	0.76	0.00002	0.0003	0.02	0.01
Certified standard, IAEA 086, ppm															
IAEA-086	0.0019	0.009	0.001	0.0067	0.0013	0.0034	0.0005	0.003	0.0005	0.010	0.009	0.00009	bdl	9.58	0.105
replicate	0.0017	0.008	0.010	0.0061	0.0011	0.0032	0.0036	0.003	0.0003	0.055	0.006	bdl	bdl	8.71	0.084
replicate 2	0.0021	0.010	0.011	0.0073	0.0014	0.0036	0.0041	0.003	0.0004	0.017	0.007	bdl	bdl	9.96	0.089
replicate 3	0.0024	0.011	0.013	0.0094	0.0017	0.0050	0.0053	0.004	0.0005	0.013	0.012	bdl	bdl	10.81	0.090
average	0.0021	0.010	0.011	0.0076	0.0014	0.0039	0.0044	0.003	0.0004	0.028	0.008	bdl	bdl	9.83	0.087
st dev (ppm)	0.0004	0.002	0.001	0.0017	0.0003	0.0010	0.0009	0.001	0.0001	0.023	0.003			1.06	0.003
recommended value															
95% confidence interval															

Table 26. Concentration measurements in ppm of in-house hair standard continued.

	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
In-house standard, bulk digests							
5 mg A	0.71491	0.37	18.371	15.618	38.195	2.079	0.8502
5 mg B	0.71453	0.43	18.387	15.613	38.170	2.076	0.8492
5 mg C	0.71308	n/a	18.502	15.614	38.196	2.065	0.8441
average	0.71417	0.40	18.420	15.615	38.187	2.073	0.8478
2 st dev	0.00193	0.08	0.143	0.006	0.030	0.015	0.0066
15 mg A	0.71487	0.39	18.386	15.619	38.181	2.077	0.8495
15 mg B	0.71458	0.43	18.402	15.616	38.184	2.075	0.8487
15 mg C	0.71426	0.33	18.392	15.618	38.193	2.077	0.8492
average	0.71457	0.38	18.393	15.618	38.186	2.076	0.8491
2 st dev	0.00061	0.09	0.016	0.003	0.012	0.002	0.0008
30 mg A	0.71450	0.43	18.411	15.624	38.195	2.075	0.8486
30 mg B	0.71465	0.50	18.375	15.613	38.173	2.077	0.8497
30 mg C	0.71490	0.50	18.347	15.613	38.164	2.080	0.8510
average	0.71468	0.48	18.377	15.617	38.178	2.077	0.8498
2 st dev	0.00041	0.08	0.064	0.012	0.032	0.006	0.0024
50 mg A	0.71491	0.54	18.370	15.612	38.161	2.077	0.8498
50 mg B	0.71429	0.33	18.332	15.608	38.128	2.080	0.8514
50 mg C	0.71494	0.45	18.346	15.607	38.146	2.079	0.8508
average	0.71471	0.44	18.349	15.609	38.145	2.079	0.8507
2 st dev	0.00073	0.21	0.038	0.005	0.033	0.003	0.0016
75 mg A	0.71479	0.39	18.387	15.614	38.171	2.076	0.8491
75 mg B	0.71466	0.19	18.406	15.610	38.161	2.073	0.8480
75 mg C	0.71465	0.34	18.382	15.608	38.155	2.076	0.8491
average	0.71470	0.31	18.392	15.611	38.162	2.075	0.8488
2 st dev	0.00015	0.20	0.025	0.006	0.016	0.003	0.0013
IAEA 086							
IAEA-086	0.71735	0.12	17.386	15.589	37.117	2.135	0.8967
replicate	0.71732	0.20	17.358	15.592	37.110	2.138	0.8983
replicate 2	0.71735	0.14	17.346	15.597	37.087	2.138	0.8992
replicate 3	0.71731	0.11					
average	0.71733	0.14	17.363	15.593	37.105	2.137	0.8980
2 st dev	0.00004	0.08	0.041	0.009	0.031	0.004	0.0026
In-house hair standard, solid residues from 0.1 M HCl leach (ppm)							
residue	0.71451	0.94	18.460	15.623	38.203	2.070	0.8463
replicate 1	0.71417	0.93	18.544	15.638	38.275	2.064	0.8432
replicate 2	0.71409	0.73	18.384	15.615	38.170	2.076	0.8494
replicate 3	0.71348	0.44	18.472	15.626	38.209	2.068	0.8459
replicate 4	0.71404	0.68	18.477	15.627	38.220	2.068	0.8457
replicate 5	0.71414	0.59	18.483	15.633	38.235	2.069	0.8458
replicate 6	0.71369	0.59	18.406	15.609	38.155	2.073	0.8480
average	0.71402	0.70	18.461	15.624	38.210	2.070	0.8463
2 st dev	0.00068	0.37	0.106	0.020	0.080	0.008	0.0039
In-house hair standard, leachate from 0.1 M HCl leach (ppm)							
Leachate	0.71495	0.22	18.357	15.618	38.233	2.083	0.8507
replicate 1	0.71496	0.27	18.305	15.603	38.139	2.084	0.8524
replicate 2	0.71493	0.28	18.342	15.615	38.174	2.081	0.8513
replicate 3	0.71484	0.28	18.339	15.613	38.171	2.081	0.8513
replicate 4	0.71495	0.28	18.338	15.615	38.170	2.082	0.8515
replicate 5	0.71494	0.27	18.357	15.616	38.174	2.080	0.8507
replicate 6	0.71489	0.30	18.327	15.603	38.137	2.081	0.8513
average	0.71492	0.27	18.338	15.612	38.171	2.082	0.8513
2 st dev	0.00009	0.05	0.036	0.013	0.064	0.003	0.0011

Table 27. Isotope composition of in-house bulk hair standard at varying sample size, testing for homogeneity.

At sample sizes of 5 mg, there is significantly poorer reproducibility. In addition, some of the concentrations (*eg,* Mg, K, Ca, Sr, Pb) were anomalously high compared to the larger sample sizes. All samples were blank corrected for a process blank digested and analyzed in parallel with the samples, but these results suggest that the process blank may have been more variable – and sometimes higher – than the blank correction accounted for. In addition, because these small samples are multiplied by a larger dilution factor, the variability is also magnified. Finally, it is quite possible that this hair is inhomogeneous at this sample size. For samples utilized in this study, the average sample size for bulk hair was 40.1 ±12.1 mg (1σ), with a minimum sample size of 9.5 mg. Sample sizes were larger for aliquots used in the leaching procedure, since the solid residue was the goal sample and it typically only represents a small proportion of the strontium in the sample (Tipple et al., 2013).

6.4.2 Reproducibility of leaching protocol Because the leaching protocol of Tipple et al. (2013) requires hair that has not been powdered, no certified standard exists. However, we used a large batch of hair from a local salon that appeared to come from a single individual as an in-house standard. This was the same standard used for the leaching and homogenization validation discussed above. Seven replicates of this sample, in addition to the validation measurements, were processed in parallel with the samples, as shown in Table 28. The distribution coefficients for various elements will be reviewed in the discussion section.

.

	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Blanks in µg																
Leachate blank	0.032	0.006	0.012	0.12	bdl	0.27	bdl	bdl	bdl	0.0001	0.004	bdl	0.0002	bdl	0.009	bdl
replicate	0.246	0.021	0.016	0.29	bdl	0.25	0.004	bdl	0.0005	bdl	0.003	bdl	bdl	bdl	0.023	bdl
replicate 2	0.200	0.015	0.023	0.25	0.05	0.21	0.006	bdl	0.0004	0.0014	0.015	bdl	bdl	bdl	0.008	bdl
Residue blank	0.182	0.036	0.015	0.18	0.09	0.64	0.034	0.000	0.0003	0.0003	0.006	bdl	0.0009	bdl	0.044	bdl
replicate	bdl	bdl	0.014	0.32	bdl	bdl	0.005	0.000	0.0013	bdl	0.002	0.000	bdl	bdl	0.004	bdl
replicate 2	0.246	0.024	bdl	0.29	0.05	0.14	0.004	bdl	0.0016	0.0007	0.065	0.002	0.0006	bdl	0.010	bdl
In-house hair standard, solid residues from 0.1 M HCl leach (ppm)																
residue	3.0	21.2	6.42	122.5	bdl	195	bdl	0.020	0.026	0.048	7.66	0.008	0.13	19.9	45.7	bdl
replicate 1	bdl	14.8	6.21	127.5	bdl	140	bdl	0.020	0.068	0.047	8.25	0.006	0.10	18.3	33.2	bdl
replicate 2	0.7	17.3	4.68	116.3	bdl	154	bdl	0.012	0.025	0.040	6.49	0.005	0.13	15.6	45.2	bdl
replicate 3	bdl	19.6	5.42	114.2	bdl	196	2.28	0.013	0.035	0.044	6.39	0.005	0.12	14.9	42.9	0.013
replicate 4	3.0	25.7	4.87	126.7	0.99	242	0.93	0.012	0.047	0.054	6.85	0.006	0.13	15.3	53.3	0.032
replicate 5	3.4	21.2	5.58	115.6	1.00	212	0.88	0.015	0.045	0.055	6.93	0.005	0.11	13.4	53.9	0.023
replicate 6	8.2	24.8	4.69	115.1	1.51	248	0.49	0.013	0.036	0.048	5.97	0.007	0.09	11.4	63.5	0.036
mean	3.7	20.7	5.41	119.7	1.17	198	1.15	0.015	0.040	0.048	6.93	0.006	0.12	15.6	48.3	0.026
st dev (ppm)	2.7	3.9	0.71	5.7	0.30	41	0.78	0.003	0.015	0.005	0.78	0.001	0.02	2.9	9.7	0.010
In-house hair standard, leachate from 0.1 M HCl leach (ppm)																
Leachate	29.5	223.8	5.62	9.32	18.2	1580	0.18	0.005	0.021	0.26	5.02	0.003	0.13	3.06	353	bdl
replicate 1	13.3	184.9	6.20	8.81	12.6	1443	0.39	0.006	0.033	0.27	6.53	0.002	0.12	3.09	347	bdl
replicate 2	35.6	199.4	4.57	9.56	23.4	1397	0.25	0.004	0.013	0.22	3.71	0.003	0.13	2.81	356	bdl
replicate 3	26.4	183.6	4.06	10.61	16.3	1292	0.29	0.007	0.034	0.19	2.85	0.002	0.11	2.55	239	bdl
replicate 4	15.9	130.3	2.89	8.37	12.8	1063	0.06	0.004	0.034	0.24	2.77	0.003	0.11	2.56	214	0.014
replicate 5	34.4	138.2	3.12	9.57	23.3	960	0.15	0.007	0.023	0.13	2.45	0.002	0.08	2.03	177	0.010
replicate 6	48.7	125.0	2.71	15.32	30.0	774	0.17	0.007	0.023	0.37	4.55	0.005	0.08	1.98	128	bdl
mean	29.1	169.3	4.16	10.22	19.5	1216	0.21	0.006	0.026	0.24	3.98	0.003	0.11	2.58	259	0.012
st dev (ppm)	12.1	38.3	1.37	2.35	6.4	291	0.11	0.001	0.008	0.07	1.47	0.001	0.02	0.45	93	0.003
sum of solid residue and leachates (ppm)																
residual + leachate	32.5	245.1	12.04	131.8	18.2	1775	0.18	0.024	0.047	0.31	12.68	0.011	0.27	23.00	399	bdl
replicate 1	13.3	199.7	12.41	136.3	12.6	1583	0.39	0.026	0.101	0.32	14.78	0.008	0.23	21.38	380	bdl
replicate 2	36.3	216.7	9.25	125.9	23.4	1551	0.25	0.016	0.038	0.26	10.20	0.009	0.27	18.45	401	bdl
replicate 3	26.4	203.2	9.48	124.8	16.3	1487	2.56	0.019	0.069	0.24	9.24	0.007	0.24	17.47	282	0.013
replicate 4	18.9	156.0	7.76	135.1	13.8	1305	0.99	0.015	0.081	0.30	9.62	0.009	0.24	17.83	267	0.046
replicate 5	37.9	159.4	8.70	125.2	24.3	1172	1.03	0.022	0.068	0.18	9.38	0.006	0.19	15.44	231	0.033
replicate 6	56.9	149.8	7.40	130.4	31.5	1022	0.66	0.020	0.059	0.42	10.52	0.013	0.17	13.37	192	0.036
mean	31.7	190.0	9.58	129.9	20.0	1414	0.87	0.020	0.066	0.29	10.92	0.009	0.23	18.13	307	0.032
st dev (ppm)	14.3	35.9	1.96	4.8	6.7	260	0.82	0.004	0.021	0.07	2.06	0.002	0.04	3.29	86	0.014

Table 28. Concentration measurements of in-house standard processed using the Tipple et al (2013) leaching protocol.

		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Blanks in µg																
Leachate blank		bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.000	bdl	bdl	bdl	bdl	bdl	bdl	bdl
	replicate	bdl	0.0004	0.0000	bdl	0.0005	bdl	0.000	0.000	0.0001	0.0002	bdl	bdl	bdl	bdl	bdl
	replicate 2	bdl	0.0002	0.0001	bdl	0.0003	bdl	0.000	0.001	0.0004	0.0003	bdl	bdl	bdl	bdl	bdl
Residue blank		bdl	bdl	bdl	bdl	0.0001	0.00002	0.000	0.000	bdl	bdl	0.0000	bdl	bdl	bdl	bdl
	replicate	bdl	0.0003	bdl	bdl	bdl	0.00001	0.001	0.002	bdl	0.0001	bdl	bdl	bdl	bdl	bdl
	replicate 2	bdl	0.0005	0.0001	bdl	0.0004	bdl	0.002	0.001	0.0004	0.0001	0.0000	0.0001	0.0000	0.0000	bdl
In-house hair standard, solid residues from 0.1 M HCl leach (ppm)																
residue		bdl	1.94	0.039	0.0027	0.023	0.003	1.15	0.017	bdl	1.13	0.000	0.0069	0.0006	0.0026	0.0036
	replicate 1	bdl	1.29	0.043	0.0026	0.013	0.001	1.13	0.019	bdl	0.76	0.000	0.0097	0.0005	0.0023	0.0036
	replicate 2	bdl	1.42	0.048	0.0016	0.009	0.001	1.14	0.014	bdl	0.81	0.000	0.0068	0.0004	0.0021	0.0033
	replicate 3	0.003	1.65	0.048	0.0047	0.022	0.002	1.60	0.044	bdl	0.81	0.005	0.0086	0.0005	0.0018	0.0003
	replicate 4	0.004	1.92	0.047	0.0009	0.013	0.003	1.30	0.037	0.001	0.95	0.009	0.0158	0.0015	0.0058	0.0011
	replicate 5	0.002	1.70	0.058	0.0008	0.011	0.003	2.03	0.064	0.001	0.78	0.005	0.0151	0.0009	0.0041	0.0004
	replicate 6	bdl	1.85	0.068	0.0009	0.023	0.004	1.18	0.037	0.011	0.76	0.003	0.0056	0.0005	0.0019	0.0003
mean		0.003	1.68	0.050	0.0020	0.016	0.003	1.36	0.033	0.005	0.86	0.003	0.0098	0.0007	0.0029	0.0018
st dev (ppm)		0.001	0.25	0.010	0.0014	0.006	0.001	0.34	0.018	0.006	0.14	0.003	0.0041	0.0004	0.0015	0.0016
In-house hair standard, leachate from 0.1 M HCl leach (ppm)																
Leachate		0.031	15.49	0.004	0.0010	0.031	0.038	0.14	0.010	bdl	5.06	0.000	0.0132	0.0012	0.0051	0.0086
	replicate 1	bdl	14.41	0.003	0.0012	0.041	0.044	0.18	0.006	bdl	4.90	0.000	0.0149	0.0013	0.0056	0.0067
	replicate 2	bdl	13.66	0.006	bdl	0.029	0.024	0.17	0.025	bdl	4.46	0.000	0.0133	0.0009	0.0037	0.0055
	replicate 3	0.021	12.34	0.010	0.0005	0.018	0.022	0.22	0.014	bdl	3.63	0.006	0.0089	0.0009	0.0039	0.0070
	replicate 4	0.015	10.48	0.010	0.0005	0.015	0.022	0.20	0.013	0.000	3.35	0.006	0.0094	0.0009	0.0034	0.0008
	replicate 5	0.028	9.09	0.013	0.0006	0.017	0.016	0.19	0.009	0.000	2.71	0.005	0.0072	0.0006	0.0026	0.0005
	replicate 6	0.034	7.06	0.020	bdl	0.022	0.014	1.40	0.024	0.003	2.00	0.005	0.0087	0.0007	0.0036	0.0008
mean		0.026	11.79	0.010	0.0007	0.025	0.026	0.36	0.014	0.001	3.73	0.003	0.0108	0.0009	0.0040	0.0043
st dev (ppm)		0.008	3.05	0.006	0.0003	0.009	0.011	0.46	0.007	0.002	1.15	0.003	0.0029	0.0002	0.0010	0.0035
sum of solid residue and leachates (ppm)																
residual + leachate		0.031	17.43	0.043	0.0036	0.055	0.041	1.29	0.027	bdl	6.19	0.000	0.0202	0.0017	0.0076	0.0123
	replicate 1	bdl	15.70	0.045	0.0038	0.054	0.045	1.32	0.025	bdl	5.66	0.000	0.0246	0.0017	0.0080	0.0103
	replicate 2	bdl	15.08	0.054	0.0016	0.038	0.026	1.31	0.039	bdl	5.27	0.000	0.0201	0.0013	0.0058	0.0088
	replicate 3	0.024	13.99	0.058	0.0052	0.039	0.024	1.82	0.057	bdl	4.44	0.012	0.0175	0.0014	0.0057	0.0073
	replicate 4	0.019	12.40	0.057	0.0014	0.029	0.025	1.50	0.050	0.001	4.30	0.015	0.0252	0.0024	0.0092	0.0019
	replicate 5	0.030	10.79	0.072	0.0014	0.028	0.020	2.23	0.073	0.001	3.49	0.010	0.0223	0.0016	0.0067	0.0009
	replicate 6	0.034	8.91	0.088	0.0009	0.044	0.019	2.58	0.061	0.014	2.76	0.008	0.0143	0.0013	0.0055	0.0012
mean		0.028	13.47	0.060	0.0026	0.041	0.029	1.72	0.047	0.005	4.59	0.006	0.0206	0.0016	0.0069	0.0061
st dev (ppm)		0.006	2.96	0.016	0.0016	0.011	0.010	0.51	0.018	0.007	1.21	0.006	0.0039	0.0004	0.0014	0.0047

Table 28. Concentration measurements of in-house standard continued.

		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Blanks in µg																
Leachate blank		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.00008	bdl
	replicate	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	0.0000	bdl	bdl	0.00001
	replicate 2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	bdl	bdl	bdl	0.00003
Residue blank		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.00021	bdl
	replicate	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0003	0.0005	bdl	bdl	0.00004	0.00000
	replicate 2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	0.0000	bdl	bdl	0.00001
In-house hair standard, solid residues from 0.1 M HCl leach (ppm)																
residue		bdl	bdl	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0207	2.79	bdl	0.0047	0.09	0.033
	replicate 1	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0212	3.29	bdl	0.0053	0.08	0.032
	replicate 2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0135	2.95	bdl	0.0042	0.08	0.045
	replicate 3	0.0001	0.0004	0.0001	0.0003	bdl	0.0002	bdl	0.0003	0.0000	0.0153	0.06	0.0001	0.0044	0.12	0.054
	replicate 4	0.0002	0.0007	0.0001	0.0005	0.0001	bdl	bdl	bdl	bdl	0.0162	0.02	0.0001	0.0041	0.12	0.047
	replicate 5	0.0001	0.0005	bdl	0.0005	0.0001	0.0003	bdl	0.0002	0.0001	0.0171	0.00	0.0001	0.0159	0.18	0.071
	replicate 6	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0171	0.01	0.0002	0.0026	0.19	0.081
mean		0.0001	0.0005	0.0001	0.0004	0.0001	0.0002	bdl	0.0002	0.0001	0.0173	1.30	0.0001	0.0059	0.12	0.052
st dev (ppm)		0.0000	0.0002	0.0000	0.0001	0.0000	0.0001		0.0000	0.0000	0.0028	1.60	0.0000	0.0045	0.04	0.018
In-house hair standard, leachate from 0.1 M HCl leach (ppm)																
Leachate		0.0002	0.0006	bdl	0.0006	bdl	0.0003	bdl	0.0003	bdl	0.0017	0.046	0.0001	bdl	0.31	0.026
	replicate 1	0.0002	0.0005	bdl	0.0006	bdl	0.0003	bdl	0.0003	bdl	0.0021	bdl	0.0001	bdl	0.52	0.031
	replicate 2	0.0001	0.0005	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0014	bdl	0.0001	bdl	0.26	0.039
	replicate 3	0.0002	0.0007	0.0008	0.0005	0.0001	0.0003	0.0004	bdl	bdl	0.0009	bdl	0.0002	0.0014	0.23	0.030
	replicate 4	0.0005	0.0006	0.0001	0.0005	0.0001	bdl	bdl	0.0003	0.0001	0.0009	bdl	0.0002	bdl	0.23	0.036
	replicate 5	0.0002	0.0005	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0012	bdl	0.0004	bdl	0.20	0.040
	replicate 6	0.0001	0.0004	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.0034	0.002	0.0003	bdl	0.17	0.042
mean		0.0002	0.0005	0.0004	0.0005	0.0001	0.0003	bdl	0.0003	bdl	0.0017	0.024	0.0002	bdl	0.28	0.035
st dev (ppm)		0.0001	0.0001	0.0005	0.0001	0.0000	0.0000		0.0000		0.0009	0.031	0.0001		0.12	0.006
sum of solid residue and leachates (ppm)																
residual + leachate		0.0002	0.0006	bdl	0.0010	bdl	0.0003	bdl	0.0003	bdl	0.0224	2.84	0.0001	0.0047	0.40	0.059
	replicate 1	0.0002	0.0008	bdl	0.0006	bdl	0.0003	bdl	0.0003	bdl	0.0233	3.29	0.0001	0.0053	0.60	0.063
	replicate 2	0.0001	0.0005	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0149	2.95	0.0001	0.0042	0.35	0.084
	replicate 3	0.0003	0.0011	0.0009	0.0009	0.0001	0.0004	0.0004	0.0003	0.0000	0.0163	0.06	0.0003	0.0058	0.36	0.084
	replicate 4	0.0007	0.0013	0.0002	0.0010	0.0002	bdl	bdl	0.0003	0.0001	0.0171	0.02	0.0003	0.0041	0.35	0.083
	replicate 5	0.0003	0.0010	bdl	0.0009	0.0001	0.0003	bdl	0.0002	0.0001	0.0184	0.00	0.0005	0.0159	0.38	0.111
	replicate 6	0.0001	0.0007	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.0205	0.01	0.0005	0.0026	0.36	0.123
mean		0.0003	0.0009	0.0006	0.0007	0.0001	0.0003	bdl	0.0003	0.0001	0.0190	1.31	0.0003	0.0061	0.40	0.087
st dev (ppm)		0.0002	0.0003	0.0005	0.0003	0.0001	0.0001		0.0000	0.0000	0.0032	1.61	0.0002	0.0044	0.09	0.023

Table 28. Concentration measurements of in-house continued.

6.4.3 Comparison of data from multiple laboratories Many researchers who interpret isotopic data about hair do not have the equipment and personnel to produce high quality data in their own laboratories. A substantial amount of institutional and financial resources as well as experienced technicians are required to consistently produce high quality results. In addition, each sample type and analysis requires extensive optimization and validation. If analyses are not done on a routine basis, a laboratory will have difficulty maintaining the QA/QC records to ensure accurate and precise sample measurements. It is more efficient to have a smaller number of laboratories that are high throughput. However, consumers of isotopic data must then depend on a laboratories internal QA/QC to ensure data is suitable for use. Participation in inter-laboratory calibration studies, such as those conducted by the National Institute of Standards and Technology (NIST) or the Forensic Isotope Ratio Mass Spectrometry (FIRMS), are one of the primary ways which consumers of isotope data have for ensuring quality data. However, these studies require substantial investment of time and resources, and laboratories may only validate each of their commercially-offered analyses every few years, if at all. Laboratories also typically know when they are participating in these comparison study, and additional efforts in instrument maintenance, calibration and standard preparation typically mean that errors are minimized for samples in these studies. In addition, laboratory inter-calibration studies will not include blanks, potential isotopic offsets and precision involved with external sample preparation by the end user. It is best practice for consumers of isotopic data to include two types of standards as blinded unknowns among their samples when submitting to a commercial laboratory: 1) certified standards and 2) in-house standards that most closely match the sample matrix and preparation of samples. Certified standards will indicate the accuracy of measured values compared to internationally-agreed upon values. In-house standards, ideally measured at multiple laboratories, will provide the precision and external reproducibility of samples run for a project.

The W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University does not currently have validated methods for $\delta^{18}O$ and $\delta^{2}H$ of hair. Because of concerns about quality control related in particular to $\delta^{2}H$ measured values of hair from discussions in the literature (Bowen et al 2005; Chesson et al 2009; Coplen and Qi 2012; Meier-Augenstein et al 2011; Qi and Coplen 2011), we sent out certified standards USGS 42 and 43 (Indian and Tibetan hair) for blind analysis by three external laboratories. Keratin (the protein which makes up hair) has many exchangeable hydrogen sites that typically equilibrate with the

local humidity. This means that if proper precautions are not taken, the measured values can reflect a mixture of the isotopic composition of the hydrogen endogenous to the hair as well as of the humidity of the laboratory in which they were analyzed. Particularly when multiple laboratories are used during the course of the study, this could seriously compromise the conclusions resulting from the analysis.

In addition, we wished to develop two in-house hair standards that would a) provide sufficient sample to run frequent check standards and b) be more similar in isotopic composition to our target subject pool of modern Americans. This would allow us to provide the best estimate of accuracy and precision for unknown samples, as the sample preparation (including homogenization) is identical to that of unknown samples. Americans are well known to be substantially different in $\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$ and $\delta^{18}O$ from Europeans and Asians (O'Connell and Hedges, 1999; Ehleringer et al, 2008; Thompson et al, 2010; Valenzuela et al, 2012; Bartelink et al, 2014). Hence, hair from two anonymous donors from local hair salons was collected, cleaned, and powdered following normal protocols. The two salons were selected with different demographics of clientele. One was a SuperCuts, and the clientele at the time of collection was dominantly Caucasian males. The other ("Transformations by Michelle") was a salon catering to African-American women. No other information is available about the donors. Locks of hair that appeared to be from a single donor was selected based upon similar length, color, and physical proximity. However, there is no guarantee that the hair collected was limited to a single donor.

All three external laboratories are light stable isotope facilities that routinely accept samples from outside researchers, use at least two standards in scale normalization and run secondary standards in parallel with samples.

After noting that the $\delta^{2}H$ values for the certified standards were significantly outside error for all three labs (Table 29), each lab was contacted with the results in order to determine what factors might be causing the discrepancies. The offset between USGS 42, 43 and our in-house standards 1 and 2 were quite consistent within a single laboratory, but there was less consistency between laboratories. This held true for all isotope systems analyzed, but the difference was particularly striking for $\delta^{2}H$ values, which had the largest spread in measured values.

These discrepancies have important implications for forensic practitioners. Using the δ^2H values from Laboratories B and C from the individuals contributing in-house samples 1 and 2, we would conclude that these individuals could *only* have come from a small area of central Texas. However, the samples were collected from Phoenix, Arizona, so such a conclusion would send an investigation in a very wrong direction. This analysis used the maps from Ehleringer et al (2008)[4]. All laboratories confirmed that the measured samples met all internal quality controls (Table 4).

Several possibilities for the discrepancies of measured values between laboratories were suggested: 1) different protocols for equilibration of samples and standards and 2) different standards used in normalization. Measurement of exchangeable hydrogen requires co-equilibration of samples and standards, as local humidity from the laboratory contributes to the measured values. Only by making corrections using known standards can the absolute values be measured. However, the conditions under which this equilibration occur can vary between laboratories, as some use high temperature equilibration, while others use room temperature equilibration in a dessicator with known water standards. Several differences in preparation protocol distinguished the different laboratories. Utah's laboratory requires that bulk powdered hair be sent, and the samples are encapsulated on site, intended to avoid differences in equilibration rate due to encapsulation. The other two laboratories accept (and prefer) receiving samples already encapsulated in silver capsules. Another difference is in the selection of standards used for normalization, and the measurement protocol; Laboratories B and C analyze exchangeable δ^2H in keratin alone, while Laboratory A analyzes both $\delta^{18}O$ and δ^2H in the same sample by separating the gases on a GC column and jumping the magnet – essentially analyzing H_2 and O_2 on the same detector at different times. One other difference is that the size samples requested by the labs vary from 0.15 mg to 1.22 mg.

It is important to note that these analyses were *not* designed as an inter-laboratory comparison study, as are conducted most competently by NIST and FIRMS. We compared a small number of samples and was not intended to assert anything about the global quality of all analytical protocols from these laboratories, but simply to provide confirmation that isotope values for the specific sample types measured in the course of the larger study would be accurate

[4] *cf* Figure 3A in Ehleringer et al, (2008) Hydrogen and oxygen isotope ratios in human hair are related to geography. *PNAS* **105**:8, 2788-2793, doi: 10.1073/pnas.0712228105.

and precise for the purposes of the current research. Prior to sample submission and reporting, none of the laboratories were informed that they were being tested in blind analysis of standards, as we did not anticipate releasing the data publicly. However, the results have important implications for forensic practitioners in determining region-of-origin, and we believe it is important to make the forensic community aware of the issues uncovered during the course of this work. As a consequence, we have anonymized the reporting laboratories because we did not receive their consent to participate prior to the study.

USGS 42 (Tibetan Human Hair)					
	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{34}S$ (‰)
Certified value	-21.09 ±0.10	8.05 ±0.10	8.56 ±0.10	-78.50 ±2.3	7.84 ±0.25
Revised certified value[5]				-72.99 ±2.2	
Lab A	-21.05	7.93	**9.9**	**-84.6**	**8.55**
Lab B	-21.11	8.13	**8.3**	**-103.4**	8.04
Lab C	**-20.86**	8.12	n/a	**-114.0**	**8.47**
ASU	-21.25	7.91	n/a	n/a	n/a

USGS 43 (Indian Human Hair)					
	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{34}S$ (‰)
Certified value	-21.28 ±0.10	8.44 ±0.10	14.11 ±0.10	-50.30 ±2.8	10.46 ±0.22
Revised certified value				-44.0 ±2.0	
Lab A	-21.24	8.36	**15.7**	**-53.4**	**11.22**
Lab B	-21.28	8.37	**13.9**	**-73.7**	10.62
Lab C	-21.15	8.49	n/a	**-67.6**	10.85
ASU	-21.46	8.35	n/a	n/a	n/a

Table 29. Agreement for certified standards USGS 42 and 43, prepared according to each laboratory's requirements and analyzed as unknowns. Values that are >1σ from the certified value is highlighted in red. Values that are >2 σ from the certified value is also highlighted in bold.

[5] On September 9th, 2016, USGS released revisions of the certified values of USGS 42 and 43 for $\delta^{2}H$, due to adoption of a new analytical method using chromium that minimizes formation of cyanide and optimizes quantitative conversion of hydrogen in keratin samples into gaseous hydrogen.

Sample preparation and measurement for δ^2H of keratin			
	Lab A	Lab B[6]	Lab C
Preferred sample type	Powdered hair	Encapsulated powdered hair	Encapsulated powdered hair
Requested sample size	0.15 mg	1.22 mg	0.35 mg
Analysis type	$\delta^{18}O$ and δ^2H (continuous flow)	δ^2H only	δ^2H only
USGS 42	-84.6‰	-103.4‰	-114.0‰
USGS 43	-53.4‰	-73.7‰	-67.6‰
H-Std 1 (ASU)	-80.2 ±1.4‰ (n=3)	-100.24 ±0.48‰ (n=3)	-97.86 ±0.32‰ (n=3)
H-Std 2 (ASU)	-80.5 ±2.5‰ (n=3)	-102.0 ±1.4‰ (n=3)	-97.3 ±1.3‰ (n=3)
Primary standard 1	DS (Dall Sheep horn, Alaska)	KHS (keratin)	Keratin – SC Lot SJ powdered
Primary standard 1 value (‰)	-172.7‰	-54.1‰	-121.6‰
Measured standard 1 value ±1 sd	-172.7 ±1.2‰ (n=8)	-54.1 ±1.3‰ (n=4)	-120.8 ±1.0‰ (n=8)
Primary standard 2	ORX (oryx antelope horn, Ethiopia)	CBS (keratin)	CBS (Caribou hoof, powdered)
Primary standard 2 value (‰)	-34.0‰	-197.0‰	-197.0‰
Measured standard 2 value ±1 sd	-34.0 ±1.7‰ (n=7)	-197.0 ±1.7‰ (n=4)	-198.5 ±0.1‰ (n=2)
Primary standard 3			KHS (Kudo horn, powdered)
Primary standard 3 value			-54.1‰
Measured standard 3 value			-55.3 ±0.5‰
Secondary check standards and values	POW (commercially available powdered keratin); -100.9‰ "known" value;	BWB (keratin) -108‰ "known" value; measured value is -108.8 ±1.7 (n=4)	Animas River algae 1 (powdered), -238.5; AZ Elk (hair, powdered), -106.0, BWB-II – new (baleen, powdered), -

[6] QA from initial round of analyses

	measured value is -98.9 ±1.9 (n=6)		109.8; CCHIX-1 (feathers, powdered), -106.3; Chitin – TCI (powdered), -30.4; CHS (cow hoof, powdered), -182.4; Grizz 2 (hair, powdered), -91.8; IAEA-085 (hair, powdered), -66.3; TURK-1 (feathers, powdered), -63.4

Table 30. Protocols used in each of the laboratories for hydrogen isotope analysis of keratin.

After noting that the δ^2H values for the certified standards were significantly outside error for all three labs, each lab was contacted with the results in order to determine what factors might be causing the discrepancies. It was noted that the offset between USGS 42, 43 and our in-house standards 1 and 2 were quite consistent within a single laboratory, but that there was less consistency between laboratories. This statement held true for all isotope systems analyzed, but the difference was particularly striking for δ^2H values that had the largest spread in measured values. All laboratories confirmed that the measured samples met all internal quality controls (Table 30).

These discrepancies have important implications for forensic practitioners. Using the δ^2H values from Laboratories B and C from the individuals contributing in-house samples 1 and 2, we would conclude that these individuals could *only* have come from a small area of central Texas. The samples were collected from Phoenix, Arizona, so such a conclusion would send an investigation in a very wrong direction. This analysis used the maps from Ehleringer et al (2008)[7].

Several possibilities for the discrepancies include: 1) different protocols for equilibration of samples and standards and 2) different standards used in normalization. Measurement of exchangeable hydrogen requires co-equilibration of samples and standards, as local humidity from the laboratory contributes to the measured values. Only by making corrections using known

[7] *cf* Figure 3A in Ehleringer et al (2008) Hydrogen and oxygen isotope ratios in human hair are related to geography. *PNAS* **105**:8, 2788-2793, doi: 10.1073/pnas.0712228105.

standards can the absolute values be measured. However, the conditions under which this equilibration occurs can vary between laboratories, as some use high temperature equilibration, while others use room temperature equilibration in a dessicator with known water standards. Several differences in preparation protocol distinguished the different laboratories. Utah's laboratory requires that bulk powdered hair be sent, and the samples are encapsulated on site. This is intended to avoid differences in equilibration rate due to encapsulation. The other two laboratories accept (and prefer) receiving samples already encapsulated in silver capsules. The other difference was in the selection of standards used for normalization, and the measurement protocol; NAU and UC Davis analyze exchangeable δ^2H in keratin alone, while the SIRFER lab at Utah analyzes both $\delta^{18}O$ and δ^2H in the same sample by separating the gases on a GC column and jumping the magnet – essentially analyzing H_2 and O_2 on the same detector at different times. One other difference is that the size samples requested by the labs vary from 0.15 mg to 1.22 mg.

Based upon discussions with the laboratories involved in the analyses as well as working anthropologists with extensive experience in stable isotope analysis, this is an underappreciated issue with important forensic implications.

As discussed above, on September 9th, 2017 the USGS released revised δ^2H values for certified standards USGS 42 and 43, due to improved measurement protocols. However, the changes are relatively minor and can not be responsible for the discrepancies between the results and certificate.

In order to resolve these substantial discrepancies, Lab B agreed to assist in testing the two hypotheses of 1) normalization issues and 2) sample packaging issues. We resent blind aliquots of USGS 42, 43 (n=1 each) and the two proposed in-house standards (n=3 each) as both silver capsules packed at ASU according to Lab B's guidelines and also as tubes of hair powder to be packed by technicians at Lab B. The samples were then run with two sets of normalization standards: USGS 42 – 43 as well as their typical standard CBS-KHS.

		normalization standards	δ^2H_{VSMOW}	δ^2H error (‰)	Δ^2H	%H
USGS 42	**certified value**		**-78.5 ±2.3**			**6.1**
	revised certified value		**-72.9 ±2.2**			**6.2**
	Lab A	DS-ORX	-84.6	-11.7		5.4
	Lab B	CBS-KHS	-103.4	-30.5		5.2
	Lab B - ASU prep	USGS 42-43	-76.7	-3.8		5.2
	Lab B - Lab B prep	USGS 42-43	-76.2	-3.3		5.1
	Lab B - ASU prep	CBS-KHS	-103.6	-30.7		5.2
	Lab B - Lab B prep	CBS-KHS	-103.0	-30.1		5.1
	Lab C	CBS-KHS	-114.0	-41.1		6.3
USGS 43	**certified value**		**-50.30 ±2.8**		**-28.2**	**6.1**
	revised certified value		**-44.4 ±2.0**		**-28.5**	**6.2**
	Lab A	DS-ORX	-53.4	-9.0	-31.2	5.5
	Lab B	CBS-KHS	-73.7	-29.3	-29.7	5.2
	Lab B - ASU prep	USGS 42-43	-49.8	-5.4	-27.0	5.3
	Lab B - Lab B prep	USGS 42-43	-48.0	-3.6	-28.2	5.1
	Lab B - ASU prep	CBS-KHS	-72.9	-28.5	-30.8	5.3
	Lab B - Lab B prep	CBS-KHS	-70.8	-26.4	-32.2	5.1
	Lab C	CBS-KHS	-67.6	-23.2	-46.4	5.5

Table 31. Comparison of δ^2H values from the three laboratories using different normalization schemes and different sample preparation. Δ^2H is the offset between USGS 42 and 43, and shows far less variation than the absolute values of the standards run as unknowns.

Sample preparation location had very little impact on the reported isotope values, suggesting that the equilibration precautions taken were sufficient, despite the significant humidity differences between the source lab (ASU) and the analysis lab. However, there were substantial differences between the samples depending on the normalization used.

Based upon discussions with the laboratories involved in the analyses as well as working anthropologists with extensive experience in stable isotope analysis, the issue of inter-laboratory reproducibility is an underappreciated issue with important forensic implications – despite previous literature documenting the problem (Meier-Augenstein et al 2011; Pestle, Crowley and Weirauch 2014; Benson et al 2010b; Table 31).

It is important to note that USGS 42-43, although proposed as normalization standards (Qi and Coplen 2011; Coplen and Qi 2012), do not bracket many typical samples, and encompass a relatively narrow range of possible values. The total range of δ^2H values between USGS 42 and USGS 43 is -28.5‰; nearly half of American hair from the main portion of this study is outside the normalization range of USGS 42 - 43. In contrast, the typical normalization

standards for Lab A standards (DS-ORX) span 138.7‰, Lab B standards (CBS-KHS) cover >142.9‰, and Lab C standards span 75.4‰. All samples analyzed for this project fell well within the normalized range for all three labs. All the standards used for normalization are keratin, but are different types of keratin; USGS 42 and 43 are natural human hair, while the rest are standards from animal horn or hoof.

As an indication of the relative importance of these normalization concerns, the error in the δ^2H values ranged from -3.3 to -41.1‰; the entire range of δ^2H values in hair for the entire United States is 49‰ (Ehleringer et al., 2008). This discrepancy has been demonstrated previously with the certified values of USGS 42 and 43 (*cf* Figure 3 in Coplen & Qi, 2012), but it is clear there are substantial issues when getting measured values from outside laboratories. Coplen and Qi recommend using USGS 42 and 43 as bracketing standards for analysis of human hair, but the narrow isotopic range of USGS 42 and 43 does not cover much of the expected range of values for populations in the United States, many laboratories have not adopted these recommendations. This clearly remains an ongoing issue. We highly recommend that laboratories measure certified standards or in-house standards routinely to compare values between references in the literature until such time that the IRMS community uses universal standards for normalization. In addition, reporting such standards would allow correction in the case when studies have switched analytical facilities in the middle of a study (*e.g.*, Herrmann, 2015).

		$\delta^{13}C_{VPDB}$ (‰)	%C	$\delta^{15}N_{AIR}$ (‰)	%N	C/N	$\delta^{34}S_{VCDT}$	%S
USGS 42	**certified value**	**-21.09 ±0.10**	**45.70**	**8.05 ±0.10**	**15.30**	**2.99**	**7.84 ±0.25**	**4.40**
	Lab A	-21.05	44.20	7.93	17.01	2.60	8.55	4.28
	Lab B	-21.11	44.86	8.13	15.14	2.96	8.04	3.84
	Lab C	-20.86	44.33	8.12	15.02	2.95	8.47	4.78
	ASU	-21.05	45.09	7.86	15.23	2.96	n/a	
USGS 43	**certified value**	**-21.28 ±0.10**	**45.70**	**8.44 ±0.10**	**15.30**	**2.99**	**10.46 ±0.22**	**4.50**
	Lab A	-21.24	44.02	8.36	16.88	2.61	11.22	4.85
	Lab B	-21.28	44.28	8.37	14.83	2.99	10.62	3.80
	Lab C	-21.15	43.99	8.49	14.89	2.96	10.85	4.87
	ASU	-21.16	45.33	8.34	15.25	2.97	n/a	
H Std 1	Lab A	-18.00	44.92	9.31	16.30	2.76	5.83	2.27
		-18.10	45.37	9.33	16.37	2.77	6.35	2.18
		-18.03	45.74	9.37	16.58	2.76	5.64	2.14
	mean	-18.05	45.34	9.34	16.42	2.76	5.94	2.20
	st dev	0.05	0.41	0.03	0.15	0.01	0.37	0.07
	Lab B	-18.10	45.67	9.34	14.48	3.15	7.19	2.21
		-18.14	45.06	9.36	14.23	3.17	7.69	2.10
		-18.12	45.64	9.39	14.47	3.15	6.84	2.22
	mean	-18.12	45.45	9.37	14.39	3.16	7.24	2.18
	st dev	0.02	0.34	0.02	0.14	0.01	0.43	0.06
	Lab C	-17.98	45.31	9.48	14.44	3.14	6.91	2.37
		-17.95	45.20	9.48	14.38	3.14	7.02	2.25
		-18.11	45.26	9.42	14.42	3.14	7.33	2.41
	mean	-18.02	45.25	9.46	14.41	3.14	7.09	2.34
	st dev	0.08	0.05	0.03	0.03	0.00	0.22	0.08
	ASU	-18.05	46.07	9.27	14.56	3.16	n/a	
		-18.06	45.68	9.28	14.44	3.16		
		-18.08	45.85	9.27	14.51	3.16		
	mean	-18.06	45.86	9.27	14.50	3.16		
	st dev	0.01	0.20	0.00	0.06	0.00		
H Std 2	Lab A	-16.77	45.12	9.21	16.83	2.68	4.06	5.09
		-16.72	44.94	9.13	16.79	2.68	3.10	4.86
		-16.70	44.84	9.17	16.72	2.68	3.59	5.08
	mean	-16.73	44.97	9.17	16.78	2.68	3.58	5.01
	st dev	0.04	0.14	0.04	0.06	0.00	0.48	0.13
	Lab B	-16.82	44.94	9.18	14.71	3.05	2.35	4.00
		-16.78	44.83	9.16	14.70	3.05	2.24	4.01
		-16.78	45.00	9.04	14.75	3.05	2.14	4.03
	mean	-16.80	44.92	9.13	14.72	3.05	2.24	4.01
	st dev	0.02	0.09	0.07	0.03	0.00	0.10	0.02
	Lab C	-16.83	45.31	9.48	14.44	3.14	3.01	4.99
		-16.84	45.20	9.48	14.38	3.14	2.83	5.08
		-16.84	45.26	9.42	14.42	3.14	3.14	5.03
	mean	-16.83	45.25	9.46	14.41	3.14	3.00	5.03
	st dev	0.01	0.05	0.03	0.03	0.00	0.16	0.05
	ASU	-16.75	44.93	9.03	14.72	3.05	n/a	
		-16.75	44.84	9.05	14.68	3.05		
		-16.72	44.78	9.03	14.70	3.05		
	mean	-16.74	44.85	9.04	14.70	3.05		
	st dev	0.02	0.08	0.01	0.02	0.00		

Table 32. Inter-comparison of USGS 42, 43 and two in-house American human hair standards 1 and 2 for carbon, nitrogen and sulfur isotopes and concentrations by IRMS.

		H Std 1					H Std 2				
	standards and sample prep	$\delta^{18}O$	mass fraction of oxygen	$\delta^{2}H$	mass fraction of total hydrogen	O/H	$\delta^{18}O$	mass fraction of oxygen	$\delta^{2}H$	mass fraction of total hydrogen	O/H
Lab A	DS-ORX	11.5	23.2	-80.0	5.8	**3.98**	12.3	21.4	-80.0	5.5	**3.85**
		11.3	22.8	-78.9	5.8	**3.96**	11.0	22.9	-83.2	5.8	**3.93**
		11.5	23.1	-81.6	5.9	**3.93**	11.9	21.8	-78.3	5.7	**3.84**
	mean	11.44	23.0	-80.2	5.8	**3.96**	11.7	22.0	-80.5	5.7	**3.88**
	st dev	0.12	0.2	1.4	0.1	**0.03**	0.6	0.8	2.5	0.1	**0.05**
Lab B	CBS-KHS	**10.0**	**22.8**	-100.7	5.5	4.19	**10.1**	**21.6**	-101.5	5.3	4.07
		9.9	**23.0**	-99.7	5.4	4.23	**10.3**	**21.5**	-101.0	5.3	4.06
		9.9	**23.0**	-100.3	5.5	4.21	**10.0**	**21.6**	-103.6	5.3	4.11
	mean	**9.90**	**22.9**	-100.2	5.4	4.21	**10.2**	**21.5**	-102.0	5.3	4.08
	st dev	**0.05**	**0.1**	0.5	0.0	0.02	**0.1**	**0.1**	1.4	0.0	0.03
	USGS 42-43			**-71.6**	**5.7**				**-73.2**	**5.7**	
	ASU prep			**-74.9**	**5.6**				**-74.9**	**5.6**	
				-73.9	**5.7**				**-74.7**	**5.7**	
	mean			**-73.5**	**5.67**				**-74.2**	**5.67**	
	st dev			**1.7**	**0.03**				**0.9**	**0.03**	
	USGS 42-43			**-73.5**	**5.7**				**-71.6**	**5.7**	
	Lab B prep			**-72.9**	**5.6**				**-72.1**	**5.6**	
				-72.8	**5.7**				**-72.8**	**5.7**	
	mean			**-73.1**	**5.67**				**-72.2**	**5.67**	
	st dev			**0.4**	**0.03**				**0.6**	**0.03**	
	CBS-KHS			-97.8	5.7				-99.5	5.7	
	ASU prep			-101.5	5.6				-101.5	5.6	
				-100.4	5.7				-101.3	5.7	
	mean			-99.9	5.67				-100.8	5.67	
	st dev			1.9	0.03				1.1	0.03	
	CBS-KHS			-100.0	5.7				-97.7	5.7	
	Lab B prep			-99.2	5.6				-98.3	5.6	
				-99.2	5.7				-99.2	5.7	
	mean			-99.4	5.67				-98.4	5.67	
	st dev			0.4	0.03				0.7	0.03	
Lab C	CBS-KHS			-98.0	5.7				-98.7	5.6	
				-98.1	5.6				-97.0	5.6	
				-97.5	5.7				-96.2	5.5	
	mean			-97.9	5.67				-97.3	5.6	
	st dev			0.3	0.03				1.3	0.0	

Table 33. Intercomparison of measured values for two in-house human hair standards used for quality control through this project. The values in bold are for the laboratory and preparation that was most accurate compared to the certified values for USGS 42 and 43 analyzed as unknowns.

6.4.4 Impact of freezing storage on light stable isotope compositions Circumstances can not always be anticipated prior to the beginning of a study. The original intent of the study as originally proposed was to mechanically clean and dry samples on site, then complete additional mechanical and chemical cleaning in the laboratories at Arizona State University when more time was available. However, the number of samples collected during the initial stages of the study at the University of Tennessee overwhelmed the local facilities for drying hair samples without cross-contamination, sample degradation, or sample loss. High humidity retarded the

drying process, particularly when samples had significant amounts of soil adhering to the hair with decompositional fluids. Also, because insects matured rapidly in high temperatures, samples collected with maggot eggs hatched within a few hours and the larvae began crawling away from the sample, spreading material with them and risking both cross-contamination and significant sample loss. Attempts to create on-site containment units that would still permit samples to dry proved unsuccessful. Drying at high heat or killing maggots by either physical or chemical means were both rejected as potentially inducing isotopic change through exchange with maggot body fluids (in the case of physically crushing them) or altering the hair structure.

The most reasonable alternative was to freeze samples upon collection. However, this was of concern because no literature study on the effect of freezing on the isotopic composition of hair was known to this study's authors. Freezing has the potential to modify the isotopic composition of hair through physical damage from ice crystal formation and subsequent chemical reactions with decompositional fluids or soil particles. In addition, evaporation (which induces a large isotope fractionation) in a cold, low-humidity environment such as a freezer, can cause isotope fractionation.

Two of the donor cadavers to the University of Tennessee were already frozen prior to placement, in order to coordinate placement with the logistical needs of the facility. Hence, some samples were frozen prior to the study's start.

It was also noted that standard evidence-packaging guidelines for law enforcement typically requires freezing evidence for potential future biological evidence retrieval of DNA. However, some smaller agencies already have samples stored for many years without access to freezing facilities, and both ARF and FARF have stored hair samples long-term at room temperature in manila envelopes. Hence, in actual case work, analysts may come across samples stored either dried at room temperature or frozen.

To evaluate the impact of short-term freezing as used for the current study, we decided to compare samples with and without freezing for two weeks or six months. Key aspects of the experimental design included:

-comparing 20 samples without freezing, frozen for two weeks and six months;

-comparing samples packaged in plastic clamshell materials and butcher paper;

-including samples from the widest possible range of hair types;

-comparing a second set of frozen and room temperature samples stored for up to three years;

-10% of all samples were frozen, cleaned, processed and analyzed in triplicate for the most accurate representation of sample reproducibility;

-anonymizing samples prior to the start of the freezing study, including the triplicates. (Sample identity was not revealed until all analyses were complete.);

-running four standards as unknowns in parallel with samples: USGS 42, USGS 43, ASU H-Std 1 and ASU H-Std 2.

Because some concerns had arisen from previous work in relation to storage in plastic (Fraser, Meier-Augenstein, and Kalin 2008), we chose to examine packaging material as well. A unique aspect of this research is that we partnered with the Mesa Police Department to use both law enforcement packaging materials and evidence packaging guidelines to most closely reflect actual forensic case work samples.

Ancestral diversity is an included variable because Mongoloid hair is known to absorb more explosive volatiles than Caucasian or Negroid hair (Oxley et al, 2007), while Negroid hair is known to absorb more cocaine, morphine, and nicotine per dose than Caucasians (Apelberg et al, 2012; Kidwell et al, 2000). Negroid hair shows more damage than Caucasians when exposed to UV radiation, and mechanical properties such as the amount of water swelling has also been demonstrated to vary by hair type (Ji et al, 2013; Franbourg et al, 2003).

In addition, previous studies typically used modern hair from barbershops, which is unlikely to closely reflect forensic casework samples. Hence, we used hair samples representing a range of hair treatments (dying, straightening, and coloring), ancestry (Caucasian, Asian, African), and conditions (decompositional samples, modern samples) because hair that has been damaged through chemical or physical means may be more susceptible to alteration than intact hair (Figure 5; Table 34).

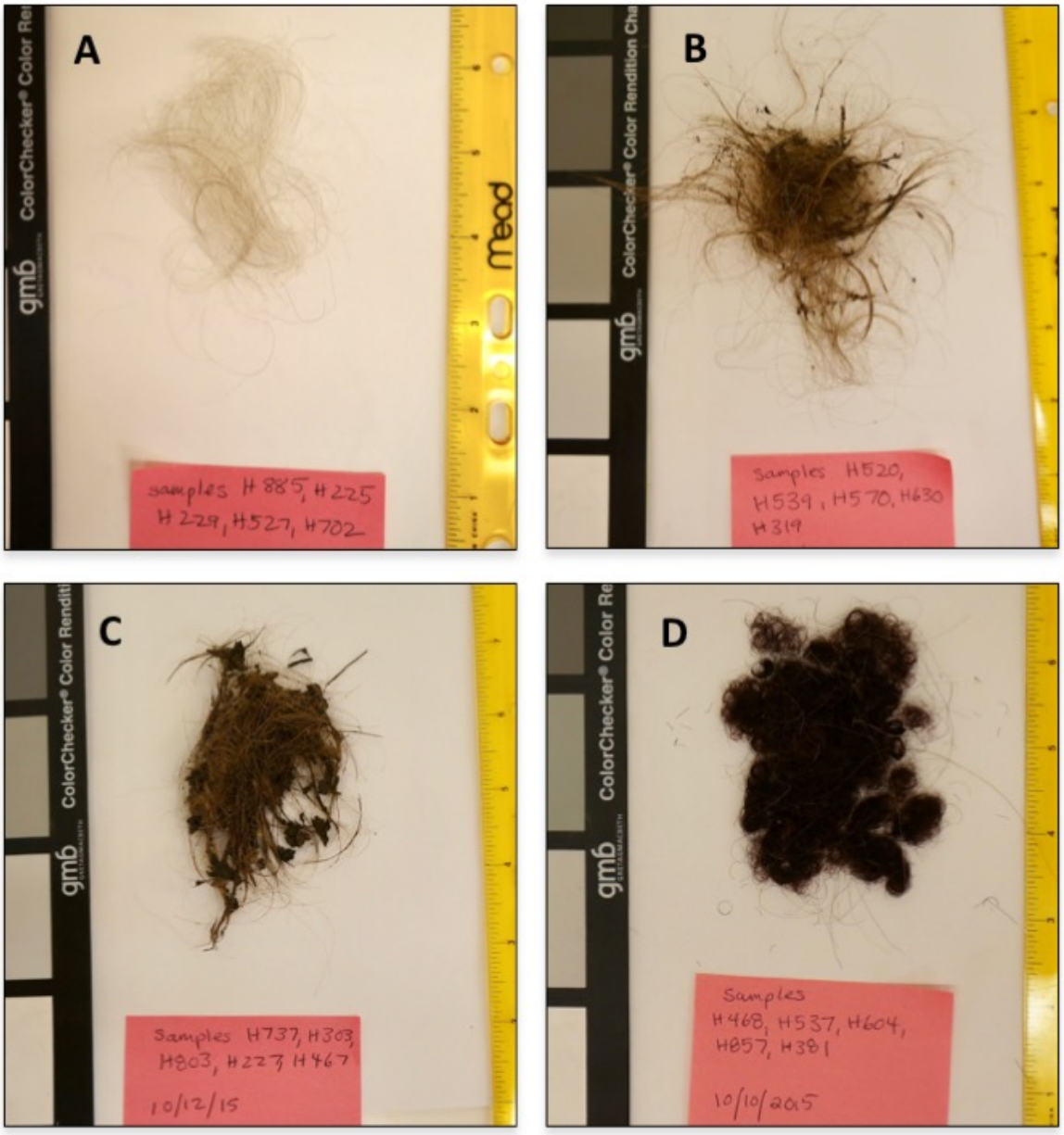

Figure 5. Photographs of some hair samples used in the freezing validation study, illustrating the diversity of hair condition and texture used. Photo A is of a sample from an elderly female donor at FARF, collected at intake. Photo B is from a FARF donor, one week after placement. Photo C is from a FARF donor, six months after placement. Photo D is a modern sample from a salon with a clientele of dominantly African ancestry.

The Mesa Police Department Forensic Services Laboratory is an ANAB - ASCLD/LAB accredited laboratory, with an accredited Crime Scene Unit. Senior Crime Scene Specialists Christine Lowenhagen, Lisa Morgante, and Christopher Zemojtel and Crime Scene Supervisors

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

Kristal Kolhepp and Elizabeth Wiltrout were consulted to make sure that the current Mesa Police Evidence Unit packaging guidelines were followed.

Samples were packaged in either plastic clamshell boxes or white butcher paper. The plastic clamshell boxes are standard issue in the Mesa Police Department Crime Scene Unit, and are commonly use to package small evidence items such as cartridge casings or cigarette butts. The white butcher paper was folded in a pharmacist's fold in order to enclose the hair. The paper or plastic container were then put in a manila envelope and sealed with evidence tape before being placed in a -20°C freezer for the required time (Figure 6).

Figure 6. Photographs of packaged samples. Photo A shows a typical sample divided into aliquots for the five storage conditions. Photos B and C show the sealed evidence envelope.

Experimental samples		
Ancestry	Cosmetic treatment or condition	n
African	Color and relaxer	2
African	Color only	1
African	Relaxer only	1
African	-	2
Asian	-	2
European	-	2
European	Colored	4
European	Decomposed remains, 1 week to 10 months, Texas	4
European	Decomposed remains, 1 to 5 days, Tennessee	2

Table 34. List of experimental samples used in the freezing study. Cosmetic color treatment was determined if a strong color band was visible near the root end, or if the hair color appeared unnatural. Cosmetic relaxer treatment was determined by visual textural analysis. There may be additional cosmetic treatments that were not visually obvious.

These experimental samples were good representations of the short-term stability of hair samples in frozen storage, but do not indicate stability over many years. ARF had been collecting hair samples at intake and splitting them in two aliquots: one was stored in a manila envelope at room temperature, and the other was frozen at -20°C. Ten paired hair samples from donors at ARF in storage from 8.7 months to 4.1 years were analyzed to compare longer-term storage.

Samples were analyzed at the Stable Isotope Facility at the University of California, Davis. Standards run during the freezing study are listed in Tables 35 and 36.

		$\delta^{13}C_{VPDB}$ (‰)	%C	$\delta^{15}N_{AIR}$ (‰)	%N
		Analysis standards			
G-13	Bovine Liver	**-21.7**		**7.72**	
	measured (n=4)	-21.72 ±0.06		7.73 ±0.05	
G-18	Nylon 5	**-27.7**		**-10.3**	
	measured (n=57)	-27.72 ±0.05		-10.31 ±0.12	
G-20	Glutamic acid	**-16.7**	**40.8**	**-6.8**	**9.5**
	measured (n=16)	-16.63 ±0.09		-6.64 ±0.19	
G-21	Enriched Alanine	**43**		**41.1**	
	measured (n=8)	43.02 ±0.05		41.13 ±0.08	
		Standards run as blind unknown samples			
USGS 42	Tibetan Human Hair	**-21.09 ±0.10**	**45.7**	**8.05 ±0.10**	**15.3**
	measured (n=6)	-21.12 ±0.08	46.0 ±0.3	8.03 ±0.07	15.4 ±0.3
USGS 43	Indian Human Hair	**-21.28 ±0.10**	**45.7**	**8.44 ±0.10**	**15.3**
	measured (n=6)	-21.34 ±0.07	45.1 ±0.5	8.37 ±0.13	15.1 ±0.2
ASU H Std 1	relaxed, color-treated hair of African ancestry (Arizona)	**-18.06 ±0.10**	**45.5 ±0.6**	**9.36 ±0.05**	**14.9 ±0.2**
	measured (n=5)	-18.15 ±0.03	45.8 ±2.7		
ASU H Std 2	probable European hair (Arizona)	**-16.78 ±0.05**	**45.0 ±0.2**	**9.20 ±0.09**	**15.2 ±0.1**
	measured (n=5)	-16.88 ±0.03	45.6 ±1.4	9.10 ±0.07	15.0 ±0.5

Table 35. Standards run as knowns and unknowns during carbon and nitrogen isotope analyses during the freezing study. Values in bold are certified or known. The known values for the two ASU hair standards are taken as the average and expanded standard deviation from the analyses from the four labs conducted in the inter-laboratory comparison study.

		$\delta^{18}O_{VSMOW}$ (‰)	%O	$\delta^{2}H_{VSMOW}$ (‰)	% total H
		Analysis standards			
alanine (lab standard for linearity and elemental concentration)		+19.79 ±0.34 (n=12)	36.0 ±0.2		
nylon (lab standard used for order correction)		+7.34 ±0.71 (n=52)	n/a		
cellulose (internal check)		+33.4 ±3.2 (n=6)	n/a		
IAEA 600 caffeine		-6.1 ±0.9 (n=8)			
PE (lab polyethylene standard for linearity and elemental concentration)				-40.6 ±3.5 (n=16)	14.3 ±0.2
trk (lab keratin standard used for order correction)				-42.4 ±4.1 (n=121)	n/a
USGS 42	Tibetan Human Hair	**+8.56 ±0.10**	**22.0**	**-72.9 ±2.2**	**6.2**
	measured (n=7)	+8.57 ±0.19	n/a	-76.1 ±.3.0	n/a
USGS 43	Indian Human Hair	**+14.11 ±0.10**	**22.0**	**-44.4 ±2.0**	**6.1**
	measured (n=7)	+14.10 ±0.17	n/a	-46.9 ±3.2	n/a
		Standards run as blind unknown samples			
USGS 42	Tibetan Human Hair	**+8.56 ±0.10**	**22.0**	**-72.9 ±2.2**	**6.2**
	measured	+8.37 ±0.77 (n=9)	23.0 ±0.7 (n=9)	-75.0 ±2.0 (n=8)	5.6 ±0.2 (n=5)
USGS 43	Indian Human Hair	**+14.11 ±0.10**	**22.0**	**-44.4 ±2.0**	**6.1**
	measured	+15.08 ±1.42 (n=9)	23.0 ±0.8 (n=9)	-44.7 ±3.4 (n=7)	5.5 ±0.1 (n=6)
ASU H Std 1	relaxed, color-treated hair of African ancestry (Arizona)	**+9.90 ±0.05**	**22.9 ±0.1**	**-67.5 ±1.1**	**5.7 ±0.1**
	measured (n=6)	+9.66 ±0.74	23.2 ±0.5	-69.7 ±2.3	5.7 ±0.1
ASU H Std 2	probable European hair (Arizona)	**+10.16 ±0.12**	**21.5 ±0.1**	**-67.5 ±1.3**	**5.7 ±0.1**
	measured (n=6)	+10.05 ±1.08	21.1 ±0.5	-68.5 ±2.9	5.6 ±0.1

Table 36. Standards run as knowns and unknowns during hydrogen and oxygen isotope analyses during the freezing study. Values in bold are certified or known. The known values for the two ASU hair standards are taken as the value and precision from lab B, which provided the most accurate measurements for USGS 42 and 43.

years in storage	storage conditions	$\delta^{13}C$	$\delta^{15}N$	$\delta^{18}O_{VSMOW}$	$\delta^{2}H_{VSMOW}$	wt % C	wt % N	C/N	wt% O	wt% H	O/H
4.1	frozen	-17.52	9.22	11.7	-56.5	43.91	14.44	3.04	23.5	5.2	4.51
	ambient	-17.80	9.21	11.6	-66.9	45.02	14.59	3.09	22.9	5.5	4.17
2.8	frozen	-15.16	8.19	10.6	-68.1	43.95	14.45	3.04	23.1	5.4	4.29
	ambient	-15.34	8.36	9.9	-72.9	44.20	14.14	3.13	23.7	5.6	4.26
1.9	frozen	-16.87	8.45	13.7	-55.6	44.34	14.58	3.04	23.3	5.3	4.38
	ambient	-17.09	8.38	13.4	-59.7	45.13	14.47	3.12	22.7	5.4	4.16
1.6	frozen	-15.69	7.25	10.1	-59.6	44.10	14.49	3.04	23.2	5.3	4.42
	ambient	-15.72	6.96	9.6	-62.9	44.70	14.66	3.05	23.2	5.3	4.34
1.0	frozen	-17.61	9.01	11.9	-65.7	44.46	14.45	3.08	23.1	5.5	4.22
		-17.66	9.10	12.1	-65.3	44.59	14.49	3.08	23.0	5.6	4.13
		-17.56	8.88	12.3	-58.5	44.50	14.48	3.07	22.9	5.4	4.25
	mean	-17.61	8.99	12.07	-63.2	44.52	14.48	3.08	22.98	5.5	4.20
	σ	0.05	0.11	0.20	4.1	0.07	0.02	0.00	0.07	0.08	0.06
	ambient	-17.76	9.14	12.4	-66.8	45.02	14.53	3.10	22.7	5.5	4.11
	frozen	-16.73	8.77	13.4	-58.9	43.98	14.61	3.01	23.1	5.3	4.33
		-16.76	8.87	12.5	-56.4	43.56	14.48	3.01	23.2	5.3	4.39
		-16.78	8.84	12.6	-53.8	44.20	14.70	3.01	22.8	5.2	4.36
0.9	mean	-16.76	8.82	12.83	-56.4	43.91	14.60	3.01	23.04	5.3	4.36
	σ	0.02	0.05	0.46	2.5	0.32	0.11	0.00	0.18	0.06	0.03
	ambient	-16.88	8.72	13.7	-57.1	44.70	14.46	3.09	22.8	5.3	4.27
0.7	frozen	-15.69	9.39	13.4	-48.6	44.18	14.35	3.08	23.1	5.2	4.45
	ambient	-15.54	9.32	13.3	-58.3	42.21	13.69	3.08	23.1	5.4	4.27

Table 37. Comparison of hair samples stored at -20°C or ambient conditions for 0.7 months to 4.1 years at the University of Tennessee, Knoxville facility. Some data is missing due to limited sample available.

years in storage	$\delta^{13}C$	$\delta^{15}N$	$\delta^{18}O_{VSMOW}$	$\delta^{2}H_{VSMOW}$	wt % C	wt % N	C/N	wt% O	wt% H	O/H
4.1	0.28	0.02	0.12	10.5	-1.11	-0.15	-0.05	0.55	-0.30	0.35
2.8	0.18	-0.17	0.66	4.8	-0.24	0.31	-0.08	-0.63	-0.19	0.03
1.9	0.22	0.07	0.34	4.1	-0.79	0.10	-0.08	0.60	-0.13	0.22
1.6	0.04	0.29	0.48	3.3	-0.61	-0.17	-0.01	0.01	-0.08	0.07
1.0	0.15	-0.15	-0.32	3.7	-0.79	0.14	-0.02	0.25	-0.06	0.09
0.9	0.12	0.11	-0.90	0.8	-0.79	0.14	-0.08	0.21	-0.06	0.09
0.7	-0.15	0.07	0.10	9.7	1.96	0.66	-0.01	0.02	-0.21	0.18
average	0.12	0.03	0.07	5.26	-0.34	0.15	-0.05	0.14	-0.15	0.15
median	0.15	0.07	0.12	4.07	-0.79	0.14	-0.05	0.21	-0.13	0.09
σ	0.14	0.16	0.53	3.53	1.05	0.28	0.04	0.41	0.09	0.11

Table 38. Summary of the differences between the frozen and ambient samples from Table 37.

An examination of the hair samples in longer-term storage (Tables 37 and 38) suggested that for samples in storage for decades there could be an offset not seen in in samples stored for only a couple of years. The average offset for $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, weight percent carbon, nitrogen, and oxygen are all less than the offset standard deviation. However, we have a limited data set of seven samples, so this should not be taken as a blanket statement that these variables are not effected by freezing. For instance, the samples stored longer than 0.7 months all had positive offsets in $\delta^{13}C$, with ambient samples being isotopically lighter than paired frozen samples. The same samples also had lower weight percent carbon in the frozen samples, and C/N ratios were higher in ambient samples. This combination of observations suggests that carbon was being lost from the frozen samples, with a preferential loss of isotopically heavy carbon. Most evaporative processes preferentially lose isotopically light isotopes. However, these differences are small, and far smaller than the isotopic differences between trophic levels or dietary groups. There did not appear to be any systematic difference between ambient and frozen samples for $\delta^{18}O$ values.

$\delta^{2}H$ offsets were all positive, with ambient samples being depleted in ^{2}H. This difference was more than one standard deviation from the average, although less than 2σ; there was also a weak positive correlation in the offset magnitude with length of time in storage. The variations, while small, were several times larger than the external reproducibility of samples and suggest a systematic bias due to storage. The combination of O/H ratios and weight percent hydrogen measurements suggest that frozen samples were systematically losing a small amount of preferentially isotopically heavy hydrogen. This was also contrary to the typical pattern of

evaporation resulting in loss of isotopically light hydrogen. Although relatively small, an offset of 5-10‰ in δ^2H is sufficient to change the predicted region of origin for an individual (*cf* Figure 3 in Ehleringer et al 2008).

The maximum length of storage of samples was just over four years. There may well be cold cases in which samples have been stored for decades – either frozen or in ambient conditions. The current study should not be taken to indicate that storage conditions are not critical. Depending on the storage container, temperature, humidity, and stability of temperature and humidity, some samples could have undergone significant isotopic shifts that were not visible from the current short-term study.

Results from the 20 samples stored including control samples and four storage conditions are presented in Tables 39-42.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
1	African American, treatment unknown	A	-18.30	9.06	46.72	15.16	3.08	11.3	22.0	-61.4	5.4
		B	-18.39	8.71	45.05	14.40	3.13	11.4	21.8	-69.2	5.7
			-18.43	8.67	46.67	15.07	3.10	11.0	21.9	-66.2	5.6
			-18.54	9.01	46.80	15.04	3.11	11.2	23.1	-63.5	5.6
			-18.45	8.80	46.17	14.84	3.11	11.22	22.3	-66.3	5.60
			0.08	0.19	0.98	0.38	0.02	0.22	0.7	2.9	0.06
		C	-18.24	9.05	45.51	14.83	3.07	10.8	21.8	-66.8	5.5
		D	-18.24	8.93	46.68	15.07	3.10	11.4	21.9	-69.2	5.6
			-18.25	8.91	46.80	15.22	3.07	11.3	22.0	-68.4	5.6
			-18.35	8.98	47.64	15.34	3.11	10.8	22.7	-61.9	5.4
			-18.28	8.94	47.04	15.21	3.09	11.17	22.2	-66.5	5.54
			0.06	0.03	0.52	0.13	0.02	0.37	0.4	4.0	0.13
		E	-18.18	9.07	44.71	14.73	3.03	10.7	21.3	-59.1	5.4
		mean	-18.29	8.98	46.03	14.95	3.08	11.04	21.9	-64.0	5.50
		σ	0.10	0.11	0.94	0.22	0.03	0.28	0.4	3.5	0.08
2	African American, treatment unknown	A	-16.89	8.84	45.57	15.08	3.02	14.0	22.9	-53.2	5.5
		B	-16.92	8.87	45.33	15.17	2.99	14.1	22.0	-43.7	5.3
		C	-16.83	8.98	43.91	14.63	3.00	14.5	20.9	-44.0	5.3
		D	-16.93	8.81	46.07	15.35	3.00	14.0	21.9	-52.8	5.5
								13.8	22.0	-46.0	5.5
			-16.93	8.91	45.84	15.24	3.01	14.2	21.9	-50.2	5.4
			-16.93	8.86	45.96	15.29	3.00	14.02	21.9	-49.6	5.46
			0.00	0.07	0.16	0.08	0.01	0.17	0.1	3.4	0.07
		E	-16.89	8.76	41.29	13.80	2.99	13.9	21.4	-43.7	5.3
		mean	-16.89	8.86	44.41	14.80	3.00	14.11	21.8	-46.9	5.38
		σ	0.04	0.08	1.91	0.61	0.01	0.25	0.7	4.4	0.11

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair samples undergoing different storage conditions. Storage conditions are A: no storage; B: plastic clamshell, 2 weeks; C: butcher paper, 2 weeks; D: plastic clamshell, 6 months; and E: butcher paper, 6 months. The weight percent carbon and nitrogen values for treatment E of sample 9 may be inaccurate due to sample loss after weighing. These values are excluded from the mean and average for those measurements of that

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
3	African American, color treated	A	-19.01	9.40	45.95	13.94	3.30	8.8	22.8	-72.0	5.8
		B	-19.03	9.21	45.46	14.05	3.24	8.5	22.7	-67.2	5.5
		C	-18.79	9.13	44.79	13.92	3.22	8.9	21.5	-64.6	5.5
		D	-19.06	9.31	45.84	13.85	3.31	8.7	22.6	-77.2	5.8
		E	-18.87	9.32	44.82	14.01	3.20	9.0	22.2	-65.6	5.6
		mean	-18.95	9.27	45.37	13.95	3.25	8.78	22.4	-69.3	5.66
		σ	0.11	0.11	0.55	0.08	0.05	0.22	0.5	5.2	0.15
4	African American, dyed and treated with relaxer	A	-18.36	8.96	46.39	15.00	3.09	11.2	22.4	-60.5	5.6
		B	-18.67	8.86	47.17	15.34	3.08	12.0 11.5	22.7 23.6	-58.4	5.4
		C	-18.21	9.15	45.42	15.00	3.03	11.5	23.9	-57.9	5.4
		D	-18.37	9.12	45.45	14.94	3.04	11.3	22.7	-64.0	5.5
		E	-18.56	8.84	45.47	14.89	3.05	11.4	23.3	-63.4	5.6
		mean	-18.43	8.98	45.98	15.03	3.06	11.43	23.1	-61.0	5.51
		σ	0.18	0.14	0.78	0.18	0.03	0.21	0.6	2.8	0.11
5	African American, dyed and treated with relaxer	A	-17.99	9.27	44.07	14.25	3.09	10.3	23.3	-67.1	5.7
		B	-18.60	9.25	47.74	14.37	3.32	10.4	22.6	-72.6	5.9
		C	-18.40	9.37	44.70	13.98	3.20	9.9	23.8	-73.7	5.7
		D	-18.00	9.48	45.81	14.53	3.15	10.6	22.9	-66.3	5.7
		E	-18.02	9.22	44.95	14.45	3.11	10.2	22.5	-62.9	5.5
		mean	-18.20	9.32	45.45	14.31	3.18	10.27	23.0	-67.2	5.72
		σ	0.28	0.11	1.42	0.21	0.09	0.26	0.5	4.0	0.16

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
6	African American, treated with relaxer	A	-18.52	8.94	46.54	14.68	3.17	10.0	22.4	-67.1	5.5
		B	-18.63	9.12	47.14	14.97	3.15	9.6	22.1	-66.3	5.6
		C	-18.49	9.02	45.17	14.79	3.05	9.9	22.2	-65.7	5.4
			-18.45	9.09	45.09	14.72	3.06	9.7	21.4	-58.8	5.4
			-18.45	9.07	45.02	14.80	3.04	9.8	24.0	-59.8	5.3
			-18.46	9.06	45.09	14.77	3.05	9.80	22.6	-61.4	5.37
			0.03	0.03	0.08	0.04	0.01	0.10	1.3	3.7	0.06
		D	-18.58	9.16	46.52	14.93	3.12	9.7	22.4	-63.0	5.6
		E	-18.50	9.03	44.48	14.27	3.12	9.8	21.6	-70.7	5.5
			-18.51	9.00	44.12	14.15	3.12	10.2	20.4	-62.6	5.5
			-18.53	9.09	44.12	13.92	3.17	9.7	21.5	-63.9	5.3
			-18.51	9.04	44.24	14.11	3.13	9.91	21.1	-65.7	5.44
			0.01	0.05	0.21	0.18	0.03	0.28	0.7	4.3	0.14
		mean	-18.54	9.07	45.91	14.69	3.12	9.81	22.1	-64.7	5.49
		σ	0.07	0.08	1.20	0.34	0.04	0.15	0.6	2.4	0.10
7	Asian	A	-17.74	9.44	45.91	15.33	2.99	10.0	22.7	-63.8	5.5
		B	-17.67	9.78	44.10	14.86	2.97	10.0	23.1	-57.2	5.4
		C	-17.57	9.87	44.74	14.97	2.99	9.9	22.1	-57.0	5.2
		D	-17.76	9.49	45.62	15.30	2.98	9.8	24.0	-63.1	5.5
		E	-17.50	9.70	44.50	14.96	2.98	9.6	22.3	-63.1	5.4
		mean	-17.65	9.66	44.97	15.08	2.98	9.85	22.8	-60.9	5.4
		σ	0.11	0.18	0.76	0.22	0.01	0.19	0.7	3.4	0.13

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
8	Asian	A	-18.35	8.79	46.88	15.38	3.05	10.7	22.5	-72.8	5.6
		B	-18.52	8.34	46.28	15.31	3.02	10.8	21.5	-68.1	5.4
		C	-18.55	8.56	45.49	14.96	3.04	10.6	21.6	-75.9	5.6
		D	-18.29	8.74	47.29	15.58	3.04	10.5	22.2	-74.1	5.6
		E	-18.55	8.48	44.89	14.86	3.02	10.7	21.5	-70.0	5.5
		mean	-18.45	8.59	46.17	15.22	3.03	10.7	21.9	-72.2	5.5
		σ	0.13	0.19	0.98	0.30	0.01	0.10	0.5	3.1	0.08
9	Caucasian, dyed	A	-17.96	9.18	46.56	15.47	3.01	10.8	21.9	-70.3	5.6
		B	-17.88	9.16	46.40	15.58	2.98	10.7	22.3	-70.8	5.5
		C	-17.78	9.41	41.92	14.08	2.98	10.8	20.9	-71.5	5.4
			-17.85	9.31	44.60	14.98	2.98	10.6	21.4	-69.1	5.4
			-17.72	9.49	44.90	15.10	2.97	10.4	21.6	-65.4	5.4
			-17.78	9.40	43.81	14.72	2.98	10.56	21.3	-68.7	5.4
			0.06	0.09	1.64	0.56	0.00	0.20	0.4	3.1	0.01
		D	-17.79	9.34	45.23	15.17	2.98	9.7	21.7	-67.9	5.5
								10.0	23.3		
		E	-17.78	9.21	29.43	9.89	2.98	10.5	21.6	-65.1	5.6
		mean	-17.84	9.26	45.50	15.23	2.98	10.5	21.9	-68.6	5.5
		σ	0.08	0.11	1.27	0.38	0.01	0.39	0.5	2.3	0.08

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
10	Caucasian, dyed	A	-17.70	9.10	46.40	15.50	2.99	10.4	21.7	-71.3	5.7
			-17.81	9.25	46.05	15.34	3.00	10.5	21.8	-71.1	5.6
			-17.81	9.35	45.52	15.28	2.98	10.9	23.5	-63.7	5.5
			-17.77	9.23	45.99	15.37	2.99	10.63	22.3	-68.7	5.6
			0.06	0.13	0.45	0.11	0.01	0.26	1.0	4.3	0.06
		B	-17.80	9.24	46.16	15.51	2.98	10.6	22.0	-70.4	5.5
		C	-17.76	9.23	44.81	15.00	2.99	10.9	20.8	-70.3	5.8
		D	-17.80	9.28	44.96	15.09	2.98	10.2	23.2	-71.0	5.6
		E	-17.64	9.27	43.20	14.47	2.98	10.1	21.0	-64.1	5.4
		mean	-17.76	9.25	45.02	15.09	2.98	10.48	21.9	-68.9	5.6
		σ	0.07	0.02	1.19	0.40	0.01	0.35	1.0	2.8	0.14
11	Caucasian, probably dyed	A	-17.84	9.01	46.60	14.68	3.17	10.1	22.1	-76.1	5.6
		B	-17.67	9.02	45.25	14.40	3.14	9.7	21.9	-66.3	5.4
		C	-17.67	8.92	43.92	14.22	3.09	9.6	21.6	-70.5	5.6
		D	-17.60	8.96	45.75	14.64	3.13	10.0	23.5	-69.4	5.6
		E	-17.76	9.01	45.13	14.37	3.14	9.6	22.0	-66.9	5.5
		mean	-17.71	8.99	45.33	14.46	3.13	9.80	22.2	-69.8	5.5
		σ	0.09	0.04	0.98	0.20	0.03	0.23	0.7	3.9	0.11
12	Caucasian, treatment unknown	A	-16.79	8.63	46.88	15.28	3.07	9.0	21.9	-80.7	5.7
		B	-16.62	8.57	46.53	15.43	3.02	8.9	22.0	-68.9	5.5
		C	-16.76	8.70	45.27	14.89	3.04	9.2	22.5	-72.5	5.5
		D	-16.69	8.74	46.71	15.29	3.05	8.6	21.8	-73.1	5.5
		E	-16.81	8.78	45.01	15.03	3.00	9.2	21.3	-75.5	5.5
		mean	-16.73	8.68	46.08	15.18	3.04	9.0	21.9	-74.1	5.5
		σ	0.08	0.09	0.87	0.22	0.03	0.23	0.5	4.4	0.10

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
13	Caucasian, no known treatment	A	-18.80	8.33	45.61	15.44	2.95	13.6	21.6	-58.4	5.4
		B	-18.64	8.25	45.35	15.34	2.96	13.5	22.7	-55.8	5.3
		C	-18.79	8.35	45.29	15.35	2.95	13.7	21.6	-59.5	5.5
		D	-18.77	8.42	42.44	14.43	2.94	13.6	22.8	-54.3	5.4
		E	-18.73	8.42	45.36	15.52	2.92	13.4	21.4	-57.8	5.5
			-18.75	8.35	44.81	15.22	2.94	13.5	22.0	-57.1	5.4
			0.07	0.07	1.33	0.44	0.01	0.14	0.7	2.1	0.08
14	Caucasian, no known treatment	A	-18.43	8.82	46.40	15.19	3.05	10.4	22.5	-71.7	5.7
		B	-18.23	8.97	45.53	15.27	2.98	10.7	22.2	-65.3	5.3
		C	-18.46	8.79	44.93	15.04	2.99	11.0	21.7	-69.0	5.4
		D	-18.24	8.89	45.98	15.44	2.98	10.4	23.3	-64.3	5.4
		E	-18.44	8.77	44.36	14.88	2.98	10.8	21.6	-72.9	5.4
			-18.28	8.82	45.05	15.14	2.98	10.5	21.6	-69.7	5.4
			-18.46	8.83	44.48	14.52	3.06	10.7	23.1	-63.5	5.3
			-18.39	8.81	44.63	14.85	3.01	10.64	21.6	-68.7	5.3
			0.10	0.03	0.37	0.31	0.05	0.14	0.0	4.8	0.08
		mean	-18.35	8.86	45.49	15.16	3.00	10.6	22.3	-67.8	5.45
		σ	0.11	0.08	0.73	0.22	0.03	0.22	0.6	3.0	0.14

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
15	Caucasian, dyed, Surface 2 donor, 1 day exposure	A	-16.54	9.62	44.24	13.80	3.21	11.8 11.8	22.2 23.8	-58.5	5.7
		B	-16.59	9.50	45.08	14.44	3.12	11.6	22.4	-56.9	5.5
		C	-16.39	9.37	43.34	14.21	3.05	10.5	23.8	-55.4	5.4
		D	-16.49	9.55	44.82	14.15	3.17	11.1	22.6	-52.7	5.4
		E	-16.65	9.53	42.92	13.75	3.12	11.0	22.4	-58.2	5.6
			-16.50	9.47	43.57	14.01	3.11	11.1	22.6	-55.8	5.3
			-16.60	9.55	43.76	14.04	3.12	11.3	24.1	-52.8	5.5
			-16.58	9.52	43.42	13.93	3.12	11.1	23.0	-55.6	5.45
			0.07	0.04	0.44	0.16	0.01	0.16	0.9	2.7	0.13
		mean	-16.52	9.51	44.18	14.11	3.13	11.2	23.0	-55.8	5.48
		σ	0.08	0.09	0.79	0.25	0.06	0.49	0.5	2.1	0.12
16	Caucasian, dyed, Surface 2 donor, 5 days exposure (Tennessee)	A	-16.28	9.74	45.83	14.42	3.18	10.5	23.2	-58.0	5.6
		B	-16.28	9.64	45.32	14.90	3.04	10.8	22.5	-56.2	5.4
		C	-16.11	9.79	44.24	14.71	3.01	10.3	22.1	-52.6	5.4
		D	-16.07	9.67	44.44	14.58	3.05	10.9	22.6	-47.9	5.3
		E	-16.19	9.51	43.06	14.29	3.01	10.7 10.9	23.3 23.5	-54.3	5.3
		mean	-16.19	9.67	44.58	14.58	3.06	10.6	22.6	-53.8	5.41
		σ	0.10	0.10	1.07	0.24	0.07	0.25	0.5	3.8	0.15
17	Caucasian, treatment unknown, 10 months exposure (Texas)	A	-17.73	9.77	46.73	15.33	3.05	13.6	22.6	-51.1	5.6
		B	-17.77	9.63	45.96	15.21	3.02	13.0	22.1	-44.3	5.3
		C	-17.67	9.77	44.27	14.71	3.01	13.5	21.8	-46.5	5.5
		D	-17.74	9.81	46.61	15.32	3.04	13.7	22.5	-43.6	5.5
		E	-17.70	10.03	45.50	15.03	3.03	13.6	21.7	-46.4	5.4
		mean	-17.72	9.80	45.81	15.12	3.03	13.49	22.1	-46.4	5.47
		σ	0.04	0.14	1.00	0.26	0.02	0.31	0.4	2.9	0.09

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\delta^{13}C$	$\delta^{15}N$	wt % C	wt % N	C/N	$\delta^{18}O_{VSMOW}$	wt% O	$\delta^{2}H_{VSMOW}$	wt% H
18	Caucasian, treatment unknown, 1 week exposure, decompositional environment, but no decompositional fluid (Texas)	A	-16.53	10.46	47.06	15.54	3.03	12.6	22.0	-52.3	5.5
		B	-16.53	10.66	44.83	14.84	3.02	12.7	21.4	-51.6	5.6
		C	-16.47	10.37	45.45	15.14	3.00	12.1	21.1	-53.1	5.6
		D	-16.58	10.42	46.33	15.33	3.02	12.4	21.8	-54.7	5.6
		E	-16.47	10.43	45.24	15.04	3.01	12.6	21.1	-55.3	5.6
			-16.54	10.50	45.02	15.00	3.00	12.2	21.5	-55.9	5.6
			-16.46	10.46	44.88	14.96	3.00	11.7	21.4	-48.4	5.4
			-16.49	10.46	45.05	15.00	3.00	12.2	21.3	-53.2	5.5
			0.05	0.04	0.18	0.04	0.00	0.41	0.2	4.2	0.12
		mean	-16.52	10.47	45.74	15.17	3.02	12.40	21.5	-53.0	5.55
		σ	0.04	0.11	0.93	0.28	0.01	0.26	0.3	1.2	0.03
19	Caucasian, treatment unknown, 1 week exposure, associated with decompositional fluid (Texas), same as	A	-16.57	10.38	46.27	15.53	2.98	12.6	21.8	-54.7	5.5
		B	-16.56	10.61	46.31	15.43	3.00	12.7	21.8	-55.0	5.5
		C	-16.73	10.41	45.30	14.93	3.03	12.7	21.4	-52.5	5.5
		D	-16.77	10.42	46.15	15.31	3.01	12.9	22.1	-46.3	5.4
		E	-16.65	10.47	45.42	14.90	3.05	12.7	21.4	-56.6	5.4
		mean	-16.65	10.46	45.89	15.22	3.02	12.71	21.7	-53.0	5.48
		σ	0.09	0.09	0.49	0.29	0.03	0.12	0.3	4.0	0.05
20	Caucasian, treatment unknown, 6 months exposure, associated with significant dirt and vegetation	A	-16.45	9.31	45.65	14.94	3.05	13.1	23.8	-49.9	5.6
		B	-16.40	9.15	45.84	15.23	3.01	13.2	22.4	-43.1	5.4
		C	-16.56	9.20	44.96	14.85	3.03	13.2	21.7	-43.0	5.2
		D	-16.49	8.91	42.95	14.19	3.03	13.5	21.7	-50.2	5.4
		E	-16.50	9.21	43.79	14.58	3.00	*14.3*	*22.1*	-46.2	5.2
			-16.36	9.11	42.78	14.13	3.03				
			-16.43	9.16	43.29	14.35	3.02				
			0.10	0.07	0.71	0.32	0.02				
		mean	-16.47	9.15	44.54	14.71	3.03	13.5	22.3	-46.5	5.4
		σ	0.06	0.14	1.34	0.43	0.02	0.49	0.9	3.5	0.2

Table 39. Carbon, nitrogen, oxygen, and hydrogen isotope composition of experimental hair continued.

number		storage	$\Delta^{13}C$	$\Delta^{15}N$	Δ wt % C	Δ wt % N	Δ C/N	$\Delta^{18}O$	Δ wt % O	$\Delta^{2}H$	Δ wt % H
1	African American, treatment unknown	B	-0.16	-0.26	-0.55	-0.32	0.03	-0.10	0.31	-4.92	0.17
		C	0.06	-0.02	-1.21	-0.33	-0.01	-0.48	-0.19	-5.40	0.12
		D	0.02	-0.12	0.32	0.05	0.01	-0.15	0.22	-5.13	0.12
		E	0.12	0.00	-2.00	-0.42	-0.05	-0.66	-0.65	2.27	-0.01
		mean	0.01	-0.10	-0.86	-0.26	0.00	-0.35	-0.08	-3.30	0.10
		σ	0.12	0.12	0.99	0.21	0.03	0.27	0.44	3.72	0.08
2	African American, treatment unknown	B	-0.03	0.03	-0.24	0.08	-0.03	0.07	-0.83	9.57	-0.22
		C	0.06	0.13	-1.66	-0.45	-0.02	0.48	-1.95	9.24	-0.24
		D	-0.04	0.01	0.38	0.21	-0.02	-0.02	-0.96	3.60	-0.07
		E	0.00	-0.08	-4.28	-1.28	-0.03	-0.18	-1.49	9.56	-0.21
		mean	0.00	0.02	-1.45	-0.36	-0.02	0.09	-1.31	7.99	-0.18
		σ	0.05	0.09	2.07	0.68	0.01	0.28	0.51	2.93	0.08
3	African American, color treated	B	-0.03	-0.20	-0.49	0.11	-0.06	-0.37	-0.12	4.81	-0.27
		C	0.21	-0.28	-1.16	-0.02	-0.08	0.09	-1.25	7.39	-0.26
		D	-0.05	-0.09	-0.11	-0.09	0.01	-0.18	-0.19	-5.18	0.06
		E	0.14	-0.08	-1.13	0.07	-0.10	0.16	-0.61	6.44	-0.20
		mean	0.07	-0.16	-0.72	0.02	-0.06	-0.07	-0.54	3.37	-0.17
		σ	0.13	0.09	0.51	0.09	0.05	0.25	0.52	5.80	0.15
4	African American, dyed and treated with relaxer	B	-0.31	-0.10	0.79	0.34	-0.02	0.58	0.73	2.03	-0.21
		C	0.15	0.19	-0.97	0.00	-0.06	0.33	1.50	2.53	-0.24
		D	-0.01	0.16	-0.94	-0.05	-0.05	0.17	0.25	-3.53	-0.11
		E	-0.20	-0.12	-0.91	-0.11	-0.04	0.22	0.92	-2.95	-0.04
		mean	-0.09	0.03	-0.51	0.04	-0.04	0.32	0.85	-0.48	-0.15
		σ	0.20	0.16	0.86	0.20	0.02	0.18	0.52	3.20	0.09
5	African American, dyed and treated with relaxer	B	-0.61	-0.02	3.67	0.11	0.23	0.02	-0.70	-5.44	0.15
		C	-0.41	0.09	0.63	-0.27	0.11	-0.44	0.42	-6.52	-0.03
		D	-0.01	0.21	1.74	0.27	0.06	0.27	-0.47	0.87	-0.02
		E	-0.03	-0.06	0.88	0.19	0.02	-0.18	-0.88	4.19	-0.23
		mean	-0.26	0.06	1.73	0.08	0.10	-0.08	-0.41	-1.72	-0.03
		σ	0.29	0.12	1.38	0.24	0.09	0.30	0.58	5.12	0.16
6	African American, treated with relaxer	B	-0.11	0.18	0.60	0.29	-0.02	-0.37	-0.30	0.80	0.16
		C	0.06	0.12	-1.44	0.09	-0.12	-0.21	0.12	5.74	-0.08
		D	-0.06	0.22	-0.02	0.25	-0.05	-0.30	-0.03	4.14	0.13
		E	0.01	0.10	-2.30	-0.57	-0.04	-0.09	-1.29	1.41	-0.01
		mean	-0.03	0.15	-0.79	0.02	-0.06	-0.24	-0.37	3.02	0.05
		σ	0.07	0.06	1.32	0.40	0.04	0.12	0.63	2.32	0.11
7	Asian	B	0.07	0.34	-1.81	-0.47	-0.03	0.00	0.35	6.59	-0.14
		C	0.18	0.43	-1.17	-0.36	-0.01	-0.14	-0.59	6.82	-0.28
		D	-0.01	0.05	-0.29	-0.03	-0.01	-0.24	1.24	0.70	0.05
		E	0.24	0.25	-1.41	-0.37	-0.02	-0.46	-0.41	0.77	-0.05
		mean	0.12	0.27	-1.17	-0.31	-0.02	-0.21	0.15	3.72	-0.11
		σ	0.11	0.16	0.64	0.19	0.01	0.19	0.83	3.45	0.14
8	Asian	B	-0.17	-0.45	-0.60	-0.07	-0.03	0.03	-1.06	4.71	-0.16
		C	-0.20	-0.23	-1.39	-0.42	-0.01	-0.11	-0.95	-3.06	0.03
		D	0.07	-0.05	0.41	0.20	-0.01	-0.21	-0.33	-1.31	0.06
		E	-0.20	-0.31	-1.99	-0.52	-0.03	0.03	-0.99	2.79	-0.05
		mean	-0.13	-0.26	-0.89	-0.20	-0.02	-0.06	-0.83	0.78	-0.03
		σ	0.13	0.17	1.04	0.33	0.01	0.12	0.34	3.59	0.10

Table 40. Differences between samples stored and controls for carbon, nitrogen, oxygen, and hydrogen isotopes. Weight percent carbon and nitrogen for treatment E for sample 9 are excluded from the mean and standard deviation due to probable sample loss after weighing.

number			$\Delta^{13}C$	$\Delta^{15}N$	Δ wt % C	Δ wt % N	Δ C/N	$\Delta^{18}O$	Δ wt % O	$\Delta^{2}H$	Δ wt % H
9	Caucasian, dyed	B	0.08	-0.03	-0.16	0.11	-0.03	-0.09	0.32	-0.49	-0.09
		C	0.17	0.22	-2.75	-0.75	-0.03	-0.26	-0.67	1.63	-0.20
		D	0.16	0.16	-1.33	-0.30	-0.03	-1.00	0.56	2.43	-0.05
		E	0.18	0.02	*-17.12**	*-5.58**	-0.03	-0.31	-0.30	5.26	-0.04
		mean	0.15	0.09	-1.41	-0.31	-0.03	-0.41	-0.02	2.21	-0.09
		σ	0.05	0.11	1.30	0.43	0.00	0.40	0.56	2.38	0.07
10	Caucasian, dyed	B	-0.03	0.01	0.18	0.14	-0.02	-0.03	-0.32	-1.72	-0.07
		C	0.02	0.00	-1.18	-0.37	0.00	0.31	-1.57	-1.58	0.15
		D	-0.02	0.05	-1.03	-0.28	-0.01	-0.46	0.82	-2.26	0.01
		E	0.14	0.04	-2.79	-0.90	-0.01	-0.55	-1.30	4.61	-0.24
		mean	0.02	0.02	-1.21	-0.35	-0.01	-0.18	-0.59	-0.24	-0.04
		σ	0.08	0.02	1.22	0.43	0.00	0.40	1.08	3.24	0.16
11	Caucasian, probably dyed	B	0.16	0.01	-1.34	-0.28	-0.03	-0.41	-0.15	9.76	-0.28
		C	0.16	-0.09	-2.68	-0.47	-0.08	-0.48	-0.52	5.59	-0.05
		D	0.23	-0.05	-0.84	-0.05	-0.05	-0.14	1.37	6.71	-0.05
		E	0.07	0.00	-1.47	-0.32	-0.03	-0.52	-0.05	9.20	-0.14
		mean	0.16	-0.03	-1.59	-0.28	-0.05	-0.39	0.16	7.82	-0.13
		σ	0.07	0.05	0.78	0.17	0.02	0.17	0.83	1.99	0.11
12	Caucasian, treatment unknown	B	0.17	-0.06	-0.36	0.15	-0.05	-0.10	0.08	11.78	-0.23
		C	0.03	0.07	-1.61	-0.39	-0.03	0.18	0.58	8.17	-0.20
		D	0.10	0.12	-0.18	0.01	-0.01	-0.39	-0.15	7.58	-0.23
		E	-0.01	0.15	-1.87	-0.25	-0.07	0.16	-0.69	5.22	-0.17
		mean	0.07	0.07	-1.00	-0.12	-0.04	-0.04	-0.05	8.19	-0.20
		σ	0.08	0.09	0.86	0.25	0.03	0.27	0.52	2.71	0.03
13	Caucasian, no known treatment	B	0.16	-0.08	-0.26	-0.10	0.00	-0.13	1.04	2.60	-0.16
		C	0.01	0.02	-0.32	-0.09	0.00	0.14	-0.08	-1.10	0.07
		D	0.02	0.09	-3.17	-1.00	-0.01	0.01	1.18	4.12	0.00
		E	0.06	0.10	-0.25	0.09	-0.03	-0.23	-0.21	0.54	0.02
			0.06	0.03	-1.00	-0.27	-0.01	-0.05	0.48	1.54	-0.02
			0.07	0.08	1.44	0.49	0.02	0.16	0.73	2.29	0.10
14	Caucasian, no known treatment	B	0.20	0.15	-0.87	0.08	-0.07	0.32	-0.31	6.42	-0.36
		C	-0.03	-0.04	-1.47	-0.15	-0.07	0.51	-0.32	2.63	-0.24
		D	0.20	0.06	-0.43	0.24	-0.08	0.01	0.79	7.40	-0.24
		E	0.04	-0.02	-1.78	-0.35	-0.05	0.25	-0.88	2.95	-0.34
		mean	0.10	0.04	-1.14	-0.04	-0.07	0.27	-0.18	4.85	-0.29
		σ	0.11	0.09	0.60	0.26	0.01	0.21	0.70	2.42	0.07
15	Caucasian, dyed, Surface 2 donor, 1 day exposure	B	-0.05	-0.13	0.83	0.64	-0.08	-0.26	-0.65	1.59	-0.17
		C	0.15	-0.25	-0.91	0.41	-0.16	-1.28	0.79	3.13	5.36
		D	0.05	-0.07	0.57	0.35	-0.04	-0.67	-0.40	5.81	-0.08
		E	-0.04	-0.10	-0.82	0.13	-0.09	-0.69	0.03	2.92	0.14
		mean	0.03	-0.14	-0.08	0.38	-0.09	-0.72	-0.06	3.37	1.31
		σ	0.10	0.08	0.91	0.21	0.05	0.42	0.63	1.77	2.70
16	Caucasian, dyed, Surface 2 donor, 5 days exposure (Tennessee)	B	0.00	-0.09	-0.51	0.48	-0.14	0.26	-0.66	1.83	-0.20
		C	0.17	0.05	-1.60	0.29	-0.17	-0.21	-1.16	5.39	-0.25
		D	0.22	-0.07	-1.39	0.16	-0.13	0.33	-0.63	10.04	-0.36
		E	0.10	-0.22	-2.77	-0.13	-0.16	0.30	0.18	3.74	-0.37
		mean	0.12	-0.08	-1.57	0.20	-0.15	0.17	-0.57	5.25	-0.29
		σ	0.09	0.11	0.93	0.26	0.02	0.25	0.55	3.51	0.08

Table 40. Differences between samples stored and controls for carbon, nitrogen, oxygen, and hydrogen isotopes continued.

number			$\Delta^{13}C$	$\Delta^{15}N$	Δ wt % C	Δ wt % N	Δ C/N	$\Delta^{18}O$	Δ wt % O	$\Delta^{2}H$	Δ wt % H
17	Caucasian, treatment unknown, 10 months exposure (Texas)	B	-0.04	-0.15	-0.77	-0.12	-0.03	-0.66	-0.42	6.83	-0.25
		C	0.06	-0.01	-2.46	-0.62	-0.04	-0.08	-0.73	4.59	-0.06
		D	-0.01	0.04	-0.12	-0.01	-0.01	0.13	-0.07	7.53	-0.05
		E	0.03	0.25	-1.23	-0.30	-0.02	-0.03	-0.87	4.78	-0.12
		mean	0.01	0.03	-1.14	-0.26	-0.02	-0.16	-0.52	5.93	-0.12
		σ	0.04	0.17	0.99	0.27	0.01	0.35	0.35	1.47	0.09
18	Caucasian, treatment unknown, 1 week exposure, decompositional environment, but no decompositional fluid (Texas)	B	0.00	0.20	-2.23	-0.70	-0.01	0.16	-0.53	0.72	0.06
		C	0.06	-0.09	-1.61	-0.40	-0.03	-0.46	-0.83	-0.83	0.03
		D	-0.06	-0.04	-0.73	-0.21	-0.01	-0.21	-0.13	-2.42	0.06
		E	0.04	0.00	-2.01	-0.54	-0.02	-0.42	-0.63	-0.90	-0.01
		mean	0.01	0.02	-1.64	-0.46	-0.02	-0.23	-0.53	-0.86	0.03
		σ	0.05	0.13	0.66	0.21	0.01	0.28	0.30	1.28	0.03
19	Caucasian, treatment unknown, 1 week exposure, associated with decompositional fluid (Texas), same as donor 18	B	0.01	0.23	0.05	-0.10	0.02	0.10	-0.02	-0.34	-0.03
		C	-0.16	0.03	-0.96	-0.60	0.06	0.13	-0.42	2.18	-0.04
		D	-0.20	0.04	-0.12	-0.22	0.03	0.33	0.27	8.36	-0.13
		E	-0.08	0.09	-0.85	-0.63	0.07	0.13	-0.42	-1.93	-0.11
		mean	-0.11	0.10	-0.47	-0.39	0.05	0.17	-0.15	2.07	-0.08
		σ	0.09	0.09	0.51	0.27	0.02	0.11	0.33	4.53	0.05
20	Caucasian, treatment unknown, 6 months exposure, associated with significant dirt and vegetation	B	0.06	-0.16	0.19	0.29	-0.05	0.06	-1.45	6.86	-0.15
		C	-0.10	-0.11	-0.68	-0.09	-0.03	0.06	-2.16	6.93	-0.35
		D	-0.03	-0.39	-2.70	-0.76	-0.03	0.43	-2.13	-0.27	-0.21
		E	0.02	-0.15	-2.36	-0.59	-0.04	1.17	-1.76	3.68	-0.36
		mean	-0.01	-0.20	-1.39	-0.29	-0.03	0.43	-1.88	4.30	-0.27
		σ	0.07	0.13	1.37	0.48	0.01	0.52	0.33	3.41	0.11

Table 40. Differences between samples stored and controls for carbon, nitrogen, oxygen, and hydrogen isotopes continued.

storage		$\Delta^{13}C$	$\Delta^{15}N$	Δ wt % C	Δ wt % N	Δ C/N	$\Delta^{18}O$	Δ wt % O	$\Delta^{2}H$	Δ wt % H
plastic clamshell, two weeks	mean	-0.03	-0.03	-0.19	0.03	-0.02	-0.05	-0.23	3.20	-0.12
	σ	0.19	0.18	1.20	0.32	0.07	0.28	0.60	4.70	0.15
butcher paper, two weeks	mean	0.03	0.01	-1.33	-0.25	-0.04	-0.10	-0.50	2.67	0.16
	σ	0.15	0.17	0.77	0.30	0.06	0.42	0.91	4.52	1.23
plastic clamshell, six months	mean	0.03	0.02	-0.50	-0.06	-0.02	-0.11	0.06	2.46	-0.06
	σ	0.11	0.14	1.11	0.34	0.04	0.35	0.82	4.76	0.13
butcher paper, six months	mean	0.03	-0.01	-1.65	-0.36	-0.04	-0.10	-0.61	3.23	-0.13
	σ	0.11	0.14	1.10	0.37	0.05	0.43	0.63	3.24	0.14

Table 41. The isotopic and elemental concentration differences between storage condition and control for all 20 samples.

	number of donors		$\Delta^{13}C$	$\Delta^{15}N$	Δ wt % C	Δ wt % N	Δ C/N	$\Delta^{18}O$	Δ wt % O	$\Delta^{2}H$	Δ wt % H
African-American, modern (n=6)	6	mean	-0.05	0.00	-0.43	-0.08	-0.01	-0.06	-0.31	1.48	-0.06
		σ	0.18	0.15	1.54	0.36	0.07	0.31	0.81	5.25	0.15
Asian, modern (n=2)	2	mean	0.00	0.00	-1.03	-0.26	-0.02	-0.14	-0.34	2.25	-0.07
		σ	0.17	0.32	0.81	0.26	0.01	0.17	0.79	3.62	0.12
Caucasian, modern (n=6)	6	mean	0.10	0.04	-1.22	-0.23	-0.03	-0.13	-0.03	4.06	-0.13
		σ	0.08	0.08	0.96	0.33	0.03	0.35	0.75	3.93	0.13
decompositional samples (n=6)	6	mean	0.01	-0.05	-1.05	-0.14	-0.05	-0.06	-0.62	3.34	0.10
		σ	0.10	0.15	1.02	0.41	0.07	0.49	0.72	3.47	1.13
modern samples, no known treatment (n=7)	7	mean	0.03	0.01	-1.07	-0.22	-0.03	-0.05	-0.26	3.40	-0.11
		σ	0.12	0.19	1.07	0.35	0.03	0.27	0.78	4.72	0.15
modern samples, dyed (n=4)	4	mean	0.10	-0.02	-1.22	-0.23	-0.04	-0.26	-0.25	3.29	-0.11
		σ	0.10	0.12	0.93	0.31	0.03	0.32	0.78	4.45	0.13
modern samples, relaxer (±dyed) (n=3)	3	mean	-0.13	0.08	0.14	0.05	0.00	0.00	0.02	0.27	-0.05
		σ	0.22	0.12	1.61	0.27	0.09	0.32	0.81	3.98	0.14

Table 42. The isotopic and elemental concentration differences between storage condition and control for samples, broken down by hair condition or ancestry.

6.4.5 Intake and recovery samples at FARF The current study was designed to look at bodies decaying for approximately one year. In order to increase the number of subjects studied, at FARF in Texas we collected a number of hair mats in direct association with donors in surface placements. We analyzed intake and recovery samples for $\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$ and $\delta^{18}O$ measurements (Tables 43 and 44). These measurements were outside the scope of our original grant, but we were able to compare measurements for an additional 10 donors, doubling the number of donors evaluated. Samples were limited to the FARF site. Tiffany Saul, the graduate student responsible for sample collection at the University of Tennessee, Knoxville, completed a

similar study with hair mats from donors at ARF. Those sample analyses were covered from independent funds, and were presented in her doctoral thesis (Saul, 2017).

Due to the small sample sizes typically collected during intake at both ARF and FARF, we restricted the analyses to the light stable isotopes, as these are the most commonly used in estimating provenance of unknown human remains. In addition, insufficient material was available for all analyses for intake samples in particular. We strongly encourage all human decompositional facilities to collect larger amounts of head hair during intake.

Donor	length of exposure (days)	last residence	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{VPDB}$ (‰)	weight % N	weight % C	C/N	$\delta^{2}H_{VSMOW}$ (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H
Hair mat 1	0	USA Houston, TX, USA	10.40	-17.49	14.5	43.2	3.0	-57.2	16.38	6.0	22.8	3.8
	312		9.77	-17.44	15.3	44.0	2.9					
Hair mat 2	0	San Antonio, TX, USA	9.18	-16.08	15.1	43.6	2.9					
	163		8.98	-15.86	16.1	45.1	2.8	-55.6	14.34	5.4	21.5	4.0
			9.07	-16.02	16.0	44.9	2.8					
			9.05	-15.93	15.2	43.2	2.8					
	167		9.30	-16.00	15.3	43.8	2.9	-57.4	14.30	5.4	21.9	4.0
		mean	9.14	-15.98	15.5	44.0	2.8					
		σ	0.14	0.05	0.4	0.9	0.0					
Hair mat 3	0	San Antonio, TX, USA	9.28	-17.33	14.5	42.1	2.9	-70.9	15.55	5.5	21.6	3.9
	123		8.98	-17.35	15.7	45.6	2.9	-69.2	14.34	5.7	22.6	4.0
Hair mat 4	0	San Marcos, TX, USA	8.83	-17.28	14.9	43.2	2.9	-67.5	15.48	5.6	21.8	3.9
	69		8.68	-17.42	15.6	44.0	2.8	-61.3	14.68	5.5	21.6	3.9
Hair mat 5	0	San Antonio, TX, USA	8.18	-17.31	18.6	54.2	2.9	-72.2	14.63	6.2	23.7	3.8
	91		8.26	-17.78	15.0	44.5	3.0					
Hair mat 6	0	Berwyn, IL, USA	9.22	-17.04	15.8	45.4	2.9	-78.9	12.56	5.4	21.3	4.0
	65		9.37	-16.64	15.2	43.8	2.9					
	69		9.16	-16.93	16.2	45.7	2.8	-75.7	12.90	5.6	22.1	4.0
Hair mat 7	0	Nashville, TN, USA	8.36	-16.85	15.6	44.0	2.8	-69.8	13.59	6.8	26.3	3.9
	69		8.52	-16.93	15.2	43.9	2.9					
Hair mat 8	0	Kempner, TX, USA	9.13	-16.83	12.9	37.1	2.9	-61.8	15.98	5.3	20.1	3.8
	46		8.92	-16.81	15.4	43.6	2.8					
Hair mat 9	0	San Antonio, TX, USA	9.04	-16.93	14.6	43.2	3.0	-71.2	15.29	5.9	23.2	3.9
			8.75	-16.81	16.2	45.3	2.8	-69.4	13.80	5.6	21.8	3.9
			8.92	-16.87	16.0	44.8	2.8	-69.9	13.63	5.6	21.8	3.9
	3		8.84	-16.63	15.0	43.4	2.9					
		mean	8.84	-16.77	15.7	44.5	2.8					
		σ	0.09	0.13	0.6	1.0	0.1					
Hair mat 10	0	Buerne, TX, USA	10.35	-16.41	15.4	44.1	2.9					
	3		10.39	-16.24	15.4	43.8	2.8					
	7		10.76	-16.23	15.4	43.4	2.8					
	7*		10.22	-16.19	16.1	44.4	2.8	-60.9	13.87	5.2	20.6	4.0

Table 43. Carbon, nitrogen, oxygen, and hydrogen isotope results from 10 donors at FARF in Texas. Limited sample availability limited some analyses. For Hair Mat donor 10, at seven days of exposure, two samples were collected contemporaneously from either side of the head. The sample denoted by the asterisk came from hair submerged in a mixture of decompositional fluids and mud.

Donor	length of exposure (days)	last residence	$\Delta^{15}N$	$\Delta^{13}C$	Δ weight %N	Δ weight %C	Δ C/N	$\Delta^{2}H$	$\Delta^{18}O$	Δ weight % H	Δ weight % O	Δ O/H
Hair mat 1	312	USA Houston, TX, USA	0.63	-0.05	-0.7	-0.9	0.1					
Hair mat 2	163	San Antonio, TX, USA	-0.20	0.22	1.0	1.5	-0.1					
	167		-0.04	0.10	0.4	0.3	-0.1					
Hair mat 3	123	San Antonio, TX, USA	0.29	0.02	-1.2	-3.5	0.0	-1.7	1.21	0.1	1.0	0.1
Hair mat 4	69	San Marcos, TX, USA	0.15	0.14	-0.7	-0.8	0.1	-6.2	0.80	-0.1	-0.3	0.0
Hair mat 5	91	San Antonio, TX, USA	-0.08	0.47	3.6	9.7	0.0					
Hair mat 6	65	Berwyn, IL, USA	0.15	0.40	-0.6	-1.6	0.0					
	69		-0.05	0.11	0.4	0.3	-0.1	3.2	0.34	0.2	0.8	0.0
Hair mat 7	69	Nashville, TN, USA	-0.16	0.08	0.4	0.1	-0.1					
Hair mat 8	46	Kempner, TX, USA	0.21	-0.02	-2.6	-6.6	0.0					
Hair mat 9	3	San Antonio, TX, USA	-0.20	0.16	1.1	1.3	-0.1	1.5	-1.58	-0.30	-1.39	-0.04
Hair mat 10	3	Buerne, TX, USA	0.04	0.17	0.0	-0.3	0.0					
	7		0.40	0.18	0.0	-0.7	0.0					
	7*		-0.14	0.23	0.7	0.3	-0.1					
		mean	0.07	0.16	0.12	-0.06	-0.03	-0.81	0.19	-0.02	0.03	0.02
		median	0.00	0.15	0.18	-0.08	-0.04	-0.13	0.57	0.01	0.26	0.01
		σ	0.25	0.14	1.39	3.48	0.06	4.14	1.24	0.23	1.10	0.05
		n	14	14	14	14	14	4	4	4	4	4

Table 44. Differences between samples after exposure from intake samples for carbon, nitrogen, oxygen and hydrogen isotope results from ten donors at FARF in Texas. Limited sample availability limited analyses. For Hair Mat donor 10, at seven days of exposure, two samples were collected contemporaneously from either side of the head. The sample denoted by the asterisk came from hair submerged in a mixture of decompositional fluids and mud.

6.4.6 Time series hair samples

6.4.6.1 Elemental concentrations The elemental concentrations of serially collected samples at both ARF and FARF are shown below. For reference, the concentration of the bioavailable leaches are listed for each sample, to illustrate the many orders of magnitude discrepancy between the natural concentration in hair compared to soil. Table 45 lists the bulk concentration of hair, Table 46 lists the leachate solution from the Tipple et al. (2013) protocol, and Table 47 lists the solid residue from the leaching protocol of Tipple et al. (2013).

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Tennessee																		
Surface 1	0		87.1	39.5	10.0	174	39.5	220	0.43	0.036	0.91	1.0	19.6	0.049	0.25	11.71	85.6	0.16
	1		62.7	67.5	28.6	724	230.9	319	1.45	0.046	0.56	0.9	36.3	0.062	0.16	10.38	71.1	bdl
	2		37.6	16.3	12.1	423	17.5	255	0.63	0.058	1.07	4.3	32.5	0.047	0.30	9.82	73.7	0.18
		replicate	42.5	14.6	10.6	474	15.6	256	0.60	0.026	0.11	3.9	24.3	0.044	0.13	10.73	74.4	0.15
	5		29.8	11.1	11.0	301	21.7	99	0.83	0.062	2.28	4.8	60.2	0.087	0.31	11.94	81.8	0.12
		replicate	172.1	14.7	16.0	381	41.5	133	1.23	0.073	2.77	5.0	67.6	0.098	0.75	11.74	87.4	0.13
	10		14.3	13.6	8.3	130	16.7	133	0.56	0.067	1.03	11.7	39.2	0.087	0.37	11.54	86.3	0.13
	20		34.2	27.5	26.4	115	21.9	274	1.89	0.221	1.95	77.3	265.1	1.020	0.42	10.54	82.7	0.76
	39		27.0	48.5	27.6	129	27.5	617	1.44	0.384	1.55	104.0	495.7	1.543	0.58	11.36	101.4	0.96
	67		12.6	74.8	129.2	126	31.9	772	5.75	0.510	4.07	72.8	424.4	1.474	0.64	12.63	131.1	0.49
	106		23.3	38.9	35.1	119	48.1	350	2.14	0.122	2.02	24.2	185.6	0.150	0.24	11.81	95.5	0.14
	174		107.3	65.1	17.4	124	63.2	571	0.95	0.117	4.31	12.2	114.0	0.173	0.70	11.18	94.4	0.26
	336	side A	36.8	77.5	26.4	113	19.7	777	1.89	0.163	2.87	26.7	73.6	0.174	0.83	10.42	61.3	0.41
		side B	72.3	114.2	53.3	146	110.3	985	3.04	0.269	4.37	42.9	191.2	0.342	0.61	10.96	61.5	0.18
Bioavailable soil leach (ppm)			<LOQ	14.2	<LOD	<LOQ	14.2	174	<LOD	<LOQ	2.31	6.8	21.7	6.185	<LOQ	<LOQ		<LOQ
σ (n=3)				0.4			0.1	4				0.1	1.9	0.150				
Surface 2	0		77.5	181.6	33.4	112	58.9	11879	5.07	0.036	0.88	1.8	24.0	0.025	0.37	6.17	179.3	0.08
	2		85.8	195.3	35.4	121	120.4	6696	8.07	0.038	1.42	11.5	26.9	0.067	0.49	7.35	289.1	0.03
	10		445.0	203.0	44.8	132	476.2	3000	5.41	0.120	3.17	127.2	119.9	0.913	0.40	15.94	176.6	1.05
	39		118.1	110.4	59.8	233	169.9	1991	4.20	0.387	2.41	179.4	551.4	2.634	0.54	18.47	157.3	6.99
	106		93.5	213.3	973.3	325	327.5	1498	111.3	2.312	35.56	318.2	2857.6	5.406	1.92	19.11	133.3	6.92
	174		46.7	141.4	141.1	123	83.6	1567	7.96	0.378	7.53	246.6	544.0	3.257	0.75	8.60	118.7	0.82
	336		24.4	24.0	221.4	108	41.4	767	16.29	0.806	3.40	25.6	929.5	3.159	0.57	7.67	36.8	2.85
Bioavailable soil leach (ppm)			0.7	25.1	<LOD	<LOQ	22.0	234	<LOD	<LOQ	3.86	9.9	45.6	7.091	<LOQ	50.45		20.18
Surface 3	0		45.5	92.0	20.9	545	167.8	869	2.22	0.017	0.44	1.0	27.8	0.006	0.15	8.17	80.0	0.13
	2		14.6	48.3	15.2	128	16.1	595	4.18	0.036	1.38	5.8	30.2	0.045	0.17	11.47	122.8	0.04
		replicate	15.8	49.6	14.2	128	15.8	569	1.52	0.033	1.29	5.7	31.8	0.049	0.19	11.67	127.2	bdl
	6		117.1	81.7	9.1	136	140.3	749	0.75	0.025	1.31	42.9	27.5	0.244	0.59	11.13	131.5	0.06
	35		26.5	61.4	30.4	194	58.9	1314	4.07	0.069	2.41	86.7	52.3	0.713	0.19	10.06	134.0	0.18
	102		136.8	116.8	49.0	214	68.4	915	3.17	0.271	0.38	167.9	208.7	2.040	0.34	12.19	183.1	0.51
	170		83.7	86.8	24.4	120	54.4	1321	2.51	0.504	3.90	159.3	892.1	2.839	2.11	6.56	89.2	0.52
	332		47.0	59.9	35.0	157	24.2	808	1.96	1.112	1.92	100.7	1287.6	4.277	0.73	10.45	74.7	0.54
Bioavailable soil leach (ppm)			1.3	39.0	<LOQ	1	37.5	398	<LOD	<LOQ	2.40	14.80	65.78	6.335	3.67	<LOQ		15.27

Table 45. Elemental concentrations of bulk hair samples in ppm over time. For comparison purposes, the concentration of the donor-specific bioavailable soil leach is also shown.

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Tennessee																	
Surface 1	0		0.045	0.69	0.020	0.0002	0.15	0.10	0.93	0.37	bdl	1.24	0.026	0.051	0.0006	bdl	bdl
	1		0.050	0.44	0.022	0.0004	0.19	0.11	0.33	1.85	bdl	3.44	0.023	0.041	0.0009	bdl	0.010
	2		bdl	0.26	0.048	0.0002	0.16	0.13	3.87	1.70	bdl	1.58	0.035	0.067	0.0031	bdl	bdl
		replicate	0.021	0.14	0.037	0.0026	0.06	0.13	0.25	2.65	bdl	1.41	0.028	0.052	0.0019	0.008	0.016
	5		0.036	0.11	0.096	0.0003	0.17	0.11	0.26	2.46	bdl	1.71	0.037	0.077	0.0054	0.023	0.055
		replicate	0.059	bdl	0.094	0.0092	0.21	0.12	0.55	3.93	bdl	1.91	0.037	0.077	0.0057	0.025	0.063
	10		0.039	0.17	0.036	0.0003	0.18	0.10	1.11	2.28	bdl	1.49	0.027	0.053	0.0031	0.011	0.029
	20		0.030	0.53	0.088	0.0003	0.17	0.07	0.51	0.42	bdl	2.70	0.102	0.249	0.0232	0.096	0.204
	39		0.024	0.65	0.101	0.0005	0.23	0.11	0.21	0.72	0.0052	3.66	0.131	0.302	0.0290	0.121	0.249
	67		0.182	0.75	0.179	0.0003	0.16	0.12	0.25	1.07	bdl	3.87	0.276	0.602	0.0624	0.258	0.518
	106		0.087	0.36	0.061	0.0002	0.17	0.09	0.69	1.15	bdl	2.01	0.084	0.178	0.0162	0.064	0.119
	174		0.088	0.59	0.109	0.0032	0.09	0.12	4.51	1.90	0.0000	2.79	0.083	0.162	0.0162	0.072	0.014
	336	side A	0.041	0.89	0.093	0.0035	0.21	0.12	4.50	1.19	0.0039	3.73	0.209	0.375	0.0446	0.185	0.037
		side B	0.167	1.26	0.089	0.0094	0.10	0.23	0.45	0.63	0.0199	6.11	0.292	0.546	0.0609	0.240	0.046
Bioavailable soil leach (ppm)			5.752	244.42	0.710			2.99	<LOD	<LOQ		180.1	9.06	15.26	1.78	10.45	2.04
σ (n=3)			0.683	4.96	0.206			0.47				4.3	0.20	0.09	0.07	0.54	0.06
Surface 2	0		0.023	21.96	0.039	0.0013	0.20	0.63	3.52	0.16	bdl	4.79	0.110	0.164	0.0053	0.020	0.046
	2		0.024	13.81	0.070	0.0005	0.72	0.03	3.61	0.12	bdl	5.02	0.117	0.151	0.0065	0.024	0.052
	10		0.445	5.13	0.126	bdl	0.24	0.06	2.54	0.15	bdl	6.40	0.356	0.705	0.0751	0.312	0.590
	39		0.178	1.59	0.070	0.0003	0.07	0.25	1.34	0.09	bdl	5.92	0.556	1.518	0.1365	0.585	1.154
	106		1.802	2.33	0.874	0.0006	1.65	0.30	0.29	0.43	bdl	13.22	1.970	4.957	0.4612	1.856	3.506
	174		0.198	1.76	0.172	0.0061	0.05	0.25	3.42	0.09	0.0000	6.86	0.933	2.524	0.2108	0.834	0.160
	336		0.282	1.38	0.109	0.0130	0.15	0.50	0.56	0.19	0.0062	5.54	1.378	3.885	0.3510	1.416	0.285
Bioavailable soil leach (ppm)			18.109	314.50	0.692			2.97	<LOD	0.63		183.1	5.71	8.40	0.98	6.93	1.45
Surface 3	0		0.032	1.50	0.023	0.0003	0.90	0.07	0.98	0.07	bdl	1.38	0.180	0.226	0.0034	0.009	bdl
	2		bdl	1.06	0.134	bdl	0.75	0.04	0.56	0.40	bdl	1.54	0.183	0.338	0.0238	0.096	0.182
		replicate	0.038	1.07	0.052	0.0009	0.85	0.04	1.23	0.09	bdl	1.60	0.196	0.364	0.0269	0.109	0.182
	6		0.104	1.35	0.053	0.0005	0.63	0.04	1.31	0.08	bdl	2.39	0.113	0.242	0.0140	0.054	0.111
	35		0.042	1.26	0.090	0.0002	0.61	0.10	0.34	0.21	bdl	3.38	0.231	0.591	0.0426	0.176	0.331
	102		0.076	1.40	0.051	0.0084	0.31	0.08	0.57	0.13	bdl	4.22	0.607	1.446	0.1158	0.484	0.632
	170		0.053	0.72	0.084	0.0025	0.09	0.08	0.61	0.09	0.0066	2.70	0.126	0.382	0.0266	0.109	0.020
	332		0.029	0.99	0.104	0.0064	0.30	0.26	5.84	0.16	0.0110	4.87	0.383	1.005	0.0810	0.332	0.062
Bioavailable soil leach (ppm)			30.182	488.57	0.160			2.63	<LOD	<LOQ		247.2	8.66	12.15	1.55	8.75	1.90

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Tennessee																	
Surface 1	0		bdl	0.0010	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.0048	bdl	bdl	0.0013	3.37	0.0010
	1		0.0004	0.0015	bdl	0.0011	bdl	bdl	bdl	bdl	bdl	0.0016	bdl	bdl	0.0010	10.05	0.0008
	2		bdl	0.0030	bdl	0.0018	bdl	bdl	bdl	bdl	bdl	0.0036	bdl	bdl	0.0030	7.85	0.0026
		replicate	0.0004	0.0024	0.0038	0.0013	0.0005	bdl	bdl	bdl	bdl	0.0015	bdl	bdl	0.0076	8.33	0.0008
	5		0.0010	0.0043	0.0043	0.0031	0.0006	0.0020	0.0025	0.0014	0.0003	0.0021	bdl	bdl	0.0015	8.59	0.0011
		replicate	bdl	0.0049	bdl	0.0057	bdl	bdl	bdl	bdl	bdl	0.0165	bdl	bdl	0.0302	8.99	0.0038
	10		0.0007	0.0038	0.0047	0.0032	0.0006	0.0016	0.0031	0.0016	0.0002	0.0017	bdl	bdl	0.0012	8.14	0.0011
	20		0.0043	0.0220	0.0300	0.0197	0.0041	0.0114	0.0145	0.0090	0.0013	0.0047	0.0097	bdl	0.0022	3.16	0.0066
	39		0.0056	0.0279	0.0392	0.0236	0.0050	0.0139	0.0171	0.0112	0.0015	0.0441	0.0084	bdl	0.0051	4.26	0.0084
	67		0.0106	0.0547	0.0777	0.0484	0.0101	0.0283	0.0367	0.0217	0.0029	0.0069	bdl	bdl	0.0029	6.41	0.0138
	106		0.0023	0.0129	0.0155	0.0097	0.0019	0.0055	0.0068	0.0044	0.0005	0.0024	bdl	bdl	0.0011	5.67	0.0023
	174		0.0029	0.0133	0.0022	0.0127	0.0021	0.0055	0.0010	0.0040	0.0006	0.0028	0.0105	0.0001	0.0025	4.64	0.0035
	336	side A	0.0074	0.0360	0.0047	0.0296	0.0054	0.0153	0.0019	0.0095	0.0016	0.0035	0.0052	bdl	0.0013	4.03	0.0046
		side B	0.0093	0.0483	0.0062	0.0337	0.0068	0.0182	0.0022	0.0129	0.0016	0.0062	0.0062	0.0005	0.0023	3.79	0.0067
Bioavailable soil leach (ppm)			0.47	2.40	0.25	1.54	0.27	0.58	<LOQ	0.33	<LOQ	<LOD	<LOD	<LOD		1.99	0.41
σ (n=3)			0.08	0.19	0.01	0.03	0.04	0.03								0.07	0.05
Surface 2	0		0.0008	0.4457	0.0057	0.0043	0.0007	0.0024	0.0034	0.0034	0.0003	0.1328	0.0078	bdl	0.0031	0.57	0.0098
	2		0.0011	0.0187	0.0057	0.0041	0.0009	0.0024	0.0026	0.0019	0.0002	0.1024	0.0422	bdl	0.0037	0.49	0.0101
	10		0.0117	0.0804	0.0786	0.0507	0.0103	0.0285	0.0321	0.0206	0.0024	0.0071	bdl	bdl	bdl	0.71	0.0229
	39		0.0246	0.1748	0.1582	0.0942	0.0205	0.0533	0.0687	0.0400	0.0054	0.0081	0.0080	bdl	0.0011	2.02	0.0294
	106		0.0677	0.4895	0.4662	0.2830	0.0581	0.1650	0.2154	0.1345	0.0181	0.0724	0.0354	bdl	0.0029	4.35	0.1088
	174		0.0313	0.1696	0.0211	0.1210	0.0245	0.0644	0.0078	0.0453	0.0063	0.0155	0.0084	bdl	0.0020	2.14	0.0292
	336		0.0604	0.3741	0.0404	0.2335	0.0464	0.1227	0.0153	0.0850	0.0122	0.0523	0.0138	0.0001	0.0027	2.21	0.0832
Bioavailable soil leach (ppm)			0.36	1.37	0.16	0.79	0.16	<LOQ	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		2.69	0.30
Surface 3	0		0.0003	0.0010	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.0063	bdl	bdl	0.0011	0.22	0.0006
	2		0.0034	0.0148	0.0188	0.0118	0.0024	0.0061	0.0064	0.0037	0.0005	0.0152	0.0107	bdl	bdl	0.25	0.0027
		replicate	0.0034	0.0166	0.0215	0.0125	0.0024	0.0062	0.0067	0.0045	0.0006	0.0074	0.0091	bdl	0.0017	0.23	0.0024
	6		0.0022	0.0104	0.0119	0.0075	0.0016	0.0042	0.0045	0.0032	0.0004	0.0026	0.0071	bdl	0.0013	0.29	0.0166
	35		0.0071	0.0332	0.0465	0.0296	0.0056	0.0153	0.0200	0.0104	0.0014	0.0051	0.0032	bdl	0.0006	1.48	0.0060
	102		0.0100	0.0446	0.0497	0.0227	0.0054	0.0140	0.0168	0.0137	0.0013	0.0086	bdl	bdl	0.0261	1.43	0.0101
	170		0.0046	0.0226	0.0032	0.0194	0.0038	0.0101	0.0016	0.0074	0.0011	0.0047	0.0062	0.0001	0.0008	3.66	0.0090
	332		0.0130	0.0620	0.0087	0.0490	0.0098	0.0255	0.0033	0.0167	0.0027	0.0046	0.0073	0.0001	0.0014	1.48	0.0143
Bioavailable soil leach (ppm)			0.45	1.99	0.24	1.19	0.25	0.60	0.09	0.44	<LOQ	<LOD	<LOD	<LOD		1.63	0.22

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Burial 1	0	19.2	25.9	2.3	211	21.4	147	0.85	0.007	0.43	0.1	9.4	0.010	0.05	6.00	112.1	0.07
	102	20.3	65.0	38.5	120	15.7	647	4.05	0.358	1.97	322.0	385.9	7.417	0.79	6.91	77.2	3.99
	381	50.5	45.0	550.0	162	98.1	127	18.37	3.696	7.73	13.3	879.5	11.012	0.95	3.63	9.8	2.57
Bioavailable soil leach (ppm)		<LOQ	9.78	<LOD	<LOQ	12.6	127	<LOD	<LOD	<LOQ	3.51	<LOQ	2.959	<LOQ	<LOQ		<LOQ
Burial 2	0	27.4	55.9	4.1	130	21.8	1428	0.58	0.012	0.68	0.8	12.7	0.024	0.12	11.41	138.6	0.09
	380	29.7	20.6	39.4	202	32.2	519	2.27	1.102	2.50	85.8	1363.0	11.926	1.44	8.28	95.8	2.34
Bioavailable soil leach (ppm)		0.84	19.45	<LOD	<LOQ	11.0	161	<LOD	<LOD	<LOQ	2.82	<LOQ	45.805	3.91	<LOD		34.19
Burial 3	0	58.3	74.1	41.1	1176	563.6	462	6.78	0.093	14.41	1.3	101.8	0.034	0.17	7.24	99.2	bdl
	379	27.1	29.4	137.0	191	37.4	366	6.30	2.403	4.60	239.2	2049.5	11.644	1.43	8.70	96.4	6.86
Texas																	
Surface 4	0	17.9	11.4	3.2	134	13.5	98	0.58	0.013	2.59	0.2	28.6	0.022	0.50	8.22	107.6	0.23
	1	19.6	12.0	3.7	178	7.7	112	0.63	0.010	1.36	0.1	20.2	0.005	0.10	8.07	108.8	0.12
	2	44.4	12.8	3.5	164	19.3	124	0.56	0.017	1.45	0.2	18.9	0.006	0.22	7.07	95.8	0.08
	3	61.3	9.7	4.7	172	22.9	175	0.70	0.016	1.52	0.1	23.3	0.006	0.17	7.29	111.6	0.13
	5	27.9	7.0	3.2	141	16.8	106	0.61	0.019	1.10	0.5	18.8	0.010	0.17	7.50	94.7	0.23
	5 replicate	45.5	7.9	4.0	155	19.2	124	0.95	0.020	1.09	0.5	18.8	0.020	0.13	8.20	102.3	0.15
	320	20.6	35.3	143.7	117	34.0	525	9.59	0.378	0.20	4.8	91.7	0.065	0.18	1.91	118.9	0.07
Bioavailable soil leach (ppm)		<LOQ	24.98	<LOD	<LOQ	15.2	186	<LOD	<LOQ	<LOQ	5.09	12.22	5.214	5.24	<LOD		<LOQ
Surface 5	0	922.5	45.9	3.5	83	407.0	119	0.62	0.012	0.56	0.1	13.4	0.004	0.09	8.87	71.6	59.70
	1	44.3	40.9	5.1	87	18.2	151	0.92	0.012	0.60	0.1	10.6	0.005	0.07	7.37	65.5	57.12
	2	1289.6	96.7	15.8	385	846.9	287	2.14	0.025	0.51	0.1	18.8	0.006	0.22	8.45	66.2	24.09
	3	45.3	49.9	5.3	109	27.2	210	1.03	0.025	0.71	0.9	12.6	0.010	0.16	11.84	91.6	12.26
	5	2218.0	9.7	11.5	334	1894.8	72	2.56	0.251	0.97	5.1	122.6	0.439	0.31	7.51	70.8	23.75
		2895.5	5.2	11.1	414	2399.2	70	3.05	0.318	0.89	5.8	151.6	0.454	0.37	9.46	86.9	29.52
	360	87.5	136.4	1321.2	1024	185.5	1003	35.42	1.791	1.80	13.3	1052.8	0.282	1.11	3.28	69.0	5.72
Bioavailable soil leach (ppm)		0.69	23.99	<LOD	<LOQ	15.0	199	<LOD	<LOQ	<LOQ	5.22	38.77	5.759	4.98	<LOD		<LOQ
Surface 6	0	93.0	83.9	6.6	105	43.3	2982	0.56	0.044	0.50	0.3	10.0	0.010	0.17	8.47	65.6	0.12
	1	106.5	78.9	10.4	99	58.7	1905	0.73	0.048	0.84	0.4	17.3	0.013	0.32	10.38	50.5	0.08
	2	141.4	68.3	9.4	136	105.6	987	0.98	0.044	0.77	0.4	37.1	0.012	0.19	8.47	55.2	0.05
	2 replicate	123.3	60.0	7.8	134	97.8	899	0.94	0.029	0.18	0.2	17.1	0.008	0.13	7.99	50.7	0.05
	3	148.6	52.4	9.7	125	80.1	567	0.68	0.053	1.41	0.5	25.8	0.012	0.23	10.33	56.3	0.08
	5	32.0	47.1	26.9	913	143.4	636	2.02	0.032	0.65	0.4	30.9	0.008	0.10	5.48	49.5	0.09
Bioavailable soil leach (ppm)		<LOD	24.22	<LOD	<LOQ	33.2	239	<LOD	<LOQ	<LOQ	3.45	<LOQ	5.1	3.93	<LOD		<LOQ
	replicate	<LOQ	24.81	<LOD	<LOQ	26.5	301	<LOD	<LOQ	<LOQ	15.98	<LOQ	37.1	9.60	<LOQ		<LOQ

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)	Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Burial 1	0	bdl	0.21	0.079	bdl	0.02	0.01	0.67	0.02	bdl	0.15	0.001	0.002	0.0001	bdl	bdl
	102	0.019	0.39	0.250	0.0011	0.01	0.66	1.18	0.10	0.0132	1.56	0.393	1.219	0.0961	0.417	0.833
	381	0.743	0.36	0.651	0.0039	0.09	0.08	3.30	0.13	0.0328	3.43	1.386	4.597	0.3896	1.609	0.354
Bioavailable soil leach (ppm)		9.104	235.54	0.659			2.59	<LOD	0.34		237.0	12.02	14.45	2.52	14.11	3.07
Burial 2	0	bdl	2.61	0.066	0.0002	0.06	0.08	1.32	0.13	bdl	0.75	0.125	0.201	0.0028	0.008	0.012
	380	0.025	0.68	0.291	0.0127	0.08	0.43	3.07	0.18	0.0215	5.56	0.762	2.671	0.1902	0.796	0.156
Bioavailable soil leach (ppm)		125.599	256.61	<LOQ			<LOQ	<LOD	<LOQ		543.0	231.07	399.78	50.22	228.76	40.45
Burial 3	0	bdl	0.22	0.105	0.0002	0.02	0.01	3.36	0.99	bdl	0.56	0.005	0.011	bdl	bdl	0.038
	379	0.201	0.72	0.376	0.0156	0.03	0.66	4.75	0.15	0.0451	5.85	0.665	2.325	0.1634	0.663	0.128
Texas																
Surface 4	0	bdl	0.20	0.137	0.0001	0.07	0.06	0.84	0.11	bdl	0.18	0.002	0.004	0.0003	bdl	bdl
	1	bdl	0.21	0.070	0.0001	0.03	0.02	1.23	0.10	bdl	0.21	0.005	0.010	0.0010	bdl	bdl
	2	bdl	0.17	0.034	0.0000	0.04	0.02	2.48	0.03	bdl	0.16	0.008	0.014	0.0012	bdl	0.009
	3	bdl	0.27	0.117	bdl	0.03	0.01	1.19	0.06	bdl	1.03	0.008	0.016	0.0015	bdl	0.013
	5	bdl	0.18	0.048	bdl	0.05	0.03	0.91	0.06	bdl	0.43	0.012	0.026	0.0026	0.008	0.023
	5 replicate	0.015	0.13	0.037	0.0015	0.03	0.04	0.26	0.07	bdl	0.47	0.015	0.029	0.0033	0.012	0.021
	320	0.215	0.82	0.026	0.0040	0.02	0.14	1.27	0.06	0.0069	4.89	0.533	1.102	0.1291	0.499	0.092
Bioavailable soil leach (ppm)		201.711	265.95	0.068			4.77	<LOD	<LOQ		292.4	17.65	29.20	4.00	21.67	4.85
Surface 5	0	0.339	1.06	0.075	bdl	0.02	0.02	0.61	1.04	bdl	0.44	0.002	0.004	0.0002	bdl	bdl
	1	bdl	1.03	0.072	bdl	0.03	0.01	0.89	1.48	bdl	0.53	0.004	0.008	0.0007	bdl	0.005
	2	0.333	1.54	0.062	0.0001	0.02	0.01	1.03	0.34	bdl	0.39	0.004	0.006	0.0006	bdl	bdl
	3	bdl	1.11	0.109	0.0001	0.03	0.02	1.18	0.19	bdl	0.59	0.013	0.025	0.0025	0.009	0.023
	5	2.631	0.15	0.124	bdl	0.01	0.05	2.47	0.45	bdl	0.57	0.038	0.094	0.0106	0.047	0.137
		3.355	0.11	0.055	bdl	0.01	0.06	0.19	0.43	bdl	0.63	0.077	0.182	0.0221	0.099	0.242
	360	1.858	1.39	0.229	0.0101	0.39	0.27	1.21	0.45	0.0000	5.71	0.801	1.701	0.1962	0.757	0.170
Bioavailable soil leach (ppm)		193.891	275.43	0.292			3.81	<LOD	<LOQ		335.1	18.57	31.92	4.34	22.60	4.82
Surface 6	0	0.029	18.27	0.044	0.0001	0.01	0.04	2.00	0.09	bdl	2.06	0.005	0.010	0.0011	0.005	0.008
	1	0.050	12.51	0.043	0.0005	0.07	0.10	2.01	0.07	bdl	2.15	0.008	0.014	0.0015	0.004	0.010
	2	0.133	4.46	0.043	0.0002	0.02	0.06	2.10	0.10	bdl	4.14	0.005	0.008	0.0010	bdl	bdl
	2 replicate	0.113	4.21	0.026	0.0065	0.03	0.06	1.63	0.04	bdl	3.50	0.005	0.008	0.0009	0.003	0.001
	3	0.065	3.28	0.058	0.0004	0.07	0.07	1.27	0.19	bdl	0.84	0.004	0.008	0.0008	bdl	0.011
	5	0.024	1.03	0.056	bdl	0.02	0.05	1.23	0.05	bdl	0.40	0.007	0.014	0.0015	bdl	0.013
Bioavailable soil leach (ppm)		135.236	257.0	0.071			2.75	<LOD	<LOD		290.1	9.97	15.45	2.18	13.23	2.72
	replicate	165.876	301.2	<LOQ			4.54	<LOD	<LOQ		325.8	28.74	41.44	6.82	34.44	7.55

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Burial 1	0	bdl	bdl	bdl	0.0007	bdl	bdl	bdl	bdl	bdl	bdl	0.0073	bdl	bdl	0.13	0.0001
	102	0.0168	0.0858	0.1166	0.0688	0.0148	0.0406	0.0516	0.0307	0.0043	0.0102	0.0060	bdl	0.0019	0.91	0.0840
	381	0.0710	0.3174	0.0463	0.2723	0.0544	0.1490	0.0191	0.1156	0.0164	0.0338	0.0342	0.0001	0.0030	1.75	0.3628
Bioavailable soil leach (ppm)		0.62	3.36	0.35	2.01	0.36	0.80	<LOQ	0.43	<LOQ	<LOD	<LOD	<LOD		2.44	0.58
Burial 2	0	0.0001	0.0012	bdl	0.0008	bdl	0.0005	bdl	bdl	bdl	0.0035	bdl	bdl	0.0010	0.74	0.0026
	380	0.0309	0.1495	0.0194	0.1160	0.0235	0.0643	0.0081	0.0448	0.0060	0.0106	0.0067	0.0006	0.0018	0.91	0.1481
Bioavailable soil leach (ppm)		7.29	33.13	3.22	16.06	3.17	7.08	0.67	3.29	0.52	<LOD	<LOD	<LOD		10.91	2.36
Burial 3	0	bdl	bdl	bdl	0.0026	bdl	bdl	bdl	bdl	0.0003	0.0010	bdl	bdl	0.0041	0.09	0.0038
	379	0.0234	0.1182	0.0157	0.0918	0.0192	0.0507	0.0063	0.0371	0.0055	0.0117	0.0157	bdl	0.0014	1.45	0.0895
Texas																
Surface 4	0	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0029	0.0207	0.0044	0.0003	0.95	0.0001
	1	bdl	0.0011	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0019	bdl	0.0002	0.0023	0.39	0.0001
	2	0.0001	0.0006	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.0024	0.0047	0.0014	bdl	0.33	0.0005
	3	bdl	0.0011	bdl	0.0008	bdl	bdl	bdl	bdl	bdl	bdl	0.0054	0.0008	0.0017	0.20	0.0003
	5	0.0003	0.0019	bdl	0.0015	0.0003	0.0008	bdl	0.0005	bdl	bdl	0.0095	0.0009	0.0003	0.43	0.0003
	5 replicate	0.0005	0.0024	0.0028	0.0012	0.0003	bdl	bdl	bdl	bdl	0.0038	bdl	0.0015	0.0061	0.44	0.0062
	320	0.0165	0.0725	0.0097	0.0541	0.0103	0.0285	0.0035	0.0209	0.0029	0.0083	0.0081	0.0000	bdl	0.45	0.0129
Bioavailable soil leach (ppm)		1.02	4.17	0.45	2.22	0.41	0.93	0.09	0.50	0.08	<LOD	<LOD	<LOD		1.26	0.30
Surface 5	0	bdl	bdl	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	bdl	0.0086	0.0002	0.0014	0.24	0.0005
	1	bdl	0.0004	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	bdl	0.0108	0.0002	0.0006	0.15	0.0006
	2	0.0002	0.0005	bdl	0.0002	bdl	bdl	bdl	bdl	0.0000	0.0033	0.0114	bdl	0.0018	0.30	0.0007
	3	0.0003	0.0022	bdl	0.0015	0.0003	0.0007	bdl	0.0005	bdl	0.0065	0.0852	bdl	0.0020	0.32	0.0005
	5	0.0031	0.0156	0.0215	0.0152	0.0029	0.0082	0.0095	0.0053	0.0007	0.0241	0.0083	bdl	bdl	0.40	0.0032
	5	0.0046	0.0253	0.0364	0.0213	0.0043	0.0112	0.0125	0.0078	0.0010	bdl	0.0071	bdl	bdl	0.49	0.0064
	360	0.0284	0.1403	0.0193	0.1102	0.0231	0.0574	0.0091	0.0530	0.0084	0.0448	bdl	bdl	bdl	0.82	0.0300
Bioavailable soil leach (ppm)		1.01	4.57	0.48	2.24	0.40	0.90	0.09	0.54	0.08	<LOD	<LOD	<LOD		2.10	0.35
Surface 6	0	0.0002	0.0011	bdl	0.0011	0.0001	0.0006	bdl	0.0003	0.0001	0.0117	0.0644	bdl	0.0009	1.48	0.0163
	1	0.0003	0.0010	bdl	0.0008	0.0001	0.0004	bdl	0.0004	0.0000	0.0185	0.0324	bdl	0.0012	1.96	0.0099
	2	0.0001	0.0007	bdl	0.0009	bdl	0.0006	bdl	bdl	bdl	0.0163	0.0484	bdl	0.0011	1.23	0.0180
	2 replicate	0.0002	0.0005	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0150	0.0086	0.0002	0.0015	1.10	0.0195
	3	0.0002	bdl	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0094	0.0128	bdl	0.0018	0.92	0.0059
	5	0.0004	0.0009	bdl	0.0010	0.0001	bdl	bdl	bdl	bdl	bdl	0.0251	bdl	0.0005	0.69	0.0032
Bioavailable soil leach (ppm)		0.64	2.61	0.23	1.15	0.21	0.46	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		1.06	0.26
	replicate	1.48	6.56	0.68	3.19	0.55	1.16	0.11	0.54	<LOQ	<LOD	<LOD	<LOD		1.63	0.56

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Surface 7	0		77.1	35.4	1.6	229	36.7	99	0.34	0.009	0.49	0.1	12.0	0.004	0.06	5.42	98.5	5.94
	1		14.2	24.6	2.1	117	6.3	102	0.89	0.011	0.41	0.0	8.7	0.002	0.63	6.32	111.8	98.02
	2		10.0	20.3	2.0	103	2.7	76	0.52	0.012	0.31	0.1	7.8	0.002	0.07	5.70	97.1	76.77
	3		30.9	19.2	5.6	108	15.1	98	0.79	0.023	0.43	1.2	10.9	0.006	0.06	6.82	136.4	66.81
	5		50.6	28.1	8.1	105	25.6	126	1.13	0.034	0.81	2.5	18.4	0.014	0.15	5.92	107.5	115.17
Bioavailable soil leach (ppm)			<LOD	20.69	<LOD	<LOQ	21.7	427	<LOD	1.523	<LOQ	1.78	<LOQ	2.2	<LOQ	<LOD		<LOD
Burial 4			2504.2	56.5	9.4	129	1673.0	160	1.53	0.017	0.45	0.2	20.0	0.007	0.37	13.16	12.3	0.46
		replicate	2503.8	57.7	9.8	130	1677.1	163	2.17	0.018	0.52	0.2	21.3	0.008	0.36	13.37	11.9	0.16
	0	replicate 2	2441.3	55.5	9.3	127	1622.5	144	1.38	0.016	0.52	0.2	19.7	0.006	0.37	12.93	11.8	0.35
		average	2483.1	56.6	9.5	129	1657.6	156	1.69	0.017	0.50	0.2	20.3	0.007	0.37	13.15	12.0	0.32
		σ	36.2	1.1	0.2	2	30.4	10	0.42	0.001	0.04	0.0	0.8	0.001	0.01	0.22	0.3	0.15

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Surface 7	0		0.059	0.29	0.044	0.0003	0.01	0.01	1.09	0.15	bdl	0.65	0.000	0.001	bdl	bdl	bdl
	1		bdl	0.45	0.044	0.0001	0.00	0.05	0.81	1.72	bdl	0.30	0.001	0.002	0.0001	bdl	bdl
	2		bdl	0.43	0.045	0.0002	0.00	0.06	0.75	1.39	0.0191	0.25	0.001	0.002	0.0001	bdl	bdl
	3		bdl	0.40	0.030	0.0002	0.00	0.05	0.85	1.15	bdl	0.45	0.016	0.038	0.0034	0.013	0.019
	5		0.016	0.46	0.050	0.0003	0.00	0.14	0.85	2.30	0.0169	0.53	0.024	0.052	0.0056	0.021	0.045
Bioavailable soil leach (ppm)			192.355	268.37	<LOQ			1.44	<LOD	<LOQ		247.7	8.42	10.47	1.58	9.71	2.04
Burial 4			1.001	0.23	0.036	0.0002	3.52	0.07	1.58	0.07	bdl	0.43	0.012	0.022	0.0021	bdl	0.010
		replicate	1.011	0.23	0.033	0.0003	3.55	0.07	1.51	0.11	bdl	0.46	0.009	0.017	0.0019	bdl	0.009
	0	replicate 2	0.972	0.21	0.057	bdl	3.55	0.07	1.46	0.05	bdl	0.41	0.018	0.030	0.0030	bdl	0.013
		average	0.995	0.22	0.042	0.0002	3.54	0.07	1.52	0.08	bdl	0.43	0.013	0.023	0.0023	bdl	0.011
		σ	0.021	0.01	0.013	0.0001	0.02	0.00	0.06	0.03		0.02	0.005	0.007	0.0006		0.002

	exposure time (days)		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Surface 7	0		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0874	0.0080	bdl	0.0017	0.05	0.0004
	1		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0044	bdl	0.0001	0.0005	0.17	0.0005
	2		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0013	0.0223	bdl	0.0012	0.14	0.0006
	3		0.0005	0.0029	0.0026	0.0015	0.0004	0.0010	0.0019	0.0008	0.0001	0.0008	bdl	bdl	0.0005	0.16	0.0006
	5		0.0007	0.0037	0.0029	0.0023	0.0004	0.0009	0.0012	0.0008	0.0001	0.0025	bdl	bdl	0.0021	0.25	0.0005
Bioavailable soil leach (ppm)			0.36	1.84	0.17	0.92	0.16	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	<LOD		0.77	0.19
Burial 4			bdl	0.0009	bdl	0.0008	bdl	bdl	bdl	bdl	bdl	0.0015	0.0063	0.0002	0.0014	0.85	0.0024
		replicate	0.0002	bdl	bdl	0.0010	bdl	bdl	bdl	bdl	0.0001	0.0021	0.0178	bdl	0.0009	0.84	0.0018
	0	replicate 2	bdl	0.0009	bdl	0.0006	bdl	bdl	bdl	bdl	bdl	bdl	0.0109	0.0005	bdl	0.81	0.0018
		average	bdl	0.0009	bdl	0.0008	bdl	bdl	bdl	bdl	bdl	0.0018	0.0117	0.0004	0.0011	0.83	0.0020
		σ		0.0000		0.0002						0.0004	0.0058	0.0002	0.0003	0.02	0.0004

Table 45. Elemental concentrations of bulk hair samples continued.

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Tennessee																		
Surface 1	0		78.0	30.8	3.14	28.03	34.9	182	0.07	0.008	0.13	0.86	5.1	0.008	0.10	4.09	73.1	0.09
	1		53.2	95.9	6.52	52.63	40.4	1955	0.07	0.018	0.03	1.93	8.8	0.019	0.15	5.87	87.5	0.01
	10		18.0	17.8	12.68	136.5	86.0	193	0.17	0.018	0.19	9.56	23.9	0.021	0.10	2.76	66.4	bdl
	20		12.4	22.3	10.69	20.55	17.5	255	0.48	0.094	0.08	70.60	113.0	0.53	0.26	2.79	81.1	0.02
	106		37.9	33.8	9.67	13.47	61.2	334	0.17	0.033	0.08	21.30	73.1	0.042	0.16	4.10	89.1	0.03
	174		29.6	39.7	5.60	7.19	48.6	414	0.34	0.015	0.01	7.84	20.6	0.024	0.06	1.69	74.1	0.02
	336	side A	9.0	65.0	4.69	5.30	13.2	699	0.12	0.014	0.01	23.02	12.1	0.038	0.07	1.05	54.3	0.01
		side B	42.0	96.0	19.74	21.81	105.8	861	0.73	0.041	0.09	38.73	55.8	0.106	0.11	1.83	52.2	0.03
Bioavailable soil leach (ppm)			<LOQ	14.2	<LOD	<LOQ	14.2	174	<LOD	<LOQ	2.31	6.8	21.7	6.18	<LOQ	<LOQ		<LOQ
σ (n=3)				0.4			0.1	4				0.1	1.9	0.15				
Surface 2	0		49.3	148.4	11.48	26.64	54.1	3195	0.16	0.004	0.03	1.31	4.8	0.006	0.21	1.87	152.2	0.05
	2		61.2	169.6	24.65	36.32	108.2	4541	0.44	0.009	0.02	6.41	7.0	0.016	0.30	3.25	234.8	0.04
	10		556.0	218.4	47.94	19.65	656.6	3111	1.41	0.094	0.15	148.4	101.1	0.38	0.57	10.69	114.7	0.72
		replicate	540.3	227.7	54.90	24.16	637.1	3242	1.74	0.122	0.18	154.2	128.7	0.42	0.38	12.03	110.0	0.90
		replicate 2	550.7	245.4	47.71	20.19	653.7	3599	1.71	0.117	0.17	154.5	111.0	0.40	0.44	12.20	120.0	0.07
		average	549.0	230.5	50.18	21.33	649.1	3317	1.62	0.111	0.17	152.4	113.6	0.40	0.46	11.64	114.9	0.56
		σ	8.0	13.7	4.08	2.46	10.5	253	0.18	0.015	0.01	3.4	14.0	0.02	0.10	0.83	5.0	0.43
	39		110.6	117.6	53.75	120.4	185.5	2043	1.97	0.208	0.17	178.8	429.9	0.72	0.43	16.15	129.6	3.11
		replicate	213.1	212.8	73.30	180.4	341.5	4094	2.12	0.302	0.46	313.2	635.6	1.05	0.83	29.24	271.0	7.61
	106		49.6	136.5	276.87	100.1	132.0	1462	8.66	0.683	0.56	226.0	923.1	0.80	0.72	11.37	134.5	0.21
	174		26.0	117.0	48.92	11.78	56.5	1600	1.20	0.163	0.07	250.1	237.5	1.26	0.31	3.10	81.1	0.14
	336		21.7	12.1	66.37	32.93	17.8	843	2.56	0.583	0.85	25.99	592.4	0.70	0.30	4.04	38.5	1.21
Bioavailable soil leach (ppm)			0.7	25.1	<LOD	<LOQ	22.0	234	<LOD	<LOQ	3.86	9.9	45.6	7.09	<LOQ	50.45		20.18
Surface 3	0		34.4	54.1	2.18	44.22	29.2	542	0.62	0.009	0.02	1.07	3.2	0.004	0.21	2.38	93.8	0.02
	2		8.8	25.9	2.20	13.23	8.0	364	0.09	0.003	0.08	3.50	2.7	0.018	0.08	1.61	77.9	bdl
	6		91.4	75.1	2.65	15.67	112.7	852	0.10	0.007	0.02	46.49	4.1	0.15	0.26	1.71	108.7	bdl
	35		15.2	37.8	4.23	6.63	22.8	555	0.15	0.015	0.07	62.10	8.8	0.23	0.12	1.33	115.0	0.04
	102		68.3	111.9	15.82	23.10	121.6	1152	0.25	0.061	0.06	171.59	39.5	0.92	0.24	2.43	229.2	0.11
	170		29.9	80.9	7.98	18.35	39.9	1148	0.36	0.295	0.03	192.11	290.0	1.12	0.24	0.52	70.8	0.16
	332		10.9	42.7	9.82	14.83	9.9	580	0.33	0.148	0.01	82.85	118.8	0.72	0.20	0.82	59.4	0.08
Bioavailable soil leach (ppm)			1.3	39.0	<LOQ	1.37	37.5	398	<LOD	<LOQ	2.40	14.80	65.8	6.34	3.67	<LOQ		15.27

Table 46. Elemental concentrations of hair leachates in ppm over time. For comparison purposes, the concentration of the donor-specific bioavailable soil leach is also shown.

Tennessee

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Surface 1	0		0.053	0.62	bdl	0.000	0.054	0.10	0.02	0.11	bdl	1.04	0.01	0.016	0.0004	bdl	0.0039
	1		0.056	2.02	0.008	0.003	0.101	0.12	1.17	0.35	0.002	3.79	0.04	0.077	0.0083	0.034	0.0064
	10		0.027	0.18	0.005	0.000	0.037	0.09	0.03	0.12	bdl	1.32	0.01	0.028	0.0025	0.011	0.0206
	20		0.025	0.42	0.005	0.006	0.033	0.06	0.02	0.04	bdl	2.30	0.07	0.17	0.0167	0.068	0.0143
	106		0.085	0.39	0.005	0.002	0.062	0.07	0.67	0.10	0.001	1.89	0.03	0.066	0.0062	0.025	0.0054
	174		0.075	0.43	0.002	0.002	0.025	0.08	0.05	0.02	0.000	1.91	0.04	0.092	0.0104	0.042	0.0086
	336	side A	0.015	0.78	0.001	0.003	0.017	0.12	0.03	0.02	0.001	3.13	0.07	0.13	0.0165	0.068	0.0132
		side B	0.13	1.10	0.005	0.005	0.042	0.21	0.10	0.04	0.008	5.31	0.10	0.20	0.0216	0.087	0.0181
Bioavailable soil leach (ppm)			5.752	244	0.71			2.99	<LOD	<LOQ		180.1	9.06	15.26	1.78	10.45	2.04
σ (n=3)			0.683	5	0.21			0.47				4.3	0.20	0.09	0.07	0.54	0.06
Surface 2	0		0.02	7.43	bdl	0.000	0.094	0.20	0.12	0.06	bdl	3.23	0.01	0.02	0.0005	bdl	0.0047
	2		0.03	10.42	0.007	0.001	0.692	0.02	0.90	0.03	0.000	4.22	0.05	0.06	0.0030	0.012	0.0029
		replicate	0.66	5.58	0.008	0.002	0.144	0.06	2.13	0.03	0.002	6.71	0.29	0.69	0.0739	0.316	0.0667
		replicate 2	0.66	5.75	0.008	0.001	0.159	0.06	0.86	0.03	0.002	7.14	0.32	0.75	0.0803	0.345	0.0735
	10	average	0.66	6.01	0.007	0.004	0.146	0.06	1.07	0.03	0.002	7.12	0.31	0.73	0.0791	0.338	0.0705
		σ	0.002	0.60	0.002	0.004	0.012	0.00	0.98	0.00	0.000	0.39	0.03	0.03	0.0048	0.020	0.0035
		replicate	0.20	1.72	0.005	0.000	0.016	0.23	0.05	0.04	bdl	6.17	0.66	1.81	0.1612	0.699	1.3546
	39	replicate	0.33	3.31	0.011	0.012	0.063	0.51	1.09	0.05	0.003	11.64	1.22	3.22	0.2859	1.180	0.2320
	106		0.47	1.32	0.012	0.011	0.463	0.31	0.05	0.02	bdl	6.98	0.86	2.52	0.2110	0.868	0.1765
	174		0.063	1.89	0.004	0.004	0.017	0.18	0.09	0.02	0.002	7.64	0.26	0.87	0.0681	0.283	0.0609
	336		0.049	1.42	0.010	0.013	0.101	0.54	0.61	0.05	0.000	5.63	1.13	3.28	0.2935	1.183	0.2450
Bioavailable soil leach (ppm)			18.109	315	0.69			2.97	<LOD	0.63		183.1	5.71	8.40	0.98	6.93	1.45
Surface 3	0		0.026	1.30	0.003	0.003	0.587	0.09	0.80	0.02	0.004	1.16	0.10	0.17	0.0026	0.007	0.0006
	2		bdl	0.65	bdl	0.000	0.166	0.03	0.01	0.02	bdl	0.88	0.07	0.12	0.0113	0.049	0.0820
	6		0.11	1.39	bdl	bdl	0.265	0.05	0.01	0.03	bdl	2.61	0.09	0.18	0.0163	0.068	0.1135
	35		0.025	0.73	0.003	0.002	0.182	0.08	0.04	0.04	0.000	2.25	0.06	0.16	0.0145	0.057	0.0116
	102		0.13	1.72	0.004	0.004	0.107	0.13	0.70	0.04	0.001	6.03	0.14	0.38	0.0335	0.139	0.0284
	170		0.044	0.59	0.003	0.002	0.068	0.08	0.17	0.01	0.002	2.39	0.05	0.17	0.0125	0.051	0.0114
	332		0.009	0.67	0.005	0.005	0.039	0.20	0.12	0.01	0.001	3.08	0.13	0.35	0.0325	0.136	0.0279
Bioavailable soil leach (ppm)			30	489	0.16			2.63	<LOD	<LOQ		247.2	8.66	12.15	1.55	8.75	1.90

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Tennessee																	
Surface 1	0		0.0001	0.0006	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0002	bdl	bdl	bdl	3.0457	0.0002
	1		0.0015	0.0067	0.0010	0.0061	0.0011	0.0031	0.0004	0.0025	0.0004	0.0003	0.0056	0.0000	bdl	10.4771	0.0015
	10		0.0006	0.0029	0.0035	0.0021	0.0003	0.0011	0.0010	0.0014	0.0001	0.0204	bdl	bdl	bdl	7.7260	0.0005
	20		0.0032	0.0144	0.0022	0.0132	0.0027	0.0074	0.0010	0.0060	0.0008	0.0006	bdl	bdl	0.0013	3.0384	0.0043
	106		0.0011	0.0063	0.0008	0.0049	0.0010	0.0024	0.0003	0.0021	0.0003	0.0008	0.0023	0.0000	bdl	5.1994	0.0014
	174		0.0018	0.0088	0.0012	0.0072	0.0016	0.0036	0.0004	0.0025	0.0004	0.0006	bdl	bdl	bdl	3.4661	0.0012
	336	side A	0.0030	0.0155	0.0021	0.0122	0.0025	0.0065	0.0008	0.0043	0.0006	0.0003	0.0004	bdl	0.0002	3.6358	0.0016
		side B	0.0037	0.0196	0.0026	0.0147	0.0030	0.0081	0.0008	0.0056	0.0008	0.0010	bdl	bdl	bdl	3.3654	0.0022
Bioavailable soil leach (ppm)			0.47	2.40	0.25	1.54	0.27	0.58	<LOQ	0.33	<LOQ	<LOD	<LOD	<LOD		1.99	0.41
σ (n=3)			0.08	0.19	0.01	0.03	0.04	0.03								0.07	0.05
Surface 2	0		bdl	0.1209	bdl	0.0004	bdl	bdl	bdl	0.0004	bdl	0.0016	bdl	bdl	bdl	0.2255	0.0072
	2		0.0006	0.0072	0.0005	0.0026	0.0006	0.0015	0.0002	0.0011	0.0002	0.0025	bdl	0.0000	bdl	0.3376	0.0110
	10		0.0143	0.0787	0.0107	0.0640	0.0133	0.0360	0.0046	0.0262	0.0039	0.0033	0.0019	bdl	bdl	0.7252	0.0125
		replicate	0.0150	0.0844	0.0112	0.0697	0.0146	0.0392	0.0048	0.0284	0.0040	0.0040	0.0114	bdl	bdl	0.7517	0.0139
		replicate 2	0.0151	0.0834	0.0117	0.0696	0.0146	0.0405	0.0048	0.0277	0.0039	0.0031	bdl	bdl	0.0022	0.7387	0.0153
		average	0.0148	0.0821	0.0112	0.0678	0.0142	0.0385	0.0047	0.0274	0.0040	0.0035	0.0066	bdl	bdl	0.7385	0.0139
		σ	0.0004	0.0031	0.0005	0.0033	0.0008	0.0023	0.0001	0.0011	0.0001	0.0005	0.0067			0.0132	0.0014
	39		0.0279	0.1669	0.1901	0.1104	0.0234	0.0626	0.0782	0.0440	0.0056	0.0142	bdl	bdl	bdl	2.0847	0.0170
		replicate	0.0458	0.2721	0.0319	0.1914	0.0386	0.1013	0.0127	0.0691	0.0098	0.0070	0.0027	0.0001	bdl	3.9998	0.0311
	106		0.0361	0.2230	0.0252	0.1521	0.0311	0.0845	0.0108	0.0620	0.0085	0.0075	bdl	0.0000	0.0012	2.8276	0.0301
	174		0.0136	0.0762	0.0103	0.0625	0.0133	0.0360	0.0045	0.0250	0.0035	0.0011	0.0007	0.0000	bdl	2.4140	0.0168
	336		0.0523	0.3041	0.0365	0.2125	0.0443	0.1163	0.0146	0.0804	0.0115	0.0048	bdl	0.0001	bdl	2.3721	0.0328
Bioavailable soil leach (ppm)			0.36	1.37	0.16	0.79	0.16	<LOQ	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		2.69	0.30
Surface 3	0		0.0001	0.0005	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0008	bdl	0.0001	bdl	0.2018	0.0004
	2		0.0017	0.0078	0.0107	0.0059	0.0012	0.0031	0.0026	0.0019	0.0002	0.0002	bdl	bdl	bdl	0.1612	0.0008
	6		0.0023	0.0115	0.0142	0.0089	0.0016	0.0046	0.0044	0.0030	0.0003	0.0038	bdl	bdl	bdl	0.2749	0.0017
	35		0.0023	0.0115	0.0016	0.0097	0.0018	0.0048	0.0006	0.0031	0.0004	0.0017	0.0037	0.0000	bdl	1.0117	0.0029
	102		0.0061	0.0287	0.0043	0.0253	0.0050	0.0129	0.0016	0.0089	0.0013	0.0017	bdl	0.0000	bdl	3.2434	0.0051
	170		0.0022	0.0124	0.0018	0.0109	0.0025	0.0063	0.0008	0.0051	0.0007	0.0003	0.0007	0.0001	bdl	3.1568	0.0036
	332		0.0057	0.0301	0.0043	0.0252	0.0051	0.0137	0.0017	0.0095	0.0013	0.0001	0.0003	0.0000	bdl	0.9849	0.0075
Bioavailable soil leach (ppm)			0.45	1.99	0.24	1.19	0.25	0.60	0.09	0.44	<LOQ	<LOD	<LOD	<LOD		1.63	0.22

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Burial 1	0	18.8	19.2	1.90	27.64	10.4	134	bdl	bdl	0.02	0.03	1.4	0.003	0.03	4.35	112.3	bdl
	381	20.3	12.6	186.49	30.67	25.5	89	2.48	1.595	0.17	10.91	241.4	1.60	0.34	0.95	6.0	0.25
Bioavailable soil leach (ppm)		<LOQ	9.8	<LOD	<LOQ	12.6	127	<LOD	<LOD	<LOQ	3.51	<LOQ	2.96	<LOQ	<LOQ		<LOQ
Burial 2	0	23.0	52.3	2.06	21.24	27.9	543	0.09	bdl	0.02	0.50	1.2	0.007	0.07	1.89	132.4	bdl
		32.7	65.2	1.75	22.95	32.5	671	0.09	0.011	0.02	0.58	1.7	0.007	0.08	2.33	180.3	0.03
	380	9.1	16.2	15.65	23.97	11.5	427	0.25	0.397	0.02	85.74	245.2	2.42	0.83	1.70	80.1	0.27
Bioavailable soil leach (ppm)		0.8	19.5	<LOD	<LOQ	11.0	161	<LOD	<LOD	<LOQ	2.82	<LOQ	45.80	3.91	<LOD		34.2
Burial 3	0	bdl	17.6	4.83	97.74	bdl	114	bdl	bdl	bdl	0.07	1.5	bdl	bdl	bdl	47.2	bdl
	379	17.4	33.6	199.08	31.33	35.6	375	3.71	0.984	0.27	235.74	529.1	3.81	1.03	16.72	86.6	1.04
Texas																	
Surface 4	0	9.6	7.6	0.94	19.43	9.4	72	bdl	0.001	0.01	0.06	1.3	0.001	0.02	5.57	93.8	bdl
	replicate	21.3	16.7	4.38	121.3	16.7	166	0.34	0.005	0.09	0.10	6.7	0.004	0.10	7.61	113.1	0.01
	1	57.3	19.5	4.74	95.40	18.4	382	0.20	0.025	0.07	0.08	6.1	0.021	0.17	11.45	227.0	0.08
	3	82.8	20.1	6.63	61.38	41.7	345	0.19	0.015	0.23	0.58	15.0	0.012	0.22	12.25	232.4	0.04
	5	103.1	14.3	11.09	38.71	68.7	268	0.18	0.022	0.10	0.85	9.5	0.008	0.15	6.97	182.9	0.06
Bioavailable soil leach (ppm)		<LOQ	25.0	<LOD	<LOQ	15.2	186	<LOD	<LOQ	<LOQ	5.09	12.2	5.21	5.24	<LOD		<LOQ
Surface 5	0	893	61.3	28.23	26.42	441.3	232	0.18	0.013	0.07	0.20	3.0	0.003	0.20	7.09	110.4	10.61
	1	25	21.7	1.04	5.42	11.6	78	0.07	0.008	0.02	0.04	1.9	bdl	0.01	3.38	61.5	0.28
	replicate	36	26.1	1.10	9.88	15.9	100	0.08	0.007	0.02	0.05	2.2	0.004	0.02	4.62	68.6	6.51
	2	1111	47.4	0.81	8.62	403.4	168	0.05	0.008	0.01	0.06	1.3	0.002	0.10	5.87	52.8	1.11
	3	29	32.8	1.29	11.81	20.2	148	0.04	0.009	0.01	0.63	2.9	0.004	0.06	5.99	63.8	0.07
	5	1663	5.3	4.65	231.0	1595.9	83	0.40	0.199	0.08	4.49	61.1	0.14	0.25	3.09	74.4	3.35
Bioavailable soil leach (ppm)		0.7	24.0	<LOD	<LOQ	15.0	199	<LOD	<LOQ	<LOQ	5.22	38.8	5.76	4.98	<LOD		<LOQ
Surface 6	0	91.6	100.3	3.24	13.91	48.1	1553	0.13	0.014	0.04	0.23	1.4	0.003	0.18	2.00	66.6	0.01
	replicate	57.8	37.1	2.16	12.99	31.9	737	0.05	0.011	0.02	0.12	1.0	0.002	0.09	1.91	54.3	0.02
	1	86.3	54.2	2.58	15.86	49.0	933	0.62	0.007	0.02	0.27	1.7	0.004	0.13	2.00	41.5	bdl
	replicate	109.2	61.3	3.03	19.74	53.8	975	0.08	0.009	0.05	0.29	2.3	0.010	0.18	2.22	47.1	bdl
	3	190.1	65.5	4.93	29.47	107.2	841	0.09	0.017	0.03	0.51	5.3	0.008	0.21	2.32	39.8	bdl
	5	16.2	19.0	1.23	145.7	19.1	285	0.04	0.006	0.05	0.30	3.9	0.002	0.03	0.58	41.6	0.01
Bioavailable soil leach (ppm)		<LOD	24.2	<LOD	<LOQ	33.2	239	<LOD	<LOQ	<LOQ	3.45	<LOQ	5.1	3.93	<LOD		<LOQ
	replicate	<LOQ	24.8	<LOD	<LOQ	26.5	301	<LOD	<LOQ	<LOQ	15.98	<LOQ	37.1	9.60	<LOQ		<LOQ

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)	Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Burial 1	0	bdl	0.26	bdl	0.000	0.011	0.01	0.02	0.10	bdl	0.15	bdl	bdl	bdl	bdl	bdl
	381	0.18	0.09	0.037	0.002	0.018	0.08	0.45	0.01	0.001	2.83	0.69	2.55	0.2059	0.862	0.1872
Bioavailable soil leach (ppm)		9.1	236	0.66			2.59	<LOD	0.34		237.0	12.02	14.45	2.52	14.11	3.07
Burial 2	0	0.017	1.14	bdl	0.009	0.034	0.04	0.04	0.12	bdl	0.57	0.01	0.019	0.0003	0.001	bdl
		0.021	1.40	0.003	0.001	0.027	0.05	0.03	0.23	0.000	0.71	0.02	0.024	0.0005	0.001	bdl
	380	0.010	0.60	0.022	0.010	0.004	0.42	0.02	0.04	0.002	4.53	0.39	1.44	0.1070	0.459	0.0932
Bioavailable soil leach (ppm)		126	257	<LOQ			<LOQ	<LOD	<LOQ		543.0	231.07	399.78	50.22	228.8	40.45
Burial 3	0	bdl	0.15	bdl	0.000	0.008	0.01	0.25	0.23	bdl	0.17	bdl	bdl	bdl	bdl	bdl
	379	0.30	0.80	0.020	0.015	0.053	0.61	0.20	0.02	0.000	6.69	0.46	1.76	0.0984	0.536	0.1115
Texas																
Surface 4	0	bdl	0.15	bdl	0.000	0.014	0.04	0.01	0.03	bdl	0.10	0.00	0.001	0.0001	bdl	bdl
	replicate	0.0110	0.27	0.133	0.001	0.035	0.02	0.71	0.06	0.005	0.21	0.00	0.004	0.0008	0.003	0.0005
	1	0.014	0.51	0.012	bdl	0.028	0.04	2.59	0.18	0.000	0.29	0.01	0.012	0.0014	0.005	0.0006
	3	0.0234	0.49	0.045	0.001	0.022	0.02	2.93	0.10	0.007	0.80	0.02	0.032	0.0039	0.014	0.0028
	5	0.0607	0.41	0.014	0.002	0.023	0.09	1.63	0.05	0.009	0.87	0.02	0.053	0.0060	0.024	0.0051
Bioavailable soil leach (ppm)		202	266	0.068			4.77	<LOD	<LOQ		292.4	17.65	29.20	4.00	21.67	4.85
Surface 5	0	0.35	1.86	0.012	0.001	0.047	0.03	1.71	0.41	0.000	0.63	0.00	0.005	0.0004	0.002	bdl
	1	bdl	0.55	bdl	0.000	0.005	0.01	0.01	0.16	bdl	0.30	0.00	0.002	0.0002	bdl	bdl
	replicate	0.013	0.80	0.002	0.000	0.020	0.01	0.06	0.28	0.002	0.37	0.00	0.003	0.0003	0.001	0.0002
	2	0.33	1.15	0.004	0.000	0.007	0.01	0.49	0.07	0.002	0.31	0.00	0.002	0.0002	0.001	0.0002
	3	0.022	0.79	0.003	0.000	0.008	0.01	0.13	0.04	0.002	0.38	0.01	0.012	0.0014	0.005	0.0012
	5	2.25	0.16	0.007	0.002	0.012	0.07	1.18	0.10	0.004	0.96	0.06	0.15	0.0174	0.074	0.0174
Bioavailable soil leach (ppm)		194	275	0.29			3.81	<LOD	<LOQ		335.1	18.57	31.92	4.34	22.60	4.82
Surface 6	0	0.041	13.09	0.004	0.000	0.011	0.03	0.28	0.01	bdl	1.91	0.00	0.002	0.0003	0.001	0.0025
	replicate	0.032	4.90	0.002	0.001	0.013	0.02	0.10	0.02	0.009	0.92	0.00	0.002	0.0003	0.001	0.0002
	1	0.047	7.08	bdl	0.008	0.037	0.06	0.15	0.02	bdl	1.27	0.00	0.003	0.0004	0.002	0.0003
	replicate	0.047	7.06	0.006	0.001	0.032	0.06	0.16	0.03	bdl	1.28	0.00	0.005	0.0009	0.004	0.0040
	3	0.11	4.93	bdl	0.000	0.019	0.06	0.08	0.07	bdl	1.08	0.00	0.006	0.0006	bdl	0.0044
	5	0.026	0.59	0.001	0.001	0.004	0.04	0.32	0.00	0.000	0.24	0.00	0.007	0.0009	0.003	0.0007
Bioavailable soil leach (ppm)		135	257	0.071			2.75	<LOD	<LOD		290.1	9.97	15.45	2.18	13.23	2.72
	replicate	166	301	<LOQ			4.54	<LOD	<LOQ		325.8	28.74	41.44	6.82	34.44	7.55

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Burial 1	0	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.1267	0.0007
	381	0.0387	0.1886	0.0277	0.1662	0.0342	0.0935	0.0116	0.0687	0.0101	0.0092	0.0017	0.0001	bdl	1.5240	0.1287
Bioavailable soil leach (ppm)		0.62	3.36	0.35	2.01	0.36	0.80	<LOQ	0.43	<LOQ	<LOD	<LOD	<LOD		2.44	0.58
Burial 2	0	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0007	bdl	0.0002	0.0022	0.2155	0.0020
		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0002	bdl	0.0002	bdl	0.2752	0.0014
	380	0.0189	0.0946	0.0130	0.0752	0.0160	0.0440	0.0054	0.0309	0.0044	0.0005	bdl	0.0001	bdl	0.7862	0.0452
Bioavailable soil leach (ppm)		7.29	33.13	3.22	16.06	3.17	7.08	0.67	3.29	0.52	<LOD	<LOD	<LOD		10.91	2.36
Burial 3	0	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0391	bdl
	379	0.0231	0.1117	0.0164	0.0968	0.0204	0.0567	0.0070	0.0423	0.0064	0.0068	0.0019	0.0000	bdl	1.5280	0.0533
Texas																
Surface 4	0	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0003	bdl	0.0034	bdl	0.7513	0.0000
	replicate	0.0001	0.0006	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0024	0.0030	0.0028	bdl	0.5502	0.0009
	1	0.0003	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0004	0.0049	0.0061	bdl	0.6960	0.0022
	3	0.0006	0.0031	0.0003	0.0018	0.0003	0.0009	bdl	0.0007	bdl	0.0048	0.0029	0.0020	0.0012	0.3672	0.0069
	5	0.0009	0.0045	0.0006	0.0032	0.0006	0.0015	0.0003	0.0010	0.0001	0.0005	0.0016	0.0026	bdl	0.9362	0.0008
Bioavailable soil leach (ppm)		1.02	4.17	0.45	2.22	0.41	0.93	0.09	0.50	0.08	<LOD	<LOD	<LOD		1.26	0.30
Surface 5	0	bdl	0.0006	bdl	0.0007	bdl	bdl	bdl	bdl	bdl	0.0019	bdl	0.0002	bdl	0.3549	0.0010
	1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0004	0.0019	bdl	bdl	0.1128	0.0002
	replicate	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0003	bdl	0.0001	bdl	0.1291	0.0002
	2	0.0001	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0025	0.0005	0.0002	bdl	0.2449	0.0002
	3	0.0002	0.0010	0.0002	0.0010	0.0002	0.0005	0.0001	0.0004	0.0001	0.0013	bdl	0.0001	bdl	0.2227	0.0006
	5	0.0035	0.0177	0.0025	0.0140	0.0028	0.0081	0.0009	0.0052	0.0007	0.0006	0.0017	0.0001	bdl	0.4684	0.0034
Bioavailable soil leach (ppm)		1.01	4.57	0.48	2.24	0.40	0.90	0.09	0.54	0.08	<LOD	<LOD	<LOD		2.10	0.35
Surface 6	0	0.0001	0.0003	bdl	0.0002	bdl	bdl	bdl	0.0002	bdl	0.0005	bdl	0.0001	0.0013	0.8767	0.0070
	replicate	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0005	bdl	0.0002	bdl	0.6618	0.0061
	1	0.0001	0.0005	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	0.0011	bdl	0.0002	0.0017	1.1755	0.0022
	replicate	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0009	bdl	0.0002	0.0023	1.2191	0.0018
	3	0.0001	0.0005	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.0015	bdl	bdl	bdl	0.8387	0.0033
	5	0.0001	0.0005	0.0001	0.0005	0.0001	0.0002	0.0000	0.0002	0.0000	0.0006	bdl	0.0000	bdl	0.4403	0.0004
Bioavailable soil leach (ppm)		0.64	2.61	0.23	1.15	0.21	0.46	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		1.06	0.26
	replicate	1.48	6.56	0.68	3.19	0.55	1.16	0.11	0.54	<LOQ	<LOD	<LOD	<LOD		1.63	0.56

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Surface 7	0		57.4	25.4	0.40	125.8	28.4	77	0.03	0.003	0.02	0.02	1.2	0.002	0.01	1.86	79.2	0.30
	1		8.3	13.6	0.52	11.11	3.9	75	0.03	0.005	0.01	0.03	0.9	0.001	0.04	2.18	85.0	11.45
	2		7.1	10.3	0.85	15.59	bdl	55	0.07	0.003	0.01	0.04	1.3	bdl	0.03	2.90	85.2	0.46
			15.3	11.6	1.21	14.26	10.5	72	0.08	0.006	bdl	0.87	1.5	0.002	0.02	2.27	105.8	0.01
		replicate	26.5	13.1	1.18	17.75	13.7	80	0.10	0.011	0.01	0.88	1.9	0.002	0.03	2.66	106.9	5.42
	3	replicate 2	19.8	12.3	0.68	13.67	11.6	79	0.04	0.007	0.00	0.95	1.2	0.003	0.02	2.79	103.2	6.41
		average	20.6	12.3	1.02	15.23	11.9	77	0.07	0.008	0.01	0.90	1.5	0.002	0.02	2.57	105.3	3.95
		σ	5.6	0.8	0.30	2.20	1.6	5	0.03	0.002	0.00	0.04	0.3	0.000	0.01	0.27	1.9	3.45
	5		215.1	101.2	3.97	77.67	127.0	555	0.08	0.045	0.02	12.54	6.6	0.025	0.12	5.82	451.7	97.17
Bioavailable soil leach (ppm)			<LOD	20.7	<LOD	<LOQ	21.7	427	<LOD	1.523	<LOQ	1.78	<LOQ	2.2	<LOQ	<LOD		<LOD
Burial 4	0		3969	14.7	2.22	47.90	2758	230	0.07	0.008	0.08	0.18	6.7	0.004	0.33	10.80	18.8	0.05

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Surface 7	0		0.039	0.29	0.007	0.000	0.002	0.01	0.36	0.03	0.003	0.38	0.00	0.000	0.0000	0.000	0.0001
	1		0.003	0.35	0.011	0.001	0.002	0.04	0.31	0.54	0.002	0.25	0.00	0.001	0.0001	0.000	bdl
	2		bdl	0.29	bdl	0.000	0.001	0.04	0.01	0.16	bdl	0.24	0.00	0.001	0.0001	bdl	bdl
			0.014	0.26	0.002	0.004	0.006	0.04	0.01	0.07	bdl	0.20	0.01	0.030	0.0030	0.012	0.0023
		replicate	0.017	0.31	0.004	0.002	0.009	0.06	0.03	0.19	0.005	0.22	0.01	0.034	0.0032	0.012	0.0024
	3	replicate 2	0.014	0.28	0.003	0.001	0.006	0.05	bdl	0.15	0.003	0.21	0.01	0.025	0.0023	0.009	0.0020
		average	0.015	0.28	0.003	0.002	0.007	0.05	0.02	0.14	0.004	0.21	0.01	0.030	0.0028	0.011	0.0022
		σ	0.002	0.02	0.001	0.002	0.002	0.01	0.01	0.06	0.002	0.01	0.00	0.005	0.0005	0.002	0.0002
	5		0.15	1.98	0.007	0.012	0.009	0.52	0.63	1.14	0.005	2.20	0.05	0.112	0.0131	0.052	0.0107
Bioavailable soil leach (ppm)			192	268	<LOQ			1.44	<LOD	<LOQ		247.7	8.42	10.47	1.58	9.71	2.04
Burial 4	0		1.64	0.32	0.002	0.002	0.541	0.10	0.61	0.03	0.002	0.55	0.00	0.008	0.0009	0.003	0.0006

	exposure time (days)		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Surface 7	0		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0007	0.0012	0.0001	bdl	0.0377	0.0003
	1		0.0000	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0004	bdl	0.0001	bdl	0.1266	0.0005
	2		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0897	0.0002
			0.0004	0.0019	0.0002	0.0012	0.0002	0.0006	0.0001	0.0005	0.0001	0.0004	bdl	0.0001	0.0008	0.1046	0.0004
		replicate	0.0005	0.0021	0.0004	0.0017	0.0003	0.0008	0.0001	0.0006	0.0001	0.0010	bdl	0.0002	bdl	0.1287	0.0007
	3	replicate 2	0.0004	0.0017	0.0002	0.0013	0.0002	0.0007	0.0001	0.0005	0.0001	0.0001	bdl	0.0001	bdl	0.1146	0.0004
		average	0.0004	0.0019	0.0003	0.0014	0.0002	0.0007	0.0001	0.0005	0.0001	0.0005	#DIV/0!	0.0001	0.0008	0.1160	0.0005
		σ	0.0001	0.0002	0.0001	0.0003	0.0001	0.0001	0.0000	0.0001	0.0000	0.0005	#DIV/0!	0.0000	#DIV/0!	0.0121	0.0002
	5		0.0022	0.0114	0.0016	0.0082	0.0016	0.0041	0.0007	0.0036	0.0005	0.0015	0.0013	0.0003	bdl	1.0331	0.0019
Bioavailable soil leach (ppm)			0.36	1.84	0.17	0.92	0.16	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	<LOD		0.77	0.19
Burial 4	0		0.0001	0.0006	0.0001	0.0007	0.0001	0.0003	0.0000	0.0003	0.0001	0.0004	0.0007	0.0004	bdl	1.2611	0.0010

Table 46. Elemental concentrations of hair leachates continued.

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Tennessee																		
Surface 1	0		bdl	3.2	5.0	112	bdl	13	0.55	0.020	0.04	0.05	6.8	0.031	0.06	7.69	1.7	0.12
	1		4.7	43.7	54.6	179	21.4	442	2.85	0.147	0.10	0.44	35.6	0.070	0.09	7.26	4.4	0.10
	5		27.3	10.6	9.0	295	19.3	91	0.51	0.061	0.34	4.92	59.3	0.069	0.25	10.85	76.3	0.11
	10		bdl	1.0	4.7	101	bdl	5	0.35	0.052	0.04	0.32	15.2	0.056	0.07	7.71	2.8	0.09
	20		7.4	2.3	11.0	109	1.8	11	0.64	0.112	0.06	3.23	135.9	0.587	0.10	8.45	3.2	0.46
	39		23.0	44.2	21.8	124	25.1	589	0.88	0.328	0.13	89.24	437.3	1.383	0.51	10.69	94.2	0.92
	67		11.6	77.3	256.5	118	52.1	636	9.92	0.605	0.43	62.59	462.5	1.194	0.62	10.48	106.7	0.40
	106		3.0	4.5	8.3	131	1.1	36	0.47	0.061	0.05	2.51	94.0	0.120	0.07	10.34	12.6	0.15
	174		1.5	7.6	35.8	115	6.1	38	1.99	0.111	0.27	1.24	75.9	0.115	0.14	9.40	7.6	0.16
	336	side A	2.4	10.0	25.9	102	3.8	63	2.06	0.157	0.27	2.75	57.6	0.130	0.20	9.26	5.9	0.13
		side B	3.4	5.8	24.5	93	3.2	32	0.79	0.105	0.06	1.20	83.7	0.169	0.09	7.01	3.7	0.11
Bioavailable soil leach (ppm)			<LOQ	14.2	<LOD	<LOQ	14.2	174	<LOD	<LOQ	2.31	6.8	21.7	6.18	<LOQ	<LOQ		<LOQ
σ (n=3)				0.4			0.1	4				0.1	1.9	0.15				
Surface 2	0		bdl	2.1	6.9	91	bdl	16	1.86	0.014	0.06	0.03	6.8	0.014	0.07	3.53	1.2	0.06
	2		28.3	51.6	233.2	628	24.8	190	58.78	0.228	0.49	1.32	121.2	0.249	1.45	26.44	9.7	0.25
	10		17.4	4.3	17.4	91	5.3	30	2.21	0.088	0.20	2.70	73.1	0.919	0.07	5.37	0.9	0.36
		replicate	5.8	3.0	19.7	80	2.4	16	0.90	0.064	0.17	0.96	76.5	0.855	0.07	5.19	0.8	0.39
		replicate 2	bdl	4.9	42.7	84	6.1	24	2.52	0.101	0.25	3.06	100.2	0.837	0.11	5.53	1.2	0.44
		average	11.6	4.1	26.6	85	4.6	23	1.87	0.084	0.21	2.24	83.3	0.870	0.08	5.36	1.0	0.40
		σ	8.2	1.0	14.0	6	1.9	7	0.9	0.019	0.04	1.12	14.7	0.043	0.02	0.17	0.2	0.04
	39		bdl	1.0	9.2	119	2.0	6	0.47	0.125	0.39	0.71	129.1	2.216	0.06	4.66	0.8	2.09
		replicate	bdl	1.2	12.3	130	1.2	6	1.10	0.131	0.48	0.62	220.9	2.479	0.09	6.74	0.9	2.90
	106		0.5	9.9	117.9	129	19.0	17	7.29	0.374	0.67	3.77	645.1	3.963	0.20	6.54	2.3	2.43
	174		2.2	17.9	179.7	98	27.6	80	11.21	0.337	0.51	10.12	516.0	2.260	0.20	4.07	3.6	0.93
	336		2.0	12.9	157.8	57	24.9	34	10.11	0.277	0.69	9.60	392.3	1.612	0.19	3.14	2.1	1.45
Bioavailable soil leach (ppm)			0.7	25.1	<LOD	<LOQ	22.0	234	<LOD	<LOQ	3.86	9.9	45.6	7.09	<LOQ	50.45		20.18
Surface 3	0		11.6	16.7	1.4	118	1.7	85	0.39	bdl	0.02	0.18	6.6	0.003	0.05	10.51	18.9	0.01
	2		2.8	6.4	3.7	71	1.9	38	0.67	0.006	0.09	0.33	7.8	0.011	0.04	6.07	7.2	0.15
	6		3.8	15.5	3.5	98	bdl	104	0.45	0.008	0.09	4.24	9.8	0.126	0.06	8.82	13.8	bdl
	35		1.0	5.9	9.9	102	1.1	45	0.78	0.028	0.06	5.93	20.6	0.397	0.07	8.59	8.0	0.12
	102		7.5	49.5	152.6	262	33.2	303	8.46	0.403	0.38	51.34	270.6	1.923	0.29	18.95	59.2	0.46
	170		2.4	4.1	8.1	97	0.7	52	0.57	0.306	0.06	7.41	796.8	2.239	0.11	5.01	4.3	0.33
	332		1.2	15.2	46.0	144	6.9	125	2.07	0.939	0.13	23.44	1199.9	3.680	0.28	9.77	13.5	0.49
Bioavailable soil leach (ppm)			1.3	39.0	<LOQ	1.37	37.5	398	<LOD	<LOQ	2.40	14.80	65.8	6.34	3.67	<LOQ		15.27
Burial 1	0		bdl	6.9	1.6	151	bdl	18	0.37	bdl	0.03	bdl	3.8	0.008	bdl	2.14	5.4	0.07
	102		28.6	70.9	218.5	121	40.4	548	17.45	1.196	5.86	278.73	1846.6	6.901	1.10	5.96	68.0	4.84
	381		5.4	24.1	278.6	103	45.1	6	9.43	1.416	0.69	1.70	409.8	8.326	0.28	1.69	0.9	1.94
Bioavailable soil leach (ppm)			<LOQ	9.8	<LOD	<LOQ	12.6	127	<LOD	<LOD	<LOQ	3.51	<LOQ	2.96	<LOQ	<LOQ		<LOQ
Burial 2	0		bdl	14.9	1.6	127	bdl	79	0.19	bdl	0.02	0.07	5.3	0.016	0.03	9.15	16.4	0.03
		replicate	4.4	19.7	2.6	177	bdl	96	0.52	bdl	0.03	0.08	7.4	0.022	0.03	13.04	21.4	0.12
	380		1.4	1.4	15.7	164	1.5	12	0.70	0.638	0.18	3.07	1104.9	8.821	0.37	5.94	3.7	1.57
Bioavailable soil leach (ppm)			0.8	19.5	<LOD	<LOQ	11.0	161	<LOD	<LOD	<LOQ	2.82	<LOQ	45.80	3.91	<LOD		34.2
Burial 3	0		bdl	6.3	6.4	125	bdl	bdl	bdl	bdl	0.41	bdl	2.0	bdl	bdl	bdl	2.0	bdl
	379		2.8	24.5	291.1	170	39.3	15	10.55	1.637	0.32	11.84	1645.9	8.322	0.59	6.94	5.6	4.30

Table 47. Elemental concentrations of solid residues from the leachates in ppm over time. For comparison purposes, the concentration of the donor-specific bioavailable soil leach is also shown.

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Tennessee																	
Surface 1	0		bdl	0.06	0.011	0.000	0.098	0.00	0.13	0.28	bdl	0.11	0.017	0.033	0.0004	bdl	bdl
	1		0.091	0.43	0.020	0.001	0.147	0.01	1.22	2.51	0.004	0.40	0.146	0.286	0.0066	0.026	0.0039
	5		0.036	0.10	0.027	0.003	0.200	0.09	1.10	3.21	0.000	1.46	0.049	0.094	0.0050	0.019	0.0035
	10		bdl	0.01	0.013	0.000	0.123	0.00	0.10	2.24	bdl	0.08	0.011	0.022	0.0006	bdl	0.0051
	20		0.007	bdl	0.030	0.001	0.055	0.00	0.12	0.64	0.006	0.20	0.019	0.045	0.0031	0.013	0.0344
	39		0.030	0.63	0.062	0.004	0.237	0.10	1.71	0.96	0.005	3.19	0.118	0.272	0.0260	0.106	0.0245
	67		0.444	0.74	0.040	0.003	0.162	0.10	1.51	1.34	0.006	3.93	0.416	0.905	0.0953	0.373	0.0726
	106		0.006	0.05	0.013	0.000	0.164	0.01	0.38	1.85	0.001	0.33	0.024	0.050	0.0029	0.012	0.0021
	174		0.051	0.06	0.016	0.001	0.147	0.01	0.17	1.30	0.007	0.36	0.070	0.143	0.0132	0.050	0.0097
	336	side A	0.032	0.09	0.017	0.001	0.183	0.01	0.15	1.13	0.005	0.56	0.159	0.285	0.0329	0.130	0.0246
		side B	0.019	0.05	0.010	0.001	0.057	0.00	0.18	0.39	0.010	0.34	0.112	0.197	0.0211	0.078	0.0150
Bioavailable soil leach (ppm)			5.752	244	0.71			2.99	<LOD	<LOQ		180.1	9.06	15.26	1.78	10.45	2.04
σ (n=3)			0.683	5	0.21			0.47				4.3	0.20	0.09	0.07	0.54	0.06
Surface 2	0		bdl	0.07	0.038	0.000	0.034	0.00	0.77	0.07	bdl	0.09	0.020	0.026	0.0008	bdl	0.0047
	2		0.156	0.85	0.135	0.014	2.626	0.00	26.90	0.76	0.012	1.32	0.397	0.534	0.0273	0.101	0.0177
	10		0.016	bdl	0.008	0.001	0.061	bdl	0.68	0.07	bdl	0.22	0.221	0.429	0.0449	0.179	0.3396
		replicate	0.020	0.05	0.009	0.001	0.064	bdl	0.72	0.05	0.005	0.17	0.235	0.436	0.0448	0.182	0.0336
		replicate 2	0.056	0.09	0.015	0.010	0.089	bdl	0.90	0.05	bdl	0.31	0.376	0.688	0.0737	0.292	0.0518
		average	0.031	0.07	0.011	0.004	0.071	bdl	0.77	0.06	bdl	0.24	0.277	0.518	0.0545	0.218	0.1416
		σ	0.022	0.03	0.003	0.005	0.015		0.12	0.01		0.07	0.085	0.147	0.0167	0.064	0.1716
	39		bdl	0.02	0.027	bdl	0.037	0.00	0.13	0.04	bdl	0.05	0.040	0.123	0.0120	0.056	0.1316
		replicate	0.011	0.02	0.028	0.006	0.083	0.00	0.23	0.06	0.011	0.13	0.087	0.259	0.0256	0.110	0.0271
	106		0.175	0.11	0.034	0.005	2.068	0.00	0.19	0.05	bdl	0.64	0.165	0.412	0.0416	0.168	0.0364
	174		0.249	0.25	0.021	0.001	0.026	0.00	0.44	0.05	0.004	1.60	0.914	2.566	0.2068	0.815	0.1552
	336		0.235	0.17	0.042	0.001	0.079	0.02	0.31	0.06	0.004	1.02	0.618	1.677	0.1521	0.605	0.1201
Bioavailable soil leach (ppm)			18.109	315	0.69			2.97	<LOD	0.63		183.1	5.71	8.40	0.98	6.93	1.45
Surface 3	0		0.003	0.21	0.034	0.001	0.223	0.01	0.39	0.03	bdl	0.30	0.048	0.112	0.0005	0.002	bdl
	2		bdl	0.10	0.036	0.000	0.254	0.00	0.14	0.04	bdl	0.14	0.037	0.085	0.0025	0.010	0.0169
	6		bdl	0.22	0.057	bdl	0.389	0.00	0.31	0.04	bdl	0.47	0.066	0.159	0.0058	0.023	0.0345
	35		0.010	0.07	0.033	0.005	0.413	0.00	0.21	0.03	bdl	0.40	0.082	0.200	0.0094	0.036	0.0070
	102		0.231	0.63	0.087	0.001	0.610	0.02	1.20	0.21	0.003	3.22	0.415	0.983	0.0713	0.299	0.0570
	170		0.004	0.04	0.025	0.000	0.081	0.00	0.18	0.04	0.003	0.36	0.084	0.239	0.0154	0.062	0.0116
	332		0.057	0.20	0.048	0.001	0.228	0.03	0.47	0.04	0.004	1.59	0.275	0.705	0.0532	0.208	0.0381
Bioavailable soil leach (ppm)			30	489	0.16			2.63	<LOD	<LOQ		247.2	8.66	12.15	1.55	8.75	1.90
Burial 1	0		bdl	0.05	0.016	0.000	0.010	0.00	0.08	0.08	bdl	0.02	bdl	bdl	bdl	bdl	bdl
	102		0.236	0.44	0.253	0.016	0.114	0.63	5.27	0.08	0.026	1.59	0.527	1.535	0.1397	0.602	0.1270
	381		0.379	0.11	0.418	0.001	0.061	0.00	0.26	0.09	0.030	0.54	0.673	2.216	0.1871	0.759	0.1617
Bioavailable soil leach (ppm)			9.1	236	0.66			2.59	<LOD	0.34		237.0	12.02	14.45	2.52	14.11	3.07
Burial 2	0		bdl	0.20	0.050	0.010	0.052	0.01	0.23	0.09	bdl	0.14	0.019	0.028	0.0004	0.001	bdl
		replicate	bdl	0.25	0.075	bdl	0.035	0.01	0.90	0.11	0.002	0.18	0.028	0.043	0.0005	0.001	bdl
	380		0.011	0.04	0.198	0.001	0.024	0.01	0.06	0.06	0.013	0.92	0.384	1.250	0.0869	0.349	0.0649
Bioavailable soil leach (ppm)			126	257	<LOQ			<LOQ	<LOD	<LOQ		543.0	231.07	399.78	50.22	228.8	40.45
Burial 3	0		bdl	0.05	0.070	bdl	bdl	0.00	0.23	0.36	bdl	0.02	bdl	bdl	bdl	bdl	bdl
	379		0.418	0.17	0.284	0.001	0.029	0.01	0.12	0.07	0.023	1.10	0.628	1.904	0.1402	0.556	0.1035

Table 47. Elemental concentrations of solid residues continued.

Tennessee

	exposure time (days)	Rb	Sr	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Surface 1	0	bdl	0.06	0.0001	0.0005	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	0.0012	bdl	bdl	bdl	0.0855	0.0004
	1	0.091	0.43	0.0011	0.0043	0.0007	0.0037	0.0008	0.0022	0.0003	0.0020	0.0003	0.0025	0.0394	0.0000	bdl	0.3620	0.0041
	5	0.036	0.10	0.0008	0.0046	0.0006	0.0034	0.0006	0.0017	0.0002	0.0015	0.0002	0.0065	0.0025	0.0000	bdl	7.7586	0.0018
	10	bdl	0.01	0.0002	0.0006	bdl	0.0007	bdl	0.0005	bdl	0.0004	bdl	0.0161	bdl	bdl	bdl	0.2774	0.0005
	20	0.007	bdl	0.0007	0.0036	0.0055	0.0036	0.0008	0.0023	0.0035	0.0022	0.0003	0.0016	bdl	bdl	0.0029	0.1634	0.0024
	39	0.030	0.63	0.0052	0.0253	0.0037	0.0209	0.0045	0.0130	0.0017	0.0097	0.0015	0.0069	0.0032	0.0001	0.0053	3.9246	0.0089
	67	0.444	0.74	0.0150	0.0712	0.0098	0.0578	0.0118	0.0311	0.0043	0.0257	0.0036	0.0277	0.0062	0.0001	0.0018	6.0751	0.0236
	106	0.006	0.05	0.0005	0.0026	0.0003	0.0025	0.0005	0.0014	0.0002	0.0012	0.0001	0.0010	0.0052	bdl	0.0003	0.7018	0.0012
	174	0.051	0.06	0.0019	0.0097	0.0012	0.0071	0.0015	0.0042	0.0005	0.0033	0.0005	0.0029	0.0027	0.0001	bdl	0.3490	0.0027
	336 side A	0.032	0.09	0.0049	0.0249	0.0032	0.0180	0.0036	0.0096	0.0012	0.0097	0.0010	0.0061	0.0029	0.0001	0.0004	0.4466	0.0033
	side B	0.019	0.05	0.0034	0.0154	0.0019	0.0105	0.0021	0.0055	0.0007	0.0035	0.0006	0.0013	0.0025	0.0002	0.0010	0.0850	0.0030
Bioavailable soil leach (ppm)		5.752	244	0.47	2.40	0.25	1.54	0.27	0.58	<LOQ	0.33	<LOQ	<LOD	<LOD	<LOD		1.99	0.41
σ (n=3)		0.683	5	0.08	0.19	0.01	0.03	0.04	0.03								0.07	0.05
Surface 2	0	bdl	0.07	bdl	0.0424	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0442	0.0153	bdl	0.0005	0.0038	0.0251
	2	0.156	0.85	0.0027	0.0448	0.0022	0.0152	0.0028	0.0063	0.0011	0.0067	0.0009	0.7723	0.0403	0.0002	0.0185	0.0580	0.0691
	replicate	0.016	bdl	0.0065	0.0365	0.0348	0.0187	0.0042	0.0107	0.0133	0.0083	0.0012	0.0085	bdl	bdl	0.0043	0.0367	0.0166
	replicate 2	0.020	0.05	0.0060	0.0378	0.0035	0.0197	0.0042	0.0107	0.0013	0.0083	0.0012	0.0103	0.0217	bdl	0.0007	0.0219	0.0183
	10 average	0.056	0.09	0.0101	0.0524	0.0058	0.0321	0.0066	0.0184	0.0022	0.0131	0.0017	0.0136	bdl	bdl	0.0034	0.0628	0.0260
	σ	0.031	0.07	0.0075	0.0422	0.0147	0.0235	0.0050	0.0133	0.0056	0.0099	0.0014	0.0108	bdl	bdl	0.0028	0.0405	0.0203
	replicate	bdl	0.03	0.0022	0.0088	0.0174	0.0075	0.0014	0.0045	0.0067	0.0028	0.0003	0.0026			0.0019	0.0207	0.0050
	39	0.011	0.02	0.0028	0.0448	0.0165	0.0103	0.0021	0.0058	0.0080	0.0064	0.0008	0.0118	0.0060	bdl	bdl	0.0419	0.0141
	replicate	0.175	0.11	0.0066	0.1118	0.0042	0.0243	0.0050	0.0143	0.0019	0.0126	0.0019	0.0172	0.0040	bdl	0.0018	0.3368	0.0248
	106	0.249	0.25	0.0298	0.1656	0.0187	0.1054	0.0210	0.0555	0.0069	0.0406	0.0057	0.0193	0.0066	0.0001	0.0006	0.1842	0.0205
	174	0.235	0.17	0.0232	0.1430	0.0138	0.0793	0.0156	0.0414	0.0051	0.0304	0.0042	0.0386	0.0078	0.0001	0.0007	0.1690	0.0399
	336																	
Bioavailable soil leach (ppm)		18.109	315	0.36	1.37	0.16	0.79	0.16	<LOQ	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		2.69	0.30
Surface 3	0	0.003	0.21	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0053	bdl	bdl	0.0025	0.0381	0.0002
	2	bdl	0.10	0.0004	0.0017	0.0017	0.0014	0.0002	0.0009	0.0006	0.0007	0.0001	0.0033	bdl	bdl	bdl	0.0155	0.0005
	6	bdl	0.22	0.0008	0.0043	0.0043	0.0030	0.0005	0.0019	0.0015	0.0012	0.0001	0.0110	bdl	bdl	bdl	0.0294	0.0009
	35	0.010	0.07	0.0014	0.0069	0.0009	0.0058	0.0011	0.0031	0.0004	0.0026	0.0004	0.0076	0.0159	bdl	0.0014	0.0825	0.0022
	102	0.231	0.63	0.0108	0.0482	0.0065	0.0381	0.0073	0.0202	0.0027	0.0166	0.0022	0.0127	0.0092	0.0000	0.0004	0.8419	0.0176
	170	0.004	0.04	0.0022	0.0107	0.0013	0.0084	0.0018	0.0046	0.0006	0.0032	0.0005	0.0014	0.0026	0.0000	bdl	0.3031	0.0044
	332	0.057	0.20	0.0073	0.0366	0.0045	0.0248	0.0051	0.0134	0.0016	0.0093	0.0013	0.0046	0.0043	0.0001	0.0001	0.3723	0.0071
Bioavailable soil leach (ppm)		30	489	0.45	1.99	0.24	1.19	0.25	0.60	0.09	0.44	<LOQ	<LOD	<LOD	<LOD		1.63	0.22
Burial 1	0	bdl	0.05	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0029	bdl	bdl	bdl	0.0028	bdl
	102	0.236	0.44	0.0285	0.1337	0.0211	0.1347	0.0277	0.0800	0.0105	0.0653	0.0103	0.0310	0.0106	0.0004	bdl	1.0792	0.1061
	381	0.379	0.11	0.0314	0.1415	0.0192	0.1079	0.0216	0.0588	0.0075	0.0462	0.0069	0.0215	0.0120	0.0001	0.0011	0.0631	0.2030
Bioavailable soil leach (ppm)		9.1	236	0.62	3.36	0.35	2.01	0.36	0.80	<LOQ	0.43	<LOQ	<LOD	<LOD	<LOD		2.44	0.58
Burial 2	0	bdl	0.20	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0051	bdl	bdl	0.0030	0.0289	0.0031
	replicate	bdl	0.25	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0025	0.0026	0.0001	bdl	0.0344	0.0029
	380	0.011	0.04	0.0122	0.0583	0.0070	0.0399	0.0080	0.0210	0.0026	0.0148	0.0022	0.0032	0.0030	0.0001	0.0002	0.0883	0.0995
Bioavailable soil leach (ppm)		126	257	7.29	33.13	3.22	16.06	3.17	7.08	0.67	3.29	0.52	<LOD	<LOD	<LOD		10.91	2.36
Burial 3	0	bdl	0.05	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0209
	379	0.418	0.17	0.0190	0.0880	0.0114	0.0658	0.0132	0.0357	0.0044	0.0284	0.0037	0.0177	0.0109	0.0001	0.0007	0.1469	0.0928

Table 47. Elemental concentrations of solid residues continued.

Texas

	exposure time (days)		Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
Surface 4	0	replicate	bdl	1.6	1.3	99	bdl	4	0.26	0.002	0.04	0.01	3.5	0.000	0.02	1.74	2.4	0.06
			5.7	3.7	3.6	167	1.4	18	0.69	0.005	0.09	0.06	5.4	0.003	0.05	6.00	26.0	0.03
	1		17.9	7.3	2.5	324	5.9	34	0.76	0.016	0.17	0.14	9.6	bdl	0.12	7.81	25.0	0.18
	3		8.9	3.6	4.7	329	1.1	14	0.62	0.008	0.16	0.02	12.4	0.002	0.03	4.73	4.6	0.15
	5		8.8	3.8	9.3	346	2.2	22	2.15	0.027	0.12	0.11	18.0	0.012	0.05	4.96	8.1	0.26
Bioavailable soil leach (ppm)			<LOQ	25.0	<LOD	<LOQ	15.2	186	<LOD	<LOQ	<LOQ	5.09	12.2	5.21	5.24	<LOD		<LOQ
Surface 5	0		9.3	8.5	4.9	161	2.7	19	0.67	0.012	0.06	bdl	6.5	0.004	0.04	7.96	13.5	34.86
	1	replicate	bdl	3.3	2.3	72	bdl	4	0.94	0.004	0.05	0.01	3.3	0.001	0.01	2.90	1.8	61.88
			bdl	3.1	1.8	76	bdl	6	0.74	bdl	0.03	bdl	2.7	bdl	0.02	2.16	1.4	70.95
	2		17.4	4.7	2.0	79	6.0	10	0.99	0.008	0.03	bdl	3.1	0.003	0.03	5.05	9.7	13.63
	3		2.7	3.6	7.4	75	1.3	8	1.04	0.015	0.03	0.03	6.4	0.003	0.02	3.29	2.8	11.21
	5		14.0	1.7	18.2	120	9.0	6	1.52	0.149	0.12	0.37	60.8	0.298	0.07	5.04	3.2	18.24
Bioavailable soil leach (ppm)			0.7	24.0	<LOD	<LOQ	15.0	199	<LOD	<LOQ	<LOQ	5.22	38.8	5.76	4.98	<LOD		<LOQ
Surface 6	0	replicate	2.2	14.8	3.1	79	0.5	117	0.47	0.029	0.07	0.02	5.1	0.005	0.07	6.68	3.5	0.04
		replicate 2	10.0	6.2	3.3	96	1.0	45	0.22	0.018	0.07	0.01	5.8	0.002	0.05	6.85	2.1	0.05
		average	58.2	40.3	3.1	15	32.0	658	0.11	0.009	0.04	0.12	1.5	0.004	0.10	3.39	65.1	0.11
		σ	23.5	20.4	3.2	63	11.2	273	0.27	0.019	0.06	0.05	4.1	0.003	0.07	5.64	23.6	0.06
	1	replicate	30.4	17.8	0.1	43	18.0	335	0.19	0.010	0.02	0.06	2.3	0.001	0.02	1.95	36.0	0.04
			4.4	10.2	4.0	88	0.9	92	0.75	0.027	0.11	0.03	5.0	0.006	0.09	7.58	2.9	0.08
	3		13.3	10.4	4.2	101	1.8	80	0.29	0.025	0.15	0.03	5.6	0.005	0.09	7.78	2.2	0.11
	5		4.4	12.2	6.4	67	bdl	57	0.35	0.053	0.18	0.05	10.2	0.012	0.14	7.24	1.3	0.02
			2.6	9.6	5.7	94	2.2	101	0.79	0.034	0.14	0.10	13.3	0.005	0.05	5.91	11.8	0.02
Bioavailable soil leach (ppm)			<LOD	24.2	<LOD	<LOQ	33.2	239	<LOD	<LOQ	<LOQ	3.45	<LOQ	5.1	3.93	<LOD		<LOQ
		replicate	<LOQ	24.8	<LOD	<LOQ	26.5	301	<LOD	<LOQ	<LOQ	15.98	<LOQ	37.1	9.60	<LOQ		<LOQ
Surface 7	0		2.9	12.3	0.4	114	0.5	24	0.28	0.003	0.02	0.01	4.4	0.002	0.01	4.04	23.7	7.68
	1		2.0	6.4	0.4	94	bdl	17	0.32	0.002	0.01	bdl	3.6	bdl	0.00	3.49	9.1	83.01
	2		4.2	7.8	1.2	98	2.9	17	0.33	0.006	0.04	0.02	4.2	0.005	0.08	3.23	9.5	42.45
			bdl	3.9	5.2	91	bdl	9	0.57	0.011	0.02	0.11	7.0	0.003	0.01	3.63	6.5	55.46
		replicate	15.7	5.3	2.4	111	1.8	11	0.46	bdl	0.03	0.09	5.7	0.003	bdl	3.30	5.6	63.86
	3	replicate 2	2.3	4.4	3.1	92	0.4	10	0.38	0.018	0.01	0.09	5.3	0.003	0.01	3.09	4.5	68.87
		average	9.0	4.5	3.6	98	1.1	10	0.47	0.015	0.02	0.10	6.0	0.003	0.01	3.34	5.5	62.73
		σ	9.5	0.7	1.5	11	1.0	1	0.10	0.005	0.01	0.01	0.9	0.000	0.00	0.27	1.0	6.78
	5		29.6	95.1	80.3	583	20.0	224	8.59	0.200	0.22	5.57	74.7	0.065	0.14	34.06	241.3	611.26
Bioavailable soil leach (ppm)			<LOD	20.7	<LOD	<LOQ	21.7	427	<LOD	1.523	<LOQ	1.78	<LOQ	2.2	<LOQ	<LOD		<LOD
Burial 4	0		355.8	31.3	14.6	166	246.2	57	4.24	0.027	0.19	0.15	28.1	0.008	0.31	13.87	5.9	0.42

Table 47. Elemental concentrations of solid residues continued.

Texas

	exposure time (days)		Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Surface 4	0	replicate	bdl	0.01	0.008	0.000	0.033	0.00	0.14	0.04	bdl	0.01	0.001	0.002	0.0001	bdl	bdl
		replicate	bdl	0.04	0.025	0.001	0.086	0.02	1.19	0.09	0.002	0.04	0.001	0.002	0.0002	0.001	bdl
	1		bdl	0.05	0.032	0.001	0.073	0.00	6.69	0.11	0.027	0.05	0.011	0.022	0.0027	0.010	0.0011
	3		bdl	0.03	0.038	0.000	0.095	0.00	1.92	0.07	0.000	0.25	0.005	0.009	0.0009	0.004	0.0011
	5		0.008	0.05	0.036	0.001	0.132	0.00	1.86	0.12	0.009	0.12	0.027	0.054	0.0062	0.021	0.0042
Bioavailable soil leach (ppm)			202	266	0.068			4.77	<LOD	<LOQ		292.4	17.65	29.20	4.00	21.67	4.85
Surface 5	0		bdl	0.17	0.089	0.001	0.034	0.00	2.29	3.47	0.003	0.08	0.002	0.004	0.0004	0.001	bdl
	1	replicate	bdl	0.04	0.029	0.000	0.029	0.00	0.17	1.52	0.016	0.02	0.002	0.003	0.0003	bdl	bdl
		replicate	bdl	0.03	0.032	0.007	0.036	bdl	0.20	2.91	0.031	0.03	0.001	0.002	0.0003	0.001	bdl
	2		0.005	0.09	0.050	0.000	0.030	0.00	0.36	0.32	0.003	0.04	0.003	0.003	0.0002	0.001	bdl
	3		0.009	0.06	0.045	0.000	0.028	0.00	0.91	0.21	0.002	0.04	0.009	0.016	0.0016	0.006	0.0012
	5		0.031	0.01	0.037	0.001	0.023	0.00	1.36	0.95	0.007	0.06	0.035	0.075	0.0086	0.030	0.0067
Bioavailable soil leach (ppm)			194	275	0.29			3.81	<LOD	<LOQ		335.1	18.57	31.92	4.34	22.60	4.82
Surface 6	0	replicate	0.001	1.46	0.027	bdl	0.011	0.00	2.32	0.03	0.002	0.26	0.002	0.003	0.0003	0.001	0.0002
		replicate 2	0.028	bdl	0.36	0.032	0.001	0.015	0.00	0.67	0.08	bdl	0.10	0.001	0.002	0.0001	0.001	0.0032
		average	0.015	2.08	4.40	0.021	0.004	0.001	0.012	0.02	0.19	0.02	0.003	0.96	0.001	0.002	0.0002	0.001	bdl
		σ	0.019	2.09	2.09	0.015	0.000	0.000	0.002	0.01	1.12	0.03	0.000	0.46	0.000	0.001	0.0001	0.000	0.0021
	1	replicate	bdl	0.92	0.025	0.001	0.014	0.00	1.29	0.20	0.003	0.20	0.002	0.004	0.0004	0.002	0.0003
		replicate	bdl	0.73	0.025	0.001	0.020	0.01	1.19	0.05	bdl	0.17	0.002	0.004	0.0004	0.001	bdl
	3		bdl	0.51	0.029	0.000	0.010	0.00	0.86	0.07	bdl	0.10	0.003	0.005	0.0006	bdl	0.0037
	5		0.007	0.31	0.030	0.000	0.029	0.01	0.96	0.03	0.000	0.10	0.005	0.008	0.0009	0.003	0.0007
Bioavailable soil leach (ppm)			135	257	0.071			2.75	<LOD	<LOD		290.1	9.97	15.45	2.18	13.23	2.72
		replicate	166	301	<LOQ			4.54	<LOD	<LOQ		325.8	28.74	41.44	6.82	34.44	7.55
Surface 7	0		bdl	0.07	0.035	0.000	0.006	0.00	0.57	0.15	0.004	0.08	0.000	0.000	0.0000	bdl	bdl
	1		bdl	0.08	0.022	0.000	0.006	0.00	0.20	2.02	0.023	0.02	0.000	0.001	0.0001	0.000	bdl
	2		bdl	0.09	0.020	0.000	0.003	0.00	0.14	0.76	0.015	0.06	0.000	0.001	0.0001	bdl	bdl
	3	replicate	0.006	0.04	0.017	0.003	0.010	0.00	0.10	0.84	bdl	0.02	0.005	0.010	0.0010	0.004	0.0007
		replicate 2	bdl	bdl	0.016	0.001	0.012	0.00	0.15	1.27	0.014	0.02	0.003	0.008	0.0007	0.004	0.0045
		average	0.003	0.05	0.017	0.000	0.005	0.00	0.37	1.00	0.008	0.02	0.004	0.009	0.0008	0.003	0.0005
		σ	0.005	0.05	0.016	0.001	0.009	0.00	0.21	1.04	0.011	0.02	0.004	0.009	0.0008	0.003	0.0019
	5		0.002	0.00	0.000	0.001	0.003	0.00	0.14	0.22	0.005	0.00	0.001	0.001	0.0001	0.000	0.0022
Bioavailable soil leach (ppm)			192	268	<LOQ			1.44	<LOD	<LOQ		247.7	8.42	10.47	1.58	9.71	2.04
			0.104	1.29	0.124	0.007	0.040	0.26	3.11	15.63	0.117	1.57	0.136	0.296	0.0329	0.120	0.0216
Burial 4	0		0.158	0.09	0.062	0.001	8.197	0.04	1.22	0.08	0.005	0.19	0.035	0.061	0.0043	0.014	0.0027

Table 47. Elemental concentrations of solid residues continued.

	exposure time (days)		Rb	Sr	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
Texas																			
Surface 4	0	replicate	bdl	0.01	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0022	bdl	0.0017	bdl	0.0137	0.0000
		replicate 2	bdl	0.04	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0146	0.0027	0.0008	bdl	0.1424	0.0006
	1		bdl	0.05	bdl	0.0012	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0092	0.0072	0.0010	bdl	0.0321	0.0305
	3		bdl	0.03	0.0002	0.0017	0.0003	0.0026	0.0004	0.0013	0.0002	0.0017	0.0001	0.0047	0.0116	0.0004	0.0008	0.0041	0.0005
	5		0.008	0.05	0.0008	0.0027	0.0005	0.0022	0.0004	0.0013	0.0001	0.0007	bdl	0.0097	0.0116	0.0018	bdl	0.0405	0.0013
Bioavailable soil leach (ppm)			202	266	1.02	4.17	0.45	2.22	0.41	0.93	0.09	0.50	0.08	<LOD	<LOD	<LOD		1.26	0.30
Surface 5	0		bdl	0.17	0.0001	0.0005	bdl	0.0008	bdl	bdl	bdl	bdl	0.0001	0.0052	0.0113	0.0001	bdl	0.0353	0.0017
		replicate	bdl	0.04	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0039	0.0033	bdl	bdl	0.0056	0.0005
	1	replicate	bdl	0.03	bdl	bdl	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	0.0035	bdl	bdl	0.0020	0.0045	0.0005
	2		0.005	0.09	0.0000	bdl	bdl	bdl	bdl	bdl	0.0000	bdl	bdl	0.0046	0.0143	0.0001	0.0006	0.0263	0.0005
	3		0.009	0.06	0.0002	0.0009	0.0001	0.0007	0.0001	0.0003	0.0000	0.0004	0.0000	0.0033	0.0092	0.0000	0.0004	0.0119	0.0008
	5		0.031	0.01	0.0013	0.0054	0.0008	0.0044	0.0009	0.0022	0.0003	0.0018	0.0003	0.0061	0.0085	0.0001	bdl	0.0132	0.0037
Bioavailable soil leach (ppm)			194	275	1.01	4.57	0.48	2.24	0.40	0.90	0.09	0.54	0.08	<LOD	<LOD	<LOD		2.10	0.35
Surface 6	0		0.001	1.46	bdl	0.0002	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	0.0104	0.0100	0.0000	bdl	0.0512	0.0091
		replicate	bdl	0.36	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0174	0.0398	0.0001	0.0024	0.0460	0.0056
		replicate 2	0.028	4.40	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0015	0.1913	0.0003	bdl	0.7055	0.0076
		average	0.015	2.08	#DIV/0!	0.0002	#DIV/0!	0.0002	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.0098	0.0804	0.0001	bdl	0.2676	0.0074
		σ	0.019	2.09	#DIV/0!	0.0000	#DIV/0!	0.0004	#DIV/0!	bdl	bdl	bdl	#DIV/0!	0.0080	0.0972	0.0001		0.3793	0.0017
	1		bdl	0.92	0.0001	0.0002	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0099	0.0063	0.0001	bdl	0.0766	0.0061
		replicate	bdl	0.73	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0073	0.0357	bdl	0.0027	0.5031	0.0072
	3		bdl	0.51	0.0001	bdl	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.0087	0.0195	bdl	0.0002	0.0287	0.0050
	5		0.007	0.31	0.0001	0.0005	0.0001	0.0005	0.0001	0.0002	0.0000	0.0002	0.0000	0.0040	0.0030	0.0000	0.0001	0.1839	0.0043
Bioavailable soil leach (ppm)			135	257	0.64	2.61	0.23	1.15	0.21	0.46	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD		1.06	0.26
		replicate	166	301	1.48	6.56	0.68	3.19	0.55	1.16	0.11	0.54	<LOQ	<LOD	<LOD	<LOD		1.63	0.56
Surface 7	0		bdl	0.07	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0025	0.0101	0.0001	bdl	0.0066	0.0003
	1		bdl	0.08	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0021	0.0009	0.0001	bdl	0.0102	0.0003
	2		bdl	0.09	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0011	bdl	bdl	0.0003	0.0112	0.0005
		replicate	0.006	0.04	0.0001	0.0005	0.0001	0.0005	0.0001	0.0002	bdl	0.0002	0.0000	0.0037	bdl	0.0001	0.0007	0.0109	0.0003
	3	replicate	bdl	bdl	bdl	0.0006	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0034	bdl	bdl	0.0039	0.0054	0.0005
		replicate 2	0.003	0.05	0.0001	0.0005	bdl	0.0003	0.0001	0.0002	0.0000	0.0002	0.0000	0.0006	0.0005	0.0000	bdl	0.0076	0.0005
		average	0.005	0.05	0.0001	0.0005	0.0001	0.0004	0.0001	0.0002	0.0000	0.0002	0.0000	0.0026	0.0005	0.0001	0.0023	0.0080	0.0005
		σ	0.002	0.00	0.0000	0.0001	#DIV/0!	0.0001	0.0000	0.0000	#DIV/0!	0.0000	0.0000	0.0017	#DIV/0!	0.0000	0.0023	0.0028	0.0001
	5		0.104	1.29	0.0039	0.0173	0.0024	0.0136	0.0023	0.0069	0.0009	0.0057	0.0008	0.0081	0.0097	0.0002	bdl	0.5202	0.0044
Bioavailable soil leach (ppm)			192	268	0.36	1.84	0.17	0.92	0.16	<LOQ	<LOQ	<LOQ	<LOD	<LOD	<LOD	<LOD		0.77	0.19
Burial 4	0		0.158	0.09	0.0004	0.0023	0.0004	0.0022	0.0004	0.0009	0.0001	0.0009	0.0001	0.0020	0.0125	0.0005	0.0002	0.2818	0.0039

Table 47. Elemental concentrations of solid residues continued.

6.4.6.2 $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, and $\delta^{15}N$ The major elemental concentrations and isotopic composition of hair samples over time determined by IRMS are shown in Table 48. The difference in isotope composition and major elemental concentrations between later samples and peri-mortem intake samples are shown in Table 49. These changes are shown graphically in Figures 7-10.

Donor	length of exposure (days)		δ^2H_{VSMOW} (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	Weight % C	Weight % N	C/N
Tennessee												
Surface 1	0		-61.4	12.1	5.6	21.5	3.8	-12.60	9.8	44.0	15.8	2.8
	1		-68.7	12.7	5.4	21.2	3.9	-12.64	9.8	43.9	15.5	2.8
	2		-66.1	13.4	5.6	21.6	3.9	-12.61	9.8	44.1	15.5	2.8
	3		-64.9	14.1	5.5	21.6	3.9	-12.72	9.7	43.3	15.4	2.8
	5		-67.0	12.7	5.5	21.7	3.9	-12.71	9.9	43.4	15.4	2.8
	10		-65.7	14.0	5.6	22.0	3.9	-12.56	9.8	43.2	15.2	2.8
	20		-64.9	14.0	5.5	21.8	4.0	-12.61	9.7	42.9	15.2	2.8
	39		-64.5	13.3	5.5	21.6	3.9	-12.58	9.9	44.2	15.5	2.9
	67		-65.4	12.9	5.4	21.1	3.9	-12.69	9.8	43.0	15.3	2.8
	106		-65.5	13.8	5.5	22.1	4.0	-12.69	9.8	43.9	15.4	2.9
	174		-63.2	13.0	5.3	21.0	4.0					
	336	side A	-66.6	13.1	5.1	21.3	4.2	-12.60	10.4	43.2	14.6	3.0
		side B	-68.7	13.1	5.3	21.4	4.1	-12.42	10.3	43.3	14.7	2.9
Surface 2	0		-64.1	11.5	5.4	21.9	4.0	-15.49	9.3	44.4	15.8	2.8
	1*	replicate	-58.5	11.8 11.8	5.7	22.2 23.8		-16.54	9.6	44.2	13.8	3.2
	2		-64.5	10.7	5.5	22.6	4.1	-15.60	9.4	43.0	15.1	2.8
	5*		-58.0	10.5	5.6	23.2	4.1	-16.28	9.7	45.8	14.4	3.2
	10		-61.1	11.6	5.1	21.3	4.1	-15.67	9.3	42.6	15.4	2.8
	39		-61.0	12.4	5.3	21.4	4.1	-15.48	9.2	43.8	16.0	2.7
	106		-57.8	13.5	5.3	22.0	4.2	-15.75	9.8	41.6	14.7	2.8
	174		-55.8	13.3	5.0	21.1	4.2	-15.30	10.2	42.4	14.5	2.9
								-15.34	10.1	40.6	13.9	2.9
								-15.34	10.1	42.5	14.5	2.9
		average						-15.33	10.1	41.8	14.3	2.9
		σ						0.03	0.09	1.1	0.4	0.00
	336		-55.6	13.5	5.0	20.9	4.2	-15.40	10.2	43.1	14.7	2.9

Table 48. Measured values for $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$, elemental concentrations, and O/H and C/N for hair samples from donors over time at both sites. An asterisk by the exposure time indicates analyses were completed in the context of the freezing study, and analyzed at the Stable Isotope Facility at the University of California, Davis, rather than the lab at University of Utah. The recovery sample for Surface 1 at Tennessee was from a hair mat attached to scalp that was no longer associated with the original donor. The two samples were associated with opposite sides of the scalp, but there was no visual way to know whether side A or B was associated with the entry or exit side of the gunshot wound.

Donor	length of exposure (days)		δ^2H_{VSMOW} (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	Weight % C	Weight % N	C/N
Surface 3	0		-60.9	13.5	5.5	21.5	3.9	-15.20	9.3	44.3	16.0	2.8
	2		-63.3	12.5	5.9	23.2	4.0	-15.23	9.1	45.0	16.2	2.8
			-65.0	14.0	5.4	21.5	4.0	-15.11	9.2	44.1	15.8	2.8
			-69.4	12.8	5.5	21.7	3.9	-15.05	9.3	44.1	15.6	2.8
		average	-65.9	13.1	5.6	22.1	4.0	-15.13	9.2	44.4	15.9	2.8
		σ	3.2	0.8	0.2	0.9	0.02	0.09	0.11	0.5	0.3	0.02
	3		-61.9	12.2	5.4	21.6	4.0	-14.97	9.2	44.1	15.6	2.8
	6		-64.5	14.5	5.6	22.0	3.9	-15.09	9.1	44.9	16.1	2.8
	35		-64.1	12.5	5.6	22.0	3.9	-15.19	9.4	43.2	15.2	2.8
			-64.8	13.4	5.3	21.4	4.0	-15.11	9.5	43.0	15.0	2.9
			-62.2	13.0	5.6	22.9	4.1	-15.22	9.5	42.9	14.9	2.9
		average	-63.7	12.9	5.5	22.1	4.0	-15.17	9.5	43.0	15.0	2.9
		σ	1.3	0.4	0.2	0.7	0.06	0.05	0.04	0.2	0.1	0.02
	102		-61.1	12.9	5.5	21.7	4.0	-14.99	9.5	43.5	15.3	2.8
	170		-65.2	13.2	5.2	20.6	4.0	-15.10	10.0	41.0	13.9	3.0
		replicate						-15.29	9.9	36.9	12.4	3.0
	332		-62.7	13.3	5.1	20.9	4.1	-15.18	9.9	43.9	14.8	3.0
Burial 1	0		-67.3	14.6	5.5	21.7	3.9	-16.62	8.8	45.0	16.4	2.8
	102		-62.4	13.3	5.4	21.6	4.0	-16.42	8.9	45.1	16.3	2.8
	381		-60.6	14.6	5.2	21.2	4.1	-16.50	9.7	42.5	14.6	2.9
			-63.4	14.7	5.2	21.5	4.1					
			-64.4	14.7	5.3	21.7	4.1					
		average	-62.8	14.7	5.2	21.5	4.1					
		σ	2.0	0.0	0.1	0.2	0.02					

Table 48. Measured values for $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$ continued.

Donor	length of exposure (days)		δ^2H_{VSMOW} (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	Weight % C	Weight % N	C/N
Burial 2	0		-73.4	12.0	5.5	21.6	3.9	-16.44	8.5	44.1	15.9	2.8
	380		-69.6	12.7	5.1	20.8	4.1	-16.32	8.9	43.3	14.7	2.9
		replicate	-70.2	12.5	5.2	21.4	4.1					
Burial 3	0		-76.2	12.6	5.5	21.6	3.9	-17.20	8.7	44.3	15.9	2.8
		replicate	-72.0	12.2	5.0	20.4	4.1	-16.27	9.0	41.9	14.3	2.9
Texas												
Surface 4	0		-68.6	14.2	6.5	26.0	4.0	-15.02	9.2	44.5	16.2	2.8
	1		-68.5	15.1	5.4	21.3	3.9	-15.04	9.3	42.4	15.1	2.8
	2		-68.2	15.8	4.9	19.5	4.0	-15.34	9.6	41.9	14.7	2.9
	3		-69.0	14.7	5.4	21.5	4.0	-14.98	9.5	42.7	15.3	2.8
	5		-70.4	13.7	5.2	20.9	4.0	-14.90	9.4	42.6	15.3	2.8
		replicate	-65.9	15.2	5.4	22.6	4.2	-15.15	9.8	40.6	13.7	3.0
Surface 5	0		-69.3	15.0	5.5	21.4	3.9	-18.38	8.1	45.7	16.4	2.8
	1		-70.1	14.7	5.3	20.8	3.9	-18.29	8.3	43.5	15.8	2.8
	2		-68.1	14.8	5.5	21.2	3.8	-18.53	8.3	44.3	15.8	2.8
			-65.5	14.4	5.7	22.0	3.8	-18.38	8.3	42.9	15.2	2.8
			-66.8	14.9	5.6	21.4	3.8	-18.52	8.4	47.6	17.0	2.8
		average	-66.8	14.7	5.6	21.5	3.8	-18.48	8.3	44.9	16.0	2.8
		σ	1.3	0.3	0.1	0.4	0.01	0.08	0.04	2.4	0.9	0.02
	3		-64.5	14.6	5.7	22.1	3.9	-18.33	8.3	43.4	15.7	2.8
	5		-65.0	15.1	5.2	20.7	4.0	-18.44	8.4	44.0	15.8	2.8
	360		-61.0	14.2	4.7	20.0	4.3	-18.78	9.0	42.2	14.0	3.0

Table 48. Measured values for $\delta^{18}O$, δ^2H, $\delta^{13}C$, $\delta^{15}N$ continued.

Donor	length of exposure (days)		δ^2H_{VSMOW} (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	Weight % C	Weight % N	C/N
Surface 6	0		-58.7	14.0	5.6	22.2	4.0	-17.70	8.9	43.7	15.5	2.8
	1		-61.9	14.4	5.2	21.1	4.0	-17.79	8.7	42.2	15.1	2.8
	2		-61.1	12.8	5.4	22.3	4.1	-17.78	8.8	45.2	16.1	2.8
		replicate	-65.8	14.3	5.5	22.2	4.0					
	3		-62.2	14.7	5.4	21.4	4.0	-17.90	8.8	45.1	16.1	2.8
	5		-61.6	14.1	5.4	21.7	4.0	-18.04	8.7	44.2	15.7	2.8
Surface 7	0		-68.5	14.4	5.3	20.7	3.9	-15.17	8.5	44.8	16.2	2.8
	1		-64.5	13.3	5.9	22.7	3.9	-15.33	8.3	45.7	16.5	2.8
			-67.5	13.8	5.5	21.8	4.0	-15.18	8.4	44.3	15.8	2.8
			-68.0	14.2	5.5	21.3	3.9	-15.06	8.5	44.3	15.8	2.8
		average	-66.6	13.8	5.6	21.9	3.9	-15.19	8.4	44.8	16.0	2.8
		σ	1.9	0.5	0.2	0.7	0.06	0.14	0.07	0.8	0.4	0.02
	2		-67.4	14.7	5.5	21.5	3.9	-15.16	8.5	43.6	15.5	2.8
	3		-66.5	14.1	5.5	21.4	3.9	-15.44	8.6	44.1	16.0	2.8
	5		-68.0	14.7	5.5	21.4	3.9	-15.39	8.4	44.9	16.2	2.8
Burial 4			-69.4	14.4	5.7	22.3	3.9	-16.76	9.1	44.8	16.0	2.8
			-71.3	14.9	5.6	21.9	3.9	-16.54	9.1	43.8	15.4	2.8
	0		-69.9	14.6	5.7	22.2	3.9	-16.56	9.1	43.8	15.5	2.8
		average	-70.2	14.6	5.7	22.1	3.9	-16.62	9.1	44.1	15.6	2.8
		σ	1.0	0.3	0.1	0.2	0.02	0.12	0.02	0.6	0.3	0.02

Table 48. Measured values for $\delta^{18}O$, δ^2H, $\delta^{13}C$, $\delta^{15}N$ continued.

Donor	length of exposure (days)		Δ^2H_{VSMOW} (‰)	$\Delta^{18}O_{VSMOW}$ (‰)	change in weight % H	change in weight % O	change in O/H	$\Delta^{13}C_{VPDB}$ (‰)	$\Delta^{15}N_{AIR}$ (‰)	change in weight % C	change in weight %N	change in C/N
Tennessee												
Surface 1	1		-7.3	0.6	-0.2	-0.3	0.06	-0.04	-0.04	-0.10	-0.24	0.04
	2		-4.6	1.3	0.0	0.2	0.02	0.00	-0.08	0.12	-0.27	0.06
	3		-3.5	2.0	0.0	0.1	0.04	-0.12	-0.17	-0.66	-0.39	0.03
	5		-5.5	0.5	-0.1	0.2	0.10	-0.10	0.02	-0.57	-0.35	0.03
	10		-4.3	1.9	0.0	0.5	0.10	0.04	-0.03	-0.80	-0.58	0.05
	20		-3.4	1.9	-0.1	0.3	0.11	0.00	-0.10	-1.06	-0.51	0.02
	39		-3.0	1.2	0.0	0.1	0.04	0.03	0.01	0.21	-0.27	0.06
	67		-4.0	0.8	-0.2	-0.4	0.09	-0.09	-0.07	-0.98	-0.47	0.02
	106		-4.0	1.7	-0.1	0.6	0.15	-0.08	-0.01	-0.02	-0.39	0.07
	174		-1.8	0.9	-0.3	-0.5	0.14					
	336	side A	-5.2	1.0	-0.5	-0.2	0.30	0.01	0.58	-0.75	-1.11	0.16
		side B	-7.3	1.0	-0.3	-0.1	0.23	0.19	0.49	-0.63	-1.00	0.15
Surface 2	1*	replicate	5.6	0.2	0.3	0.4	-0.12	-1.05	0.32	-0.17	-2.03	0.40
				0.3		1.9	0.15					
	2		-0.4	-0.8	0.1	0.7	0.07	-0.11	0.12	-1.39	-0.73	0.04
	5*		6.1	-1.0	0.2	1.3	0.07	-0.80	0.43	1.42	-1.41	0.37
	10		3.0	0.1	-0.3	-0.6	0.10	-0.19	0.02	-1.80	-0.47	-0.03
	39		3.1	0.9	-0.1	-0.5	0.01	0.01	-0.07	-0.60	0.13	-0.06
	106		6.3	1.9	-0.1	0.1	0.13	-0.26	0.49	-2.83	-1.13	0.02
								0.19	0.93	-2.01	-1.31	0.12
								0.14	0.76	-3.80	-1.93	0.11
	174		8.3	1.8	-0.4	-0.8	0.2	0.14	0.78	-1.92	-1.29	0.12
		average						0.16	0.83	-2.58	-1.51	0.12
		σ						0.03	0.09	1.06	0.36	0.00
	336		8.5	2.0	-0.4	-0.9	0.1	0.1	0.9	-1.4	-1.2	0.1

Table 49. Differences between $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$, elemental concentrations, O/H ratios, and C/N ratios for intake hair samples and samples collected at later time points.

Donor	length of exposure (days)		Δ^2H_{VSMOW} (‰)	$\Delta^{18}O_{VSMOW}$ (‰)	change in weight % H	change in weight % O	change in O/H	$\Delta^{13}C_{VPDB}$ (‰)	$\Delta^{15}N_{AIR}$ (‰)	change in weight % C	change in weight %N	change in C/N
Surface 3	2		-2.4	-1.1	0.4	1.8	0.0	-0.03	-0.26	0.69	0.17	0.01
			-4.1	0.4	-0.1	0.0	0.1	0.10	-0.17	-0.11	-0.15	0.02
		average	-8.6	-0.7	0.0	0.2	0.0	0.16	-0.03	-0.18	-0.36	0.05
		σ	3.2	0.8	0.2	0.9	0.02	0.09	0.11	0.49	0.27	0.02
	3		-1.0	-1.3	-0.1	0.1	0.1	0.23	-0.14	-0.20	-0.42	0.06
	6		-3.6	0.9	0.1	0.6	0.0	0.11	-0.23	0.61	0.10	0.02
			-3.2	-1.0	0.1	0.5	0.0	0.02	0.07	-1.07	-0.81	0.08
			-3.9	-0.2	-0.2	-0.1	0.1	0.09	0.14	-1.25	-0.98	0.10
	35		-1.3	-0.6	0.2	1.4	0.1	-0.02	0.11	-1.41	-1.10	0.11
		average	-2.8	-0.6	0.0	0.6	0.1	0.0	0.1	-1.2	-1.0	0.1
		σ	1.35	0.44	0.18	0.75	0.06	0.05	0.04	0.17	0.15	0.02
	102		-0.3	-0.6	0.0	0.2	0.0	0.21	0.18	-0.76	-0.66	0.07
	170		-4.3	-0.4	-0.3	-0.8	0.1	0.11	0.69	-3.23	-2.14	0.19
		replicate						-0.08	0.51	-7.34	-3.56	0.20
	332		-1.8	-0.2	-0.3	-0.6	0.1	0.02	0.57	-0.37	-1.22	0.20
Burial 1	102		-1.5	-0.2	-0.1	0.1	0.1	-1.22	-0.45	0.87	0.34	0.00
			0.3	1.1	-0.3	-0.2	0.2					
			-2.5	1.1	-0.3	0.1	0.2					
	381		-3.5	1.1	-0.2	0.2	0.2	0.12	0.93	-2.52	-1.77	0.16
		average	-1.9	1.1	-0.3	0.0	0.2					
		σ	2.0	0.0	0.1	0.2	0.0					
Burial 2	380		3.8	0.7	-0.4	-0.8	0.2	0.12	0.40	-0.82	-1.14	0.16
		replicate	3.2	0.4	-0.3	-0.3	0.2					

Table 49. Differences between $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$ continued.

Donor	length of exposure (days)		$\Delta^{2}H_{VSMOW}$ (‰)	$\Delta^{18}O_{VSMOW}$ (‰)	change in weight % H	change in weight % O	change in O/H	$\Delta^{13}C_{VPDB}$ (‰)	$\Delta^{15}N_{AIR}$ (‰)	change in weight % C	change in weight %N	change in C/N
Texas												
Surface 4	1		0.2	0.9	-1.1	-4.6	0.0	-0.02	0.11	-2.08	-1.01	0.05
	2		0.4	1.7	-1.6	-6.4	0.0	-0.33	0.39	-2.59	-1.45	0.10
	3		-0.4	0.6	-1.1	-4.5	0.0	0.04	0.29	-1.87	-0.86	0.03
	5		-1.8	-0.5	-1.3	-5.1	0.0	0.11	0.24	-1.96	-0.88	0.03
		replicate	2.7	1.1	-1.1	-3.4	0.2	-0.14	0.65	-3.88	-2.47	0.21
Surface 5	1		-0.8	-0.3	-0.2	-0.5	0.1	0.10	0.12	-2.27	-0.65	-0.03
	2		1.2	-0.2	0.0	-0.2	0.0	-0.15	0.14	-1.43	-0.60	0.02
			3.8	-0.6	0.2	0.6	0.0	0.00	0.15	-2.86	-1.26	0.04
			2.5	-0.1	0.0	0.0	0.0	-0.13	0.23	1.89	0.59	0.01
		average	2.5	-0.3	0.1	0.1	0.0	-0.1	0.2	-0.8	-0.4	0.0
		σ	1.3	0.3	0.1	0.4	0.0	0.1	0.0	2.4	0.9	0.0
	3		4.8	-0.4	0.1	0.7	0.0	0.06	0.17	-2.28	-0.73	-0.02
	5		4.3	0.1	-0.3	-0.6	0.1	-0.06	0.29	-1.73	-0.58	-0.01
	360		8.3	-0.8	-0.9	-1.4	0.4	-0.39	0.84	-3.50	-2.36	0.22
Surface 6	1		-3.2	0.5	-0.3	-1.1	0.0	-0.09	-0.18	-1.48	-0.41	-0.02
	2		-2.3	-1.1	-0.1	0.1	0.1	-0.09	-0.14	1.55	0.56	0.00
		replicate	-7.1	0.3	-0.1	0.0	0.0					
	3		-3.4	0.7	-0.2	-0.8	0.0	-0.21	-0.09	1.39	0.60	-0.02
	5		-2.9	0.2	-0.2	-0.6	0.0	-0.34	-0.16	0.47	0.17	0.00
Surface 7	1		4.0	-1.1	0.5	2.0	0.0	-0.16	-0.13	0.90	0.25	0.01
			1.0	-0.6	0.2	1.1	0.1	-0.01	-0.09	-0.45	-0.40	0.04
			0.5	-0.2	0.2	0.7	0.0	0.11	0.01	-0.48	-0.38	0.04
		average	1.9	-0.7	0.3	1.2	0.0	0.0	-0.1	0.0	-0.2	0.0
		σ	1.91	0.46	0.21	0.67	0.06	0.14	0.07	0.79	0.37	0.02
	2		1.1	0.3	0.2	0.9	0.0	0.02	0.01	-1.16	-0.73	0.06
	3		2.0	-0.3	0.2	0.7	0.0	-0.27	0.11	-0.71	-0.27	0.00
	5		0.5	0.3	0.2	0.7	0.0	-0.22	-0.07	0.14	-0.01	0.01

Table 49. Differences between $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$ continued.

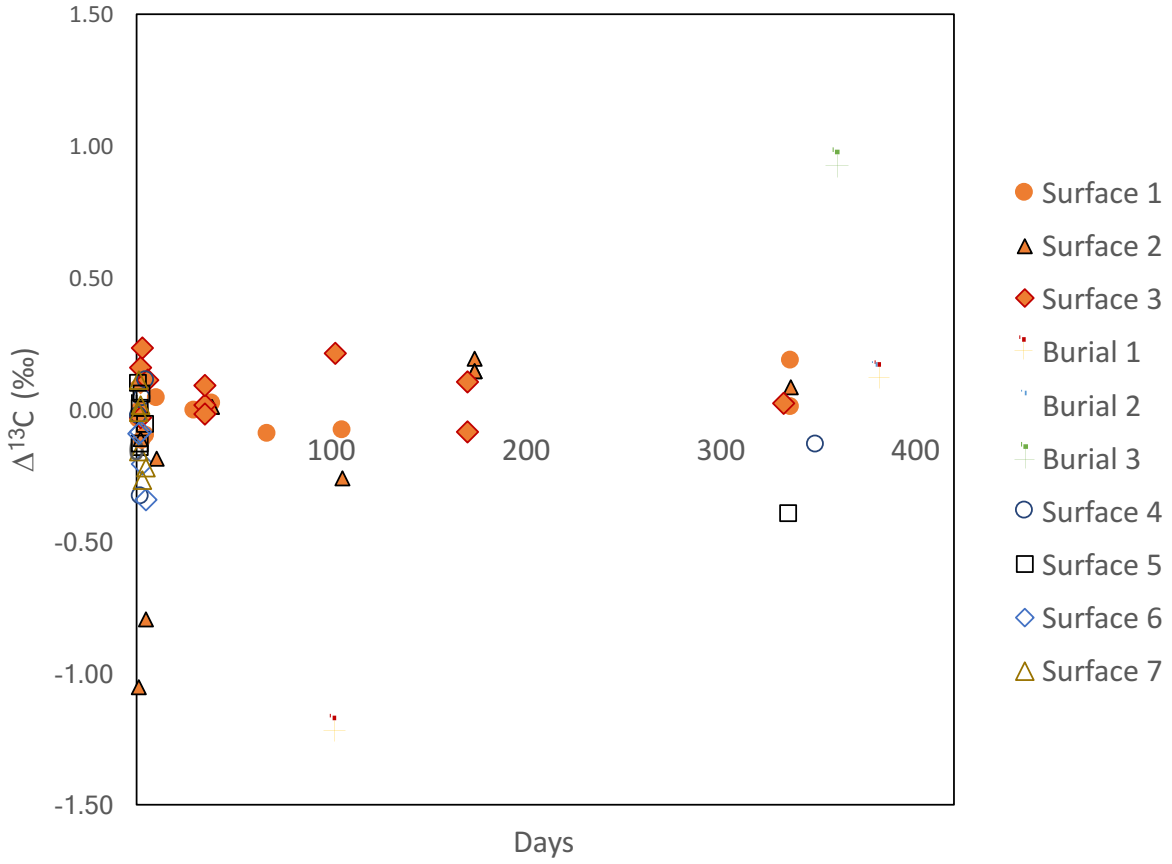

Figure 7. Changes in $\delta^{13}C_{VPDB}$ from intake hair samples. The median external reproducibility of the six samples run in triplicate was 0.09‰, and the maximum external reproducibility was 0.14‰. Samples from ARF in Tennessee are in solid symbols, while those from FARF in Texas are unfilled symbols. Shallow burial samples are crosses.

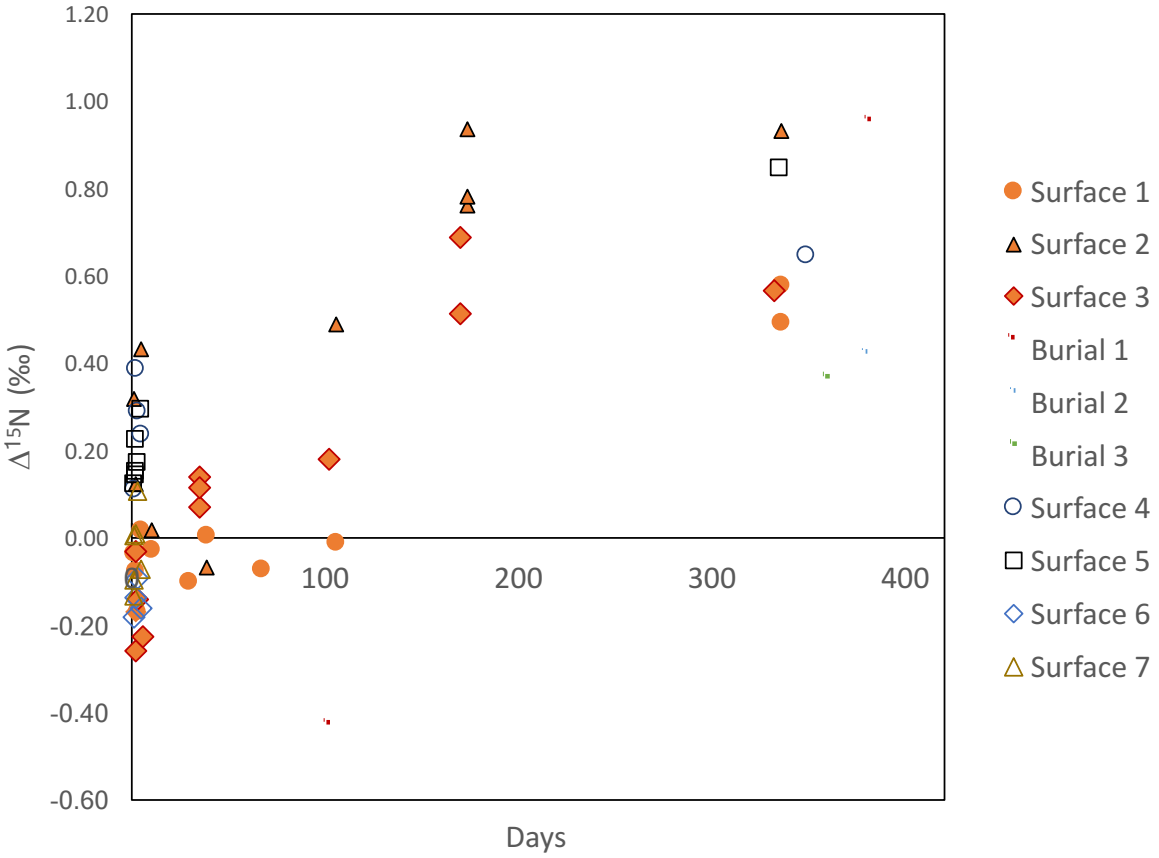

Figure 8. Changes in $\delta^{15}N_{AIR}$ from intake hair samples. The median external reproducibility of the six samples run in triplicate was 0.06‰, and the maximum external reproducibility was 0.11‰. Samples from ARF in Tennessee are in solid symbols, while those from FARF in Texas are unfilled symbols. Shallow burial samples are crosses.

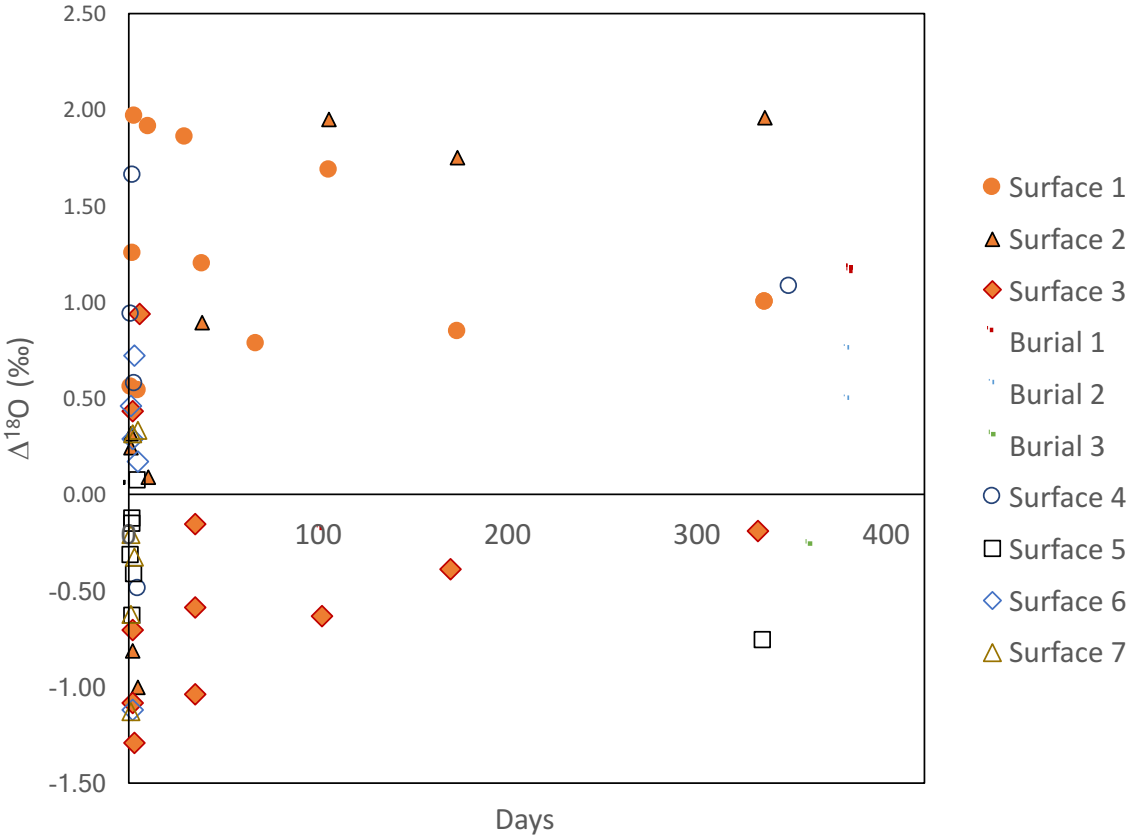

Figure 9. Changes in $\delta^{18}O_{VSMOW\text{-}SLAP}$ from intake hair samples. The median external reproducibility of the six samples run in triplicate is 0.36‰, and the maximum external reproducibility was 0.79‰. Samples from ARF in Tennessee are in solid symbols, while those from FARF in Texas are unfilled symbols. Shallow burial samples are crosses.

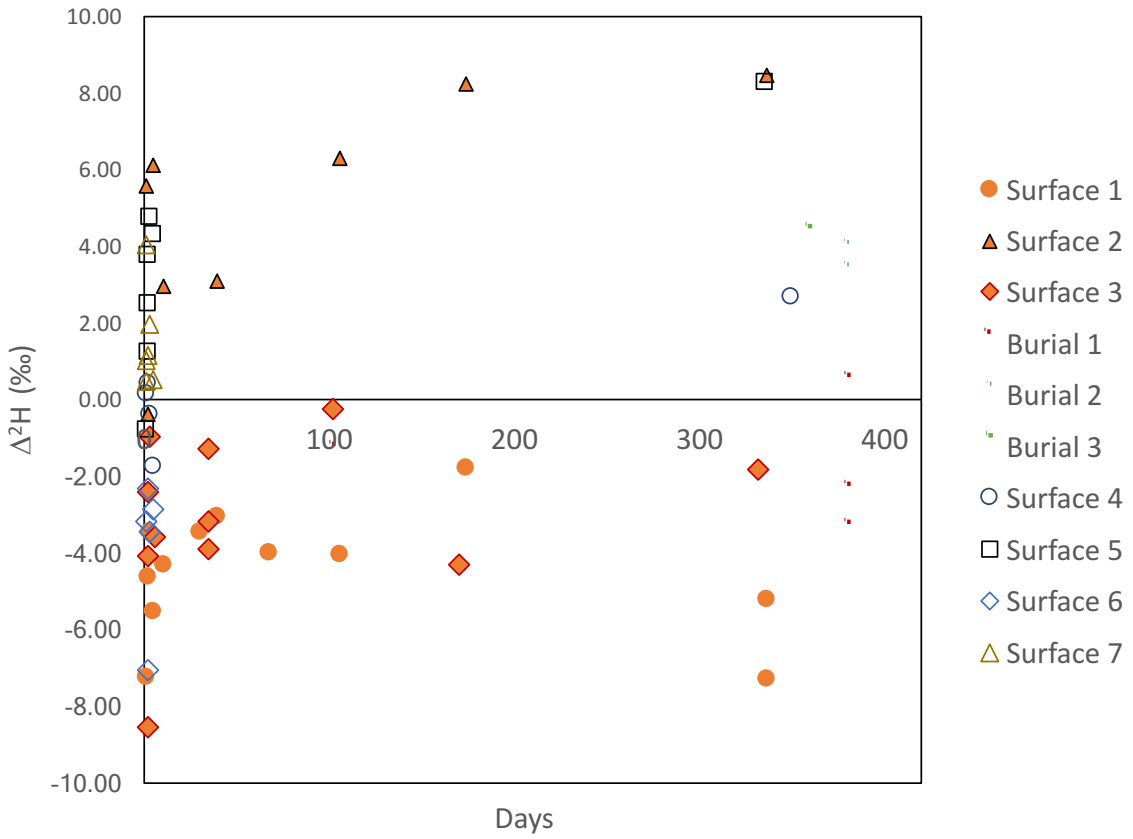

Figure 10. Changes in $\delta^2H_{VSMOW\text{-}SLAP}$ from intake hair samples. The median external reproducibility of the six samples run in triplicate is 1.63‰, and the maximum external reproducibility was 3.18‰. Samples from ARF in Tennessee are in solid symbols, while those from FARF in Texas are unfilled symbols. Shallow burial samples are crosses.

6.4.6.3 Strontium concentrations and isotope compositions The strontium concentrations and both mass-dependent and radiogenic isotope compositions for the bulk, leachate and residual hair samples are listed in Table 50, and shown in Figure 11.

	length of exposure (days)		bulk Sr (ppm)	bulk $^{87}Sr/^{86}Sr$	bulk $\delta^{88/86}Sr$ (‰)	leach Sr (ppm)	leach $^{87}Sr/^{86}Sr$	leach $\delta^{88/86}Sr$ (‰)	residue Sr (ppm)	residue $^{87}Sr/^{86}Sr$	residue $\delta^{88/86}Sr$ (‰)
Tennessee											
Surface 1	0		0.69	0.70985	-0.55	0.62	0.70965	0.00	0.06	0.70916	
	1		0.44	*0.71005*		2.02	0.70895	0.23	0.43	0.71294	0.28
	2		0.26	0.71053							
	5		0.11	0.71189			0.71172		0.10		
	10		0.17	*0.71160*		0.18	*0.71132*		0.01		
	20		0.53	0.71232	-0.42	0.42	0.71216	0.02	bdl		
	39		0.65	0.71227	-0.21				0.63	0.71214	0.19
	67		0.75	0.71405	-0.10				0.74	0.71624	0.15
	106		0.36	*0.71246*		0.39	0.71146	0.23	0.05	0.71184	
	174		0.59	0.71166	0.28	0.43	0.71140	0.11	0.06	0.71795	
	336	side A	0.89	0.71242	0.17	0.78	0.71217	0.08	0.09	0.71498	0.79
		side B	1.26	0.71236	0.09	1.10	0.71193	-0.02	0.05		
Bioavailable soil component			244 ±5 ppm (2σ, n=3)			0.71292 ±0.00004 (2σ, n=3)			0.24 ±0.27‰ (2σ, n=3)		
Surface 2	0		21.96	0.70887	0.07	7.43	0.70884	0.17	0.07	0.70882	0.09
	1									0.70906	
	2		13.81	0.70890	0.21	10.42	0.70884	0.18	0.85	0.71056	0.95
	10		5.13	0.71016	0.11	5.58	0.71024	0.18	bdl	0.71511	
		replicate				5.75	0.71032	0.22	0.05		
		replicate 2				6.70	0.71015	0.21	0.09		
		average				6.01	0.71024	0.20			
		σ				0.60	0.00009	0.02			
	39		1.59	0.71181	-0.18	1.72	0.71178	0.24	0.02		
		replicate				3.31	0.71165	0.31	0.02		
	106		2.33	0.71866	0.17	1.32	0.71408	0.36	0.11	0.72407	0.10
	174		1.76	0.71293	0.23	1.89	0.71236	0.27	0.25	0.72109	0.21
	336		1.38	0.71390	0.18	1.42	0.71234	0.17	0.17	0.72441	0.05
Bioavailable soil component:			315 ppm			0.71276			0.13‰		

Table 50. Measured radiogenic strontium ($^{87}Sr/^{86}Sr$) and mass-dependent strontium ($\delta^{88}Sr$) for hair samples over time. When possible, samples were measured as bulk, leachate and residual to evaluate the most advanced cleaning protocols developed by Tipple et al (2013). Replicates were replicate digests in the case of bulk samples, or replicate leaching protocols for leach or residue samples. Samples in italics indicate an expanded error associated with the measured value due to low concentration or ion beam intensity: <1 V on ^{88}Sr) for $^{87}Sr/^{86}Sr$, or <20% concentration match between samples and standards for $\delta^{88}Sr$. Due to limited sample, not all measurements could be completed. † indicates that the sample had additional sampling along the length of the hair, and that data is presented in Table 54. Bioavailable soil values are for grab samples prior to donor placement.

	length of exposure (days)		bulk			leach			residue		
			Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)
Surface 3	0		1.50	0.71389	-0.16	1.30	0.71385	0.01	0.21	0.71391	0.53
	2		1.06	0.71428		0.65	0.71398	-0.19	0.10	0.71421	
		replicate	1.07	0.71412							
	6		1.35	0.71404	0.12	1.39	0.71400	-0.02	0.22	0.71411	0.10
	35		1.26	0.71399	-0.26	0.73	0.71347	0.03	0.07	0.71437	
	102		1.40	0.71375	0.44	1.72	0.71306	0.05	0.63	0.71671	0.23
	170		0.72	0.71238	0.09	0.59	0.71230	0.18	0.04	0.71284	
	332		0.99	0.71287	0.20	0.67	0.71289	0.14	0.20	0.71521	0.37
Bioavailable soil component:			489 ppm			0.71241			0.11‰		
Burial 1	0		0.21	*0.71269*		0.26	0.71258		0.05	0.71226	
	102		0.39	*0.71366*					0.44	0.71592	
	381		0.36	0.72917	0.35	0.09	0.71840	0.32	0.11	0.73544	0.25
Bioavailable soil component:			236 ppm			0.71231			0.20‰		
Burial 2	0		2.61	0.71199	0.17	1.14	0.71199	0.17	0.20	0.71206	0.68
		replicate				1.40	0.71199	0.06	0.25	0.71194	
	380		0.68	0.71325	0.20	0.60	0.71332	0.18	0.04	0.71506	
Bioavailable soil component:			257 ppm			0.71511			0.29‰		
Burial 3	0		0.22			0.15			0.05		
	360		0.72	0.71517	0.04	0.80	0.71457	0.06	0.17		

Table 50. Measured radiogenic strontium ($^{87}Sr/^{86}Sr$) and mass-dependent strontium ($\delta^{88}Sr$) for hair samples continued.

	length of exposure (days)	bulk			leach			residue		
		Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)
Texas										
Surface 4	0	0.20	0.70903		0.15	0.70867		0.01	0.70954	
	0 replicate				0.27	0.70901	0.34			
	1	0.21	0.70996		0.51	0.70988		0.05		
	2	0.17	0.71008							
	3	0.27	0.71079		0.49	0.70995	0.27	0.03		
	5	0.18	0.70919		0.41	0.70895	0.31	0.05		
	5 replicate	0.13	0.70915							
	320	0.82	0.70940	0.18						
Bioavailable soil component:			266 ppm			0.70906				0.28‰
Surface 5	0	1.06	0.70993	-0.08	1.86	0.70986	0.29	0.17	0.71004	
	1	1.03	0.71009	0.01	0.55	0.71043	0.07	0.04	0.71046	
	1 replicate				0.80	0.71020	0.27	0.03	0.71034	
	2	1.54	0.70999	0.29	1.15	0.71016	0.39	0.09	0.71043	0.77
	3	1.11	0.71008	0.05	0.79	0.70993	0.39	0.06	0.71036	
	5	0.15	*0.71079*		0.16	0.71060		0.01		
	5 replicate	0.11								
	360	1.39	0.71138							
Bioavailable soil component:			275 ppm			0.70942				0.46‰

Table 50. Measured radiogenic strontium ($^{87}Sr/^{86}Sr$) and mass-dependent strontium ($\delta^{88}Sr$) for hair samples continued.

	length of exposure (days)		bulk			leach			residue		
			Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)
Surface 6	0	replicate	18.27	0.70771	0.24	13.09	0.70766	0.18	1.46	0.70767	0.75
		replicate 2				4.90	0.70771	0.20	0.36	0.70765	1.20
		average							4.40	0.70764	1.01
		σ							2.08	0.70765	0.98
	1	replicate	12.51	0.70768	0.34	7.08	0.70767	0.19	2.09	0.00001	0.23
						7.06	0.70766	0.20	0.92	0.70769	0.81
	2†	replicate	4.46	0.70774	0.26				0.73	0.70769	0.80
			4.21	0.70771	0.32						
	3		3.28	0.70771	0.34	4.93	0.70771	0.04	0.52	0.70787	*0.37*
	5		1.03	0.70787	0.14	0.59	0.70786	0.11	0.31	0.70783	0.55
Bioavailable soil component:			257 ppm, 301 ppm			0.70933					0.24‰

Surface 7	0		0.29	0.70891		0.29	0.70868	0.48	0.07	0.70876	0.57
	1		0.45	0.70899	*-0.19*	*0.35*	0.70879	0.40	0.08	0.70870	*0.31*
	2		0.43	0.70877	0.41	2.90	0.70871		0.09	0.70875	
	3	replicate	0.40	*0.70895*	*0.46*	*0.26*	0.70890	0.48	0.04	0.70898	
		replicate 2				*0.28*	0.70891	0.60	bdl		
		average				*0.31*	0.70892	0.47	0.05	0.70888	
		σ				0.28	0.70891	0.52			
	5		0.46	0.70904	0.31	0.02	0.00001	0.07			
Bioavailable soil component:			268 ppm			1.98	0.70871	0.25	1.29	0.70909	
						0.70906					0.28‰
Burial 4	0		0.21	*0.71097*		0.32	0.71065	0.11	0.09	0.71126	0.41
		replicate	0.23	*0.71069*							

Table 50. Measured radiogenic strontium ($^{87}Sr/^{86}Sr$) and mass-dependent strontium ($\delta^{88}Sr$) for hair samples continued.

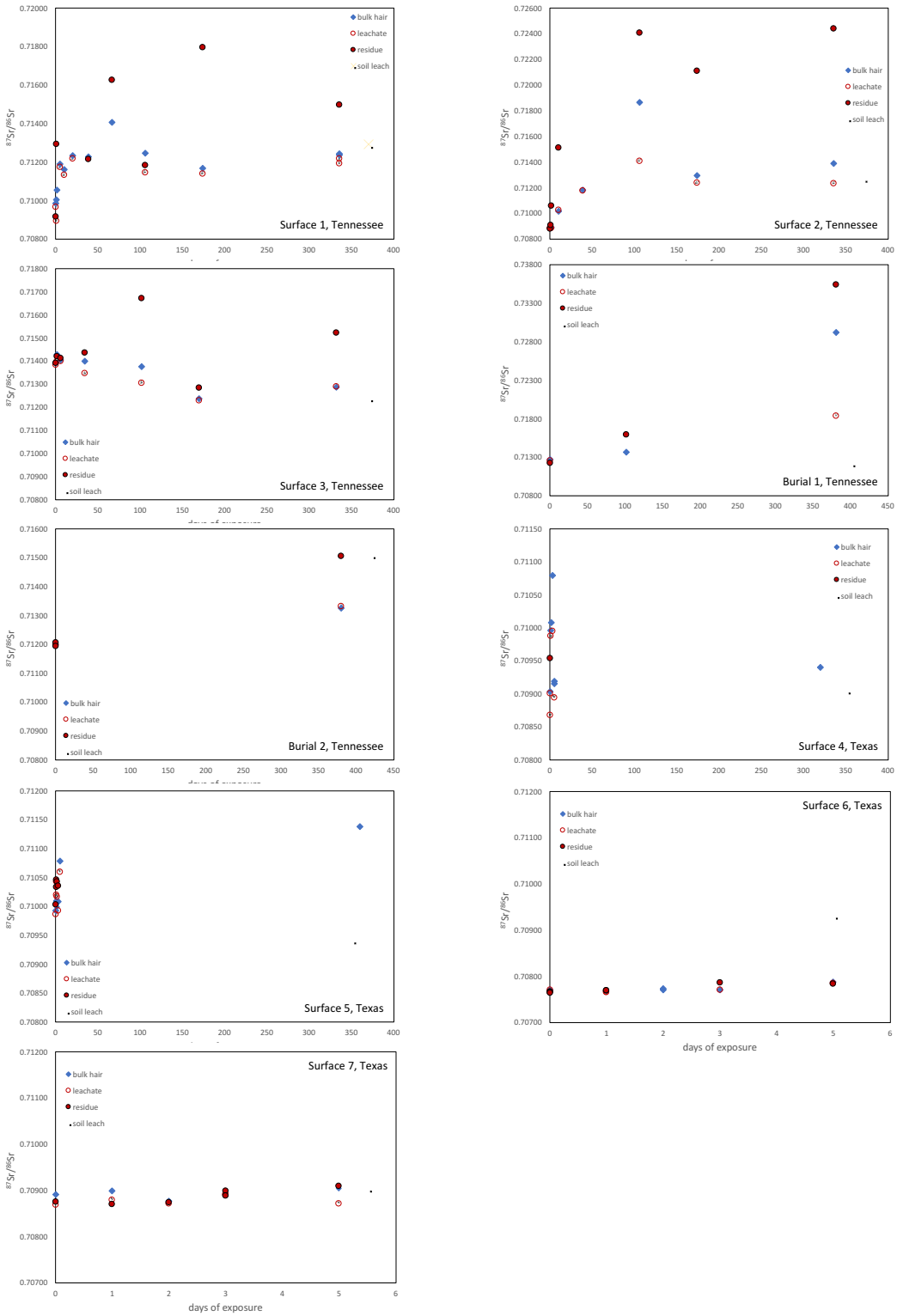

Figure 11. Variations in radiogenic Sr isotopes over time, by donor. Note that the scales differ by donor in order to best represent the range of data. Error bars are for replicate preparations of the in-house standard, by each sample type (bulk, leachate and residue). The local soil leach for each donor is also shown.

6.4.6.4 Lead concentrations and isotope compositions The lead concentrations and both mass-dependent and radiogenic isotope compositions for the bulk, leachate and residual hair samples are listed in Table 51.

	length of exposure (days)		bulk						leach						residue					
			Pb (ppm)	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	^{208}Pb/^{206}Pb	^{207}Pb/^{206}Pb	Pb (ppm)	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	^{208}Pb/^{206}Pb	^{207}Pb/^{206}Pb	Pb (ppm)	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	^{208}Pb/^{206}Pb	^{207}Pb/^{206}Pb
Tennessee																				
Surface 1	0		3.37	18.668	15.652	38.418	2.0581	0.8385	3.05	18.655	15.651	38.408	2.0590	0.8390	0.09	18.602	15.653	38.390	2.0637	0.8414
	1		10.05	18.734	15.661	38.468	2.0535	0.8360	10.48	18.737	15.661	38.469	2.0531	0.8358	0.36	18.731	15.664	38.479	2.0542	0.8362
	2		7.85	18.733	15.662	38.477	2.0539	0.8360												
		replicate	8.33	18.735	15.661	38.476	2.0536	0.8359												
	5		8.59	18.754	15.660	38.466	2.0511	0.8350							7.76	18.758	15.660	38.471	2.0509	0.8348
		replicate	8.99	18.754	15.660	38.467	2.0512	0.8350												
	10		8.14	18.621	15.665	38.513	2.0682	0.8412	7.73	18.739	15.657	38.455	2.0521	0.8356	0.28	18.738	15.667	38.480	2.0536	0.8361
	20		3.16	18.622	15.634	38.389	2.0610	0.8400	3.04	18.598	15.642	38.362	2.0626	0.8410	0.16	18.605	15.647	38.379	2.0629	0.8410
	39		4.26	18.624	15.645	38.376	2.0606	0.8400							3.93	18.624	15.645	38.376	2.0605	0.8400
	67		6.41	18.713	15.655	38.446	2.0545	0.8366							6.08	18.727	15.655	38.460	2.0536	0.8359
	106		5.67	18.679	15.654	38.423	2.0570	0.8380	5.20	18.687	15.653	38.422	2.0561	0.8376	0.70	18.690	15.659	38.442	2.0568	0.8378
	174		4.64	18.628	15.647	38.387	2.0607	0.8400	3.47	18.635	15.645	38.386	2.0599	0.8396	0.35	18.652	15.652	38.423	2.0599	0.8391
	336	side A	4.03	18.608	15.643	38.364	2.0617	0.8406	3.64	18.642	15.639	38.371	2.0583	0.8389	0.45	18.641	15.653	38.417	2.0608	0.8397
		side B	3.79	18.655	15.645	38.400	2.0584	0.8386	3.37	18.655	15.645	38.400	2.0584	0.8386	0.09	18.656	15.653	38.421	2.0595	0.8390
Bioavailable soil component									1.99	18.951	15.656	38.579	2.0360	0.8261						
		1 σ , n=3							0.07	0.032	0.008	0.028	0.0025	0.0012						
Surface 2	0		0.57	18.783	15.653	38.433	2.0460	0.8333	0.23	18.749	15.652	38.420	2.0493	0.8349	0.00	18.831	15.654	38.504	2.0452	0.8312
		replicate								18.821	15.663	38.493	2.0453	0.8322	0.23	18.782	15.653	38.428	2.0461	0.8334
	2		0.49	18.164	15.599	38.039	2.0943	0.8588	0.34	18.196	15.601	38.059	2.0916	0.8574	0.06	18.812	15.650	38.604	2.0521	0.8320
	10		0.71	18.330	15.606	38.148	2.0813	0.8514	0.73	18.543	15.618	38.305	2.0658	0.8423	0.04	18.746	15.629	38.454	2.0513	0.8338
		replicate							0.75	18.585	15.614	38.318	2.0617	0.8401	0.02	18.750	15.624	38.445	2.0503	0.8332
		replicate 2							0.74	18.537	15.620	38.300	2.0662	0.8427	0.06	18.861	15.644	38.555	2.0442	0.8294
		average							0.74	18.555	15.618	38.308	2.0645	0.8417	0.04	18.786	15.632	38.485	2.0486	0.8321
		σ							0.01	0.026	0.003	0.009	0.0025	0.0014	0.02	0.065	0.010	0.061	0.0038	0.0024
	39		2.02	18.667	15.626	38.381	2.0561	0.8371	2.09	18.710	15.626	38.418	2.0534	0.8352	0.04	18.759	15.637	38.482	2.0515	0.8336
		replicate							4.00	18.685	15.628	38.405	2.0553	0.8364	0.12	18.715	15.632	38.435	2.0536	0.8353
	106		4.35	18.803	15.638	38.505	2.0478	0.8317	2.83	18.745	15.634	38.469	2.0522	0.8341	0.34	18.810	15.639	38.523	2.0480	0.8314
	174		2.14	18.776	15.635	38.475	2.0492	0.8327	2.41	18.814	15.640	38.506	2.0467	0.8313	0.18	18.917	15.646	38.712	2.0464	0.8270
	336		2.21	18.824	15.639	38.506	2.0456	0.8308	2.25	18.815	15.637	38.496	2.0460	0.8311	0.17	18.840	15.635	38.534	2.0454	0.8299
Bioavailable soil component									2.69	18.897	15.647	38.532	2.0390	0.8280						
Surface 3	0		0.22	18.553	15.635	38.234	2.0607	0.8427	0.20	18.556	15.630	38.251	2.0615	0.8424	0.04	18.578	15.640	38.289	2.0609	0.8418
	2		0.25	18.566	15.628	38.310	2.0634	0.8417	0.16	18.490	15.614	38.207	2.0663	0.8444	0.02	18.596	15.638	38.316	2.0603	0.8409
		replicate	0.23	18.551	15.622	38.282	2.0636	0.8421												
	6		0.29	18.616	15.630	38.330	2.0588	0.8396	0.28	18.562	15.625	38.288	2.0627	0.8417	0.03	18.622	15.634	38.389	2.0615	0.8395
	35		1.48	19.068	15.669	38.658	2.0273	0.8217	1.01	19.086	15.676	38.681	2.0268	0.8213	0.08	18.955	15.671	38.615	2.0372	0.8268
	102		1.44	19.293	15.696	38.837	2.0130	0.8136	3.24	19.434	15.706	38.910	2.0022	0.8082	0.84	19.398	15.706	38.903	2.0055	0.8097
	170		3.66	19.596	15.728	39.028	1.9916	0.8026	3.16	19.612	15.728	39.039	1.9907	0.8020	0.30	19.663	15.738	39.086	1.9878	0.8004
	332		1.48	18.967	15.649	38.560	2.0330	0.8249	0.99	18.978	15.654	38.605	2.0342	0.8248	0.37	18.922	15.648	38.570	2.0383	0.8270
Bioavailable soil component									1.63	18.911	15.647	38.520	2.0730	0.8273						

Table 51. Lead isotopes for hair samples over time. When possible, samples were measured as bulk, leachate and residual to evaluate the most advanced cleaning protocols developed by Tipple et al (2013). Replicates were replicate digests in the case of bulk samples, or replicate leaching protocols for leach or residue samples. Samples in italics indicate an expanded error due to low beam intensity (<0.1 V on ^{208}Pb). Due to limited sample, not all measurements could be completed. † indicates that the sample had additional sampling along the length of the hair, and that data is presented in Table 54. Bioavailable soil values are for grab samples prior to donor placement.

	length of exposure (days)		bulk						leach						residue					
			Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Burial 1	0		0.13	18.516	15.622	38.249	2.0657	0.8437	0.13	18.495	15.616	38.237	2.0676	0.8444	0.10	18.504	15.618	38.244	2.0667	0.8441
															0.00					
	102		0.91	18.966	15.642	38.599	2.0352	0.8248							1.08	18.963	15.647	38.607	2.0360	0.8252
	381		1.75	18.994	15.648	38.633	2.0339	0.8238	1.52	18.995	15.648	38.635	2.0339	0.8238	0.06	19.112	15.658	38.788	2.0295	0.8193
Bioavailable soil component									2.44											
Burial 2	0		0.74	18.664	15.635	38.308	2.0529	0.8376	0.22	18.688	15.637	38.338	2.0515	0.8367	0.03	18.594	15.631	38.253	2.0575	0.8407
		replicate							0.28	18.704	15.636	38.349	2.0505	0.8360	0.03	18.722	15.643	38.378	2.0498	0.8355
	380		0.91	18.977	15.648	38.630	2.0356	0.8246	0.79	18.981	15.643	38.626	2.0349	0.8241	0.09	18.983	15.647	38.636	2.0353	0.8243
Bioavailable soil component									10.91	19.162	15.657	38.749	2.0220	0.8171						
Burial 3	0		0.09	18.281	15.610	38.014	2.0795	0.8539	0.04						bdl					
	360		1.45	18.958	15.648	38.612	2.0367	0.8254	1.53	18.971	15.646	38.630	2.0362	0.8247	0.15	19.017	15.653	38.763	2.0383	0.8231
TEXAS																				
Surface 4	0		0.95	18.488	15.622	38.177	2.0649	0.8450	0.55	18.491	15.624	38.184	2.0650	0.8450	0.01	18.470	15.629	38.189	2.0676	0.8462
									0.70						0.14					
	1		0.39	18.509	15.624	38.193	2.0635	0.8441	0.70	18.497	15.623	38.188	2.0645	0.8447	0.03	18.504	15.622	38.209	2.0648	0.8442
	2		0.33	18.538	15.628	38.213	2.0614	0.8430												
	3		0.20	18.593	15.629	38.274	2.0586	0.8407	0.37	18.557	15.629	38.247	2.0611	0.8422	0.00	*18.729*	*15.639*	*38.400*	*2.0504*	*0.8351*
	5		0.43	18.524	15.626	38.215	2.0630	0.8436	0.94	18.514	15.625	38.207	2.0638	0.8440	0.04	18.498	15.625	38.213	2.0660	0.8448
		replicate	0.44	18.524	15.626	38.215	2.0630	0.8436												
	320		0.45	18.924	15.646	38.532	2.0360	0.8268												
Bioavailable soil component									1.26											
Surface 5	0		0.24	18.525	15.631	38.250	2.0648	0.8438	0.36	18.488	15.627	38.244	2.0685	0.8453	0.04	18.499	15.639	38.275	2.0691	0.8454
	1		0.15	18.422	15.623	38.185	2.0728	0.8480	0.11	18.283	15.607	38.079	2.0827	0.8537	0.01	18.508	15.614	38.335	2.0710	0.8436
		replicate							0.13	18.337	15.610	38.129	2.0795	0.8513	0.00	18.422	15.610	38.191	2.0728	0.8473
	2		0.31	*18.603*	*15.691*	*38.356*	*2.0622*	*0.8434*	0.25	18.484	15.626	38.207	2.0670	0.8454	0.03	18.479	15.630	38.237	2.0692	0.8458
	3		0.32	18.565	15.629	38.252	2.0604	0.8418	0.22	18.572	15.629	38.263	2.0603	0.8416	0.01	18.565	15.626	38.268	2.0613	0.8417
	5		0.40	18.963	15.648	38.540	2.0324	0.8252	0.47	18.956	15.649	38.518	2.0320	0.8255	0.01	18.858	15.630	38.471	2.0401	0.8289
			0.49																	
	360		0.82	18.926	15.647	38.574	2.0381	0.8267												
Bioavailable soil component									2.10	19.204	15.664	38.655	2.0129	0.8157						

Table 51. Lead isotopes for hair samples over time continued.

	length of exposure (days)		bulk						leach						residue					
			Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Surface 6	0		1.48	18.537	15.631	38.321	2.0673	0.8432	0.88						0.05	18.417	15.635	38.269	2.0779	0.8489
		replicate							0.66	18.648	15.636	38.385	2.0584	0.8385	0.04	18.527	15.628	38.313	2.0680	0.8436
		replicate 2							0.02						0.71	*18.544*	*15.613*	*38.272*	*2.0641*	*0.8420*
		average														18.496	15.626	38.284	2.0700	0.8448
		σ														0.069	0.011	0.024	0.0071	0.0036
	1		1.97	18.436	15.625	38.245	2.0745	0.8475	1.18	18.491	15.629	38.285	2.0705	0.8453	0.08	18.470	15.636	38.294	2.0734	0.8466
		replicate							1.22	18.505	15.629	38.290	2.0692	0.8446	0.50	18.526	15.642	38.327	2.0688	0.8443
	2†		1.23	18.315	15.621	38.185	2.0849	0.8529												
		replicate	1.10	18.324	15.622	38.187	2.0840	0.8525												
	3		0.92	18.792	15.647	38.481	2.0478	0.8326	0.84	18.811	15.648	38.495	2.0463	0.8319	0.03					
	5		0.69	18.853	15.650	38.512	2.0427	0.8301	0.44	18.819	15.643	38.485	2.0451	0.8313	0.18	18.804	15.648	38.493	2.0470	0.8321
Bioavailable soil component									1.06											
		replicate							1.63	19.467	15.699	38.814	1.9994	0.8064						
Surface 7	0		0.05	18.481	15.624	38.259	2.0701	0.8455	0.04	18.366	15.620	38.224	2.0812	0.8505	0.01	18.380	15.625	38.250	2.0811	0.8501
	1		0.17	18.306	15.625	38.267	2.0904	0.8535	0.13	18.201	15.616	38.251	2.1016	0.8580	0.01	18.207	15.623	38.282	2.1026	0.8581
	2		0.14	18.269	15.628	38.311	2.0970	0.8554	0.09	18.226	15.615	38.235	2.0979	0.8567	0.01	18.274	15.634	38.292	2.0954	0.8555
	3		0.16	18.359	15.631	38.345	2.0887	0.8514	0.11	18.360	15.631	38.363	2.0895	0.8514	0.01	18.450	15.639	38.445	2.0838	0.8477
		replicate							0.12	18.358	15.634	38.359	2.0894	0.8516	0.01	18.515	15.649	38.438	2.0763	0.8453
		replicate 2							0.13	18.335	15.626	38.339	2.0910	0.8523	0.01	18.443	15.653	38.458	2.0851	0.8486
		average								18.351	15.631	38.353	2.0900	0.8518		18.469	15.647	38.447	2.0817	0.8472
		σ								0.014	0.004	0.013	0.0009	0.0005		0.039	0.007	0.010	0.0048	0.0017
	5		0.26	18.351	15.631	38.379	2.0913	0.8518	1.03	18.315	15.627	38.347	2.0938	0.8533	0.52	18.314	15.633	38.424	2.0982	0.8536
Bioavailable soil component									0.77	19.039	15.627	38.481	2.0209	0.8208						
Burial 4	0		0.85	18.405	15.592	38.133	2.0716	0.8471	1.26	18.405	15.597	38.146	2.0725	0.8474	0.28	18.423	15.597	38.167	2.0716	0.8466
			0.81																	
		replicate	0.84	18.400	15.593	38.135	2.0725	0.8474												

Table 51. Lead isotopes for hair samples over time continued.

The proportion of strontium remaining in the residual phase of the hair samples was variable, ranging from below detection limit to 54.3%, with a median amount of 10.0%. There did not appear to be any systematic pattern of increasing percent in the residual phase with increasing exposure time. There also was no significant correlation with placement condition (surface versus burial), or in location (Texas versus Tennessee). *Because intake samples do not have significantly higher or lower proportions of strontium partitioned in the residual phase then post-exposure samples, this suggests that the cleaning protocol utilized is fairly efficient at removing solid contaminants.*

Some donors showed minor increases in bulk Sr concentrations with exposure time (Burial 3), but this was not universal. Indeed, the most systematic and largest concentration variations were *decreases* in strontium for donors that started out at relatively high concentrations (*cf* Surface 2, Burial 2, Surface 6 in Table 45). This does not mean there are no systematics in strontium concentrations; some donors were clearly elevated, and remained elevated, relative to other donors. Despite the carbonate bedrock of Texas, the Texas donors were not significantly higher in calcium and strontium compared to the Tennessee donors.

There was a weak positive correlation ($R^2 = 0.45$) between the percent of strontium and lead in the residual phase (figure GG). This suggests that there may be an independent factor controlling the proportion of metal going into the residual phase. A potential mechanism would be the surface area of the hair sample – whether hairs were cut into small pieces or entire strands were used. Unfortunately, details of sample surface area were not documented for the hair samples, so this remains an area for future research. It is interesting to note that the donor who died from a self-inflicted gunshot wound to the head did not substantially deviate from the trend of the other donors. How gunshot residue behaves during the hair leaching protocol is unknown, and also remains an area for future research.

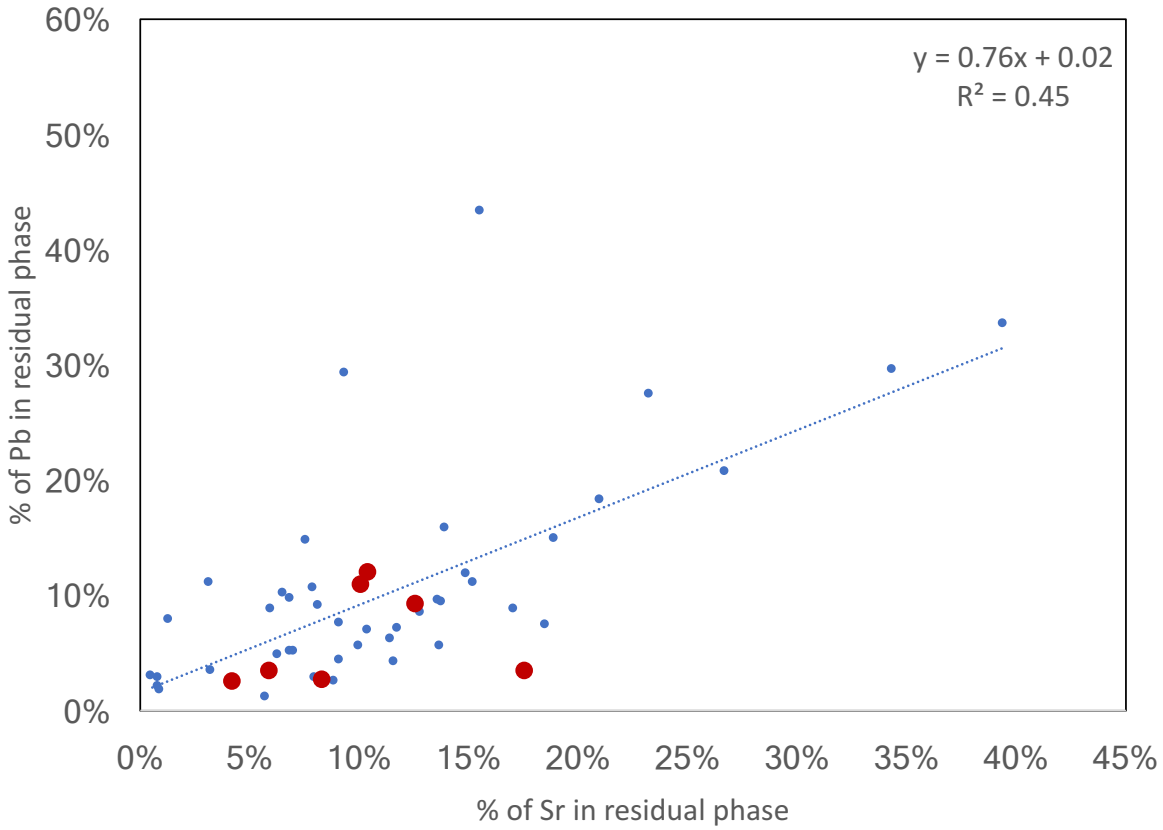

Figure 12. Correlation of percent strontium and lead in residual phase of hair samples. Larger symbols are for the donor who died from a self-inflicted gunshot wound. If those points are removed from the data set, the R^2 only increases to 0.47, and the slope (0.77) and intercept (0.02) remains the same within error.

6.4.6.5 Elemental and isotopic variations along the length of hair Hair incorporates exogenous material, particularly as it grows. We took one particularly abundant sample (Surface donor 6 from FARF in Texas, two days of environmental exposure), and analyzed the elemental concentrations and Sr and Pb isotope compositions along its length in segmental analysis. Unfortunately, we had no information about travel history for this donor, as only residential history was collected on the donor intake forms. This donor was a 79-year old, White female born in Flint, Michigan, whose cause of death was related to heart disease. Her last known place of residence was also Flint, Michigan. The hair sample detailed below represented approximately the last 31 months of her life. We cannot address the question of whether she traveled significantly during this period, but on balance her age, health, and initial and final residence in the same location suggested that perhaps she did not.

While ideally, we would have preferred the same segmental analysis for both intake and post-exposure samples, the amount of material required is significant and can be prohibitive for temporally-sequential segmental analyses from the same donor. Ideally, we have >15 mg per segment for all the listed analyses, so segmental analysis as below can require approximately 100 mg. It also requires that the hair be oriented; frequently as decomposition progresses, it can become difficult to precisely align a sufficient number of hair roots for analysis. In addition, this analysis was well beyond the original scope of proposed analyses. However, we believe this is an intriguing area for significant future research.

	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Bulk																
bulk	141	68	9.42	135.6	106	987	0.98	0.044	0.77	0.38	37.10	0.012	0.19	8.47	55.23	0.046
replicate	123	60	7.82	133.6	98	899	0.94	0.029	0.18	0.19	17.11	0.008	0.13	7.99	50.69	0.054
Leach																
0-1"	70	21	3.70	47.5	58	341	bdl	bdl	0.068	0.15	7.19	0.004	0.07	6.59	33.17	bdl
1-2 1/4"	91	15	1.68	54.9	70	320	bdl	bdl	0.059	0.14	2.83	0.003	0.04	1.99	46.55	bdl
2 1/4 - 3 3/4"	136	23	1.72	68.7	101	424	0.10	bdl	0.091	0.12	4.06	0.002	0.05	1.53	39.58	bdl
3 3/4 - 5 1/4"	182	61	4.29	54.9	130	806	0.14	0.010	0.033	0.19	20.88	0.004	0.11	2.00	45.97	bdl
5 1/4" - 7 1/4"	225	137	3.58	50.3	159	1473	0.17	0.018	0.037	0.19	8.30	0.006	0.16	2.31	43.70	bdl
7 1/4" - 9 1/4"	209	139	5.44	79.6	151	2292	0.15	0.027	0.045	0.30	15.83	0.006	0.28	2.34	42.83	bdl
9 1/4" - 12 1/4"	184	128	5.86	63.8	150	2642	0.32	0.024	0.053	0.58	9.62	0.007	0.40	2.14	43.59	bdl
Solid residue																
0-1"	11.9	0.92	4.06	80.5	1.20	6.2	0.34	0.014	0.059	bdl	5.29	bdl	0.027	1.49	bdl	0.084
1-2 1/4"	14.4	3.72	3.76	97.8	2.05	25.8	0.23	0.013	0.088	0.016	8.17	0.002	0.026	6.77	1.16	0.049
2 1/4 - 3 3/4"	8.5	7.00	5.70	92.1	1.21	53.8	0.45	0.022	0.075	0.033	12.46	0.003	0.043	7.00	3.37	0.076
3 3/4 - 5 1/4"	2.5	12.56	11.51	105.6	1.65	71.1	1.36	0.032	0.085	0.055	24.78	0.005	0.068	6.18	2.59	0.072
5 1/4" - 6 3/4"	3.9	11.50	5.54	80.4	0.90	52.9	0.29	0.032	0.103	0.014	11.10	0.009	0.117	6.53	0.99	0.031
6 3/4" - 8 1/4"	8.1	11.75	12.49	95.6	3.92	79.6	0.88	0.057	0.169	0.033	19.65	0.015	0.191	8.53	1.35	bdl
8 1/4" - 11 1/4"	14.8	9.98	7.76	80.0	2.26	81.2	0.49	0.061	0.196	0.033	14.68	0.020	0.218	11.60	0.90	0.021
Leach (Percent of leach + solid residue)																
0-1"	85%	96%	48%	37%	98%	98%	0%	0%	54%	100%	58%	100%	73%	82%	100%	0%
1-2 1/4"	86%	80%	31%	36%	97%	93%	0%	0%	40%	90%	26%	60%	61%	23%	98%	0%
2 1/4 - 3 3/4"	94%	77%	23%	43%	99%	89%	19%	0%	55%	78%	25%	45%	54%	18%	92%	0%
3 3/4 - 5 1/4"	99%	83%	27%	34%	99%	92%	9%	23%	28%	78%	46%	43%	61%	24%	95%	0%
5 1/4" - 7 1/4"	98%	92%	39%	38%	99%	97%	37%	36%	27%	93%	43%	42%	57%	26%	98%	0%
7 1/4" - 9 1/4"	96%	92%	30%	45%	97%	97%	15%	33%	21%	90%	45%	30%	59%	22%	97%	bdl
9 1/4" - 12 1/4"	93%	93%	43%	44%	99%	97%	39%	28%	21%	95%	40%	26%	64%	16%	98%	0%

Table 52. Elemental concentrations in segmental analysis from donor 6 at FARF after two days of elemental exposure.

	Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
Bulk	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
bulk	0.13	4.46	0.043	0.000	0.023	0.061	2.10	0.10	bdl	4.14	0.0047	0.0082	0.0010	bdl	bdl
replicate	0.11	4.21	0.026	0.006	0.026	0.057	1.63	0.04	bdl	3.50	0.0046	0.0077	0.0009	0.0032	0.0005
Leach															
0-1"	0.06	1.11	bdl	0.010	0.075	0.068	0.02	0.017	bdl	0.63	0.0013	0.0019	0.0002	0.0007	bdl
1-2 1/4"	0.08	1.40	0.004	0.010	0.035	0.069	0.05	0.033	bdl	0.62	0.0006	0.0014	bdl	0.0004	bdl
2 1/4 - 3 3/4"	0.11	2.71	0.004	0.008	0.038	0.066	0.06	0.018	bdl	1.92	0.0012	0.0022	0.0002	0.0007	bdl
3 3/4 - 5 1/4"	0.15	4.53	0.005	0.003	0.027	0.103	0.17	0.030	0.0025	3.92	0.0031	0.0059	0.0007	0.0025	0.0006
5 1/4" - 7 1/4"	0.17	6.00	0.003	0.001	0.029	0.113	0.32	0.024	bdl	4.97	0.0025	0.0042	0.0004	0.0015	0.0047
7 1/4" - 9 1/4"	0.17	10.22	bdl	0.001	0.024	0.101	0.44	0.025	bdl	7.99	0.0044	0.0095	0.0010	0.0032	0.0072
9 1/4" - 12 1/4"	0.17	13.87	bdl	0.013	0.025	0.060	0.29	0.058	bdl	10.72	0.0054	0.0092	0.0012	0.0043	0.0008
Solid residue															
0-1"	bdl	bdl	0.036	0.001	0.036	0.001	0.42	0.053	bdl	0.01	0.0012	0.0021	0.0002	0.0015	0.0044
1-2 1/4"	0.002	0.10	0.032	0.001	0.021	0.003	0.43	0.077	bdl	0.06	0.0013	0.0023	0.0003	0.0009	0.0028
2 1/4 - 3 3/4"	0.003	0.45	0.027	0.001	0.021	0.007	0.94	0.077	bdl	0.43	0.0019	0.0035	0.0004	0.0012	0.0033
3 3/4 - 5 1/4"	0.010	0.62	0.023	0.001	0.034	0.004	2.02	0.058	bdl	0.53	0.0043	0.0076	0.0008	0.0029	0.0007
5 1/4" - 6 3/4"	0.004	0.29	0.022	0.000	0.031	0.001	2.57	0.054	0.0043	0.31	0.0036	0.0067	0.0005	0.0025	0.0004
6 3/4" - 8 1/4"	0.010	0.52	0.027	0.001	0.020	0.001	4.46	0.163	0.0049	0.56	0.0048	0.0090	0.0010	0.0044	0.0007
8 1/4" - 11 1/4"	0.005	0.58	0.024	0.001	0.011	bdl	2.55	0.057	bdl	0.72	0.0025	0.0044	0.0006	0.0024	0.0052
Leach (Percent of leach + solid residue)															
0-1"	100%	100%	0%	92%	67%	99%	6%	24%	bdl	98%	52%	47%	44%	33%	0%
1-2 1/4"	97%	93%	11%	93%	63%	96%	11%	30%	bdl	91%	33%	37%	0%	28%	0%
2 1/4 - 3 3/4"	97%	86%	14%	93%	64%	90%	6%	19%	bdl	82%	40%	38%	30%	36%	0%
3 3/4 - 5 1/4"	94%	88%	16%	68%	44%	97%	8%	34%	100%	88%	42%	43%	47%	47%	47%
5 1/4" - 7 1/4"	98%	95%	12%	66%	49%	99%	11%	31%	0%	94%	41%	39%	45%	37%	92%
7 1/4" - 9 1/4"	94%	95%	0%	58%	55%	99%	9%	13%	0%	93%	48%	51%	49%	42%	91%
9 1/4" - 12 1/4"	97%	96%	0%	91%	70%	100%	10%	50%	bdl	94%	68%	68%	67%	65%	13%

Table 52. Elemental concentrations in segmental analysis continued.

		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Bulk																
bulk		0.0001	0.0007	bdl	0.0009	bdl	0.0006	bdl	bdl	bdl	0.016	0.0484	bdl	0.0011	1.23	0.018
	replicate	0.0002	0.0005	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.015	0.0086	0.0002	0.0015	1.10	0.020
Leach																
0-1"		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0038	bdl	0.0003	0.0024	0.91	0.0008
1-2 1/4"		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0006	0.0206	0.0003	0.0022	0.93	0.0029
2 1/4 - 3 3/4"		bdl	0.0003	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.0007	bdl	0.0001	0.0017	0.86	0.0045
3 3/4 - 5 1/4"		0.0002	0.0003	0.0001	0.0004	bdl	bdl	bdl	0.0002	bdl	0.0020	0.0021	0.0001	bdl	1.09	0.0046
5 1/4" - 7 1/4"		0.0001	0.0002	0.0006	0.0002	bdl	bdl	bdl	bdl	bdl	0.0013	bdl	0.0002	0.0016	2.12	0.0064
7 1/4" - 9 1/4"		0.0003	0.0006	0.0013	0.0005	0.0002	bdl	bdl	bdl	bdl	0.0019	bdl	bdl	0.0033	2.58	0.0078
9 1/4" - 12 1/4"		0.0003	0.0007	bdl	0.0007	bdl	bdl	bdl	bdl	bdl	0.0038	bdl	0.0002	0.0030	1.35	0.0168
Solid residue																
0-1"		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.014	bdl	0.0001	0.0039	0.01	0.006
1-2 1/4"		bdl	bdl	bdl	0.0003	bdl	bdl	bdl	bdl	bdl	0.010	bdl	0.0001	0.0025	0.06	0.032
2 1/4 - 3 3/4"		bdl	0.0003	bdl	0.0002	bdl	bdl	bdl	bdl	bdl	0.013	bdl	bdl	0.0020	0.10	0.010
3 3/4 - 5 1/4"		0.0001	0.0005	0.0001	0.0004	bdl	bdl	bdl	bdl	bdl	0.038	0.0026	0.0000	0.0004	0.06	0.010
5 1/4" - 6 3/4"		0.0001	0.0005	bdl	0.0005	bdl	bdl	bdl	bdl	bdl	0.011	0.0164	0.0000	0.0003	0.06	0.010
6 3/4" - 8 1/4"		0.0002	0.0006	bdl	0.0004	bdl	bdl	bdl	bdl	bdl	0.030	0.0184	bdl	0.0006	0.10	0.013
8 1/4" - 11 1/4"		bdl	0.0003	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.013	0.0306	bdl	0.0040	0.05	0.012
Leach (Percent of leach + solid residue)																
0-1"		bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	21%	bdl	80%	38%	99%	13%
1-2 1/4"		bdl	bdl	bdl	0%	bdl	bdl	bdl	bdl	bdl	5%	100%	72%	48%	94%	8%
2 1/4 - 3 3/4"		bdl	49%	bdl	0%	bdl	bdl	bdl	bdl	bdl	5%	bdl	100%	45%	90%	32%
3 3/4 - 5 1/4"		58%	37%	53%	52%	bdl	bdl	bdl	100%	bdl	5%	45%	68%	0%	94%	32%
5 1/4" - 7 1/4"		53%	33%	100%	29%	bdl	bdl	bdl	bdl	bdl	10%	0%	83%	83%	97%	40%
7 1/4" - 9 1/4"		62%	49%	100%	52%	100%	bdl	bdl	bdl	bdl	6%	0%	bdl	85%	96%	37%
9 1/4" - 12 1/4"		100%	66%	bdl	100%	bdl	bdl	bdl	bdl	bdl	22%	0%	100%	43%	97%	58%

Table 52. Elemental concentrations in segmental analysis continued.

There were several patterns of change in elemental concentration from root to tip of this sample. Some increase and then level off (Na, Mg, K), while others remain relatively constant (P) or only have moderate increases (<200% increase from root to tip, or R^2<0.3; Al, Ti; Table 52, Figure 13). Others appear to continue increasing in a linear trend (Ba). A few elements (As, Ag, Re, Mo, Cd, Hf) decrease in concentration from root to tip, but both Cd and Hf have very poor correlations with length, and there are no significant trends for these two elements. For Mo and As, which have the best correlation coefficients for those elements that decreased with length, both have higher proportions of metals in the solid residual phase.

Elements that at least double in concentration from root to tip, with $R^2 > 0.68$, include Na (244%), K, Rb, Nd, La, Ce, Mn, Pr, Ni, V, Mg, Sn, Co, Ca, Sr, and Ba (1760%), in order of increasing enrichment at the tip. Of note, many of the rare earth elements (REE) and uranium have significant increases toward the hair tip. This is important to note because these elements are frequently used as diagenetic indicators, as they are typically much higher in concentration in soils and natural waters than they are in biological materials (refs). Aluminum (Al) and titanium (Ti) also increase by 176% and 235%, respectively; these are often used to correct for mineral contributions to authigenic mineral fractions.[8] In geochemistry, frequently leaches are used to try to chemically isolate authigenic minerals (forming in place) from detrital or allogenic minerals transported from elsewhere. Both of these elements are relatively insoluble, so the assumption is frequently made that their presence can only be due to detrital contributions. Most other elements also increase from root to tip, although the correlation with length and increase varies, as shown in Table 52.

[8] In geochemistry, frequently leaches are used to try to chemically isolate authigenic minerals (forming in place) from detrital or allogenic minerals transported from elsewhere. Both of these elements are relatively insoluble, so the assumption is frequently made that their presence can only be due to detrital contributions.

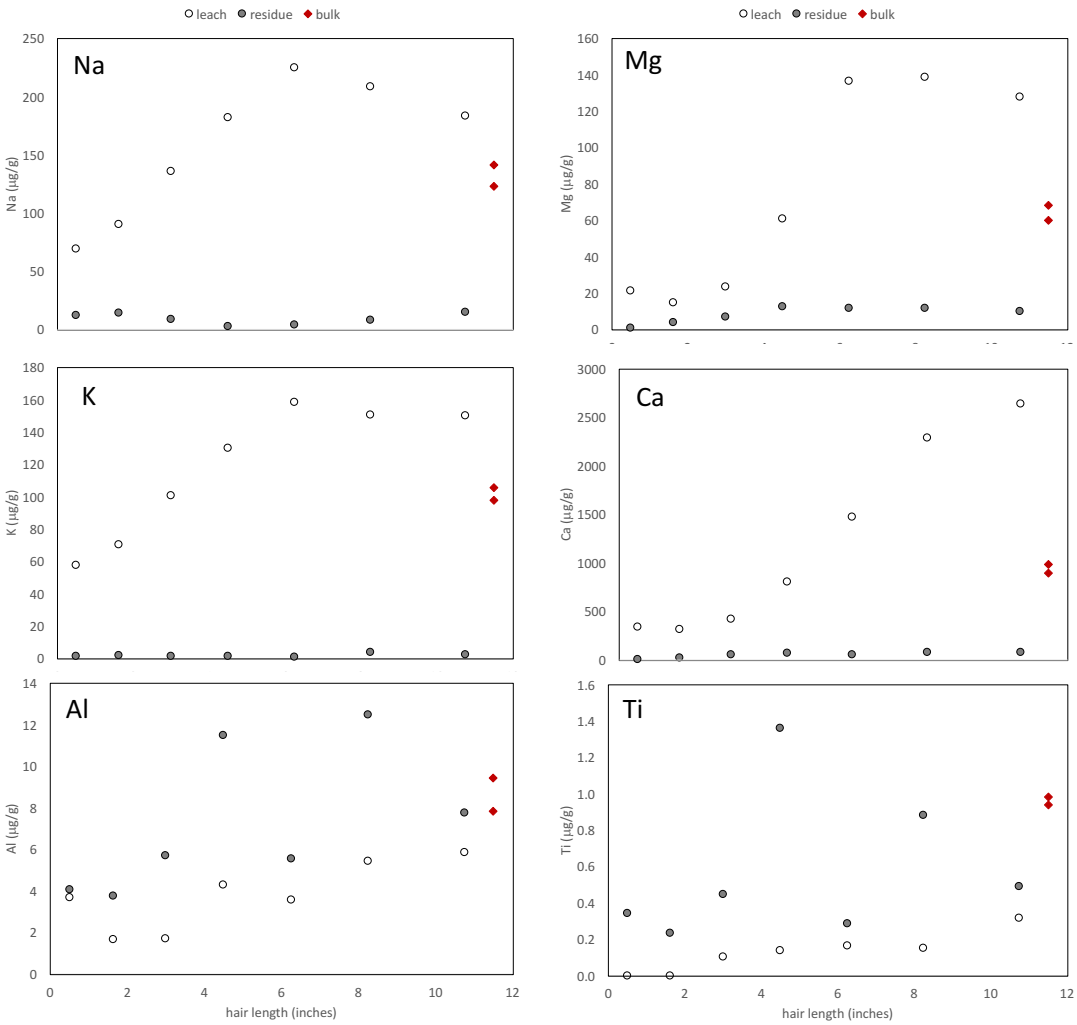

Figure 13. Variation in elemental concentration along the length of the hair for Surface 6 donor at FARF after two days of environmental exposure.

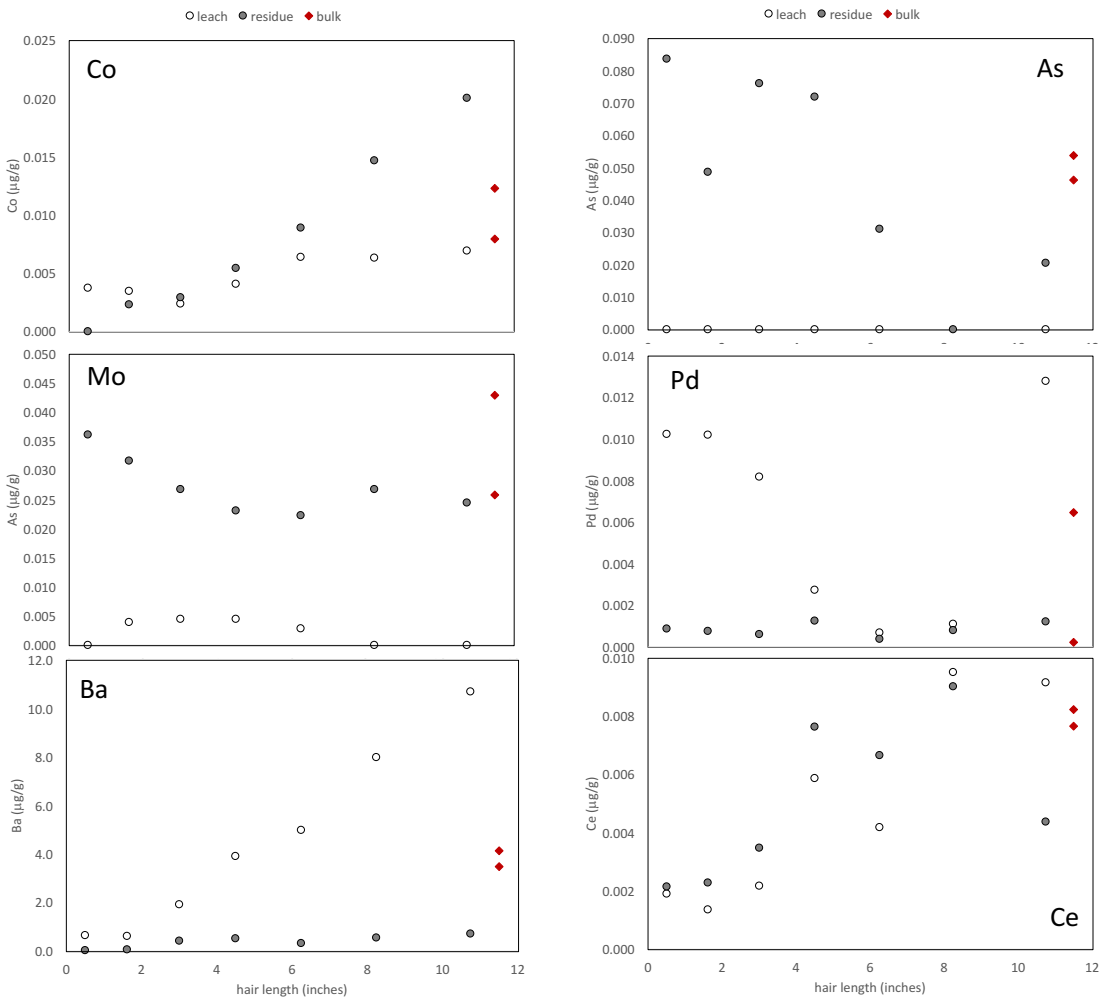

Figure 13. Variation in elemental concentration along the length of the continued.

Of particular note, there were significant variations in the amount of Ca, Sr, and Pb along the length of the hair (Figure 14A). There was a 7-fold increase toward the hair ends for Ca, and a 13-fold increase for Sr. It should be noted that waters – from tap water to soil water to seawater – all have much lower Ca/Sr ratios than human tissues. For instance, Ca/Sr of seawater is ~50, of well water at FARF is ~12, of tap water is 285, while human teeth and bone is 1,000 to 8,000 (figure 14B). Hence, if hair was absorbing Sr from a water source, we would anticipate that 1) Ca and Sr concentrations might increase along length and 2) the increase in Sr would be greater than that for Ca. This matches the observed pattern. The steady increase in Sr – and increase in Ca/Sr ratio – was consistent with strontium being absorbed into the hair from water used in showering.

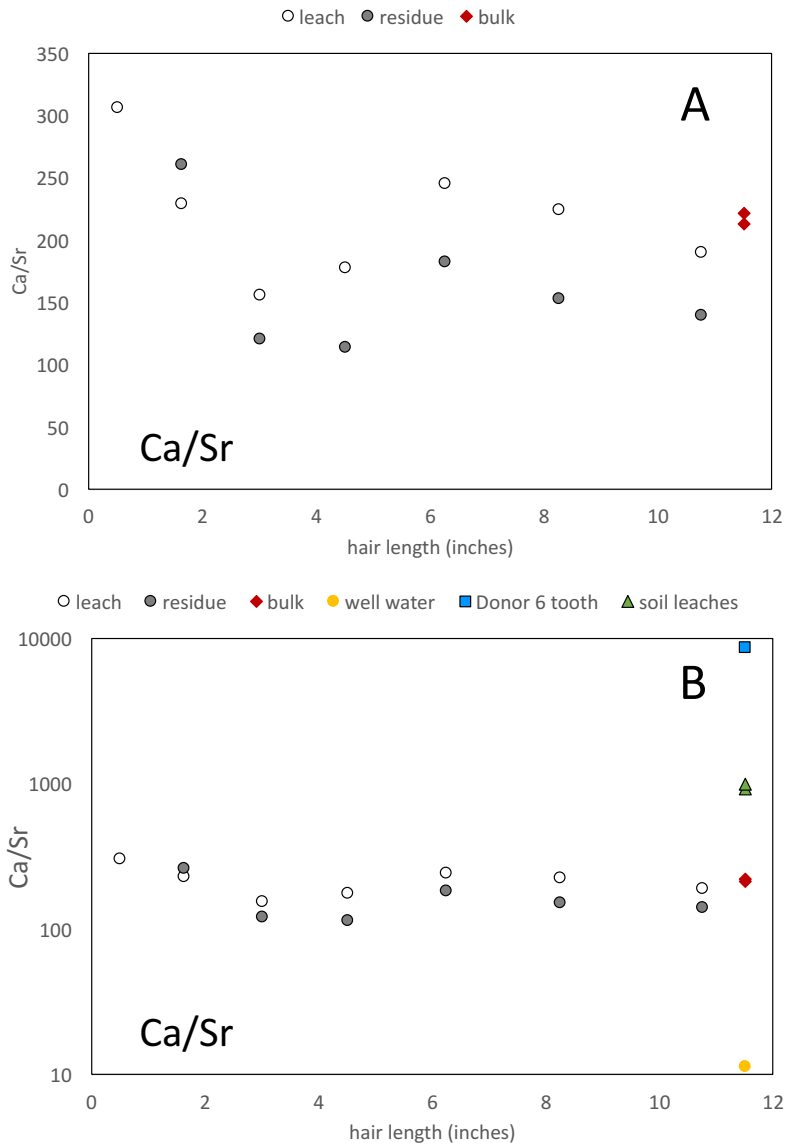

Figure 14. Variation in Ca/Sr ratio with length A. in leachate, residual and bulk hair samples. B. and compared to well water, Surface 6 tooth and soil leaches. Note that the vertical scale in figure CD.B is on a logarithmic scale due to the very large scale represented by the different sample types. Not shown is seawater (Ca/Sr ~50, and tap water ~100-200). Note there is no listed Ca/Sr for the residual fraction for the sample closest to the scalp as the value was below detection limit.

The pattern of strontium along length stands in contrast to that of phosphorus, which remains relatively constant along length (Figure 15). Phosphorus is a bioessential element in nucleic acids, ATP, and many other organic molecules; while not in typical amino acid subunits that form proteins, hair contains a variety of other molecules in addition to the keratin protein.

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

Some elements are preferentially concentrated in the solid residue from the leach, while others remain in the solid residue. This can provide insights into which element may be more exchangeable than others. Between 88 and 100% of the strontium present in the hair partitions into the leachate phase. As the residual phase is the most likely to represent endogenous strontium and is typically of the most interest for geolocation purposes, the leaching protocol requires significantly more starting material is used in order to measure radiogenic strontium in the residual, proposed to be representative of the individual's travel history (Tipple et al 2013).

A comparison of a) the increases with length along hair with b) the elemental concentration changes with environmental exposure is extremely useful for deconvoluting what elements are increasing due to taphonomic changes from those that occurred prior to death. However, *all* of these changes can be considered exogenous addition or subtraction – some occur during life (showering, dust exposure), while others occur after death (precipitation, soil exposure, insects). In a sense, differentiating between these two mechanisms is somewhat academic if the intent is to find the endogenous exposure history of an individual.

As a reminder, the Tipple *et al* (2013) leaching protocol to remove exogenous material involves sonicating in a 3:1 chloroform : methanol solvent twice for 10 minutes, followed by a sequential series of three 0.1 M hydrochloric acid leaches. In the case of samples with significant soil, dirt, maggot larvae, and other materials, this was frequently preceded by sonication with 18 MΩ water, repeated until the water was clear and no more solid particulates settled out. The three 0.1 M HCl leaching solutions (pH 0) are combined in the "leachate," while the solid residue is analyzed separately. After the acid leaches, the hair typically maintains physical integrity, but it is clear that there is some degradation in structural integrity. The remaining hair is typically limp and fragile, with frequent breakages, and often changes color to a reddish tint, pale brown, or nearly transparent. While some of this may be related to cosmetic hair coloring, this may also indicate preferential degradation of eumelanin (brown or black pigments) over pheomelanin (red pigments). Such a conclusion would require significant additional analyses to clarify.

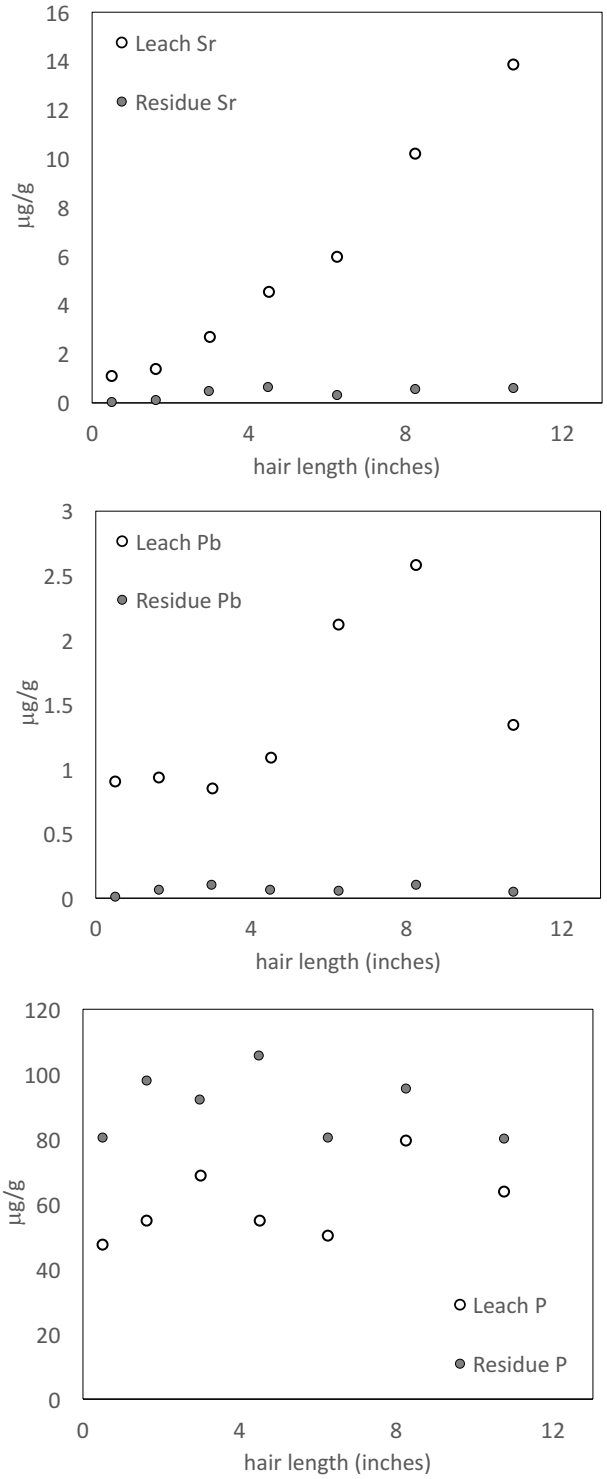

Figure 15. Distribution of strontium, lead, and phosphorus along the length of hair for donor 6, exposure on the surface for two days.

The pattern of lead variation was similar to strontium, in that more than 90% of the lead was partitioned into the leachate phase. This was not unexpected, as lead's solubility is well known. However, the pattern along length was quite distinct, with a distinct rise, followed by a drop to a more even level.

This particular individual was elevated in lead compared to the other donors, with the exception of Surface donor 1, who died from a self-inflicted gunshot wound (Table 53.). Excluding Surface donor 1, Surface donor 6 is more than 2σ above the average (0.53 ppm) for the other donors, and more than 3.6 times higher than the median value (0.40 ppm).

However, assuming a 1.25 cm / month rate of hair growth, we would get a temporal profile as shown in Figure 16.

Donor	Bulk hair Pb (ppm)	Comments
Surface 1	3.37	Gunshot wound to the head
Surface 2	0.57	
Surface 3	0.22	
Burial 1	0.13	
Burial 2	0.74	
Burial 3	0.09	
Surface 4	0.95	
Surface 5	0.24	
Surface 6	1.48	Flint, Michigan
Surface 7	0.05	
Burial 4	0.85	

Table 53. Bulk hair lead concentration for donors' intake samples, illustrating range in background values and anomalies.

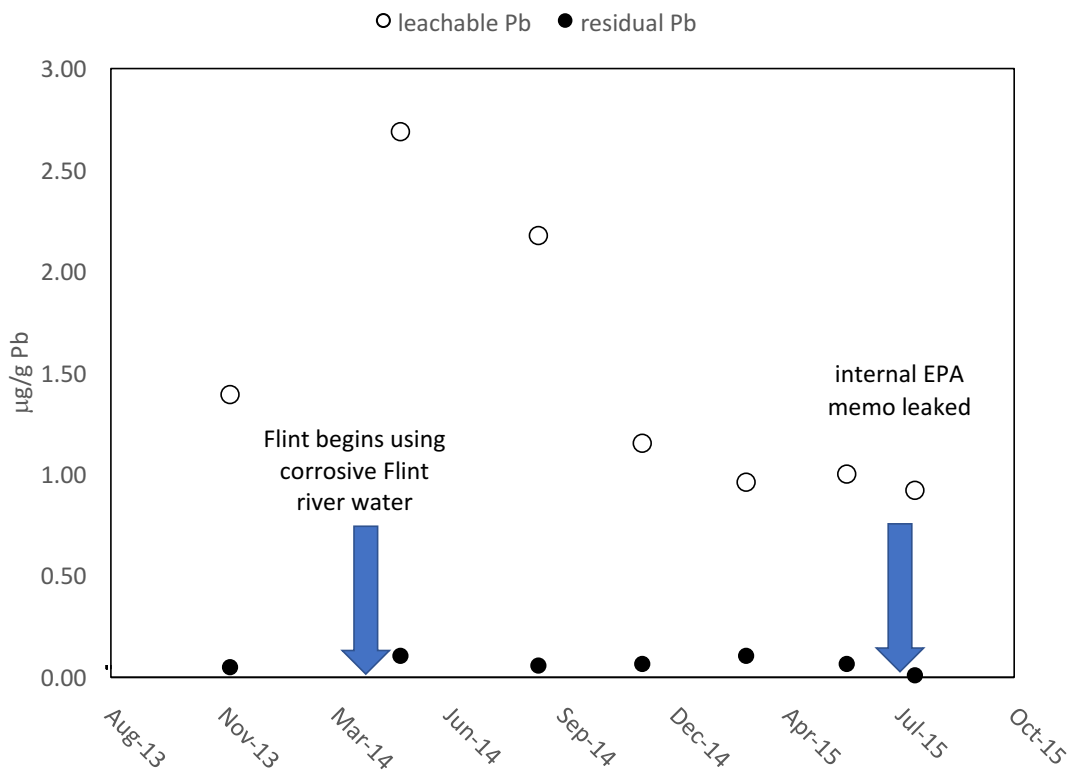

Figure 16. Total Pb concentrations for Surface donor 6, with a timeline of events related to municipal water problems with lead contamination in Flint, Michigan. Pb concentrations were placed at the approximate date corresponding to the average hair length. Hair growth rate was assumed to be 1.25 cm per month.

	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
Bulk							
bulk	0.70774	0.26	18.315	15.621	38.185	2.085	0.8529
replicate	0.70771	0.32	18.324	15.622	38.187	2.084	0.8525
Leach							
0-1"	0.70775	0.25	18.482	15.625	38.277	2.071	0.8454
1-2 1/4"	0.70774	0.30	18.484	15.623	38.274	2.071	0.8452
2 1/4 - 3 3/4"	0.70768	0.28	18.513	15.620	38.281	2.068	0.8437
3 3/4 - 5 1/4"	0.70770	0.25	18.397	15.637	38.242	2.079	0.8500
5 1/4" - 7 1/4"	0.70770	0.24	18.106	15.612	38.051	2.102	0.8622
7 1/4" - 9 1/4"	0.70768	0.18	18.230	15.623	38.177	2.094	0.8570
9 1/4" - 12 1/4"	0.70767	0.21	18.639	15.636	38.373	2.059	0.8389
Solid residue							
0-1"	n/a	n/a	18.464	15.633	38.286	2.074	0.8468
1-2 1/4"	0.70783	0.91	18.455	15.633	38.287	2.075	0.8471
2 1/4 - 3 3/4"	0.70775	0.70	18.517	15.632	38.318	2.069	0.8442
3 3/4 - 5 1/4"	0.70775	0.69	18.396	15.641	38.261	2.080	0.8502
5 1/4" - 6 3/4"	0.70777	0.97	18.070	15.633	38.081	2.107	0.8651
6 3/4" - 8 1/4"	0.70778	0.91	18.140	15.630	38.157	2.103	0.8616
8 1/4" - 11 1/4"	0.70772	1.21	18.541	15.640	38.346	2.068	0.8435

Table 54. Strontium and lead isotopes with length along hair for Surface donor 6 at FARF in Texas. Hair was exposed to the environment for two days, during which period there were heavy rains. Both bulk and results from the recommended leaching protocol of Tipple et al (2013) are shown.

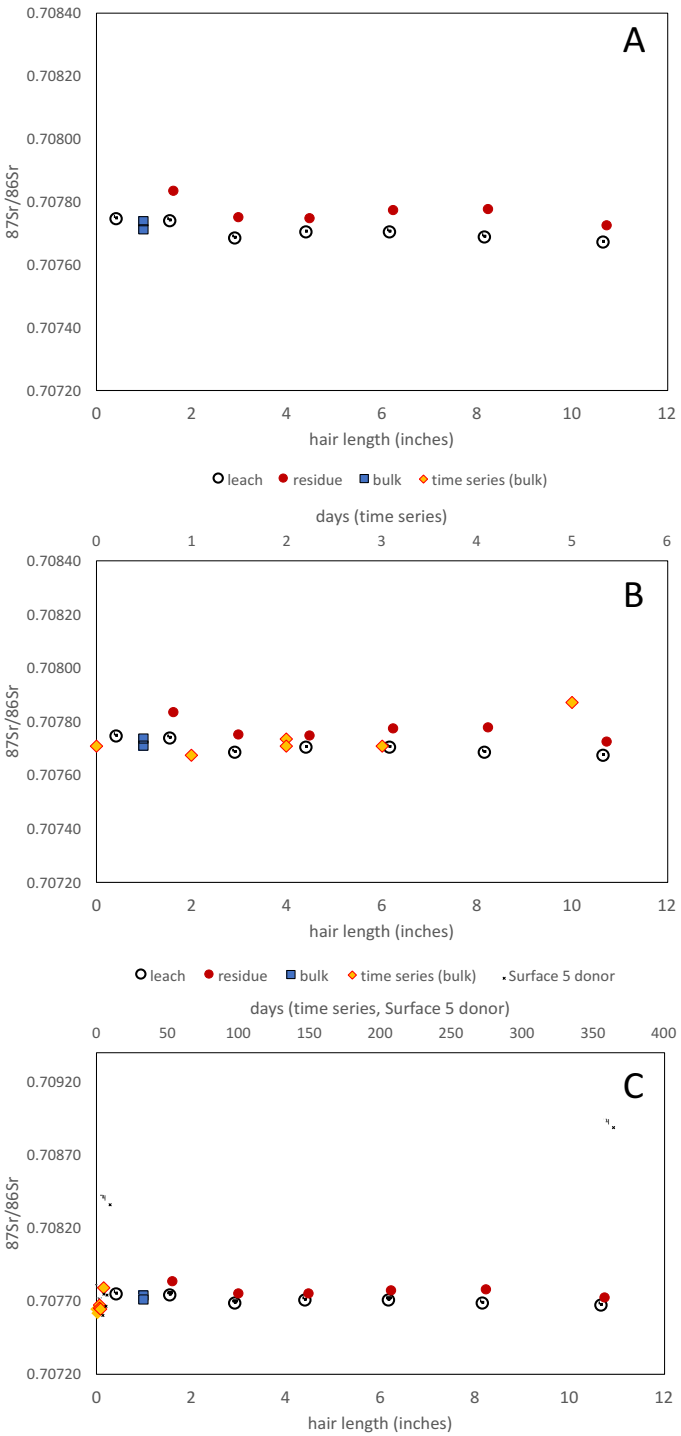

Figure 17. A) Radiogenic $^{87}Sr/^{86}Sr$ with length for bulk, leach, and residue values for hair for Surface donor 6 at FARF. B) The same values as figure A) with the addition of the variation in the bulk hair values over five days of exposure; the time axis is the secondary horizontal axis. C) The same figure, but with the addition of the variation over one year of exposure for Surface donor 5 at FARF. Note that the intake value for donor 5 was normalized to the intake value for donor 6 in order to better illustrate the scale of the changes. Note that the vertical scale is enlarged in A to show the variations.

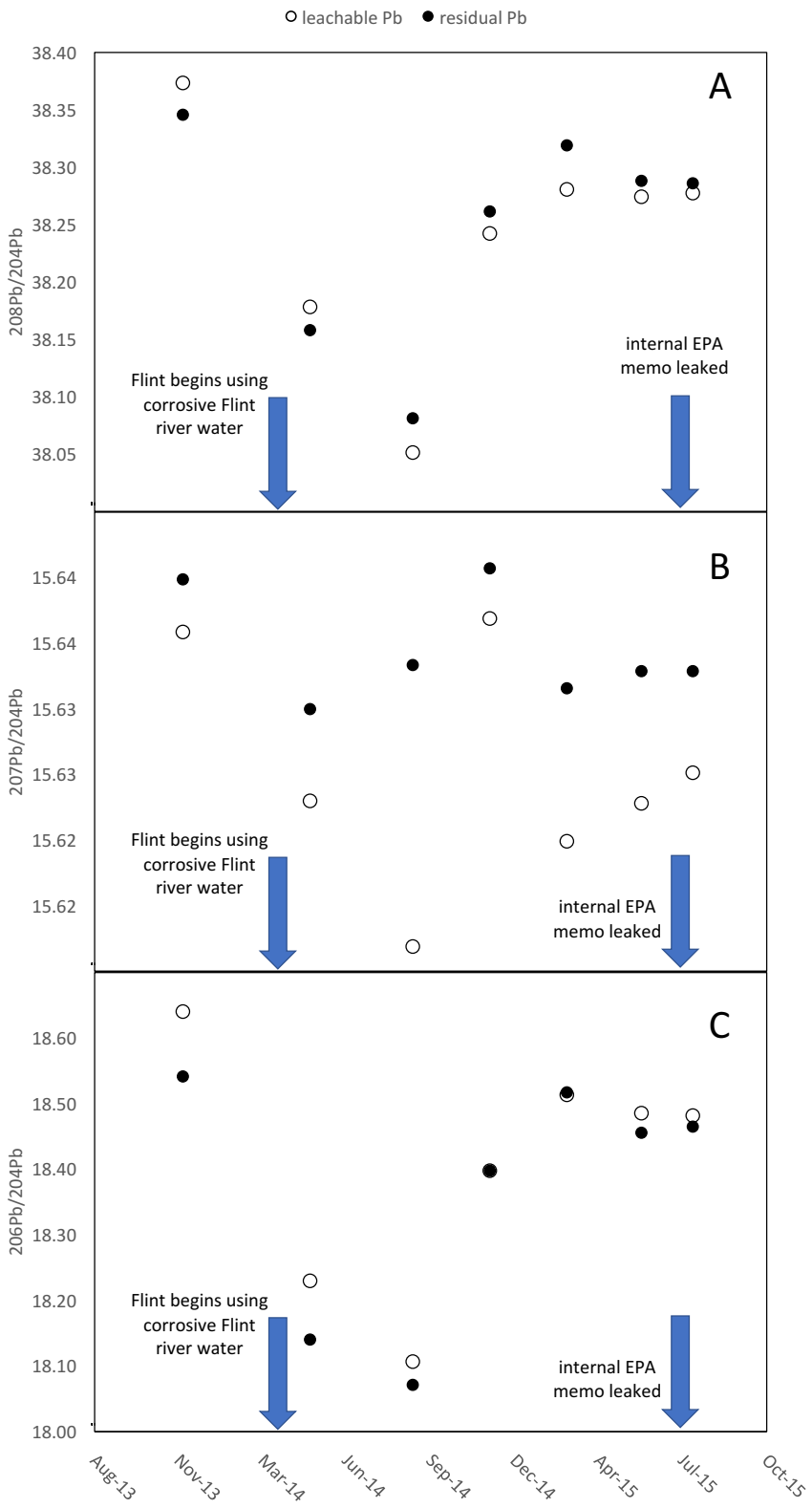

Figure 18. Variation in lead isotope ratios with date. A. $^{208}Pb/^{204}Pb$ over time, B. $^{207}Pb/^{204}Pb$ over time, and C. $^{206}Pb/^{204}Pb$ over time.

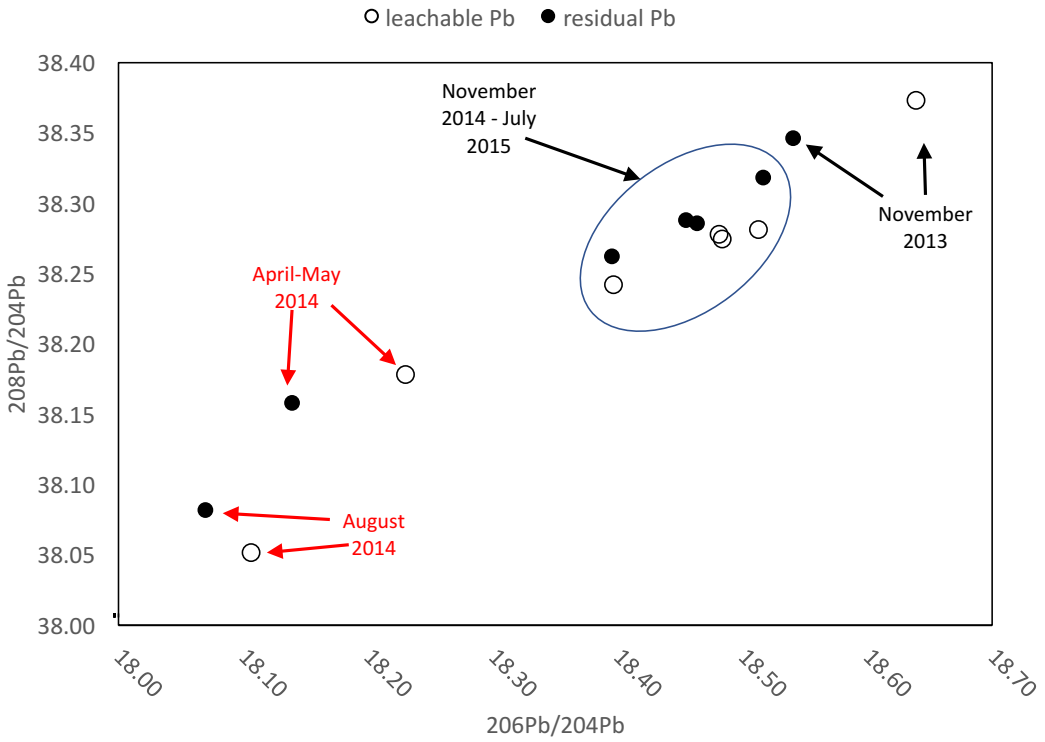

Figure 19. Covariation of lead isotopes in leachable and residual hair samples. The labels in red indicate the period of elevated lead concentrations.

This example combining lead concentrations and isotopic composition is a particularly effective example of why the combination of isotopes and elemental concentrations are highly effective in deconvoluting process and source. While a simplistic interpretation of the elevated lead concentrations with the donor's listed place of death (Flint, Michigan), and the broad coincidence of timing with changes in water source and known lead contamination might suggest that lead increases in water *preceded* the investigations into lead contamination (refs), the lead isotopes suggest that this was combined with a change in source for the lead.

Lead in hair is likely to be from a combination of factors, including drinking water, shower water, food, and environmental exposure such as living with a smoker or daily exposure to industrial sources. The lead isotopes provide a way to constrain which of these factors are most responsible for the observed increase.

This example clearly shows that a better understanding of the factors controlling the persistence of metal contamination in hair. This is critical to be able to separate spurious exogenous contamination from endogenous poisoning, and is absolutely essential in forensic

This resource was prepared by the author(s) using Federal funds provided by the U.S. Department of Justice. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

cases of poisoning. Metal contamination is likely to be controlled by different parameters than that of toxic organic exposures, which are likely to be incorporated more strongly in hair.

6.4.7 Aqueous exposure pilot experiment To conduct a very preliminary investigation of some of these factors, with the assistance of ASU undergraduate student Taghreed Adnan, we exposed hair to two different solutions, and measured the resulting solutions and solids.

The experimental design of this experiment was to take four aliquots of ~50 mg hair that appeared to be from the same individual from a salon, and place them in 50 mL centrifuge tubes. Deionized water (45 mLs) was added to two of the tubes ("deionized water experiment"), and 45 mLs of IAPSO seawater spiked with SRM 981 lead to a concentration of 24 ppb was added to the other two tubes ("seawater experiment"). Lead was added to the IAPSO seawater in order to measure the concentration of the various leachate solutions. However, because IAPSO seawater already contains lead, the resulting starting solution was isotopically intermediate between seawater and SRM 981.

Samples were allowed to sit for three days, and then the water was decanted off. Samples were then cleaned by sonicating twice in a 3:1 chloroform : methanol solution. One aliquot of each pair was then ground in a liquid nitrogen ball mill, and prepared for $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ analysis as previously described. The second aliquot was leached according to the Tipple et al (2015) protocol, with one modification. Instead of combining the three 0.1 N HCl leach solutions, each one was collected individually to evaluate the impact of the repeated cleaning steps. Elemental concentrations, radiogenic Sr, mass-dependent Sr, and Pb isotopes were measured in the starting solutions, the solutions decanted from the hair, the three individual leachate solution steps, and the final residual hair digest, as well as aliquots of the bulk hair. It should be noted that, although the hair appeared to come from the same individual, the hair was not homogenized prior to the aqueous soaking. Hence, the decanted solutions from bulk hair and leached hair should have been identical within each experiment. In addition, the concentrations of the final residual hair digest should have always been less than the bulk hair. This procedure was designed to simulate exposure, recovery, and processing of a forensic sample, although the hair was not decomposed.

The decanted solutions from the deionized water experiments had higher concentrations of some elements compared with the starting solution, suggesting that some elements leached out of the hair into the water. Mg, Ca, Fe, Zn, Sn, Ba, and Pb were particularly elevated. No elements showed decreases in concentration, although the starting solution was nearly always below instrumental detection limits. The three successive leachate solutions generally showed a pattern of decreasing concentrations; *e.g.*, calcium concentrations decreased from 116 ppm to 41 ppm to 18 ppm, suggested that the leaches were becoming less effective over time, or that the first leach liberated the most easily leachable material.

The decanted solutions from the seawater experiments had generally similar concentrations to that of the starting solution, although some concentrations were slightly lower. While some of the concentration differences were within error, the drop in some elemental concentrations indicated that the hair was able to sequester some elements including Na, Mg and K out of solution. A particularly striking example was lead; only 5-9% of the original lead in solution was present in the decanted solution, and the seawater residual hair digest had nearly seven times the amount of lead compared to the deionized water experiment residual hair digest. In fact, Ha and colleagues (2010) documented that burned human hairs can sequester substantial amount of metals, including Hg, Ag, Cu, Co, Fe, and Pb due to their porous quality of the hair. Gupta (2014) also reviewed the uses of human hair and noted that they have been used in many countries, particularly in the third world, as a way to capture heavy metals out of water.

Although concentrations were substantially higher in the seawater experiment compared with the deionized water experiment, the successive leaches again showed a pattern of decreasing concentrations with increasing number of leaches. While Mg decreased from 7.4 to 2.6 to 1.2 ppm in the deionized water experiment, in the seawater experiment, it decreased from 145 to 33 to 17 ppm.

The pattern of relative concentrations between the residual hair digests between the two experiments is quite telling. Na, Mg, K, and Pb all were substantially higher in concentration in the seawater residual digest compared to the deionized water digest, suggesting that the leaching protocol was not effective at removing the exogenous component of these metals. However, the bulk digest of the "seawater" hair was elevated in Ca and Sr, although the residual hair digest was similar in concentration to that of the bulk and residual hair digests of the deionized water

experiments, suggesting that the leaching protocol *may* have removed the exogenous component of Ca and Sr.

However, when looking at the measured isotopes of these samples, a more nuanced picture of the leaching mechanisms emerges. The $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, and $\delta^{2}H$ values all appeared unaffected by the aqueous exposure (Table 56), despite the fact that there was an offset of more than 10‰ in $\delta^{18}O$, and nearly 80‰ in $\delta^{2}H$ between the seawater and the hair. This, combined with the detailed time series hair analyses through decomposition, suggests that these isotope systems were relatively robust, despite exposure to large isotopic gradients.

Unfortunately, despite the similar concentration of strontium in the seawater and deionized water residual hair digests, the radiogenic $^{87}Sr/^{86}Sr$ values were substantially different (Table 57, Figure 20). This suggests that the strontium equilibrated with the solution within three days, and **the leaching protocol was unable to recover the original endogenous Sr isotope value.** Because the Sr concentrations of the solid residual before and after aqueous exposure were similar, additional leaching of the hair was unlikely to recover the endogenous isotope value. This is similar to the issues seen in studies of wool keratin (von Holstein et al 2014; von Holstein et al 2015).

The lead concentration of the seawater residual hair digest was 45% that of the bulk digest, but this was still 691% higher than that of the deionized water residual hair digest. Here, again, it appears that the lead equilibrated with the solution, and **the leaching protocol was unable to recover the original endogenous Pb isotope value** (Table 57, Figure 21). The lead concentration was highly elevated, so additional leaching could potentially have recovered the endogenous value. However, it would be very difficult to determine with any confidence that the endogenous value is recovered – even if 99.9% of the lead is removed. Indeed, the residual hair digest was not significantly closer isotopically to the hair values from the deionized water experiment compared with the seawater bulk digest – despite removing 55% of the lead.

The importance of these conclusions for forensic comparison can not be overstated. Unless a cadaver is known not to have been environmentally exposed to water, the measured Sr and Pb isotope values are unlikely to be endogenous. Indeed, it bears careful consideration what "endogenous" values actually represent, as they are probably a mixing between local shower water and consumed food and water.

However, again, light stable isotopes seem to be fairly robust at preserving the original isotope signature, despite extended aqueous exposure. While additional experiments including natural waters with bacteria, and variable pH, O_2 and ionic strength, as well as variable periods of time are critically needed, all preliminary results appear promising for the validity of C, N, and O isotopes. Hydrogen isotopes may have some additional caveats as discussed previously.

	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As
deionized water experiment																
water samples																
starting solution	<LOQ	0.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
decanted solution from leached hair	4.8	29.3	0.11	0.42	3.5	131	<LOQ	<LOQ	0.001	0.015	0.066	0.0001	0.002	0.027	6.2	0.0013
decanted solution from bulk hair	6.3	33.7	0.04	0.50	4.3	169	<LOQ	<LOQ	<LOQ	0.018	0.014	<LOQ	0.003	0.035	10.9	0.0014
leachate solutions																
leachate solution 1	<LOQ	7.4	0.37	1.10	0.10	116	0.015	<LOQ	0.0025	0.020	0.19	0.0002	0.011	0.14	38.0	<LOQ
leachate solution 2	0.13	2.6	0.17	0.36	<LOQ	41	0.006	<LOQ	0.0010	0.007	0.19	0.0001	0.008	0.09	14.6	<LOQ
leachate solution 3	0.09	1.2	0.09	0.25	<LOQ	18	0.006	<LOQ	0.0008	0.004	0.11	<LOQ	0.003	0.07	5.6	<LOQ
solid hair samples																
bulk hair (DI)	1.2	4.6	1.01	13	0.20	57	0.15	0.0018	0.066	0.018	1.37	0.0012	0.09	1.64	20.2	0.0021
solid hair residue (DI)	0.5	7.9	1.87	31	0.29	66	0.14	0.0060	0.580	0.062	4.66	0.0074	0.68	4.34	17.4	0.0033
seawater experiment																
water samples																
seawater starting solution	11933	1420	0.18	<LOQ	412	412	0.005	0.0013	0.0010	0.001	0.056	0.0002	0.006	<LOQ	0.06	0.0015
decanted seawater solution from leached hair	10977	1331	0.09	<LOQ	395	420	<LOQ	<LOQ	<LOQ	0.001	0.050	<LOQ	0.003	<LOQ	0.11	<LOQ
decanted seawater solution from bulk hair	9622	1152	<LOQ	<LOQ	340	355	0.005	<LOQ	<LOQ	0.001	0.005	<LOQ	0.002	<LOQ	0.14	0.0016
leachate solutions																
seawater leachate solution 1	8.8	145	0.88	0.65	0.60	137	0.010	0.0012	0.0025	0.004	0.22	0.0005	0.086	0.23	23.1	<LOQ
seawater leachate solution 2	3.4	33	0.26	0.26	0.16	39	0.005	0.0006	0.0013	0.002	0.14	0.0002	0.025	0.10	7.2	<LOQ
seawater leachate solution 3	0.68	17	0.08	0.31	<LOQ	22	<LOQ	<LOQ	0.0011	0.001	0.07	<LOQ	0.010	0.05	3.8	<LOQ
solid hair samples																
bulk hair (seawater)	20	187	1.91	16	1.24	234	0.23	0.015	0.021	0.010	1.50	0.0031	0.14	2.77	35.2	0.0014
solid hair residue (seawater)	24	34	0.94	22	1.23	52	0.15	0.014	0.494	0.041	3.25	0.0077	0.62	2.38	9.4	0.0021

Table 55. Elemental concentration of water and hair samples used in the aqueous exposure experiments. All concentrations are in ppm. Limits of quantitation and detection limit are not listed, as the dilution factors for samples were optimized by sample type, and a general correction was not possible.

	Rb	Sr	Mo	Pd	Ag	Cd	Sn	Sb	Te	Ba	La	Ce	Pr	Nd	Sm
deionized water experiment															
water samples															
starting solution	<LOQ	<LOQ	<LOQ	0.00003	<LOQ	<LOQ	0.0007	0.0006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
decanted solution from leached hair	0.0040	1.25	0.0035	0.00003	<LOQ	0.0002	0.0058	0.0018	<LOQ	0.19	0.00006	0.00009	0.00001	0.00005	<LOQ
decanted solution from bulk hair	0.0052	1.53	0.0021	0.00003	<LOQ	0.0006	0.0023	0.0020	<LOQ	0.26	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
leachate solutions															
leachate solution 1	0.0003	1.14	0.0004	0.00004	0.0024	0.0051	0.0134	0.0006	<LOQ	0.42	0.00095	0.00166	0.00006	0.00027	0.00045
leachate solution 2	<LOQ	0.41	<LOQ	0.00003	0.0009	0.0014	0.0080	0.0004	<LOQ	0.18	0.00030	0.00046	0.00002	0.00009	<LOQ
leachate solution 3	<LOQ	0.18	<LOQ	0.00003	0.0008	0.0004	0.0044	0.0004	<LOQ	0.09	0.00015	0.00026	0.00001	0.00006	<LOQ
solid hair samples															
bulk hair (DI)	0.0007	0.55	0.009	0.00006	0.0030	0.0021	0.16	0.0038	<LOQ	0.26	0.00079	0.00119	0.00011	0.00046	0.0009
solid hair residue (DI)	0.0013	0.52	0.019	0.00006	0.0036	0.0060	0.21	0.0116	<LOQ	0.29	0.00249	0.00392	0.00029	0.00118	0.0020
seawater experiment															
water samples															
seawater starting solution	0.107	7.11	0.011	0.00002	<LOQ	0.0002	0.0016	0.0008	<LOQ	0.07	0.00008	0.00011	0.00002	0.00006	<LOQ
decanted seawater solution from leached hair	0.109	7.18	0.010	0.00005	<LOQ	0.0002	0.0021	0.0006	<LOQ	0.08	0.00007	0.00012	<LOQ	<LOQ	<LOQ
decanted seawater solution from bulk hair	0.091	6.05	0.010	0.00003	<LOQ	0.0002	0.0009	0.0007	<LOQ	0.08	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
leachate solutions															
seawater leachate solution 1	0.0004	1.70	<LOQ	0.00003	0.0016	0.0016	0.0176	0.0005	<LOQ	0.04	0.00086	0.00111	0.00014	0.00058	0.00097
seawater leachate solution 2	<LOQ	0.48	<LOQ	0.00003	0.0008	0.0005	0.0106	0.0003	<LOQ	0.02	0.00020	0.00025	0.00003	0.00013	<LOQ
seawater leachate solution 3	<LOQ	0.27	<LOQ	0.00003	0.0005	0.0003	0.0086	0.0015	<LOQ	0.01	0.00007	0.00008	<LOQ	0.00004	<LOQ
solid hair samples															
bulk hair (seawater)	0.0016	2.87	0.007	0.00004	0.0036	0.0031	0.17	0.0037	<LOQ	0.10	0.00160	0.0024	0.00025	0.00103	0.0018
solid hair residue (seawater)	0.0010	0.64	0.011	0.00005	0.0018	0.0009	0.10	0.0064	<LOQ	0.03	0.00085	0.0013	0.00012	0.00052	0.0011

Table 55. Elemental concentration of water and hair samples used in the aqueous exposure experiments continued.

	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Re	Pt	Pb	U
deionized water experiment															
water samples															
starting solution	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00010	0.00012	<LOQ
decanted solution from leached hair	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00002	<LOQ	<LOQ	0.00004	0.00009	0.00027	0.00003
decanted solution from bulk hair	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00003	<LOQ	0.00003	0.00011	0.00024	0.00024	0.00003
leachate solutions															
leachate solution 1	0.00002	0.00005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00004	<LOQ	0.00001	0.00010	0.035	0.003	
leachate solution 2	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00003	<LOQ	0.00001	0.00008	0.013	0.001	
leachate solution 3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00003	<LOQ	<LOQ	0.00008	0.006	0.001	
solid hair samples															
bulk hair (DI)	0.00002	0.00008	<LOQ	0.00006	<LOQ	<LOQ	<LOQ	<LOQ	0.0011	0.0042	0.00004	0.00043	0.036	0.010	
solid hair residue (DI)	0.00004	0.00018	0.00034	0.00016	0.00003	0.00010	0.00011	0.00008	0.00001	0.0031	0.0040	0.00004	0.00084	0.036	0.012
seawater experiment															
water samples															
seawater starting solution	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00002	<LOQ	0.00001	0.00007	0.024	0.003	
decanted seawater solution from leached hair	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00002	<LOQ	<LOQ	0.00015	0.002	0.002	
decanted seawater solution from bulk hair	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00002	<LOQ	0.00001	0.00009	0.001	0.001	
leachate solutions															
seawater leachate solution 1	0.00002	0.00011	0.00016	0.00009	0.00002	0.00006	0.00009	0.00006	0.00001	0.00008	<LOQ	<LOQ	0.00009	0.38	0.019
seawater leachate solution 2	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00003	<LOQ	<LOQ	0.00010	0.13	0.006	
seawater leachate solution 3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00002	<LOQ	0.00001	0.00008	0.07	0.003	
solid hair samples															
bulk hair (seawater)	0.00004	0.00016	0.00026	0.00015	0.00003	0.00010	0.00015	0.00010	0.00001	0.0031	0.0029	<LOQ	0.00085	0.55	0.032
solid hair residue (seawater)	0.00002	0.00009	<LOQ	0.00008	0.00002	<LOQ	<LOQ	<LOQ	<LOQ	0.0015	0.0051	<LOQ	0.00045	0.25	0.014

Table 55. Elemental concentration of water and hair samples used in the aqueous exposure experiments continued.

	δ^2H_{VSMOW} (‰)	$\delta^{18}O_{VSMOW}$ (‰)	weight % H	weight % O	O/H
bulk hair (DI)	-70.47	11.37	5.08	20.35	4.00
bulk hair (seawater)	-72.82	11.58	5.25	20.96	3.99
seawater (starting solution)	6.78	1.18			
	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	weight % C	weight % N	C/N
bulk hair (DI)	9.80	-17.69	15.23	45.26	2.97
bulk hair (seawater)	9.86	-17.56	14.78	43.82	2.96

Table 56. Carbon, nitrogen, oxygen, and hydrogen isotope results of hair exposed to either deionized water or IAPSO seawater for three days at room temperature. The measured $\delta^{18}O$ and δ^2H values of the seawater solution used in the experiments are also shown.

	$^{87}Sr/^{86}Sr$	$\delta^{88/86}Sr$ (‰)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
deionized water experiment							
water samples							
starting solution	n/a	n/a	n/a	n/a	n/a	n/a	n/a
decanted solution from leached hair	0.71497	0.59	n/a	n/a	n/a	n/a	n/a
decanted solution from bulk hair	0.71496	0.48	n/a	n/a	n/a	n/a	n/a
leachate solutions							
leachate solution 1	0.71493	0.45	18.312	15.614	38.171	2.084	0.853
leachate solution 2	0.71482	0.45	18.327	15.610	38.157	2.082	0.852
leachate solution 3	0.71460	0.58	18.373	15.609	38.158	2.077	0.850
solid hair samples							
bulk hair (DI)	0.71445	0.48	18.405	15.619	38.192	2.075	0.849
solid hair residue (DI)	0.71390	0.74	18.397	15.580	38.100	2.071	0.847
seawater experiment							
water samples							
seawater starting solution	0.70920	0.68	17.048	15.491	36.805	2.159	0.909
decanted seawater solution from leached hair	0.70925	0.58	17.118	15.500	36.877	2.154	0.905
decanted seawater solution from bulk hair	0.70927	0.61	17.142	15.490	36.880	2.152	0.904
leachate solutions							
seawater leachate solution 1	0.70924	0.42	17.074	15.490	36.826	2.157	0.907
seawater leachate solution 2	0.70923	0.48	17.112	15.496	36.866	2.154	0.905
seawater leachate solution 3	0.70924	0.48	17.135	15.497	36.885	2.153	0.904
solid hair samples							
bulk hair (seawater)	0.70929	0.51	17.131	15.502	36.896	2.154	0.905
solid hair residue (seawater)	0.70925	0.72	17.164	15.502	36.920	2.151	0.903

Table 57. Strontium and lead isotopic compositions for water and hair samples in aqueous exposure experiment.

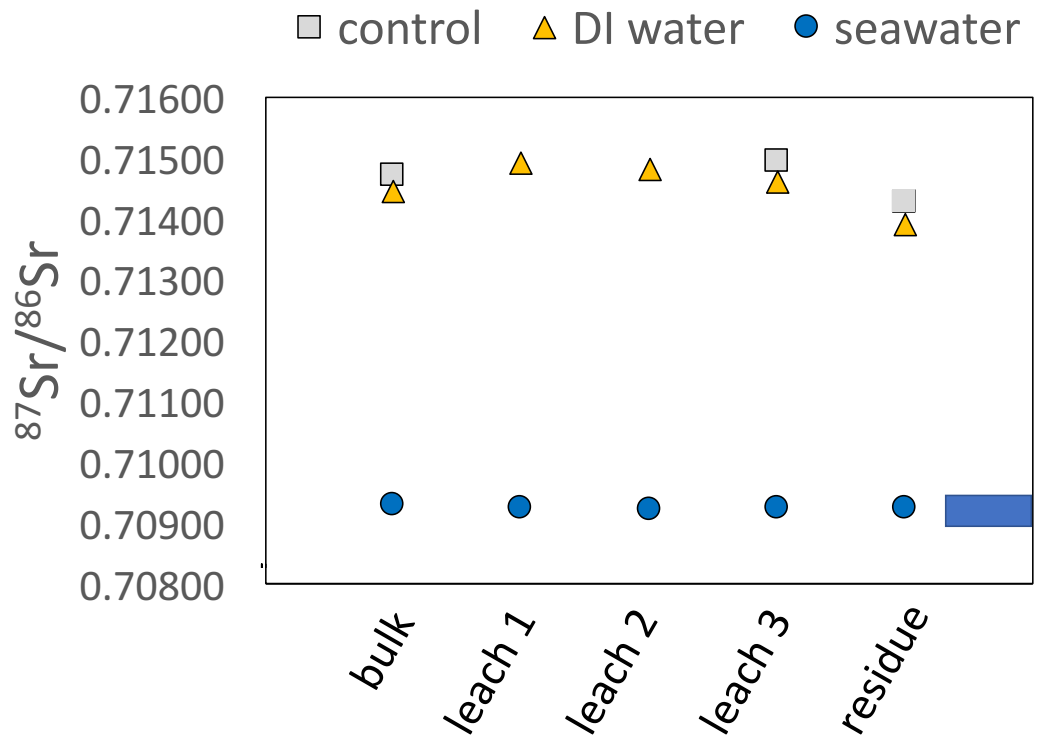

Figure 20. Radiogenic strontium isotope values of hair samples stored in either deionized water, seawater, or control (no water exposure) for three days.

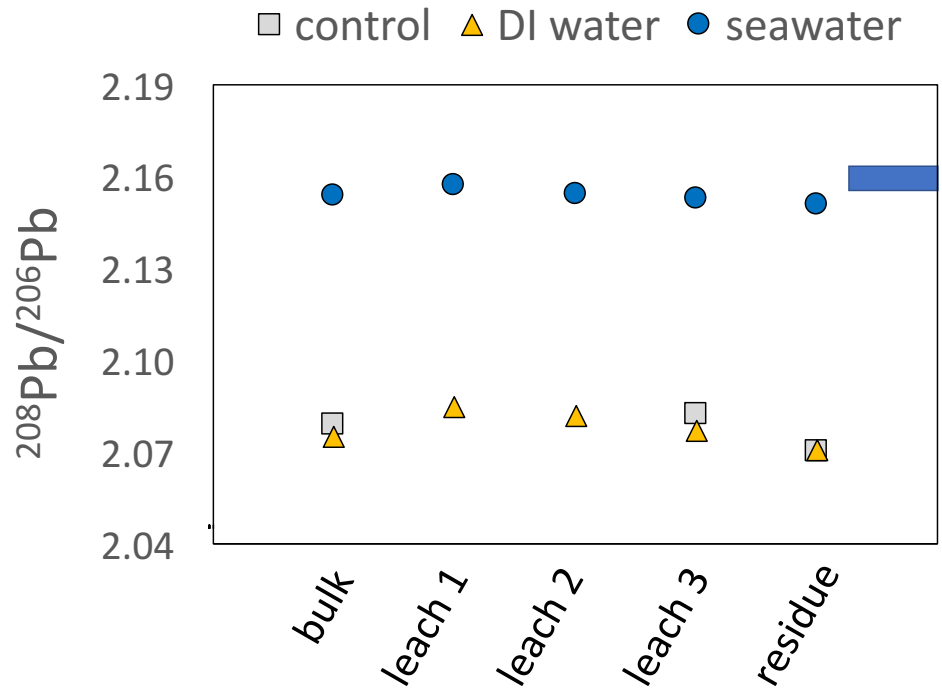

Figure 21. $^{208}Pb/^{206}Pb$ isotope values for hair samples stored in either deionized water, seawater, or control (no water exposure) for three days.

7. CONCLUSIONS

7.1 DISCUSSION OF FINDINGS

7.1.1 Accuracy of geographical predictions of origins A detailed consideration and discussion of the prediction of geographic origin from isotope measurements in human tissue is outside the scope of this research. There are numerous researchers who have done excellent work on this topic (France et al 2014, Lightfoot and O'Connell 2016, Podlesak et al 2008, Sponheimer et al 2003, West et al 2009, Bowen et al 2007, Chenery et al 2012, Daux et al 2008, Podlesak et al 2012, Kennedy et al 2011, Passey et al 2005, Chesson et al 2012, among others). However, we performed comparisons as related to the accuracy of prediction building on the substantial previous work of others. We considered each tissue and isotope system independently.

Donor	last residence	δ^2H_{VSMOW} (‰)	δ^2H 95% CI (‰)	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{18}O$ 95% CI (‰)
	ARF facility	-34	0	-5.8	0.0
Surface 1	Rock Hill, SC (6 years)	-31	2	-5.1	0.2
Surface 2					
Surface 3					
Burial 1	Roswell, GA	-34	1	-6	0.1
Burial 2	LaFollette, TN	-36	1	-6.1	0.1
Burial 3	Lenoir City, TN (11 years)	-33	1	-5.7	0.1
	FARF facility	-22	1	-3.9	0.1
Surface 4	Austin, TX	-21	0	-3.7	0.0
Surface 5	Austin, TX	-21	0	-3.7	0.0
Surface 6	Flint, MI	-62	1	-9.3	0.2
Surface 7	Conroe, TX	-20	1	-3.4	0.1
Burial 4	Austin, TX	-21	0	-3.7	0.0
Hair mat 1	Houston, TX	-19	0	-3.2	0.0
Hair mat 2	San Antonio, TX	-20	1	-3.7	0.1
Hair mat 3	San Antonio, TX	-20	1	-3.7	0.1
Hair mat 4	San Marcos, TX	-21	1	-3.7	0.1
Hair mat 5	San Antonio, TX	-20	1	-3.7	0.1
Hair mat 6	Berwyn, IL	-43	1	-6.2	0.2
Hair mat 7	Nashville, TN	-32	1	-5.4	0.1
Hair mat 8	Kempner, TX	-23	1	-4.2	0.1
Hair mat 9	San Antonio, TX	-20	1	-3.7	0.1
Hair mat 10	Boerne, TX	-25	2	-4.3	0.2

Table 58. Predicted annual precipitation for the place of last known residence for the donors in the study. When available, the length of residence in years at the last known residence is listed. Latitude, longitude and altitude values were taken from Google Earth 7.1.8.3036. Precipitation values and confidence intervals are calculated from the OIPC 3.1 (Bowen 2017).

7.1.2 Teeth and birthplace The assumptions needed to covert a measured carbonate $\delta^{18}O$ value in tooth enamel to a geographic residence history include 1) characterization of local drinking water, 2) intra-individual and inter-individual variability, and 3) conversion of carbonate $\delta^{18}O$ to drinking water.

A number of considerations exist when assessing what water value is represented in tooth enamel. Considerable literature has investigated the sources, fractionation factors, and associated variations between $\delta^{18}O$ in tooth enamel carbonate and body water. Sources of water include drinking water and food, and should include consideration of the effect of evaporative boiling during food preparation, as well as the impact of bottled water consumption. This means that there can be spatial patterns within a small region, particularly with the impact of water resource use (*cf* Tipple 2016, Ueda and Bell, 2017, Jameel et al 2016). As Tipple (2016) elegantly demonstrated in six US western areas, municipal water usage including groundwater, surface water, and transported water can cause distinct, persistent spatial isotope patterns within a municipality's tap water that are reflected in the hair of residents. In addition, temporal patterns of tap water (Kennedy et al 2011) can mean there can be substantial variability within a region. The most data available for creating isoscapes is typically precipitation databases. While there has been enormous strides in characterizing tap water isoscapes (Kennedy et al 2011, Bowen et al 2007, Coplen et al 2013, Tipple 2016), additional work remains.

There is some inherent variability within a local population, even if everyone has access to identical food and water sources (Pellegrini et al 2016, Lightfoot and O'Connell, 2016). Podlesak et al (2005) produced a body water model that considers mass, height, activity level, and 40 other parameters to create a comprehensive model that converts sources to body water. Once body water is estimated or modeled, the researcher wanting to predict geographic origins then needs to consider the fractionations associated with producing the relevant tissue (hair, bone, and teeth).

Considerations of these conversions include the tissue turnover time and the chemical bonding environment for that particular ion. For instance, $\delta^{18}O$ can be measured in both phosphate and carbonate in tooth enamel. Hydroxyapatite has the formula $Ca_5(PO_4)_3(OH)$, and phosphate is a primary component. However, in order to measure the $\delta^{18}O$ in the phosphate, significantly more sample preparation is involved, including dissolution and re-precipitation of the phosphate as silver phosphate. The assumption is that the oxygen is bound sufficiently strongly in the phosphate ion, and therefore does not exchange during this process of moving from $Ca_5(PO_4)_3(OH)$ to Ag_3PO_4. However, there are concerns about the fractionation associated with this processing and its variability (REFS).

A method that does not involve dissolution and precipitation is to measure the $\delta^{18}O$ in interstitial carbonate; measurement is performed by chemically cleaning tooth enamel and then releasing the CO_2 by addition of phosphoric acid immediately prior to analysis. This method has the advantage of less laborious sample preparation, but requires substantially more enamel due to the lower abundance of the carbonate phase compared to the phosphate phase. There are significant offsets in $\delta^{18}O$ between the phosphate and carbonate phases (Bryant et al 1996), directly related to the different bonding environments of the oxygen.

In addition, the advantage of tooth enamel is that it nominally records the locale when the individual was young, no longer varying after formation. However, there is a range of time when tooth enamel is forming, which is substantially earlier than tooth eruption. In anthropology, there is a preference for measuring molars or premolars; these dental elements have substantially more and thicker enamel than canines or incisors. Due to poor dental condition of a number of our donors, as well as concern about jaw damage when removing molars from a donor which all had soft tissue intact, we used a variety of dental elements including canines and incisors, which also means there is an age range represented.

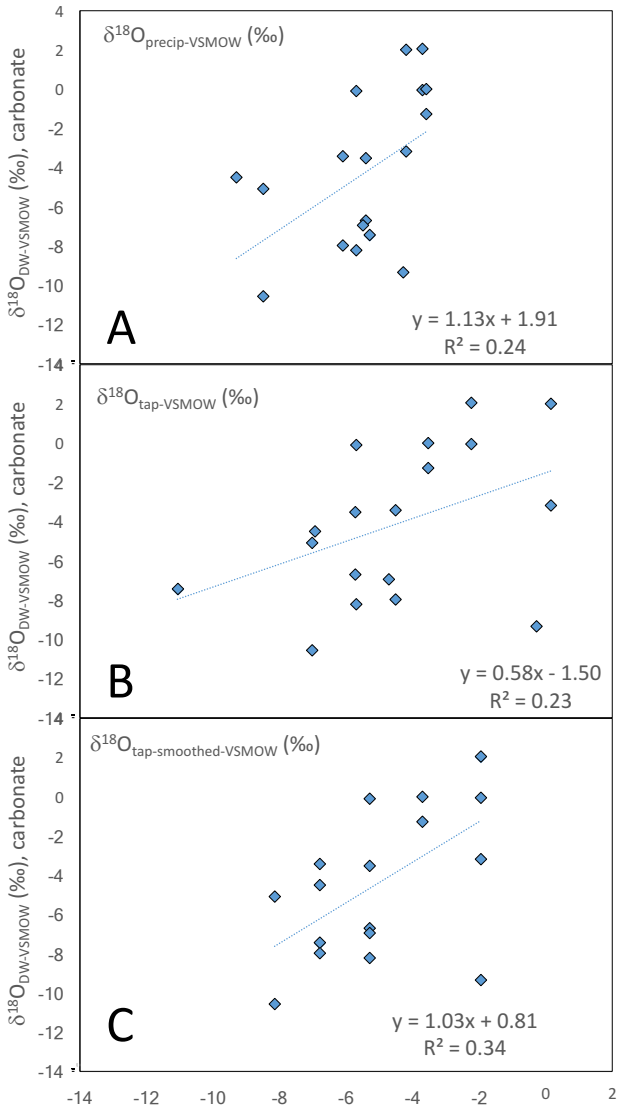

Figure 22. Plot of $\delta^{18}O_{VSMOW}$ of water from that predicted from tooth carbonate. The conversion of $\delta^{18}O$ in tooth carbonate to drinking water (y-axis) used the equation from Ehleringer et al (2009). A different potential water comparison is shown in each of the three panels: A) Annual precipitation values and 95% confidence intervals from OIPC v. 3.1 (Bowen, 2017; http://waterisotopes.org); B) tap water measurements downloaded from the database at http://wateriso.utah.edu/waterisotopes/pages/spatial_db/SPATIAL_DB.html (number of measurements utilized and data sources are in table YY); and C) smoothed tap water averages from figure 7 of Bowen et al (2007). A perfect prediction trendline would have a slope of 1 and intercept of 0.

Surface 1, 2, 3, 5, Burial 1, and 2 all had systematically isotopically lighter $\delta^{18}O$ values in the recovery teeth compared to the intake teeth. Surface 4 was isotopically heavier in $\delta^{18}O$, while Burial 3 was the same within error. This could suggest that there were systematic preservation

problems. However, there is also a more likely explanation: bias in tooth element sampling. Four of the six tooth pairs that had isotopically lighter $\delta^{18}O$ values also had incisor or canine teeth sampled during intake, with premolar or molar teeth sampled during recovery. The other two pairs had both canine or both incisor teeth sampled. When we used the Ehleringer et al (2009) equation to covert carbonate tooth $\delta^{18}O$ values to drinking water and compared it to the smoothed drinking water trends in Bowen et al (200x), we found the data represented in Figure BB.

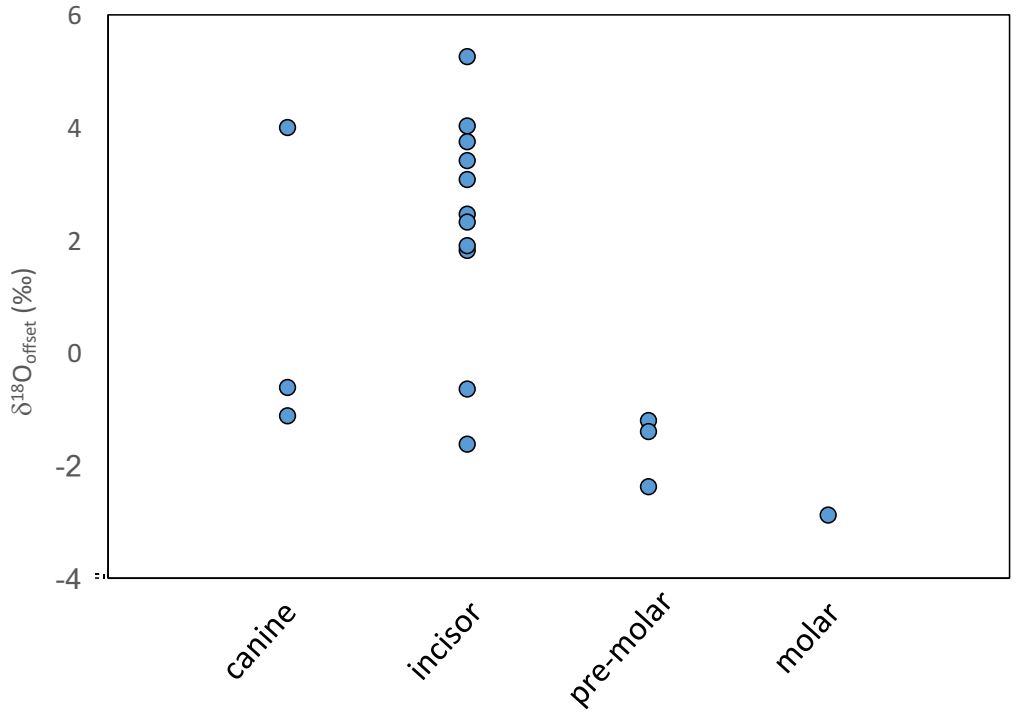

Figure 23. Tooth element plotted against the offset between the $\delta^{18}O$ drinking water value predicted from the measured $\delta^{18}O$ in enamel carbonate (Ehleringer et al 2009) and that of the estimated smoothed tap water values (Bowen et al 200x) from known residence in early life.

There appears to be a strong correlation between the offset between that converted from the measured value from the known early life residence location and tooth element. Incisors appear to be particularly problematic with respect to accurate preservation of the isotopic composition.

The other explanations for these patterns are less compelling. It is unlikely to be age related, because this would have required that most of the donors had systematically moved large distances from their birthplaces, typically toward the north or west. For example, Surface 1 was

born in Minnesota and would have needed to move to a band including Bismarck, ND; Denver, CO; or Portland, OR.

The expected range of local drinking water may not be known. Jameel et al (2016) found a range of 6.1‰ in $\delta^{18}O$ of drinking water, although the standard deviation of the dataset was only 1.0‰. However, Tipple et al (2016) showed that water management practices in the Phoenix area resulted in larger $\delta^{18}O$ drinking water ranges of ~11‰ over the course of a season, while the greater Los Angeles area had a range of 8.9‰.

In addition to the range of local drinking water, there is the issue of variability in the isotopic offset between drinking water and body water due to biological effects such as metabolic rate, disease, and activity level, as well as the other parameters considered in detail in Podlesak et al (2008; 2012). Other concerns with conversion from tooth enamel to drinking water are enumerated in Pellegrini et al (2016) and Lightfoot and O'Connell (2016). Fricke and O'Neil (1996) found a 3.5‰ range in the $\delta^{18}O_P$ of a domesticated sheep, and ascribed this to seasonal variation in drinking water. Tipple et al (2016) found a 5‰ range in $\delta^{18}O$ of hair from the Phoenix metropolitan region, but hair has a much faster growth rate than teeth, and might be expected to show a larger range than teeth, which homogenize water from food and water over a larger time. France et al (2014) found a 5.5‰ with a standard deviation of 1.5‰ (n=28) for $\delta^{18}O$ of structural carbonate in 18^{th-} and 19^{th-}century burials of known Southern United States origin, and a range of 9.3‰ with a standard deviation of 1.5‰ (n=94) in $\delta^{18}O$ of structural carbonate of known Northern US origin. Lightfoot and O'Connell (2016) considered a number of different ways of characterizing non-local individuals within a population, with values 2‰ outside the mean as the simplest. They clearly make the case that 2‰ is likely to significantly underestimate the actual $\delta^{18}O_{enamel}$ variability within a single archaeological site, and that several other statistical methods (1.5IQR or $3MAD_{NORM}$) are more appropriate. In our case, however, we were not looking at a normal human settlement with an anticipated range of values, but individuals from known regions that had been moved to a single locale after death. Hence, doing this type of statistical analysis is inappropriate.

As a preliminary evaluation of the amount of offset between the predicted drinking water, we compared the $\delta^{18}O$ values from published isoscapes (Bowen 2007) and that predicted from the carbonate in tooth enamel (Figure BB). This analysis investigated different cutoff values for

$\delta^{18}O_{DW\text{-}carbonate} - \delta^{18}O_{DW\text{-}isoscape}$ and its impact on classifying individuals as local or non-local. Using a cut-off value of 2‰ classified 79% of the individuals as non-local using local precipitation, and 58% as non-local using smoothed tap water. This high degree of misclassification suggests either that there were significant problems with the estimated drinking water from the isoscapes, the conversion of $\delta^{18}O$ of tooth carbonate to drinking water, or the measured tooth enamel values. However, if we exclude all incisor and canine dental elements and use a 3‰ cutoff, then all of the individuals would be correctly classified as coming from their known region of origin (Figure 24).

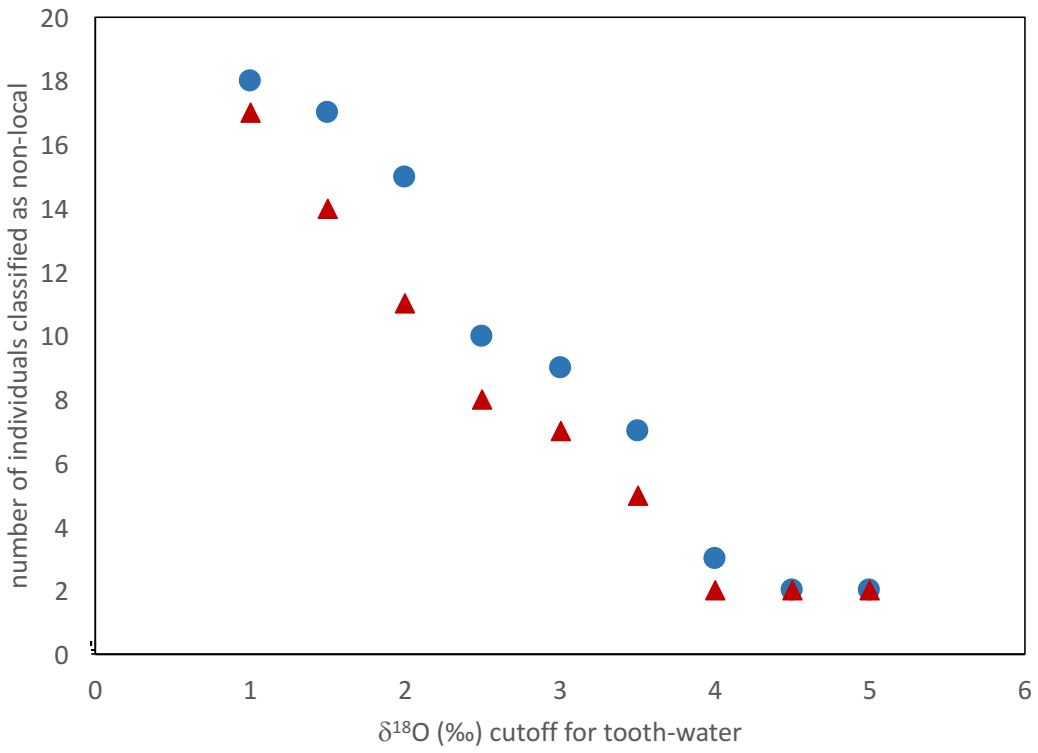

Figure 24. The number of teeth (total n=19) that would be classified as non-local using different cut-off values for $\delta^{18}O$ differences between the drinking water predicted from measured tooth enamel and estimated drinking water.

Most of the donors did not have travel during early life recorded. The forms request birthplace and last place of residence, as well as travel history. Most donors or their families filled out extensive documentation, but we cannot verify that no early travel means the donor was stationary. One donor, Burial 3, recorded a substantial amount of travel that would have

impacted the isotopic values recorded in his teeth. Lower incisors (the tooth collected at donor intake) erupt between 6-8 years of age, while lower canines (the tooth collected upon recovery approximately one year later) typically erupt between 9-10 years of age (American Dental Association Factsheet, 2017). Both the teeth had the same $\delta^{18}O$ value within error, and the predicted value most closely represented the donor's residence in California from ages 3-26.

			carbonate	precipitation		tap water	smoothed tap water	
		age	$\delta^{18}O_{VSMOW-DW}$ (‰)	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{18}O$ 95% CI (‰)	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{18}O$ 95% CI (‰)
Burial 3	North Dakota	0-1		-11.5	0.2	-14.5	-13.95	0.65
	Louisiana	1-3		-4	0.1	0.56	-1.95	0.85
	California	3-26		-5.3	0.5	-11.07	-6.8	0.7
	intake: *incisor*		-7.46					
	recovery: left lower canine		-7.44					

Table 59. Comparison of the $\delta^{18}O$ values predicted for precipitation (Bowen 2017a), tap (Bowen 2007 as found from Bowen 2017), and smoothed tap water (Bowen 2017b) for Burial 3. The conversion of $\delta^{18}O$ in tooth carbonate to drinking water used the equation in Ehleringer et al (2009). Exact locations of residence history are not listed to maintain donor anonymity.

The wide variability of the measure $\delta^{18}O$ values for canine and incisor elements was problematic. When considering diagenetic changes, many of the standard criteria were met. The Ca/P ratio for all tooth samples was between 2.06 – 2.11, very similar to the value for ideal hydroxyapatite at 2.08. The uranium concentration was below the limit of quantification for most samples, with a maximum concentration of 0.046 ppm. The Ca/Sr ratios for intake and recovery teeth were very similar per individual, although there was substantial variation between the donors. This was quite low compared to fossil teeth that are routinely considered to be well preserved (Reynard & Balter 2014).

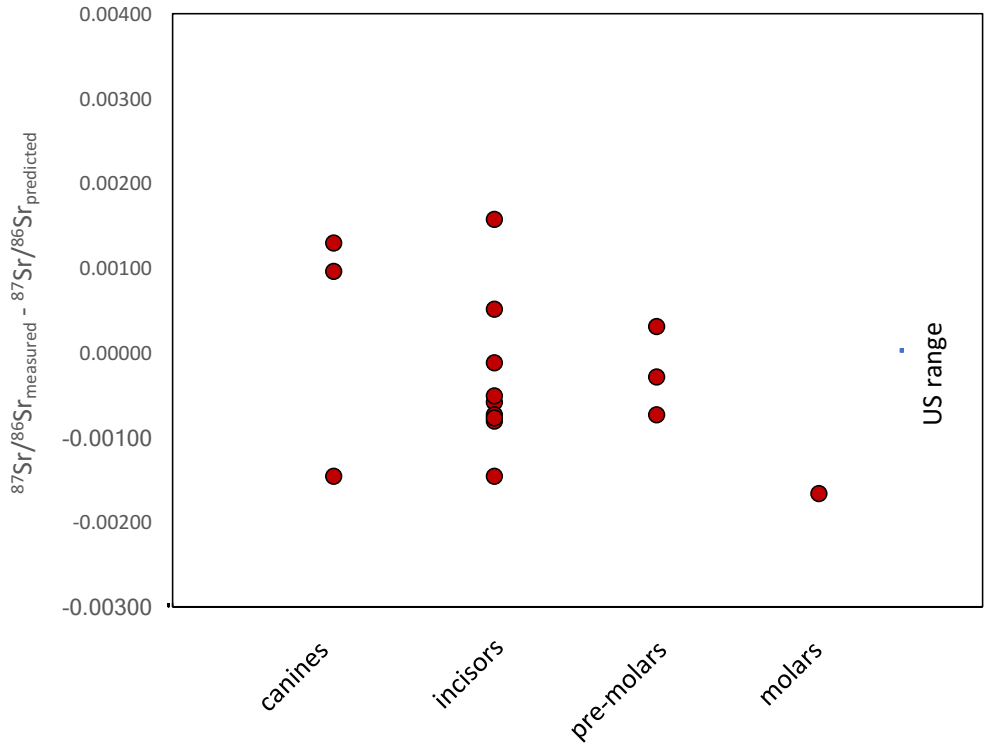

Figure 25. Offset between the measured $^{87}Sr/^{86}Sr$ values for tooth enamel and the predicted $^{87}Sr/^{86}Sr$ value from the flux-weighted catchment water model values averaged within watersheds of the Watershed Boundary Dataset (Figure 9C in Bataille and Bowen (2012). This model produced better agreement between the measured values and the predictions of the bedrock age only model (Beard and Johnson 2000, as shown in Figure 6B of Bataille and Bowen 2012), the weathered bedrock age model with modification for carbonate (Figure 6A, Bataille and Bowen 2012), or local water (Figure 9A, Bataille and Bowen 2012).

7.2 Implications for policy and practice Within the limitations of the sample size, limited environments, and exposure time studied, teeth, bone and hair $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ inferences about region of origin and diet are similar between post-mortem and pre-mortem measurements; $\delta^{2}H$ measurements have more variability but generally preserve original values. Elemental concentrations, Sr, and Pb isotopes are preserved through decomposition in teeth and bone. However, elemental concentrations, Sr, and Pb isotopes are *not* well preserved in hair, despite best practices in cleaning and sample preparation. Improvements in leaching and sample preparation are unlikely to recover endogenous values. Rare earth elements may be developed as a useful postmortem modification indicator for hair. While endogenous values may be preserved

in some cases and environments, it will be difficult to have confidence in the region of origin interpretation for bodies that have been exposed to the elements for more than a few days.

We strongly recommend that any laboratories doing isotopic analyses of unknown modern human remains be involved with regular blind testing of a variety of matrix-matched standards, and that reporting the results of recent testing and details of QA/QC should be required prior to publication. Membership in accrediting bodies such as FIRMS[9] should be strongly encouraged to have an external validation of laboratory protocols. Continuing development and frequent use of additional certified matrix-matched standards for measurement validation such as USGS 42 and 43 for hair is critical for elucidation of matrix-specific issues. Additional studies of the isotopic variability both within individuals of a local population, as well as intra-individual skeletal and dental elements of known individuals is clearly needed to place accurate error estimates on geolocation and dietary inferences.

Despite concerns developed here about the accuracy and interpretation of Sr and Pb isotopes in hair, teeth and bone are robust indicators for geolocation prediction of unknown individuals. This study strongly supports the continued implementation of isotopic signature implementation in forensic case work on a broader and more consistent basis. Costs for this type of analysis are quite modest compared to the total cost of investigation, and additional federal funding earmarked for such work has the potential to provide many scientifically solid leads for identification.

7.3 Implications for further research Additional work is needed to more thoroughly evaluate the accuracy and error rate of estimating provenance for known human remains, so that it can be applied in a consistent and intelligent way to unknown human remains. Studies such as

[9] Forensic Isotope Ratio Mass Spectrometry Network (http://www.forensic-isotopes.org/)

those proposed by IsoForensics (2016) are precisely the types of further research that are needed. To fully utilize isotopes for estimating provenance, more work on estimating variance is needed. This includes both intra-population variance (Tipple, 2016, Jameel, 2016), but also intra-individual variance utilizing multiple skeletal and dental elements, as well as hair. The latter is most likely to be similar to forensic cases, and demands further study. As populations become increasingly mobile due to military conflicts, climate change, economic refugee status, and easier transportation, understanding how these movements are reflected in human tissues becomes increasingly important. These techniques can be used in a wide variety of individual forensic cases, human rights investigations, military recovery operations, and national security intelligence. Studies should be optimized to look at each of these applications independently, while realizing that further understanding in one area will lead to insights and improved investigations in other applications.

8. REFERENCES

I. References

Aggarwal, J., Habicht-Mauche, J., & Juarez, C. (2008). Application of heavy stable isotopes in forensic isotope geochemistry: A review. *Applied Geochemistry*, 23, 2658-2666.

Alkass, K., Buchholz, B. A., Druid, H., & Spalding, K. L. (2011). Analysis of ^{14}C and ^{13}C in teeth provides precise birth dating and clues to geographical origin. *Forensic Sci. Intl.*, 209, 34-41, 10.1016/j.forsciint.2010.12.002.

Anbar, A. D. (2004). Iron stable isotopes: beyond biosignatures. *Earth Planet. Sci. Lett.*, 217, 223-236, 10.1016/S0012-821X(03)00572-7.

Anbar, A. D., & Gordon, G. W. (2008). Redox renaissance. *Geol.*, 36, 271-272, 10.1130/focus032008.1.

Anbar, A. D., & Rouxel, O. (2007). Metal Stable Isotopes in Paleoceanography. *Ann. Rev. Earth Planet. Sci.*, 35, 717-746, 10.1146/annurev.earth.34.031405.125029.

Anbar, A. D., Duan, Y., Lyons, T. W., Arnold, G. L., Kendall, B., Creaser, R. A., Kaufman, A. J., Gordon, G. W., Scott, C., Garvin, J., & Buick, R. (2007). A whiff of oxygen before the great oxidation event? *Science* 317, 1903-1906, 10.1126/science.1140325.

Anbar, A. D., Jarzecki, A. A., & Spiro, T. G. (2005). Theoretical investigation of iron isotope fractionation between $Fe(H_2O)_6^{3+}$ and $Fe(H_2O)_6^{2+}$: Implications for iron stable isotope geochemistry. *Geochim. Cosmochim. Acta*, 69, 825-837, 10.1016/j.gca.2004.06.012.

Anbar, A. D., Knab, K. A., & Barling, J. (2001). Precise determination of mass-dependent variations in the isotopic composition of molybdenum using MC-ICPMS. *Anal. Chem.*, 73, 1425-1431.

Anbar, A. D., Roe, J. E., Barling, J., & Nealson, K. H. (2000). Nonbiological fractionation of iron isotopes. *Science*, 288, 126-128.

Apelberg, B.J., Hepp, L.M., Avila-Tang, E., Kim, S., Madsen, C., Ma, J., Samet, J.M. and Breysse, P.N. (2012) Racial differences in Hair Nicotine Concentrations Among Smokers. *Nicotine and Tobacco Research,* 14(8), 933-941, doi:10.1093/ntr/ntr311.

Aranda, R., Stern, L. A., Dietz, M. E., McCormick, M. C., Barrow, J. A., & Mothershead, R. F. (2011). Forensic utility of isotope ratio analysis of the explosive urea nitrate and its precursors. *Forensic Sci. Intl.*, 206, 143-149, 10.1016/j.forsciint.2010.07.030.

Arnold, G. L., Anbar, A. D., Barling, J., & Lyons, T. W. (2004). Molybdenum isotope evidence for widespread anoxia in mid-Proterozoic oceans. *Science*, 304, 87-90, 10.1126/science.1091785.

Aufderheide, A. C., Wittmers, L. E., Rapp, G., & Wallgren, J. (1988). Anthropological Applications of Skeletal Lead Analysis. *Am. Anthro.*, 90, 931-936.

Barbaste, M., Robinson, K., Guilfoyle, S., Medina, B., & Lobinski, R. (2002). Precise determination of the strontium isotope ratios in wine by inductively coupled plasma sector field multicollector mass spectrometry (ICP-SF-MC-MS). *J. Anal. At. Spectr.*, 17, 135-137.

Barnett-Johnson, R., Pearson, T. E., Ramos, F. C., Grimes, C. B., & MacFarlane, R. B. (2008). Tracking natal origins of salmon using isotopes, otoliths and landscape geology. *Limn. Ocean.*, 53, 1633-1642.

Basu, R., Ram, S.S., Biswas, A., Ray, S.S., Mukhopadhyay, A., Chakraborty, A., Mathummal, S., and Chakrabarti, S. (2015) Investigation on the trace element profile of sewage workers in Kolkata, an Indian megacity. *J Public Health Res* 4 (473), 95-100.

Baxter, M. J., Beardah, C. C., & Westwood, S. (2000). Sample size and related issues in the analysis of lead isotope data. *J. Arch. Sci.*, 27, 973-980, 10.1006/jasc.1999.0546.

Beard, B. L., & Johnson, C. M. (2000). Strontium Isotope Composition of Skeletal Material Can Determine the Birth Place and Geographic Mobility of Humans and Animals. *J. Forensic Sci.*, 45, 1049-1061.

Bender, R.L., Dufour, D.L., Valenzuela, L.O., Cerling, T.E., Sponheimer, M., Reina, J.C., and Ehleringer, J.R. (2015). Stable isotopes (carbon, nitrogen, sulfur), diet, and anthropometry in urban Colombian women: investigating socioeconomic differences. *Am J Hum Bio* 27, 207-18, doi: 10.1002/ajhb.22640.

Benson, S. J., Lennard, C. J., Hill, D. M., Maynard, P., & Roux, C. (2010a). Forensic analysis of explosives using isotope ratio mass spectrometry (IRMS)--part 1: instrument validation of the DELTAplusXP IRMS for bulk nitrogen isotope ratio measurements. *J. Forensic Sci.*, 55, 193-204, 10.1111/j.1556-4029.2009.01241.x.

Benson, S. J., Lennard, C. J., Maynard, P., Hill, D. M., Andrew, A. S., Neal, K., Stuart-Williams, H., Hope, J., Walker, G. S., & Roux, C. (2010b). Forensic analysis of explosives using isotope ratio mass spectrometry (IRMS)--part 2: forensic inter-laboratory trial: bulk carbon and nitrogen stable isotopes in a range of chemical compounds (Australia and New Zealand). *J. Forensic Sci.*, 55, 205-212, 10.1111/j.1556-4029.2009.01242.x.

Benson, S., Lennard, C., Maynard, P., & Roux, C. (2006). Forensic applications of isotope ratio mass spectrometry--a review. *Forensic Sci. Intl.*, 157, 1-22, 10.1016/j.forsciint.2005.03.012.

Bentley, R. A. (2006). Strontium Isotopes from the Earth to the Archaeological Skeleton: A Review. *J. Archaeological Method and Theory*, 13, 135-187, 10.1007/s10816-006-9009-x.

Bergslien, E. T., Bush, M., & Bush, P. J. (2008). Identification of cremains using X-ray diffraction spectroscopy and a comparison to trace element analysis. *Forensic Sci. Intl.*, 175, 218-226, 10.1016/j.forsciint.2007.07.004.

Blome, C.D., Faith, J.R., Pedraza, D.E., Ozuna, G.B., Cole, J.C., Clark, A.K., Small, T.A. and Morris, R.R. (2005) Geologic Map of the Edwards Aquifer Recharge Zone, South-Central Texas. US Geological Survey.

Blum, J. D., Erel, Y., & Brown, K. (1994). $^{87}Sr/^{86}Sr$ ratios of Sierra Nevada stream waters: Implications for relative mineral weathering rates. *Geochim. et Cosmochim. Acta*, 58, 5019-5025.

Blum, J.D., Taliaferro, E.H., Weisse, M.T. and Holmes, R.T. (2000) Changes in Sr/Ca, Ba/Ca and $^{87}Sr/^{86}Sr$ ratios between trophic levels in two forest ecosystems in the northeastern U.S.A. *Biogeochem.* 49(1), 87-101.

Blum, J. D., Dasch, A. A., Hamburg, S. P., Yanai, R. D., & Arthur, M. A. (2008). Use of foliar Ca/Sr discrimination and $^{87}Sr/^{86}Sr$ ratios to determine soil Ca sources to sugar maple foliage in a northern hardwood forest. *Biogeochemistry*, 87, 287-296, 10.1007/s10533-008-9184-9.

Boehm, F., Eisenhauer, A., Tang, J.W., Dietzel, M., Krabbenhoft, A., Kisakurek, B., and Horn, C. (2012) Strontium isotope fractionation of planktonic foraminifera and inorganic calcite. *Geochem et Cosmochim Acta* 93, 300-14, doi: 10.1016/j.gca.2012.04.038.

Bong, W.S.H., Nakai, I., Furuya, S., Suzuki, H., Abe, Y., Osaka, K., Matsumoto, T., Itou, M., Imai, N., and Ninomiya, T. (2012) Development of heavy mineral and heavy element database of soil sediments in Japan using synchrotron radiation X-ray powder diffraction and high-energy (116 keV) X-ray fluorescence analysis. *Forensic Sci Intl* 220, 33-49, doi: 10.1016/j.forsciint.2012.01.024.

Bonilla, M.D-Z., Prevedorou, E.A., Buikstra, J., Knudson, K.J., Gordon, G. and Anbar, A. (2011). Movilidad y paleodieta en la comunidad argárica de gatas: Análisis de 87sr/86sr, d18o y d13c [Mobility and paleodiet in the agricultural community of Gatas: analysis of 87Sr/86Sr, d18O and d13C]. Abstract. *Memorial Luis Siret 1: Congreso de Prehistoria De Andalucía*.

Bontrager, A. B., & Nawrocki, S. P. (2008). A taphonomic analysis of human cremains from the Fox Hollow Farm serial homicide site. *In:* The Analysis of Burned Human Remains (pp. 211-226). Oxford, UK: Elsevier Ltd.

Booth, A. L., Wooller, M. J., Howe, T., & Haubenstock, N. (2010). Tracing geographic and temporal trafficking patterns for marijuana in Alaska using stable isotopes (C, N, O and H). *Forensic Sci. Intl.*, 202, 45-53, 10.1016/j.forsciint.2010.04.025.

Boracchi, M., Andreola, S., Collini, F., Gentile, G., Maciocco, F., Maghin, F., and Zoja, R. (2017) Can cadaverous pollution from environmental lead misguide to false positive results in the histochemical determination of gunshot residues? Study on cadaveric skin samples. *Forensic Sci Intl* 277, 16-20, doi: 10.1016/j.forsciint.2017.05.004.

Bosch, P., Alemán, I., Moren-Castilla, C., & Botella, M. (2011). Boiled versus unboiled: a study on Neolithic and contemporary human bones. *J. Archaeol. Sci.*, 38, 2561-2570, 10.1016/j.jas.2011.04.019.

Bowen, G.J. (2017). The Online Isotopes in Precipitation Calculator, version 3.1. http://www.waterisotopes.org.

Bowen, G.J., Chesson, L., Nielson, K., Cerling, T.E., and Ehleringer, J.R. (2005) Treatment methods for the determination of δ^2H and $\delta^{18}O$ of hair keratin by continuous-flow isotope-ratio mass spectrometry. *Rapid Commun Mass Spectrom* 19, 2371-78, doi: 10.1002/rcm.2069.

Bowen, G.J. and Revenaugh, J. (2003). Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research* **39** (10), 1299, doi:10.129/2003WR002086.

Bowen, G.J., West, J.B. and Hoogewerff, J. (2009) Isoscapes: Isotope mapping and its applications. *J. Geochem. Explor.* 102(3), v-vii, doi: 10.1016/j.gexplo.2009.05.001.

Bower, N. W., Getty, S. R., Smith, C. P., Simpson, Z. R., & Hoffman, J. M. (2005). Lead isotope analysis of intra-skeletal variation in a 19th century mental asylum cemetery: diagenesis versus migration. *Intl. J. Osteoarch.*, 15, 360-370.

Branca F., Robins S.P., Ferro-Luzzi A., and Golden M.H.N. (1992). Bone Turnover in Malnourished Children. *Lancet*. 340(8834/8835), 1493-1497.

Brass, G. W. (1975). The effect of weathering on the distribution of strontium isotopes in weathering profiles. *Geochim. Cosmochim. Acta*, 39, 1647-1653.

Britton, K., Grimes, V., Niven, L., Steele, T. E., McPherron, S., Soressi, M., Kelly, T. E., Jaubert, J., Hublin, J. J., & Richards, M. P. (2011). Strontium isotope evidence for migration in late Pleistocene Rangifer: implications for Neanderthal hunting strategies at the Middle Palaeolithic site of Jonzac, France. *J. Human Evol.*, 61, 176-185, 10.1016/j.jhevol.2011.03.004.

Brooks, T. R., Bodkin, T. E., Potts, G. E., & Smullen, S. A. (2006). Elemental analysis of human cremains using ICP-OES to classify legitimate and contaminated cremains. *J. Forensic Sci.*, 51, 967-973, 10.1111/j.1556-4029.2006.00209.x.

Budd, P., Haggerty, R., Pollard, A. M., Scaife, B., & Thomas, R. G. (1995). New Heavy Isotope Studies in Archaeology. *Israel J. Chem.*, 35, 125-130.

Budd, P., Montgomery, J., Barreiro, B., & Thomas, R. G. (2000). Differential diagenesis of strontium in archaeological human dental tissues. *Appl. Geochem.*, 15, 687-694.

Byrd, J, and Castner, J. (2010). *Forensic Entomology: The Utility of Arthropods in Legal Investigations,* 2nd Edition. CRC Press, Inc., Boca Raton, FL.

Calvin M. (1962). The Path of Carbon in Photosynthesis. *Science* 135(3507), 879-889.

Castro, W., Hoogewerff, J., Latkoczy, C., & Almirall, J. R. (2010). Application of laser ablation (LA-ICP-SF-MS) for the elemental analysis of bone and teeth samples for discrimination purposes. *Forensic Sci. Intl.*, 195, 17-27, 10.1016/j.forsciint.2009.10.029.

Cattermole, J.M. (1958). Geologic Map of the Knoxville Quadrangle, Tennessee. US Geological Survey.

Capo, R. C., Stewart, B. W., & Chadwick, O. A. (1998). Strontium isotopes as tracers of ecosystem processes: theory and methods. *Geoderma*, 82, 197-225.

Carlson, A. K. (1996). Lead isotope analysis of human bone for addressing cultural affinity: a case study from Rocky Mountain House, Alberta. *J. Arch. Sci.*, 23, 557-567.

Carter, J.F. and Fry, B. (2013) Ensuring the reliability of stable isotope ratio data – beyond the principle of identical treatment. *Anal Biochem Acta* 405, 2799-2814, doi: 10.1007/s00216-012-6551-0.

Cartmell LW, Aufderheide AC, Springfield A, Weems C, and Arriaza B. (1999). The Frequency and Antiquity of Prehistoric Coca-Leaf-Chewing Practices in Northern Chile: Radioimmunoassay of a Cocaine Metabolite in Human-Mummy Hair. *Lat. Amer. Antiq.* 2(3), 260-268.

Cattermole, J.M. (1958) Geologic Map of the Knoxville Quadrangle, Tennessee. US Geological Survey.

Chang, B.S., Hong, W.S., Lee, E., Yeo, S.M., Bang, I.S., Chung, Y.H., Lim, D.S., Mun, G.H., Kim, J., Park, S.O., and Shin, D.H. (2005) Ultramicroscopic observations on morphological changes in hair during 25 years of weathering. *Forensic Sci Intl* 151; 193-200, doi: 10.1016/j.forsciint.2004.12.037.

Chenery, C.A., Pashley, V., Lamb, A.L., Sloane, H.J., & Evans, J.A. (2012). The oxygen isotope relationship between the phosphate and structural carbonate fractions of human bioapatite. *Rapid Commun Mass Spectrom* 26, 309-19, doi: 10.1002/rcm.5331.

Chesson, L.A., Tipple, B.J., Mackey, G.N., Hynek, S.A., Fernandez, D.P. and Ehleringer, J.R. (2012). Strontium isotopes in tap water from the coterminous USA. *Ecosphere* 3 (7), 1-17.

Chesson, L.A., Podlesak, D.W., Cerling, T.E., and Ehleringer, J.R. (2009) Evaluating uncertainty in the calculation of non-exchangeable hydrogen fractions within organic materials. *Rapid Commun Mass Spectrom.* 23 (9), 1275-80, doi: 10.1002/rcm.4000.

Cho H, Stout SD, and Bishop TA. (2006). Cortical Bone Remodeling Rates in a Sample of African American and European American Descent Groups from the American Midwest: Comparisons of Age and Sex in Ribs. *Amer. J. Phys. Anthropol.*, 130(2), 214-226.

Choi, S. -M., Lee, H. -S., Lee, G. -H., & Han, J. -K. (2008). Determination of the strontium isotope ratio by ICP-MS ginseng as a tracer of regional origin. *Food Chem.*, 108, 1149-1154, 10.1016/j.foodchem.2007.11.079.

Christensen GJ, and Kraus BS. (1965). Initial Calcification of the Human Permanent First Molar. *J. Dent. Res.*, 44(6), 1338-1342.

Clauer, N. (1979). Relationship between the isotopic composition of strontium in newly formed continental clay minerals and their source material. *Chem. Geol.*, 27, 115-124.

Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. (2009). Strengthening forensic science in the united states: A path forward. Report. *Available at* https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf.

Coplen, T. B., & Qi, H. (2012). USGS42 and USGS43: human-hair stable hydrogen and oxygen isotopic reference materials and analytical methods for forensic science and implications for published measurement results. *Forensic Sci. Intl.*, 214, 135-141, 10.1016/j.forsciint.2011.07.035.

Craig H. (1961). Isotopic Variations in Meteoric Waters. *Science*, 133(3465), 1702-1703.

Croft, D. and Pye, K. (2003) The potential use of continuous-flow isotope-ratio mass spectrometry as a tool in forensic soil analysis: a preliminary report. *Rapid Commun Mass Spectrom* 17, 2581-4, doi: 10.1002/rcm.1174.

Croft, D. and Pye, K. (2004) Multi-technique comparison of source and primary transfer soil samples: an experimental investigation. *Sci and Just* 44, 21-28.

Damann, F.E., Tanittaisong, A. and O'Carter, D. (2012). Potential carcass enrichment of the university of tennessee anthropology research facility: A baseline survey of edaphic features. *Forensic Sci. Int.* 222, 4-10.

Dansgaard W. (1964). Stable Isotopes in Precipitation. *Tellus* 16, 436-468.

Dauphin, Y., Massard, P. and Quantin, C. (2008). In vitro diagenesis of teeth of *Sus Scofa* (Mammalia, Suidae): Micro- and nanostructural alterations and experimental dissolution. *Palaeogeogr., Palaeoclimat., Palaeoecol.*, 266, 132-141, 10.1016/j.palaeo.2008.03.021.

David, G. E., Coxon, A., Frew, R. D., & Hayman, A. R. (2010). Isotope fractionation during precipitation of methamphetamine HCl and discrimination of seized forensic samples. *Forensic Sci. Intl.*, 200, 123-129, 10.1016/j.forsciint.2010.03.043.

Davis, D. W., Gray, J., Cumming, G. L., & Baadsgaard, H. (1977). Determination of the ^{87}Rb decay constant. *Geochim.Cosmochim. Acta*, 41, 1745-1749.

Dawson, L.A. and Hillier, S. (2010). Measurement of soil characteristics for forensic applications. *Surface and Interface Anal* 42, 363-77, doi: 10.1002/sia.3315.

Dayal, M. R., Kegley, A. D., Strkalj, G., Bidmos, M. A., & Kuykendall, K. L. (2009). The history and composition of the Raymond A. Dart Collection of Human Skeletons at the University of the Witwatersrand, Johannesburg, South Africa. *Am. J. Phys. Anthro.*, 140, 324-335, 10.1002/ajpa.21072.

DeCook, K.J. (1963). Geology and Ground-Water Resources of Hays County, Texas. US Geological Survey, Water Supply Paper 1612.

DeNiro, M. J., Schoeninger, M. J., & Hastorf, C. A. (1985). Effect of heating on the stable carbon and nitrogen isotope ratios of bone collagen. *J. Arch. Sci.*, 12, 1-8.

Dibba, B., Prentice, A., Laskey, M.A., Stirling, D.M., and Cole, T.J. (1999). An Investigation of Ethnic Differences in Bone Mineral, Hip Axis Length, Calcium Metabolism and Bone Turnover between West African and Caucasian Adults Living in the United Kingdom. *Ann. Human Bio.*, 26(3), 229-343.

Dolphin, A. E., Goodman, A. H., & Amarasiriwardena, D. D. (2005). Variation in elemental intensities among teeth and between pre- and postnatal regions of enamel. *Am. J. Phys. Anthro.*, 128, 878-888, 10.1002/ajpa.20213.

Drouet, T., Herbauts, J., Gruber, W., & Demaiffe, D. (2005). Strontium isotope composition as a tracer of calcium sources in two forest ecosystems in Belgium. *Geoderma*, 126, 203-223.

Durali-Mueller, S., Brey, G. P., Wigg-Wolf, D., & Lahaye, Y. (2007). Roman lead mining in Germany: its origin and development through time deduced from lead isotope provenance studies. *J. Arch. Sci.*, 34, 1555-1567.

Ehleringer, J.R., Barnette, J., Jameel, Y., Tipple, B.J., and Bowen, G.J. (2016) Urban water – a new frontier in isotope hydrology. *Isotopes Environ Health Studies* 52, 477-486, doi: 10.1080/10256016.2016.1171217.

Ehleringer, J.R., Bowen, G.J., Chesson, L.A., West, A.G., Podlesak, D.W., & Cerling, T.E. (2008). Hydrogen and Oxygen Isotope Ratios in Human Hair are Related to Geography. *Proceedings of the National Academy of Sciences*, 105, 2788-2793. doi: 10.1073/pnas.071228105

Ehleringer, J. R., Cooper, D. A., Lott, M. J., & Cook, C. S. (1999). Geo-location of heroin and cocaine by stable isotope ratios. *Forensic Sci. Intl.*, 106, 27-35.

Ehrlich, S., Karpas, Z., Ben-Dor, L., & Halicz, L. (2001). High precision lead isotope ratio measurements by mutlicollector-ICP-MS in variable matrices. *J. Anal. At. Spectrom.*, 16, 975-977.

Epstein, S., and Zeiri, L. (1988). Oxygen and Carbon Isotopic Compositions of Gases Respired by Humans. *Proc. Nat. Acad. Sci.*, 85, 1727-1731.

Esteban, M. and Castaño, A. (2009) Non-invasive matrices in human biomonitoring: a review. *Environ Int* 35, 438-9.

Fantle, M.S. (2015) Calcium isotopic evidence for rapid recrystallization of bulk marine carbonates and implications for geochemical proxies. *Geochim Cosmochim Acta* 148, 378-401, doi: 10.1016/j.gca.2014.10.005.

Faure, G. (1986). Principles of Isotope Geology. John Wiley and Sons.

Fietzke, J. and Eisenhauer, A. (2006) Determination of temperature-dependent stable strontium isotope (88Sr/86Sr) fractionation via bracketing standard MC-ICP-MS. *Geochem Geophys Geosyst* 7, Q08009

Font, L., van der Peijl, G., van Wetten, I., Vroon, P., van der Wagt, B., and Davies, G. (2012) Strontium and lead isotope ratios in human hair: investigating a potential tool for determining recent human geographical movements. *J Anal At Spectrom* 27, 719-732, doi: 10.1039/c2ja10361c.

Franbourg, A., Hallegot, P., Baltenneck, F., Toutain, C. and Leroy, F. (2003). Current research on ethnic hair. *J. Am. Acad. Dermatol.* 48(6), S115-S119, 10.1067/mjd.2003.277.

Fraser, I., Meier-Augenstein, W. and Kalin, R.M. (2008) Stable isotope analysis of human hair and nail samples: the effect of storage on samples. *J Foren Sci* 53, 95-99, doi:10.1111/j.1556-4029.2007.00607.x.

Fuller, B.T., Fuller, J.L., Sage, N.E., Harris, D.A., O'Connell, T.C., and Hedges, R.E.M. (2005) Nitrogen balance and $\delta^{15}N$: why you're not what you eat during nutritional stress. *Rapid Commun Mass Spectrom* 19, 2497-506, doi: 10.1002/rcm.2090.

Fuller, B.T., Fuller, J.L., Sage, N.E., Harris, D.A., O'Connell, T.C., and Hedges, R.E.M. (2004) Nitrogen balance and d15N: why you're not what you eat during pregnancy. *Rapid Commun Mass Spectrom* 18, 2889-96, doi: 10.1002/rcm.1708.

Galler, P., Limbeck, A., Boulyga, S.F., Stingeder, G., Hirata, T. and Prohaska, T. (2007) Development of an On-Line Flow Injection Sr / Matrix Separation Method for Accurate, High-Throughput Determination of Sr Isotope Ratios by Multiple Collector-Inductively Coupled Plasma-Mass Spectrometry *Analytical Chemistry* **79**, 5023-5029; doi: 10.1021/ac070307h.

Gallon, C., Aggarwal, J., & Flegal, A. R. (2008). Comparison of mass discrimination correction methods and sample introduction systems for the determination of lead isotopic composition using a multicollector inductively coupled plasma mass spectrometer. *Anal. Chem.*, 80, 8355-8363, 10.1021/ac800554k.

Gat JR. (1996). Oxygen and Hydrogen Isotopes in the Hydrologic Cycle. *Annu. Rev. Earth Planet. Sci.*, 24(1), 225-262.

Gentile, N., Besson, L., Pazos, D., Delémont, O., & Esseiva, P. (2011). On the use of IRMS in forensic science: proposals for a methodological approach. *Forensic Sci. Intl.*, 212, 260-271, 10.1016/j.forsciint.2011.07.003.

Goldstein, S. J., & Jacobsen, S. B. (1987). The Nd and Sr isotopic systematics of river-water dissolved material: implications for the sources of Nd and Sr in seawater. *Chem. Geol.*, 66, 245-272.

Good, S.P., Kennedy, C.D., Stalker, J.C., Chesson, L.A., Valenzuela, L.O., Beasley, M.M., Ehleringer, J.R., and Bowen, G.J. (2014) Patterns of local and non-local water resource use across the western United States determined via stable isotope intercomparisons. *Water Resource Research* 50, 8034-8049, doi: 10.1002/2014WR015884.

Gordon, G.W., Klonowski, S., Zolotova, N. and Anbar, A.D. (2008). Coffee, cotton and cannabis: Sr isotopes and the geolocation of botanical materials. Abstract. *Isoscapes*. http://kevintu.wufoo.com/reports/isoscapes-2008-abstracts.

Gordon, G.W., Wasylenki, L., Arrua, C.R., Hurt, D. and Anbar, A.D. (2011). A blind comparison of multiple analytical methods for soil comparison in a home invasion robbery double shooting case in urban phoenix, AZ. Talk presented at the 2011 NIJ Trace Evidence Symposium.

Halicz, L., Segal, I., Fruchter, N., Stein, M., Lazar, B. (2008) Strontium stable isotopes fractionate in the soil environments? *Earth Planet Sci Lett* 272, 406-411, doi: 10.1016/j.epsl.2008.05.005.

Hanna-Attisha, M., LaChance, J., Sadler, R.C., and Schnepp, A.C. (2016) Elevated blood lead levels in children associated with the Flint drinking water crisis: a spatial analysis of risk and public health response. *Am J Public Health* 106: 283-90; doi:

Hanyu, T., Kimura, J. -I., Katakuse, M., Calvert, A. T., Sisson, T. W., & Nakai, S. (2010). Source materials for inception stage Hawaiian magmas: Pb-He isotope variations for early Kilauea. *Geochem. Geophys. Geosyst.*, 11, Q0AC0110.1029/2009GC002760.

Harbeck, M., Schleuder, R., Schneider, J., Wiechmann, I., Schmahl, W. W., & Grupe, G. (2011). Research potential and limitations of trace analyses of cremated remains. *Forensic Sci. Intl.*, 204, 191-200, 10.1016/j.forsciint.2010.06.004.

Harris, D., Horwath, W.R. and van Kessel (2001) Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. *Soil Science Soc. America J.* **65**, 1853-1856.

Hart, S.R., Ball, L. and Jackson, M. (2004). Sr isotopes by laser ablation PIMMS: Application to cpx from samoan peridotite xenoliths.Sr Isotopes by Laser Ablation PIMMS: Application to Cpx from Samoan Peridotite Xenoliths WHOI Plasma Facility Open File Technical Report 11.

Hatch MD, and Slack CR. (1966). Photosynthesis by Sugarcane Leaves. A New Carboxylation Reaction and the Pathway of Sugar Formation. *Biochem J.*, 101, 103-111.

Hatch MD, Slack CR, and Johnson HS. (1967). Further Studies on a New Pathway of Photosynthetic Carbon Dioxide Fixation in Sugarcane, and its Occurrence in Other Species. *Biochem J.* 102, 417-422.

Hedges, R. E. M. (2002). Bone Diagenesis: An overview of Processes. *Archaeometry*, 44, 319-328.

Hedges, R.E.M. and Reynard, L.M. (2007) Nitrogen isotopes and the trophic level of humans in archaeology. *J Arch. Sci.* **34**, 1240-1251, doi: 10.1016/j.jas.2006.10.015.

Hedges REM, Clement JG, Thomas CDL, and O'Connell TC. (2007). Collagen Turnover in the Adult Femoral Mid-Shaft: Modeled From Anthropogenic Radiocarbon Tracer Measurements. *Amer. J. Phys. Anthropol.*, 133(2), 808-816.

Hedman, K. M., Curry, B. B., Johnson, T. M., Fullagar, P. D., & Emerson, T. E. (2009). Variation in strontium isotope ratios of archaeological fauna in the Midwestern United States: a preliminary study. *J. Arch. Sci.*, 36, 64-73, 10.1016/j.jas.2008.07.009.

Henderson, G.L., Harkey, M.R., Zhou, C., Jones, R.T. and Jacob, P. (1998) Incorporation of Isotopically Labeled Cocaine into Human Hair: Race as a Factor. *J. Anal. Toxicol.* **22**: 156-165.

Herrmann, N., Li, Z-H. and Soto, M. (2010). Isotopic evaluation of modern human remains from the University of Tennessee William H. Bass Donated Collection. *Am. J. Phys. Anthro.* Supp. 50, 127, doi: 10.1002/ajpa.21276.

Herrmann, N., Li, Z.-H., & Warner, M. (with Trask, W., Weinand, D., & Soto, M.) (2015). *Isotopic and Elemental Analysis of the William Bass Donated Skeletal Collection and Other Modern Donated Collections* (Department of Justice Report 248669). National Criminal Justice Reference Service. 62 pps.

Hillson S. (1986). *Teeth*. Cambridge: Cambridge University Press.

Hillson S. (1996). *Dental Anthropology*. Cambridge: Cambridge University Press.

Hobson, K.A., Van Wilgenburg, S.L., Larson, K. and Wassenaar, L.I. (2009) A feather hydrogen isoscape for Mexico. *J. Geochem. Expl.* 102(3), 123-126, doi: 10.1016/j.gexplo.2009.01.001.

Hobson, K.A., Barnett-Johnson, R. and Cerling, T. (2010) "Using isoscapes to track animal migration" *In* Isoscapes: Understanding Movement, Pattern, and Process on Earth through Isotope Mapping. West, J.B. et al, eds., Springer-Verlag, doi: 10.1007/978-90-481-3354-3_13.

Hodell, D.A., Quinn, R.L., Brenner, M., & Kamenov, G. (2004). Spatial variation of strontium isotopes (87Sr/86Sr) in the Maya region: a tool for tracking ancient human migration. *J Archa Sci* 31, 585-601, doi: 10.1016/j.jas.2003.10.009.

Horstwood, M. S. A., Evans, J. A., & Montgomery, J. (2008). Determination of Sr isotope in calcium phosphates using laser ablation inductively coupled plasma mass spectrometry and their application to archaeological tooth enamel. *Geochim. et Cosmochim. Acta*, 72, 5659-5674, doi: 10.1016/j.gca.2008.08.016.

Horwitz, E. P., Chiarizia, R., & Dietz, M. L. (1992). A novel strontium-selective extraction chromatographic resin. *Solvent extraction and ion exchange*, 10, 313-336.

Huelsemann, F., Koehler, K., Braun, H., Schaenzer, W., & Flenker, U. (2013). Human dietary d15N intake: representative data for principle food items. *Am J Phys Anthro* 152, 58-66, doi: 10.1002/ajpa.22328.

Hussain, M., Hussain, N., Zainab, H., & Qaiser, S. (2007). Skeletal Preservation Techniques to Enhance Veterinary Anatomy Teaching. *Intl. J. Agro. Vet. Med. Sci.*, 1, 21-23.

IsoForensics, Inc. (2016). *A Comprehensive Test of the Methods and Models Used to Assign Geographic Origin to Human Skeletal Remains With Stable Isotope Data*. National Institute of Justice grant 2016-DN-BX-0157.

Isoforensics, Inc. (2011). Isotope analyses of hair as a trace evidence tool to reconstruct human movements: combining strontium isotope with hydrogen/oxygen data. NIJ grant 2011-DN-BX-K544

Jahren, A.H. & Kraft, R.A. (2008). Carbon and nitrogen stable isotopes in fast food: signatures of corn and confinement. *Proceed Nat Acad Sci* 105, 17855-60, doi: 10.1073/pnas.0809870105.

Jahren, A.H., Saudek, C., Yeung, E.H., Kao, W.H.L., Kraft, R., & Caballero, B. (2006). An isotopic method for quantifying sweeteners derived from corn and sugar cane. *Am J Clin Nutr* 84, 1380-4.

Jameel, Y., Brewer, S.P., Good, B.J., Tipple, B.J., Ehleringer, J.R. and Bowen, G.J. (2016) Tap water isotope ratios reflect urban water system structure and dynamics across a semi-arid metropolitan area. *Water Resources Res.* 52, 5891-5910, doi: 10.1002/2016wr019014.

Ji, J.H., Park, T-S., Lee, H-J., Kim, Y-D., Pi, L-Q., Jin, X-H. and Lee, W-S. (2013). The ethnic differences of the damage of hair and integral hair lipid after ultra violet radiation. *Ann. Dermatol.* 25(1), 54-60, doi: 10.5021/ad.2013.25.1.54.

Juarez, C. A. (2008). Strontium and geolocation, the pathway to identification for deceased undocumented Mexican border-crossers: a preliminary report. *J. Forensic Sci.*, 53, 46-49, 10.1111/j.1556-4029.2007.00610.x.

Kamenov, G.D., Kimmerle, E.H., Curtis, J.H., and Norris, D. (2014) Georeferencing a cold case victim with lead, strontium, carbon, and oxygen isotopes. *Annals of Anthropol Practice* 38, 137-54, doi: 10.1111/napa.12048.

Kawasaki, A., Oda, H., & Hirata, T. (2002). Determination of strontium isotope ratio of brown rice for estimating its provenance. *Soil Sci. Plant Nutr.*, 48, 635-640.

Keller, A.T., Regan, L.A., Lundstrom, C.C., and Bower, N.W. (2016) Evaluation of the efficacy of spatiotemporal Pb isoscapes for provenancing of human remains. *Forensic Sci Intl* 261, 83-92, doi: 10.1016/j.forsciint.2016.02.006.

Kennedy, C. D., Bowen, G. J., & Ehleringer, J. R. (2011). Temporal variation of oxygen isotope ratios ($\delta^{18}O$) in drinking water: implications for specifying location of origin with human scalp hair. *Forensic Sci. Intl.*, 208, 156-166, 10.1016/j.forsciint.2010.11.021.

Kesler, S. E., Cumming, G. L., Krstic, D., & Appold, M. S. (1994). Lead Isotope Geochemistry of Mississippi Valley-Type Deposits of the Southern Appalachians. *Econ. Geol.*, 89, 307-321.

Kidwell, D.A., Lee, E.H. and DeLauder, S.F. (2000). Evidence for bias in hair testing and procedures to correct bias. *Forensic Sci. Intl.*, 107(1-3), 39-61.

King, C. L., Tayles, N., & Gordon, K. C. (2011). Re-examining the chemical evaluation of diagenesis in human bone apatite. *J. Arch. Sci.*, 38, 2222-2230, 10.1016/j.jas.2011.03.023.

Kintz, P. (2012) Segmental hair analysis can demonstrate external contamination in postmortem

cases. *Forensic Sci Intl* 215, 73-76, doi: 10.1016/j.forsciint.2011.01.041.

Knudson KJ, Frink L, Hoffman BW, and Price TD. (2004). Chemical Characterization of Arctic Soils: Activity Area Analysis in Contemporary Yup'ik Fish Camps Using ICP-AES. *J. Archaeol. Sci.*, 31, 443-356.

Knudson, K. J., Tung, T. A., Nystrom, K. C., Price, T. D., & Fullagar, P. D. (2005). The origin of the Juch'uypampa Cave mummies: strontium isotope analysis of archaeological human remains from Bolivia. *J. Archaol. Sci.*, 32, 903-913, 10.1016/j.jas.2005.01.007.

Knudson KJ, and Buikstra JE. (2007). Residential Mobility and Resource Use in the Chiribaya Polity of Southern Peru: Strontium Isotope Analysis of Archaeological Tooth Enamel and Bone. *Int. J. Osteoarchaeol.*, 17(6), 563-580.

Knudson, K. J. and Price, T. D. (2007). Utility of multiple chemical techniques in archaeological residential mobility studies: case studies from Tiwanaku- and Chiribaya-affiliated sites in the Andes. *Am. J. Phys. Anthro.*, 132, 25-39, 10.1002/ajpa.20480.

Knudson KJ, and Tung TA. (2007). Using Archaeological Chemistry to Investigate the Geographic Origins of Trophy Heads in the Central Andes: Strontium Isotope Analysis at the Wari Site of Conchopata. *In:* Glascock MD, Speakman RJ, and Popelka-Filcoff RS, editors. Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation. Washington D.C.: American Chemical Society. pp 99 - 113.

Knudson KJ, Aufderheide AE, and Buikstra JE. (2007). Seasonality and Paleodiet in the Chiribaya Polity of Southern Peru. *J. Archaeol. Sci.* 34(3), 451-462.

Knudson KJ. (2008). Tiwanaku Influence in the South Central Andes: Strontium Isotope Analysis and Middle Horizon Migration. *Lat. Amer. Antiq.*, 19(1), 3-23.

Knudson, K. J. and Stojanowski, C. M. (2008). New directions in bioarchaeology: recent contributions to the study of human social identities. *J. Archaeol. Res.*, 16, 397-432, 10.1007/s10814-008-9024-4.

Knudson, K. J., Williams, S. R., Osborn, R., Forgey, K., & Williams, P. R. (2009). The geographic origins of Nasca trophy heads using strontium, oxygen, and carbon isotope data. *J. Anthro. Archaeol.*, 28, 244-257, 10.1016/j.jaa.2008.10.006.

Knudson KJ. (2009). Oxygen Isotope Analysis in a Land of Environmental Extremes: The Complexities of Isotopic Work in the Andes. *Int. J. Osteoarchaeol.*, 19(2), 171-191.

Knudson, K. J., & Torres-Rouff, C. (2009). Investigating cultural heterogeneity in San Pedro de Atacama, northern Chile, through biogeochemistry and bioarchaeology. *Am. J. Phys. Anthro.*, 138, 473-485, 10.1002/ajpa.20965.

Knudson, K. J., Williams, H. M., Buikstra, J. E., Tomczak, P. D., Gordon, G. W., & Anbar, A. D. (2010). Introducing $\delta^{88/86}$Sr analysis in archaeology: a demonstration of the utility of strontium isotope fractionation in paleodietary studies. *J. Archaeol. Sci.*, 37, 2352-2364, 10.1016/j.jas.2010.04.009.

Knudson KJ, and Frink L. (2010). Ethnoarchaeological Analysis of Arctic Fish Processing: Chemical Characterization of Soils on Nelson Island, Alaska. *J. Archaeol. Sci.*, 37(4):769-783.

Knudson KJ, and Frink L. (2010). Soil Chemical Signatures of a Historic Sod House: Activity Area Analysis of an Arctic Semi-Subterranean Structure on Nelson Island, Alaska. *Archaeol. Anthropol. Sci.*, 2(4), 265-282.

Knudson KJ, and Frink L. (2011). Nitrogen Isotope Analysis in the Arctic: Identifying Fish Processing and Marine Resource Use through Ethnoarchaeological Soil Analysis on Nelson Island, Alaska. *Alaska J. Anthropol.* 9(2).

Knudson KJ, Gardella KR, and Yaeger J. 2012. Provisioning Inka Feasts at Tiwanaku, Bolivia: The Geographic Origins of Camelids in the Pumapunku Complex. *J. Archaeol. Sci.* 39(2), 479-491.

Knudson KJ, O'Donnabhain B, Carver C, Cleland R, and Price TD. (2012). Migration and Viking Dublin: Paleomobility and Paleodiet through Isotopic Analyses. *J. Archaeol. Sci.*, 39(2), 308-320.

Knudson KJ, Pestle WJ, Torres-Rouff C, and Pimentel G. (2012). Assessing the Life History of an Andean Traveler through Biogeochemistry: Stable and Radiogenic Isotope Analyses of Archaeological Human Remains from Northern Chile. *Inter. J. Osteoarchaeol.* 22(4):435–451.

Kohn, M. J., Schoeninger, M. J., & Barker, W. W. (1999). Altered states: Effects of diagenesis on fossil tooth chemistry. *Geochim. Cosmochim. Acta*, 63, 2737-2747.

Komárek, M., Chrastný, V., Ettler, V., & Tlustos, P. (2006). Evaluation of extraction/digestion techniques used to determine lead isotopic composition in forest soils. *Anal. Bioanal. Chem.*, 385, 1109-1115, 10.1007/s00216-006-0543-x.

Komárek, M., Ettler, V., Chrastný, V., & Mihaljevic, M. (2008). Lead isotopes in environmental sciences: a review. *Environ. Intl.*, 34, 562-577, 10.1016/j.envint.2007.10.005.

Kortshack HP, Hartt CE, and Burr GO. (1965). Carbon Dioxide Fixation in Sugarcane Leaves. *Plant Physiol.* 40:209-213.

Krabbenhöft, A., Fietzke, J., Eisenhauer, A., Liebetrau, V., Böhm, F., & Vollstaedt, H. (2009). Determination of radiogenic and stable strontium isotope ratios ($^{87}Sr/^{86}Sr$; $\delta^{88/86}Sr$) by thermal ionization mass spectrometry applying an $^{87}Sr/^{84}Sr$ double spike. *J. Anal. At. Spectr.*, 24, 1267-1271, 10.1039/b906292k.

Krabbenhöft, A., Eisenhauer, A., Böhm, F., Vollstaedt, H., Fietzke, J., Liebetrau, V., Augustin, N., Peucker-Ehrenbrink, B., Muller, M.N., Horn, C., Hansen, B.T., Nolte, N., and Wallmann, K. (2010) Constraining the marine strontium budget with natural strontium isotope fractionations (Sr-87/Sr-86, delta Sr-88/86) of carbonates, hydrothermal solutions and river waters. *Geochim Cosmochim Acta* 74, 4097-4109, doi: 10.1016/j.gca.2010.04.009.

Kraft, R.A., Jahren, A.H., & Saudek, C.D. (2008). Clinical-scale investigation of stable isotopes in human blood: $\delta^{13}C$ and $\delta^{15}N$ from 406 patients at the Johns Hopkins Medical Institutions. *Rapid Commun Mass Spectrom* 22, 3683-92, doi: 10.1002/rcm.3780.

Kreuzer-Martin, H. W., Chesson, L. A., Lott, M. J., Dorigan, J. V., & Ehleringer, J. R. (2004a). Stable isotope ratios as a tool in microbial forensics--Part 1. Microbial isotopic composition as a function of growth medium. *J. Forensic Sci.*, 49, 954-960.

Kreuzer-Martin, H. W., Chesson, L. A., Lott, M. J., Dorigan, J. V., & Ehleringer, J. R. (2004b). Stable isotope ratios as a tool in microbial forensics--Part 2. Isotopic variation among different growth media as a tool for sourcing origins of bacterial cells or spores. *J. Forensic Sci.*, 49, 961-967.

Laidlaw, M.A.S., Filippelli, G.M., Sadler, R.C., Gonzales, C.R., Ball, A.S. and Mielke, H.W. (2016) Children's Blood Lead Seasonality in Flint, Michigan (USA), and Soil-Sourced Lead Hazard Risks. *Intl J Environ Res Public Health* 13, 358, doi: 10.3390/ijerph13040358.

Lane GA, and Dole M. (1956). Fractionation of Oxygen Isotopes during Respiration. *Science*, 123(3197), 574-576.

Lee-Thorp, J., & Sealy, J. (2008). Beyond documenting diagenesis: The fifth international bone diagenesis workshop. *Palaeogeo., Palaeoclimat., Palaeoeco.*, 266, 129-133, 10.1016/j.palaeo.2008.03.025.

Lehn, C., Mützel, E. and Rossmann, A. (2011). Multi-element stable isotope analysis of H, C, N and S in hair and nails of contemporary human remains. *Int. J. Legal Med.*, 125, 695-706, 10.1007/s00414-11-0595-0.

Levinson AA, Luz B, and Kolodny Y. (1987). Variations in Oxygen Isotopic Compositions of Human Teeth and Urinary Stones. *Appl. Geochem.*, 2, 367-371.

Longerich, H. P., Fryer, B. J., & Strong, D. F. (1987). Determination of lead isotope ratios by inductively coupled plasma-mass spectrometry (ICP-MS). *Spectrochim. Acta*, 42B, 39-48.

Longinelli, A. (1984). Oxygen Isotopes in Mammal Bone Phosphate: A New Tool for Paleohydrological and Paleoclimatological Research? *Geochim. Cosmochim. Acta*, 48:385-390.

Loudon, J.E., Sponheimer, M., Sauther M.L. and Cuozzo, F.P. (2007). Intraspecific Variation in Hair $\delta^{13}C$ and $\delta^{15}N$ Values of Ring-Tailed Lemurs (*Lemur catta*) with Known Individual Histories, Behavior, and Feeding Ecology. *Am. J. Phys. Anthro.*, 133(3), 978-985.

Lubec G., Nauer, G., Seifert, K., Strouhal, E., Porteder, H., Szilvassy, J. and Teschler, M. (1987). Structural Stability of Hair over Three Thousand Years. *J. Archaeol. Sci.*, 14(2), 113-230.

Luz, B., Kolodny, Y. and Horowitz, M. (1984). Fractionation of Oxygen Isotopes between Mammalian Bone-Phosphate and Environmental Drinking Water. *Geochim. Cosmochim. Acta*, 48:1689-1693.

Luz, B. and Kolodny, Y. (1985). Oxygen Isotope Variations in Phosphate of Biogenic Apatites, IV. Mammal Teeth and Bone. *Earth Planet. Sci. Lett.* 75, 29-36.

Lock, C. M. and Meier-Augenstein, W. (2008). Investigation of isotopic linkage between precursor and product in the synthesis of a high explosive. *Forensic Sci. Intl.*, 179, 157-162, 10.1016/j.forsciint.2008.05.015.

Ma, J., Wei, G., Liu, Y., Ren, Z., Xu, Y. and Yang, Y. (2013) Precise measurement of stable $\delta^{88/86}Sr$ and radiogenic $^{87}Sr/^{86}Sr$ strontium isotope ratios in geological standard materials using MC-ICP-MS. *China Science Bulletin* **58,** 3111-8.

Macko, S.A., Engel, M.H., Andrusevich, V., Lubec, G., O'Connell, T.C. and Hedges, R.E.M. (1999). Documenting the Diet in Ancient Human Populations through Stable Isotope Analysis

of Hair. *Philosop. Trans. Royal Soc.*, 35(1379), 65-76.

Marclay, F., Pazos, D., Delémont, O., Esseiva, P., & Saudan, C. (2010). Potential of IRMS technology for tracing gamma-butyrolactone (GBL). *Forensic Sci. Intl.*, 198, 46-52, 10.1016/j.forsciint.2009.12.014.

Marks, M.K., Love, J.C., Dadour, I.R. (2009). Taphonomy and time: estimating the postmortem interval. *In*: Steadman, D.W., ed., *Hard Evidence: Case Studies in Forensic Anthropology*, 2nd ed. Upper Saddle River, NJ: Prentice Hall. pp. 165-178.

McArthur, J. M., Howarth, R. J., & Bailey, T. R. (2001). Strontium Isotope Stratigraphy: LOWESS Version 3: Best Fit to the Marine Sr-Isotope Curve for 0-509 Ma and Accompanying Look-up Table for Deriving Numerical Age. *J. Geol.*, 109, 155-170.

McCullagh, J.S.O, Trippm J.A. and Hedges, R.E.M. (2005). Carbon Isotope Analysis of Bulk Keratin and Single Amino Acids from British and North American Hair. *Rapid Comm. Mass Spectrom.*, 19(22), 3227-3231.

McMahon, K.W., Fogel, M.L., Elsdon, T.S. and Thorrold, S.R. (2010). Carbon isotope fractionation of amino acids in fish muscle reflects biosynthesis and isotopic routing from dietary protein. *J. Animal Ecol.*, 79, 1132-1141.

McMullen, C. C., Fritze, K., & Tomlinson, R. H. (1966). The half-life of Rubidium-87. *Can. J. Phys.*, 44, 3033-3038.

Megyesi, M.S., Nawrocki, S.P. and Haskell, N.H. (2005). Using accumulated degree days to estimate the postmortem interval from decomposed human remains. *J. Forensic Sci.,* 50(3), 618–26.

Meier-Augenstein, W., & Fraser, I. (2008). Forensic isotope analysis leads to identification of a mutilated murder victim. *Sci. Just.*, 48, 153-159, 10.1016/j.scijus.2007.10.010.

Meier-Augenstein, W., Chartrand, M.M.G., Kemp, H.F. and St. Jean, G. (2011) An inter-laboratory comparative study into sample preparation for both reproducible and repeatable forensic ^{2}H isotope analysis of human hair by continuous flow isotope ratio mass spectrometry. *Rapid Commun Mass Spectrom.* 25, 3331-8, doi: 10.1002/rcm.5235.

Mekota, A.-M., Grupe, G., Ufer, S., and Cuntz (2006) Serial analysis of stable nitrogen and carbon isotope isotopes in hair: monitoring starvation and recovery phases of patients suffering from anorexia nervosa. *Rapid Commun Mass Spectrom* 20, 1604-10, doi: 10.1002/rcm.2477.

Minster, J. F., Birck, J. L. and Allegre, C. J. (1982). Absolute age of formation of chondrites studied by the ^{87}Rb-^{87}Sr method. *Nature*, 300, 414-419.

Mnookin, J. L., Cole, S. A., Dror, I. E., Fisher, B. A. J., Houck, M. M., Inman, K., Kaye, D. H., Koehler, J. J., Langenburg, G., Risinger, D. M., Rudin, N., Siegel, J., & Stoney, D. A. (2011). The need for a research culture in the forensic sciences. *UCLA Law Review*, 58, 725-779.

Monastra, V., Derry, L. A., & Chadwick, O. A. (2004). Multiple sources of lead in soils from a Hawaiian chronosequence. *Chem. Geol.*, 209, 215-231, 10.1016/j.chemgeo.2004.04.027.

Moorrees, C.F.A., Fanning, E.A., & Hunt, E.E. (1963). Age Formation Stages for Ten Permanent Teeth. *Journal of Dental Research,* 42, 1490-1502.

Morgan, J. L. L., Skulan, J. L., Gordon, G. W., Romaniello, S. J., Smith, S. M., & Anbar, A. D. (2012). Rapidly assessing changes in bone mineral balance using natural stable calcium isotopes. *Proc. Nat. Acad. Sci*., 109(25), 9989-9994.

Morgan, J. L., Gordon, G. W., Arrua, R. C., Skulan, J. L., Anbar, A. D., & Bullen, T. D. (2011). High-precision measurement of variations in calcium isotope ratios in urine by multiple collector inductively coupled plasma mass spectrometry. *Anal. Chem.*, 83, 6956-6962, 10.1021/ac200361t.

Muccio, Z., & Jackson, G. P. (2011). Simultaneous identification and $\delta^{13}C$ classification of drugs using GC with concurrent single quadrupole and isotope ratio mass spectrometers. Journal of forensic sciences, 56 Suppl 1, S203-S209, 10.1111/j.1556-4029.2010.01594.x.

Mulhern DM, and Van Gerven DP. 1997. Patterns of Femoral Bone Remodeling Dynamics in a Medieval Nubian Population. Amer J Phys Anthropol 104(1):133-146.

Müller, W., Fricke, H., Halliday, A. N., McCulloch, M. T., & Wartho, J. A. (2003). Origin and migration of the Alpine Iceman. Science (New York, N.Y.), 302, 862-866, 10.1126/science.1089837.

Nash, S.H., Kristal, A.R., Boyer, B.B., King, I.B., Metzgar, J.S. and O'Brien, D.M. (2009) Relation between stable isotope ratios in human red blood cells and hair: Implications for using the nitrogen isotope ratio of hair as a biomarker of eicosapentaenoic acid and docosahexaenoic acid. *Am. J. Clin. Nutr.* 90(6), 1642-1647, doi: 10.3945/ajcn.2009.28482.

Nash, S.H., Bersamin, A., Kristal, A.R., Hopkins, S.E., Church, R.S., Pasker, R.L., Luick, B.R., Mohatt, G.V., Boyer, B.B. and O'Brien, D.M. (2012). Stable nitrogen and carbon isotope ratios indicate traditional and market food intake in an indigenous circumpolar population. *J. Nutr.* 142 (1), 84-90.

Nash, S.H., Kristal, A.R., Bersamin, A., Hopkins, S.E., Boyer, B.B. and O'Brian, D.M. (2013) Carbon and nitrogen stable isotope ratios predict intake of sweeteners in a Yup'ik study population. *J. Nutr.* 143(2), 161-165, doi: 10.3945/jn.112.169425.

Nelson, B. K., DeNiro, M. J., Schoeninger, M. J., DePaolo, D. J., & Hare, P. E. (1986). Effects of diagenesis on strontium, carbon, nitrogen and oxygen concentration and isotopic composition of bone. Geochimica et Cosmochimica Acta, 50, 1941-1949.

Neumann, W., & Huster, E. (1974). The Half-Life of ^{87}Rb Measured as Difference between the Isotopes 87Rb and 85Rb*. Z. Physik, 270, 121-127.

Nielsen-Marsh, C. M., & Hedges, R. E. M. (2000a). Patterns of Diagenesis in Bone I: The Effects of Site Environments. Journal of Archaeological Science, 27, 1139-1150, 10.1006/jasc.1999.0537.

Nielsen-Marsh, C. M., & Hedges, R. E. M. (2000b). Patterns of Diagenesis in Bone II: Effects of Acetic Acid Treatment and the Removal of Diagenetic CO_3^{2-}. Journal of Archaeological Science, 27, 1151-1159, 10.1006/jasc.1999.0538.

O'Connell TC, and Hedges REM. 1999. Isotopic Comparison of Hair and Bone: Archaeological Analyses. J Archaeol Sci 26(6):661-665.

O'Connell TC, and Hedges REM. 1999. Investigations into the Effect of Diet on Modern Human Hair Isotopic Values. Amer J Phys Anthropol 108(4):409-425.

O'Connell TC, Hedges REM, Healey MA, and Simpson AHRW. 2001. Isotopic Comparison of Hair, Nail and Bone: Modern Analyses. J Archaeol Sci 28(11):1247-1255.

O'Connell, T.C., Kneale, C.J., Tasevska, N., & Kuhnle, G.G.C. (2012). The diet-body offset in human nitrogen isotopic values: a controlled dietary study. *Am J Phys Anthro* 149, 426-34, doi: 10.1002/ajpa.22140.

Oxley, J.C., Smith, J.L., Kirschenbaum, L.J. and Marimganti, S. (2007). Accumulation of explosives in hair – Part II: Factors affecting sorbtion. *J. Forensic Sci.* 52(6), 1291-1296, doi: 10.1111/1556-4029.2007.0.0567.x.

Pestle, W.J., Crowley, B.E., and Weirauch, M.T. (2014) Quantifying inter-laboratory variability in stable isotope analysis of ancient skeletal remains. *PLoS One* 9, e102844, doi: 10.1371/journal.pone.0102844.

Petzke, K.J., Boeing, H. and Metges, C.C. (2005) Choice of dietary protein of vegetarians and omnivores is reflected in their hair protein ^{13}C and ^{15}N abundance. *Rapid Comm Mass Spectr.* 19(11), 1392-1400, doi: 10.1002/rcm.1925.

Petzke, K.J., Fuller, B.T. and Metges, C.C. (2010) Advances in natural stable isotope ratio analysis of human hair to determine nutritional and metabolic status. *Curr. Opinion Clin. Nutr. Metabol. Care* 13(5), 532-540, doi: 10.1097/MCO.0b013e32833c3c84.

Podlesak, D.W., Torregrossa, A.-M., Ehleringer, J.R., Dearing, M.D., Passey, B.H., and Cerling, T.E. (2008) Turnover of oxygen and hydrogen isotopes in the body water, CO_2, hair and enamel of a small mammal. *Geochim Cosmochim Acta* 72, 19-35, doi: 10.1016/j.gca.2007.10.003.

Podlesak, D.W., Bowen, G.J., O'Grady, S., Cerling, T.E. and Ehleringer, J.R. (2012) δ^2H and $\delta^{18}O$ of human body water: a GIS model to distinguish residents from non-residents in the contiguous USA. *Isotopes Environ Health Stud* 48(2), 259-79, doi: 10.1080/10256016.2012.644283.

Pollard, A.M., Pellegrini, M., & Lee-Thorp, J.A. (2011). Technical Note: some observations on the conversion of dental enamel d18Op values to d18Ow to determine human mobility. *Am. J. Phys. Anthro.* 145, 499-504, doi: 10.1002/ajpa.21524.

Powell, R., Woodhead, J., & Hergt, J. (1998). Uncertainities on lead isotope analyses: deconvolution in the double-spike method. Chemical Geology, 148, 95-104.

Price, T. D., Blitz, J., Burton, J., & Ezzo, J. A. (1992). Diagenesis in prehistoric bone: Problems and solutions. Journal of Archaeological Science, 19, 513-529.

Price, T. D., Burton, J. H., & Bentley, R. A. (2002). The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry, 44, 117-135.

Price, T. D., Grupe, G., & Schröter, P. (1994a). Reconstruction of migration patterns in the Bell Beaker period by stable strontium isotope analysis. Applied Geochemistry, 9, 413-417.

Price, T. D., Johnson, C. M., Ezzo, J. A., Ericson, J., & Burton, J. H. (1994b). Residential mobility in the Prehistoric Southwest United States: A Preliminary Study using Strontium Isotope Analysis. Journal of Archaeological Science, 21, 315-330.

Price, T. D., Manzanilla, L., & Middleton, W. D. (2000). Immigration and the ancient city of Teotihuacan in Mexico: a study using strontium isotope ratios in human bone and teeth. Journal of Archaeological Science, 27, 903-913.

Price, T. D., Tiesler, V., & Burton, J. H. (2006). Early African Diaspora in colonial Campeche, Mexico: strontium isotopic evidence. American journal of physical anthropology, 130, 485-490, 10.1002/ajpa.20390.

Prohaska, T., Latkoczy, C., Schultheis, G., Teschler-Nicola, M., & Stingeder, G. (2002). Investigation of Sr isotope ratios in prehistoric human bones and teeth using laser ablation ICP-MS and ICP-MS after Rb/Sr separation. Journal of Analytical and Atomic Spectrometry, 17, 887-891, 10.1039/b203314c.

Pye, K. (2007) Geological and Soil Evidence: Forensic Applications. CRC Press

Pye, K. and Croft, D., eds. (2007) Forensic Geoscience: Principles, Techniques and Applications (Geological Society Special Publication 232. 328 pp.

Pye, K., Blott, S.J., Croft, D.J. and Carter, J.F. (2006) Forensic comparison of soil samples: Assessment of small-scale spatial variability in elemental composition, carbon and nitrogen isotope ratios, colour, and particle size distribution. *Forensic Sci Intl* 163, 59-80, doi: 10.1016/j.forsciint.2005.11.008.

Qi, H. and Coplen, T.B. (2011) Investigation of preparation techniques for δ^2H analysis of keratin materials and a proposed analytical protocol. *Rapid Commun Mass Spectrom* 25 (15), 2209-22, doi: 10.1002/rcm.5095.

Ramos, F. C., Wolff, J. A., & Tollstrup, D. L. (2004). Measuring $^{87}Sr/^{86}Sr$ variations in minerals and groundmass from basalts using LA-MC-ICPMS. Chemical Geology, 211, 135-158, 10.1016/j.chemgeo.2004.06.025.

Randall VA, and Ebling FJ. 1991. Seasonal Changes in Human Hair Growth. Brit J Dermatol 124(2):146-151.

Rauch, E., Rummel, S., Lehn, C., & Büttner, A. (2007). Origin assignment of unidentified corpses by use of stable isotope ratios of light (bio-) and heavy (geo-) elements--a case report. Forensic science international, 168, 215-218, 10.1016/j.forsciint.2006.02.011.

Regan, L.A. (2006) *Isotopic determination of region-of-origin in modern peoples: Applications for identification of U.S. war-dead from the Vietnam conflict*. (Doctoral dissertation). University of Florida, 278 pps.

Rehkämper, M., & Halliday, A. N. (1998). Accuracy and long-term reproducibility of lead isotopic measurements by multiple-collector inductively coupled plasma mass spectrometry using an external method for correction of mass discrimination. International Journal of Mass Spectrometry, 181, 123-133.

Reimann, C., Flem, B., Fabian, K., Birke, M., Ladenberger, A., Négrel, P., Demetriades, A., and Hoogewerff, J. (2012) Lead and lead isotopes in agricultural soils of Europe – The continental perspective. *Appl Geochem* 27, 532-542, doi: 10.1016/j.apgeochem.2011.12.012.

Rodrigues, C., Brunner, M., Steiman, S., Bowen, G. J., Nogueira, J. M., Gautz, L., Prohaska, T., & Máguas, C. (2011). Isotopes as tracers of the Hawaiian coffee-producing regions. Journal of agricultural and food chemistry, 59, 10239-10246, 10.1021/jf200788p.

Romaniello, S.J., Field, M.P., Smith, H.P., Gordon, G.W., Kim, M.H., and Anbar, A.D. (2015) Fully automated chromatographic purification of Sr and Ca for isotopic analysis. *J Anal At Spectrom* 30, 1906-12, doi: 10.1039/c5ja00205b.

Roy DM, Hall R, Mix AC, and Bonnichsen R. 2005. Using Stable Isotope Analysis to Obtain Dietary Profiles From Old Hair: A Case Study From Plains Indians. Amer J Phys Anthropol 128(2):444-452.

Santamaria-Fernandez, R., & Wolff, J. -C. (2011). Response to Comments on "Application of laser ablation multicollector inductively coupled plasma mass spectrometry for the measurement of calcium and lead isotope ratios in packaging for discriminatory purposes". Rapid Communications in Mass Spectrometry, 25, 3199-3200, 10.1002/rcm.5205.

Santamaria-Fernandez, R., & Wolff, J. C. (2010). Application of laser ablation multicollector inductively coupled plasma mass spectrometry for the measurement of calcium and lead isotope ratios in packaging for discriminatory purposes. Rapid communications in mass spectrometry : RCM, 24, 1993-1999, 10.1002/rcm.4603.

Scholl, M. (2006). Precipitation isotope collector designs. Retrieved from https://water.usgs.gov/nrp/proj.bib/hawaii/precip_methods.htm on 12/31/2017.

Schultz, J. J., Warren, M. W., & Krigbaum, J. S. (2008). Analysis of human cremains: gross and chemical methods. In: The Analysis of Burned Human Remains (pp. 75-94). Oxford, UK: Elsevier Ltd.

Schurr, M. R., Hayes, R. G., & Cook, D. C. (2008). Thermally induced changes in the stable carbon and nitrogen isotope ratios of charred bones. In: The Analysis of Burned Human Remains (pp. 95-108). Oxford, UK: Elsevier Ltd.

Scientific Working Group for Forensic Anthropology (SWGANTH). (2012). Resolving Commingled Human Remains. Report. *Available at* http://swganth.startlogic.com/Commingling%20Rev1.pdf.

Scott, G.R., & Turner, C.G. (1997). *The anthropology of modern human teeth*. Cambridge: Cambridge University Press.

Sealy, J. C., van der Merwe, N. J., Sillen, A., Kruger, F. J., & Krueger, H. W. (1991). $^{87}Sr/^{86}Sr$ as a Dietary Indicator in Modern and Archaeological Bone. Journal of Archaeological Science, 18, 399-416.

Sharp ZD, Atudorei V, Panarello HO, Fernandez J, and Douthitt C. 2003. Hydrogen Isotope Systematics of Hair: Archaeological and Forensic Applications. J Archaeol Sci 30:1709-1716.

Shibuya, E. K., Souza Sarkis, J. E., Neto, O. N., Moreira, M. Z., & Victoria, R. L. (2006). Sourcing Brazilian marijuana by applying IRMS analysis to seized samples. Forensic science international, 160, 35-43, 10.1016/j.forsciint.2005.08.011.

Shrag, B., Uldin, T., Mangin, P. and Froidevaux, P. (2012) Dating human skeletal remains using a radiometric method: biogenic versus diagenetic ^{90}Sr and ^{210}Pb in vertebrae. *Forensic Sci Intl* 220, 271-8, doi: 10.1016/j.forsciint.2012.03.014.

Sillen, A. (1989). Diagenesis of the Inorganic Phase of Cortical Bone. In: T. D. Price (Eds.), The Chemistry of Prehistoric Human Bone (pp. 211-228). Cambridge: Cambridge University Press.

Sillen, A., & Sealy, J. C. (1995). Diagenesis of Strontium in Fossil Bone: A Reconsideration of Nelson et al. (1986). Journal of Archaeological Science, 22, 313-320.

Silva, A. M., Crubézy, E., & Cunha, E. (2009). Bone Weight: New Reference Values Based on a Modern Portuguese Identified Skeletal Collection. International Journal of Osteoarchaeology, 19, 628-641, 10.1002/oa.998.

Simonetti, A., Buzon, M. R., & Creaser, R. A. (2008). In-situ elemental and Sr isotope investigation of human tooth enamel by laser ablation-(MC)-ICP-MS: Successes and pitfalls. Archaeometry, 50, 371-385, 10.1111/j.1475-4754.2007.00351.x.

Skulan, J., Bullen, T., Anbar, A. D., Puzas, J. E., Shackelford, L., LeBlanc, A., & Smith, S. M. (2007). Natural calcium isotopic composition of urine as a marker of bone mineral balance. Clin Chem, 53, 1155-1158, 10.1373/clinchem.2006.080143.

Sponheimer M, Codron D, Passey BH, Ruiter DJd, Cerling TE, and Lee-Thorp JA. 2009. Using Carbon Isotopes to Track Dietary Change in Modern, Historical, and Ancient Primates. Am J Phys Anthropol 140(4):661-670.

Stout SD, and Lueck R. 1995. Bone Remodeling Rates and Skeletal Maturation in Three Archaeological Skeletal Populations. 98(2):161-172.

Steadman, Dawnie L. Wolfe (ed.) 2009. Hard Evidence: Case Studies in Forensic Anthropology, 2nd Edition. Upper Saddle River, NJ: Prentice Hall.

Steiger, R. H., & Jäger, E. (1977). Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, 36, 359-362.

Thibodeau, A. M., Chesley, J. T., & Ruiz, J. (2012). Lead isotope analysis as a new method for identifying material culture belonging to the Vázquez de Coronado expedition. Journal of Archaeological Science, 39, 58-66, 10.1016/j.jas.2011.07.025.

Tipple, B.J. (2016). *Isotope Analyses of Hair as a Trace Evidence Tool to Reconstruct Human Movements: Establishing the Effects of the "Human Ecosystem" on Strontium and Oxygen Isotope Ratios* (Department of Justice Report 250339). National Criminal Justice Reference Service. 91 pps.

Tipple, B.J., Chau, T., Chesson, L.A., Fernandez, D.P., & Ehleringer, J.R. (2013). Isolation of strontium pools and isotope ratios in modern human hair. *Analytica Chimica Acta*, 798, 64-73. doi: 10.1016/j.aca.2013.08.054

Tridico, S.R., Koch, S., Michaud, A., Thomson, G., Kirkbride, K.P., and Bunce, M. (2014) Interpreting biological degradative processes acting on mammalian hair in the living and the dead: which ones are taphonomic? *Proc Biol. Sci.* 281, 20141755, doi: 10.1098/rspb.2014.1755.

Trujillo-Mederos, A., Alemán, I., Botella, M., & Bosch, P. (2012). Changes in human bones boiled in seawater. Journal of Archaeological Science, 39, 1072-1079, 10.1016/j.jas.2011.12.005.

Tümer, A. R., Akçan, R., Karacaoglu, E., Balseven-Odabasi, A., Keten, A., Kanburoglu, C., Ünal, M., & Dinç, A. H. (2012). Postmortem burning of the corpses following homicide. Journal of *Forensic and Legal Medicine*, 19, 223-228, 10.1016/j.jflm.2012.01.001.

Tütken, T., Vennemann, T. W., & Pfretzschner, H. U. (2008). Early diagenesis of bone and tooth apatite in fluvial and marine settings: Constraints from combined oxygen isotope, nitrogen and REE analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 266, 254-268,

Ubeleker, D.H. (1987). Estimating Age at Death from Immature Human Skeletons: An Overview. *Journal of Forensic Science*, 32, 1254-63.

Uitdehaag, S., Wiarda, W., Donders, T., and Kuiper, I. (2017) Forensic Comparison of Soil Samples Using Nondestructive Elemental Analysis. *J Forensic Sci* 62, 861-868, doi: 10.1111/1556-4029.13313.

Valenzuela, L.O., Chesson, L.A., O'Grady, S.P., Cerling, T.E., and Ehleringer, J.R. (2011) Spatial distributions of carbon, nitrogen, and sulfur isotope ratios in human hair across the central United States. *Rapid Commun Mass Spectrom* 25, 861-868, doi: 10.1002/rcm.4934.

Valenzuela, L.O., Chesson, L.A., Bowen, G.J., Cerling, T.E., and Ehleringer, J.R. (2012) Dietary heterogeneity among Western industrialized countries reflected in the stable isotope ratios of human hair. *PLoS One* 7, e34234, doi: 10.1371/journal.pone.0034234.

Van Deest, T. L., Murad, T. A., & Bartelink, E. J. (2011). A re-examination of cremains weight: sex and age variation in a Northern California sample. *Journal of forensic sciences*, 56, 344-349, 10.1111/j.1556-4029.2010.01658.x.

van Geldern, R. and Barth, J.A.C. (2012). Optimization of instrument set-up and post-run corrections for oxygen and hydrogen stable isotope measurements of water by isotope ratio infrared spectroscopy (IRIS). *Limnol. Oceanography: Methods* **10**, 1024-1036, doi: 10.4319/lom.2012.10.1024.

Van Wyck, N., & Johnson, C. M. (1997). Common lead, Sm-Nd, and U-Pb constraints on petrogenesis, crustal architecture, and tectonic setting of the Penokean orogeny (Paleoproterozoic) in Wisconsin. GSA Bulletin, 109, 799-808,

Vass AA, Bass WM, Wolt JD, Foss JE, Ammons JT. 1992. Time since death determinations of human cadavers using soil solution. *Journal of Forensic Sciences* 37(5):1236-1253.

Vass AA. 2011. The elusive universal postmortem interval formula. *Forensic Science International* 204(1-3), 34-40.

Vautour, G., Poirier, A. and Widory, D. (2015) Tracking mobility using human hair: What can we learn from lead and strontium isotopes? *Sci Just* 55, 63-71, doi: 10.1016/j.scijus.2014.10.001.

Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G. A. F., Diener, A., Ebneth, S., Godderis, Y., Jasper, T., Korte, C., Pawellek, F., Podlaha, O. G., & Strauss, H. (1999). $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{18}O$ evolution of Phanerozoic seawater. Chemical Geology, 161, 59-88.

Voerkelius, S., Lorenz, G. D., Rummel, S., Quétel, C. R., Heiss, G., Baxter, M., Brach-Papa, C., Deters-Itzelsberger, P., Hoelzl, S., Hoogewerff, J., Ponzevera, E., Van Bocxstaele, M., & Ueckermann, H. (2010). Strontium isotopic signatures of natural mineral waters, the reference to a simple geological map and its potential for authentication of food. Food Chemistry, 118, 933-940, 10.1016/j.foodchem.2009.04.125.

Von Holstein, I.C.C., Penkman, K.E.H., Peacock, E.E., and Collins, M.J. (2014) Wet degradation of keratin proteins: linking amino acid, elemental and isotopic composition. *Rapid Commun*

Mass Spectrom 28, 2121-23, doi: 10.1002/rcm.6999.

Von Holstein, I.C.C., Font, L., Peacock, E.E., Collins, M.J., and Davies, G.R. (2015) An assessment of procedures to remove exogenous Sr before 87Sr/86Sr analysis of wet archaeological wool textiles. *J Arch Sci* 53, 84-93, doi: 10.016/j.jas.2014.10.006.

Wakaki, S., Obata, H., Tazoe, H., and Ishikawa, T. (2017) Precise and accurate analysis of deep and surface seawater Sr stable isotopic composition by double-spike thermal ionization mass spectrometry. *Geochem J* 51, 227-239, doi: 10.2343/geochemj.2.0461.

Wassenaar, L.I., Van Wilgenburg, S.L., Larson, K. and Hobson, K.A. (2009) A groundwater isoscape (δD, $\delta^{18}O$) for Mexico. *J. Geochem. Explor.* 102(3), 123-136, doi: 10.1016/j.gexplo.2009.01.001.

Webb E, Thomson S, Nelson A, White C, Koren G, Rieder M, and Van Uum S. 2010. Assessing Individual Systemic Stress Through Cortisol Analysis of Archaeological Hair. J Archaeol Sci 37(4):807-812.

West, J.B., Sobek, A. and Ehleringer, J.R. (2008) A Simplified GIS Approach to Modeling Global Leaf Water Isoscapes. *PloS one* 3(6), doi: 10.1371/journal.pone.0002447.

West, J. B., Hurley, J. M., Dudás, F. O., & Ehleringer, J. R. (2009). The stable isotope ratios of marijuana. II. Strontium isotopes relate to geographic origin. Journal of forensic sciences, 54, 1261-1269, 10.1111/j.1556-4029.2009.01171.x.

White CD, Nelson AJ, Longstaffe FJ, Grupe G, and Jung A. 2009. Landscape Bioarchaeology at Pacatnamu, Peru: Inferring Mobility from [delta]13C and [delta]15N Values of Hair. J Archaeol Sci 36(7):1527-1537.

White CD. 1993. Isotopic Determination of Seasonality in Diet and Death from Nubian Mummy Hair. J Archaeol Sci 20:657-666.

White CD, and Schwarcz HP. 1994. Temporal Trends for Stable Isotopes in Nubian Mummy Tissues. 93:165-187.

Williams LJ, White CD, and Longstaffe FJ. 2011. Improving Stable Isotopic Interpretations Made from Human Hair through Reduction of Growth Cycle Error. Amer J Phys Anthropol 145(1):125-136.

Williams JS, and Katzenberg MA. 2012. Seasonal Fluctuations in Diet and Death during the Late Horizon: A Stable Isotopic Analysis of Hair and Nail from the Central Coast of Peru. J Archaeol Sci 39(1):41-57.

Wilson, A.S., Janaway, R.C., Holland, A.D., Dodson, H.I., Baran, E., Pollard, A.M., and Tobin, D.J. (2007a) Modelling the buried human body environment in upland climes using three contrasting field sites. *Forensic Sci Intl* 169, 6-18, doi: 10.1016/j.forsciint.2006.07.023.

Wilson, A.S., Dodson, H.I., Janaway, R.C., Pollard, A.M., and Tobin, D.J. (2007b) Selective biodegradation in hair shafts derived from archaeological, forensic and experimental contexts. *Br J. Dermatol.* 157: 450-7, doi: 10.1111/j.1365-2133.2007.07973.x.

Wilson, A.S. (2008) The decomposition of hair in the buried body environment. *In* Soil Analysis in forensic taphonomy: chemical and biological effects of buried human remains. CRC Press, pp. 123-151.

Wilson, A.S., Dodson, H.I., Janaway, R.C., Pollard, A.M., and Tobin, D.J. (2010) Evaluating histological methods for assessing hair fibre degradation. *Archaeometry* 52, 467-481, doi: 10.1111/j.1475-4754.2010.00524.x.

Wright, L. E., & Schwarcz, H. P. (1996). Infrared and Isotopic Evidence for Diagenesis of Bone Apatite at Dos Pilas, Guatemala: Palaeodietary Implications. Journal of Archaeological Science, 23, 933-944.

Yoshinaga, Y. (1996). Isotope Ratio Analysis of Lead in Biological Materials by Inductively Coupled Plasma Mass Spectrometry. Tohoku Journal of Experimental Medicine, 178, 37-47.

9. ACKNOWLEDGEMENTS

A project of this size and diversity of scientific fields and analytical type requires the help, expertise, and discussion with many colleagues. In particular, we would like to thank: Randall Debes for analyzing the water samples for $\delta^{18}O$ and $\delta^{2}H$; Natasha Zolotova, and Dr. Everett Shock for permission to use their water collection protocols; Dr. Hilairy Hartnett and Joshua Nye for analysis of DOC/DIC concentrations in water samples; Natasha Zolotova for analysis of $\delta^{13}C$ in DOC and DIC at the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University; Dr. Joy Matthews of SIF (Stable Isotope Facility) University of California, Davis for measurement of $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, and $\delta^{15}N$ in hair samples of the freezing study, as well as for extremely helpful conversations about normalization quality control in hair sample analysis; Leslie Chesson of Isoforensics, Inc. and Dr. James Ehleringer at the University of Utah for additional highly insightful discussions of normalization of light stable isotope analysis for hair samples. Dr. Suvankar Chakraborty of SIRFER (Stable Isotope Ratio Facility for Environmental Research) at the University of Utah is gratefully acknowledged for patiently answering questions regarding quality control of analyses, as well as completing many of the isotopic analyses. Melanie Caron, MSc, of CPSIL at NAU ran the carbonate analyses for tooth enamel and bone. Laboratory assistance from Trevor Martin, Allisen Dahlstedt, and Dr. Stephen Romaniello are also appreciated. Discussions with Dr. Tiffany Saul, Middle Tennessee State University and Julianne Sarancha, MS, University of California, Davis, were central in understanding the data.

Training and discussions with Mesa Police Department personnel informed much of the research behind this study. Particular appreciation goes out to Senior Crime Scene Specialists Christine Lowenhagen, Lisa Morgante, Christopher Zemojtel, Rebecca Winger, Keia Kloss, Dawn Devine, Tom Hewson and Crime Scene Supervisors Kristal Kolhepp, Aaron Stortz, and Sean Conner and former Crime Scene Supervisors Elizabeth Wiltrout and Tara Hall, and Photography Supervisor Rob Young.

10. Dissemination of Research Findings

Social media and outreach

Blog: https://asuexplorers.wordpress.com/. This blog has a built-in audience, as it was started specifically to share field experiences of ASU scientific researchers. The blog was tweeted by @forensicnews and is designed to introduce the lay public to the scientific process, forensic anthropology and isotopes specifically. (Gordon, 2016)

Podcast: Star Citizen Science interview with PI Gordon with reporter Todd Gilbert (2015). Available at http://imperialnews.network/2015/09/scsp-sataball-astronaut-bones.

Podcast: Just Hairy Isotopes. Episode 10 of *Just* Science, the Forensic Technology Center of Excellence's podcast (2017). Available at https://forensiccoe.org/s1e10/.

Twitter: PI Gordon hosted @realscientists twitter account for the week of August 30th-September 5th, 2015 and tweeted about isotopes in modern humans. Profile available at http://realscientists.org/2015/08/30/law-and-order-special-geochemistry-unit-gwyneth-gordon-joins-real-scientists/.

Outreach: "Forensics of Sherlock", panelist, Phoenix Comiccon. May 30th, 2015.

Outreach: "Tangled: The Science of Hair", panelist, Phoenix Comiccon, May 25th, 2017.

Presentations

Gordon, G.W., Saul, T., Steadman, D., Knudson, K., Wescott, D.J., Preservation of hair stable isotopes signatures during freezing *poster presented at the* 2017 AAFS conference

Gordon, G.W., Saul, T., Steadman, D., Wescott, D.J., Knudson, K. and Anbar, A.D., The isotopic taphonomy of human hair *oral presentation at the* 2017 AAFS conference DOJ grantee's symposium. Available as a webinar at https://www.forensiccoe.org/2017-NIJ-Forensic-Science-Research-and-Development-Symposium.

Gordon, G.W., Saul, T., Steadman, D., Wescott, D., Knudson, K. and Anbar, A.D., The isotopic taphonomy of human remains. *Invited keynote at the 12th International Symposium on Applied Isotope Geochemistry, Sept. 17-22, Colorado*

Saul, T. (2017) talk at the Forensic Services Department of the Mesa Police Department, May 4th, 2017

Saul, T. (2017) talk at the Forensic Science Department of the New College of Arizona State University, May 5th, 2017

Saul, T. (2017) talk at the Tennessee Association of the International Association for Identification (IAI) meeting, July 20th, 2017

Saul, T., Gordon, G., Tipple, B., Chesson, L.A., Steadman, D.W., and Wescott, D. (2018) Taphonomic Effects on Isotope Ratios of Human Hair, *oral presentation to be given at the 2018 AAFS conference*

Products

Saul, T. (2017) Taphonomic Effects on Isotope Ratios of Human Hair. *Doctoral dissertation, University of Tennessee, Knoxville.*