Journal of Archaeological Science: Reports 17 (2018) 919–931

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Differentiating mobility and migration in middle Holocene Cis-Baikal, Siberia

Ian Scharlotta

Department of Anthropology, University of Alberta, Edmonton, AB T6G 2H4, Canada
Aix Marseille Univ, CNRS, Minist Culture & Com, LAMPEA, Aix-en-Provence, France

ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 24 March 2016
Accepted 20 May 2016
Available online 26 May 2016

Keywords:
Migration
Mobility
Geochemistry
Laser-ablation
Microsampling
Hunter-gatherer

ABSTRACT

The development of analytical techniques associated with individual life history approaches to reconstructing prehistoric patterns of diet and mobility has produced significant changes in the potential information contained within a single skeleton. In the context of Early Bronze Age hunter-gatherer groups in Cis-Baikal, Siberia, a comparison of bulk versus micro-sampling strategies has altered understanding of the level of mobility and interaction. Detailed surveys of biogeochemical variation in the landscape combined with improved resolution translate into an ability to examine the provenance and track the movements of an individual through different stages in their life. Determining where an individual was on the geographic landscape during multiple phases of life, as opposed to the geochemical landscape of childhood and death, is important to differentiating between patterns of migration and smaller scale movements undertaken during life. Advances in micro-sampling capabilities have enabled new sampling strategies that include the collection of data from multiple points on individual human teeth and bones. Micro-sampling of multiple skeletal elements expands the resolution with which researchers can examine an individual's life. Technical advances have also highlighted a need to re-examine the relationship between theoretical and analytical aspects of behavioral reconstructions in prehistory. Geochemical research in Cis-Baikal has closely followed advances in analytical capabilities and provides a case study to assess the efficacy of theoretical assumptions underlying explanations of short and long distance movements during lifetime and examine potential improvements in data interpretations.

1. Introduction

The use of biogeochemical analysis to reconstruct behavioral patterns has a long history in archaeology though the specific goals for using these data (e.g., health, diet, mobility) have varied. Studies initially focused on general nutrition and metabolic interactions with different elements and compounds, leading towards dietary reconstruction. Questions about mobility, interpreted as locale of birth versus adult life and subsequent death and burial, largely stemmed from the body of earlier paleodietary research that helped to elucidate which types of chemical analyses were likely to reflect intact information as opposed to variable metabolic functions or diagenesis. Metabolic functions can vary greatly throughout life (i.e., moderated by health, age, pregnancy, environment), or be influenced in the post-depositional environment, altering the chemical analytical results.

Early paleodietary research observed that strontium was a particularly useful element, commonly substituting for calcium within the hydroxyapatite in bone and teeth and comparatively resilient through life and subsequent burial (Comar et al., 1957; Comar and Wasserman, 1964; Elias et al., 1982; Likins et al., 1960; Nelson et al., 1986; Nelson and Sauer, 1984; Price et al., 1992; Rosenthal et al., 1972; Schroeder et al., 1972; Sillen and Kavanagh, 1982). The use of strontium isotopic and trace element analysis for studying movement was pioneered by ecologists mapping the geographical movement of different species and environmental materials (Gosz et al., 1983; Koch et al., 1992). This approach was adopted by archaeologists interested in prehistoric diet and mobility. The techniques have now been used by archaeologists for decades (e.g., Ericson, 1985, 1989; Ezzo et al., 1997; Grupe and Herrmann, 1988; Price, 1989; Price et al., 1994a; Price et al., 1994b; Sealy et al., 1995; Sealy, 1989; Sealy and Sillen, 1988), and have become routine parts of scientific analyses on archaeological skeletons.

There have been considerable refinements to the technical capabilities, applications, and interpretations over the years. For example, the transition from using TIMS to SM-MC-ICP-MS and finally to LA-MC-ICP-MS that resulted in reductions in pretreatment efforts and overall sampling times and costs, the tandem-use of multiple analytical techniques, and the integration of first multi-elemental sampling and ultimately micro-sampling of these multiple skeletal elements to produce a robust body of data to reconstruct individual life histories (Dolphin et al., 2012; Dolphin et al., 2003; Dolphin et al., 2016; Farell et al., 2013; Haverkort et al., 2008; Kang et al., 2004; Knudson and Price, 2007; Scharlotta et al., 2011; Scharlotta et al., 2013; Scharlotta and Weber, 2014; Weber et al., 2003; Weber and Goriunova, 2013). However, it is rare to see the progression of methodological development within a single region, even using materials from the same individuals and/

E-mail address: frasersh@ualberta.ca.

http://dx.doi.org/10.1016/j.jasrep.2016.05.045

or cemeteries (e.g., scale of analysis/sampling, destruction of samples, duration of life history elucidated, etc.) as has been possible with hunter-gatherers from Cis-Baikal, Siberia through the work of the Baikal Archaeology Project. In many ways the assumptions behind, and applications for, such analyses have changed significantly. It is not always clear that the full data potential of skeletal materials is being employed, raising doubts about the potential extent to which the analytical data can be extrapolated to behavioral patterns.

Many of the chemical analytical methods were developed and tested using sedentary populations of varying size in which differences of birth locality, status, and diet were anticipated. Difficulties can arise when transitioning to hunter-gatherer populations that vary throughout their lifetime and may not have distinctive markers of status in either their dietary makeup, or interred artifacts. For example: How effective are the established methods at analyzing movements when applied to populations with radically different behavioral patterns? Are we producing data that reflect changes during known time periods of a prehistoric lifetime? Does the data support generalizations on behavioral patterns that may not be temporally consistent or significant to the population being investigated? Are there any means to determine if technical and/or theoretical improvements can be made to better link the scale of behavioral patterns sought in the prehistoric record with the data being produced during analyses?

This discussion is based in a series of articles and book chapters produced over the last decade by the Baikal Archaeology Project (BAP) focusing on is the Cis-Baikal region of eastern Siberia (Haverkort et al., 2010; Haverkort et al., 2008; Scharlotta et al., 2013; Scharlotta and Weber, 2014; Weber and Goriunova, 2013; Weber et al., 2011). This research was produced in an environment of rapidly changing technical and theoretical discussions about how to address hunter-gatherer and mobility research. Within the region, the dominant geological formations roughly equate to cultural micro-regions that scholars have been investigating (Fig. 1). With cultural areas corresponding to geological differences, it was a promising landscape for geochemical research into patterns of movement and interaction throughout the region. The geochemical work has focused heavily on the Khuzhir-Nuge XIV cemetery in the Little Sea region (Fig. 2), with additional data from smaller cemeteries in the Little Sea and Upper Lena regions. More cemeteries are being analyzed to provide broader temporal and spatial coverage, but without the same type of overlap in research methods.

2. Concept of mobility

The common sense concept of mobility holds that people do not remain static in their environment under most conditions in human history. Mobility is defined as the quality of being mobile and thus the ability to move. The ability to move often includes the additional inference of being in motion, sequential movements having occurred, or the movement of people specifically. Indeed, individuals will always be mobile to a certain degree: fetching water, conducting hunting and gathering trips, traveling to tend to crops and/or herds, as residents of cities, traveling to their place of employment, or changing their social status. There is the implication that mobility, as the quality of being in motion, is taking place and can be observed and recorded to some measurable extent as having occurred. Part of the difficulty is that mobility is an active process, only observable in the present; whereas archaeologically, reconstruction of a series of movements that occurred in the past is required.

In attempts to describe mobility, having broad arbitrary categories, such as 'semi-sedentary,' can simplify explanatory efforts as researchers need only identify the appropriate category to place their archaeological materials. Yet, as noted by Kelly (1992, 1995: 159), 'it is not useful to think of mobility in terms of either a single dimension of group mobility or as a dichotomy of mobile versus sedentary (cf. Nicholas, 2007). There should be a straightforward relationship between the scale at which a movement occurred in time or space, the direct interactions between the person or object being moved, the surrounding environment, and how this will manifest as the result of observation or be reconstructed through analysis.

Mobility is effectively defined as the state (or capability) of being in motion, or not at rest. Motion, however, is the action or process of movement, traveling between a starting and ending point. Physical evidence that this action has occurred must either be directly observed as a witness to the process, inferred from observation that a change of location has occurred, or reconstructed following demonstration that an object is not characteristic of the local landscape or population and originated elsewhere. The type of evidence of interaction between a moving object and its surroundings is less clear and there can be a great deal of variability (e.g., trip length, duration) involved in the concept of mobility.

Sedentariness, or the time spent being sedentary, is a variable that can potentially be quantified and studied. This is the inversely related member of the same variable as mobility in that it aims to describe the time in which an object or person is not in motion. The evidence for sedentariness is rather more straightforward for it denotes the actual interaction between the person or object and its surroundings. Sedentariness can be defined as having limited or restricted mobility such that groups or individuals are effectively not mobile. Evidence for sedentariness is also expected to vary in relevant scales; for example evidence for contact with a certain food/water source, duration of seasonal habitation within a restricted geographical area, and chemical records of where an individual lived during different periods of their life. While more terminological accurate, general discussions about sedentism or sedentariness often refers to the length of time which settlements were inhabited and whether this suggests the use of stored resources, quite different than mobility researcher investigating disparities between the birth and death locale of local human or animal populations. Efforts to replace the term mobility in discussing the movements of within and between populations would likely cause confusion; rather the specific type of patterning in movement researchers are employing should be made clear.

Differentiating, or more clearly explaining, the different scales of movement and so related behavioral activities observed in the archaeological record is significant because physical mobility is the product of cultural structures and processes both directly and indirectly. Directly, through the necessary provisioning by group members of consumables, information and social ties, mobility patterning will be specific to given cultural groups and can elucidate behavioral trends changing through time or between different groups that may produce similar archaeological assemblages. Indirectly, however, mobility is somewhat more complex and potentially more informative on cultural patterns. Any individual has choices in their allocation of time and effort to various duties and functions deemed to be of importance to either the group or the individual. Thus, differences in patterns of action speak directly to the types of choices that were important to an individual or group and so were crucial to the structure of their lives. In regions such as Cis-Baikal (Weber and Bettinger, 2010; Weber et al., 2010; Weber et al., 2002) where genetically distinct populations employed different subsistence strategies and cultural manifestations within the same geographic area with similar environmental conditions, these decisions are important to explaining how and why the archaeological record is different for these groups.

Mobility patterning in the archaeological record is a group level phenomenon while the actual parts of the pattern are the individual actions. Patterns are viewed as the aggregate of individual mobility profiles that yield patterning at the group level susceptible to cultural transmission. Mobility as a sequence of movements will include a range of variability impacted by cultural structures. Variability in observed patterns reflects changes in the direct mobility, patterns of interaction with extant ecological conditions, dietary choices, kinship structures and other cultural traits.

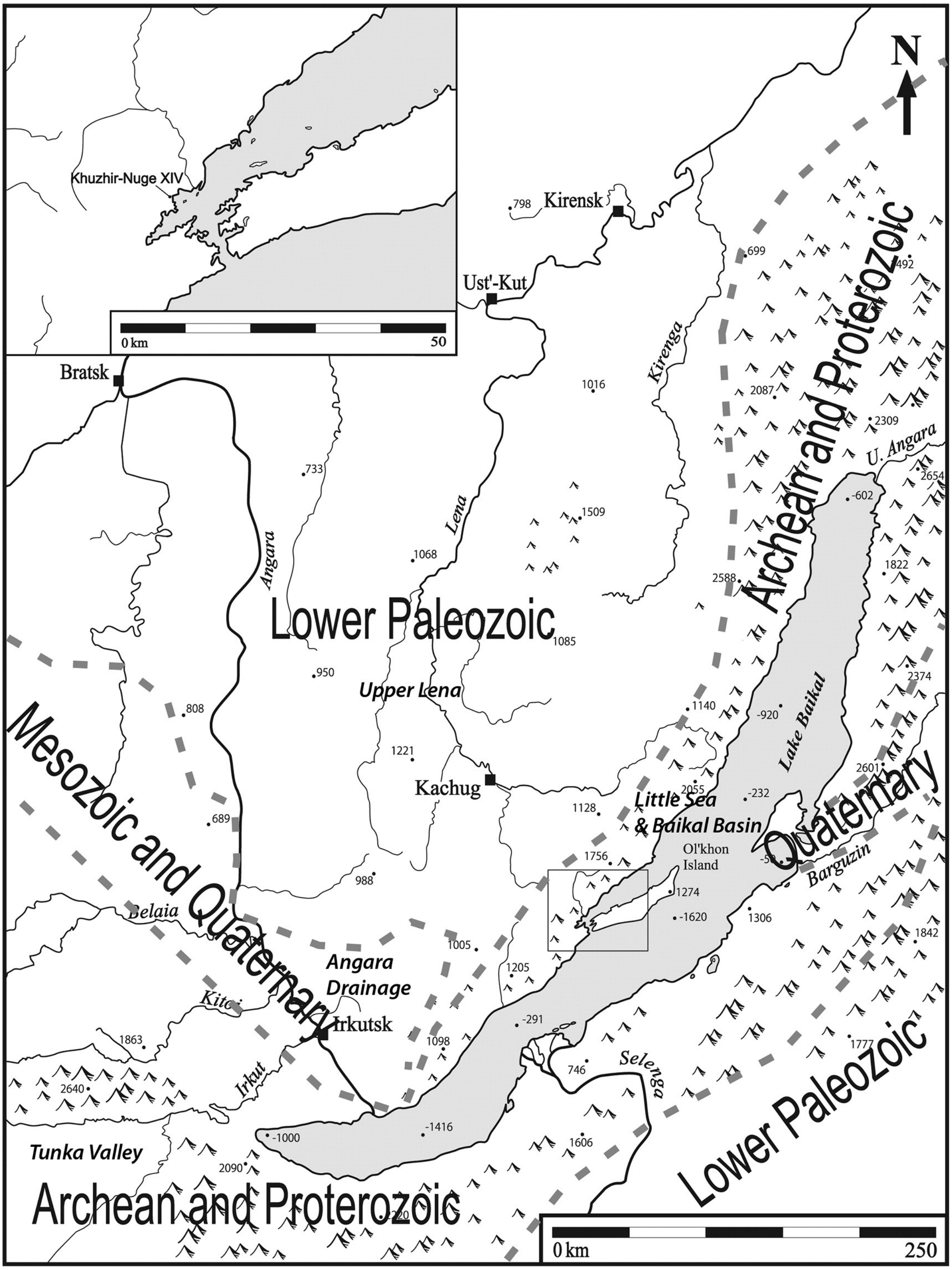

Fig. 1. Map of the Cis-Baikal, Siberia region, main geological formations, and archaeological micro-regions.

3. Scales of migration

The range of possible mobility patterns that can be effectively identified using methods that differentiate between birth and death locale are limited to those that operate on sufficiently large scales of time to mimic the effects of migration events. Mobility, as a series of movements that can be observed or reconstructed, can refer to significantly different temporal and geographic scales; the movements throughout a single season, year, or decade, all of which may not be visible using tools designed to capture once-in-a-lifetime events.

Migration is often discussed as a singular event in which individuals or small/large groups of people move permanently from one location to another in response to some type of push or pull factor. The reality of migration is that it is a process that incorporates many of the same aspects of mobility in the attempts to explain how, when, and why groups or individuals vacate one area in favor of another, but also a process that ranges in time scale from sub-annual to multi-generational (Anthony, 1990, 1992, 1997; Chapman and Dolukhanov, 1992; Lee, 1966; Lightfoot, 2008; Manning, 2005; Ravenstein, 1885, 1889). There are a number of factors and stages of preparation and movement involved

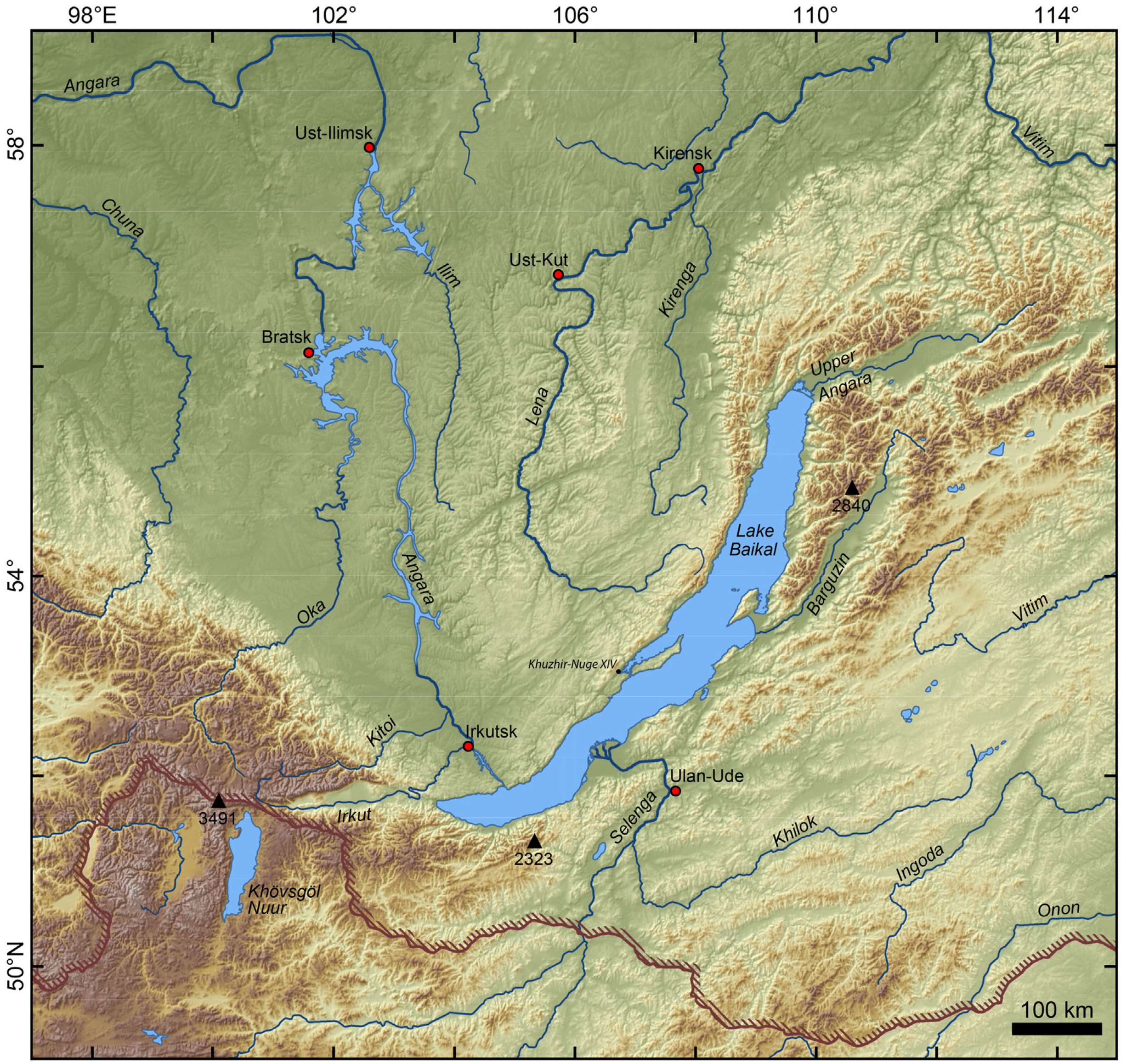

Fig. 2. Topographic map of the Cis-Baikal Region showing the location of the Khuzhir-Nuge XIV cemetery. Topography is based on elevation Shuttle Radar Topography Mission (SRTM) v4.1 data (Jarvis et al., 2008).

in even minor migration events such as seasonal relocations. Factors encouraging people to move out of or into an area often include local environmental stress, the presence of kin, knowledge of attractions, knowledge of routes and destinations, knowledge of transport costs, and inertia of other group members already moving. The distance over which these factors exhibit influence can often determine the scale at which migrations occur. For example, the difference between moving 50 km versus 500 km may rest largely in having existing kin in the region that can provide adequate knowledge and support to warrant the potentially difficult journey as opposed to remaining in the starting location or moving to the next valley/watercourse instead. Many steps could produce a pattern of movements similar to what one might expect for opportunistic hunter-gatherers roaming freely in a region, or following a prescribed seasonal round to known resource.

Part of where mobility and migration have become heavily intertwined and overlap in explaining similar actions is specifically in the concept of residential mobility; the moving of the entire residence group as well as switching between different localized populations. In theoretical models of hunter-gatherer subsistence and cultural structure (e.g., *traveler/processor*, *forager/collector*, *kinship terminology*, *or endogamous/exogamous relationships*), many of the dichotomies lie in the ability to adequately provision the entire group based on the terrain and technologies available as well as the extended social networks that provide crucial information and fallback opportunities if foraging efforts fail in one area during a given season/year (Bettinger, 1991, 2009; Binford, 1980; Ives, 1990, 1998; Woodburn, 1982). In the finer scales of geography and chronology, some aspects of migration and mobility will overlap and be visible within the archaeological record, however, there are many details that cannot be readily inferred from specific lines of evidence and an often incomplete archaeological record. For example, using only two skeletal elements (e.g., M1 and femur), or proxies for childhood and death locale, how could researchers possibly differentiate between patterns of movement experienced during life?

The difficulty in emphasizing the usefulness of geochemical methods for examination of hunter-gatherer mobility is that most approaches focus on the identification of a "local" signal and then identification of individuals as either local or non-local. The local environment may contain homogeneous underlying geochemistry over a large geographic range producing a concurrently large local population group. Non-local individuals may or may not be ascribed provenance depending on the scale of regional comparisons available. This effectively limits discussion of mobility within a cemetery population to the details of a migration or kinship structures involving long-distance exchange. The evidence for shorter term events may be hidden for lack of crossing major geologic boundaries, or having lasted long enough to permanently alter their skeleton.

Barring cases where significant annual or seasonal resources are repeatedly accessed, the consistent or predictable dietary intake and physical provenance of hunter-gatherer groups over time cannot be certain. Mixing models can only effectively resolve mobility between known regions if they are chemically distinct. Thus, to develop understanding of mobility patterns in situations where permanent resources or settlements cannot be assumed, these methods should be reexamined.

4. Scientific archaeology

Archaeologically we must consider how patterns of behavior involving mobility would be reflected in the physical world and thus the archaeological record. Perfect mobility, in a physical sense, would mean absolutely no interaction with the spatial environment, as any interaction would necessitate some type of stoppage or interruption of the motion. Perfect sedentariness would then be the state of non-motion, or having only evidence of contact with a limited spatial region without the importation of materials beyond that area. Each end-member is conceptually possible though practically impossible for living organisms; complete interaction would imply being bedridden otherwise confined to a single area and a complete lack of interaction from nonstop movement would almost certainly lead to death in fairly short order upon depletion of localized and body stores of calories and water.

There is a distinction to be made between active and effective mobility to which different proxy measures will be more or less sensitive. The difference being that *active* mobility is movement directly performed by the individual whereas *effective* mobility is the mobility observable through analyses of proxies. For example, two people sharing the same food items and water sources will have identical geochemical and stable isotope signatures; regardless of whether both were mobile, or if one remained stationary the entire time while the other performed all of the active mobility. In terms of biogeochemical analysis, the skeletal tissues record only the *effective* mobility and cannot readily distinguish between two individuals who shared the same food and water. Thus additional lines of evidence could potentially highlight variation in an otherwise homogenous population. Differences in osteoarthritis evidence and subtle differences in the geochemistry of the individual performing the active mobility as their interaction with small inputs (e.g., berries or water acquired during forays) not experienced by their sedentary companion are likely. Whether such minor signals will be observable given analytical error terms is uncertain for present capabilities.

Hunter-gatherer archaeology's relationship to discussions of mobility is uniquely poised within anthropology due to the diverse modes of subsistence and degree of physical movements undertaken relative to most agrarian and even pastoralist groups. Hunter-gatherers serve as a proxy for groups with erratic patterns of movement and interaction with their environment regardless of their actual mode of subsistence. For hunter-gatherers, in particular, being able to tell when, where, how, and oftentimes who was involved in mobility as compared with other beneficiaries within the group is a key element of many theoretical approaches to subsistence strategies and group structures. For example, efforts to demonstrate aspects of the *traveler/processor* or the *forager/collector* models of mobility can be clouded by the impacts of front-/back-loaded resources and immediate/delayed systems of foraging as well as personal/communal storage and access (Bettinger, 2009; Tushingham, 2009; Woodburn, 1982). Changing when resources are consumed impacts mobility data because it effectively alters the biogeochemical record of where an individual will appear to be during a given time period. The proxy records recovered from skeletal tissues evidence a biogeochemical record of the environment of the individual at the time of formation, that is the food and water sources in which the individual had been eating immediately prior to the formation of the tissues.

Eating foods directly at the time of procurement would represent *active* mobility and would correctly correlate with the *effective* mobility that is inferred from proxy measures access through biogeochemical analysis. On the other hand, any form of delay between procurement and consumption creates an offset between what and where an individual appears to have been as compared with where they actually were at that time. For example, take a forager in Cis-Baikal that harvested a large amount of cedar cones in the summer from the limited stands of forest that are productive for this species, and then after extracting the nuts, consumed them over the subsequent winter. From this information, the biogeochemical signature for this period of time will be that of the pine nuts, but very likely the individual would not have remained in that section of forest for the entire winter. Rather, they likely would have conserved the nuts for later access by transporting the cones/nuts to a settlement for storage and sharing with other group members. A child in this hypothetical group would show a biogeochemical signature in their molars of the area where the nuts were procured instead of the locale where they actually lived if all foods were being imported through logistical foraging efforts. Alternatively, if the nuts were only consumed by a portion of the group and not shared with all members, then multiple individuals living in the same group will present a different biogeochemical record of environmental interaction. Consideration of the type of resource, the potential for storage or other differences in how and when it might have been used, and social differentiation in who has access to a given resource could significantly alter the *effective* biogeochemical signature.

5. Geochemical analysis methods

Geochemical data is increasingly used as a proxy measure for mobility studies as its focus on materials (e.g., lithic, faunal, ceramic, housing) can often be correlated with categories of site-based concepts of mobility or sedentariness. Using geochemical data to discuss the movements of people directly within archaeology and has largely been applied to agrarian populations and to select hunter-gatherer and pastoralist populations (e.g., Balasse et al., 2002; Haverkort et al., 2008; Tafuri et al., 2006; Weber et al., 2003; Weber and Goriunova, 2013). It is useful to look at the progression of methods involved in biogeochemical analysis for mobility and/or migration studies.

6. Local/non-local discrimination

Strontium isotopes were one of the first to be used for archaeological skeletal analysis due to the lack of biopurification effects and reflective differences in the ages of the geologic formation on which an individual spent their lives. Thus if the local conditions are known for a cemetery population, then it should be possible to identify individuals with different chemical signatures. The three basic ways to do this are first to analyze a combination of tooth and bone samples from a single individual and look for differentiation between the birth and death environment (e.g., Grupe et al., 1997; Price et al., 1994b); second to analyze the cemetery population or comparable proxies to gain the local range of variability in strontium values and identify outliers (i.e., individuals beyond 2 standard deviations from the population average are categorized as non-local) (e.g., Knudson et al., 2004; Price et al., 2002); and third to analyze proxies (usually animals with limited foraging ranges, but also vegetation, soil, and water) for the local biologically available strontium values and compare the humans to these samples to attempt to determine their provenance during that phase of life corresponding with the skeletal element (e.g., Bentley et al., 2002; Evans et al., 2010; Hodell et al., 2004; Knudson et al., 2005; Kusaka et al., 2009; Laffoon et al., 2012). Individuals from other areas can be identified by differences between their teeth and bones and hopefully attributed to another neighboring area with geochemical values similar to those observed in the outlier. These approaches were developed for largely sedentary populations as a means of identifying residential mobility between different settlements and surrounding hinterlands or migration events from outside the region.

The difficulty in emphasizing the usefulness of geochemical methods for interpretations of mobility is that the theoretical frameworks focus on either differentiating birth and death locale, or more broadly the identification of a "local" signal and then identification of individuals as either local or non-local. Non-local individuals may or may not be ascribed provenance depending on regional comparisons available, or identified as not matching local geology/population averages. This effectively limits discussion of mobility within a population to the details of a migration or kinship structure involving long-distance exchange (cf. Grupe et al., 1997).

Unfortunately the local/non-local division used in geochemical provenance of skeletal materials is problematic as current models of hunter-gatherer mobility may not embody a stable geographically discrete population from which individuals come and go. Such a pattern is only expected once a landscape has been comparatively filled to capacity and territorial constraints are imposed by interactions between local populations. Thus the division of local/non-local may be inappropriate and serve to collapse different aspects of variability in diet and movement into a single measurement of provenance.

Additional refinements have focused more heavily on determining provenance directly and include the use of multi-proxy measures. In some regions, dietary isotopic information (e.g., carbon, nitrogen, sulfur) can provide clues that an individual has lived or traveled to regions with substantially different resources available, such as marine mammals or domesticates. More broadly, combinations of different isotopic markers (e.g., lead, oxygen, strontium) and/or trace elemental signatures should be used in tandem, where possible, in order to cross-reference geographic regions that are homogenous for one marker and so improve the provenance precision of analysis (e.g., Bentley and Knipper, 2005; Burton et al., 2003; Knudson and Price, 2007; Turner et al., 2009).

7. Sampling methods

Tooth enamel of permanent teeth is laid down as a series of layers beginning just before birth and continuing to approximately 14 years of age with the completion of the third molar crown (Hillson, 1996). Once formed, chemical signatures in teeth do not alter in the same way that bone remodels throughout life (Parfitt, 1979). Strontium isotopic values in different teeth, therefore, represent discrete growth periods in an individual's childhood and adolescence. Most researchers collect material from a single tooth and bone sample rather than multiple teeth for any one individual in order to minimize the destructive impact on the skeleton. At the same time, however, using a single bulk sampled data point likely underestimate the amount of mobility in prehistoric populations and a small number of researchers have addressed this problem by serially sampling teeth from a single individual (Buikstra et al., 2004; Schweissing and Grupe, 2003). This approach using multiple teeth has the advantage in covering a broader range of time as each tooth has a different time and period of development. For example, the crown of each of the three permanent molars represents approximately 3–4 years of developmental time: M1, birth to between 3 and 4 years; M2, between 2 and 3 years and 7–8 years; and M3, between 7 and 10 years and 12–16 years (Avery, 1992; Hillson, 1996).

Bulk sampling for either Thermal Ionization Mass Spectrometry (TIMS) or Multi-Collector Inductively-Coupled-Plasma Mass-Spectrometry (MC-ICP-MS) requires the destruction, through powdering, conversion of the sample to a solution and purification through columns of cation exchange resin, of a major portion of the tooth crown (cf. Balasse et al., 2002; Bentley et al., 2003; Budd et al., 2000; Hoppe et al., 2003; Müller et al., 2003). The use of these methods yields increased precision of the analysis through homogenization, purification, and ionization efficiency and to avoid isobaric interference problems. A comparison of different crown surfaces (i.e., lingual, buccal, mesial, and distal) determined that it did not matter which surface was used as the total sample size was the key determinant of producing quality data (Dolphin et al., 2005). The process of homogenization and purification is generally viewed as critical, initially due to the sample size requirements, and more recently due to recognition of significant intra-tooth variability in isotopic and elemental signatures using laser-ablation techniques (Dolphin et al., 2003; Richards et al., 2008). Intra-tooth isotopic and chemical variability should be viewed as a source of further information, but could be problematic when trying to compare with either older datasets, or employing explanatory structures that rely on homogenizing multiple years of life.

Montgomery and Evans (2006) and Montgomery et al. (2010) recommended against the use of micro-sampling techniques because of difficulties in determining the extent of delay in the maturation of mineralization in different microstructures (i.e., *striae of Retzius*) and uncertainties of the relevance of intra-tooth variations. Studies using large animals (Britton et al., 2011; Montgomery et al., 2010) found that intra-tooth sampling could produce evidence for long-term averaging effects that result from the long-duration that some elements have within the body. One problem may be that studies focusing on a single tooth may lack broader applicability in terms of the relationship between body averages and mineral deposition or maturation rates. For example, using strontium and oxygen isotopes on multiple teeth, Britton et al. (2009) observed profiles for reindeer teeth that exhibited sharp (i.e., not gradual) changes that would not be consistent long-term averaging. If long-term averaging is the dominant factor, then intra-tooth isotopic profiles should only exhibit gradual changes unless there are other mechanisms that can lead to a sharp change in isotopic composition of enamel at high resolution. An additional problem is that the residence time can potentially increase with age as bone remodeling recirculates strontium within the body (Montgomery et al., 2010). Body averages can then reflect events that are poorly related to the target of reconstruction; yielding materials formed in utero from the mother's body (and location), or strontium potentially from years earlier in development being incorporated into new tissues, suggesting that beyond a certain scale, further sub-sampling may prove challenging. Recent studies have found that micro-scale isotopic and elemental variability are sources of useful behavioral information and that micro-milled powders and laser ablation will play important roles in future research (Dolphin et al., 2012; Lewis et al., 2014; Müller and Anczkiewicz, 2016; Richards et al., 2008).

8. Cis-Baikal biogeochemical research

The BAP began conducting biogeochemical research on a large scale during this period of refinement and experimentation, beginning first with dietary isotopic studies (Katzenberg and Weber, 1999; Lam, 1994; Weber et al., 2002), and expanding into mobility studies using strontium isotopes (Haverkort et al., 2010; Haverkort et al., 2008; Scharlotta et al., 2013; Scharlotta and Weber, 2014; Weber et al., 2003). Initial biochemical research was exploratory (Lam, 1994), querying the potential dietary evidence that could be reconstructed from hunter-gatherers within the Cis-Baikal region.

The presence of diagnostic (C_4) grains and/or marine resources was not anticipated given the period of time and distance to the nearest marine waters; however, the potential results and ultimately the utility of the method in the region were largely unknown. The terrestrial and aquatic food webs were hypothesized to be enough different that a relative balance of different types of protein sources would be possible, though the entire food web was proven to be quite diverse (Katzenberg and Weber, 1999). The length of food chains, particularly within Lake Baikal, were found to be as long as in marine sources and a fruitful area for dietary and unexpectedly, for mobility research (Weber and Goriunova, 2013; Weber et al., 2010; Weber et al., 2016;

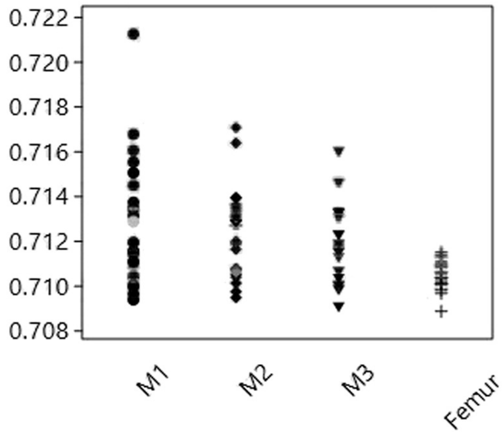

Fig. 3. $^{87}Sr/^{86}Sr$ values from Khuzhir-Nuge XIV by specimen type, following Haverkort et al., 2008.

Weber et al., 2011). While the goal of stable isotope studies was to differentiate regional and temporal dietary patterns, being able to distinguish between the aquatic resources that came from different types of watercourses (e.g., small/large rivers, shallow/deep waters in Lake Baikal) has provided an additional means by which an individual can be associated with different areas based on the distributions of characteristic watercourses.

Mobility research using strontium isotope ($^{87}Sr/^{86}Sr$) was hypothesized to hold great potential in Cis-Baikal due to the convergence between dominant geological regions and cultural micro-regions (Weber et al., 2003). Geographically and culturally discrete populations occupying differently aged rocks should make identifying local/non-local distinctions straightforward. In order to maximize the potential dataset, samples were chosen from individuals with three molars, wherever possible, as well as a long bone sample. In order to further ensure that samples were comparable, rather than picking an arbitrary portion of the molar crown, samples were consistently taken from the base of the enamel (cement-enamel junction, CEJ). The CEJ is an area that remained similarly intact regardless of the level of natural wear on the crown within regional cemeteries. This would place the timeframe associated with each molar sampled near the end of the specific time interval representing this terminal phase of the development period of the crown; the last section to form and mineralize (e.g., M1, approx. 2–3 years, M2, 6–8 years, and M3, 10–16 years old).

Initial results from a pilot study (Weber et al., 2003) were encouraging, though understanding of the geochemical environment became more complicated as the sample size for both human skeletal materials and environmental comparison samples expanded. Individuals ($n = 25$) from the Early Bronze Age (EBA) cemetery of Khuzhir-Nuge XIV (KN XIV) located in the Little Sea area of Cis-Baikal, displayed a range of $^{87}Sr/^{86}Sr$ values (0.70888–0.72126) that was smaller than faunal materials analyzed (Haverkort et al., 2008). The range of $^{87}Sr/^{86}Sr$ variability in terrestrial samples from the whole study region ($n = 58$) was from 0.70882, for a mouse in the upper Lena basin, to 0.74330, for a suslik (ground squirrel) found near the entrance to the Sarma Canyon in the Little Sea area. This range of variability in $^{87}Sr/^{86}Sr$ values was surprising based on the expectations for the dominant geologic formations within the region, but also because of the limited ranges observed for human samples, mostly within the lower half of the 0.71000–0.71500 range, and aquatic samples ($n = 38$) predominantly from 0.70880–0.71020. Even more perplexing, the highest values came from within 5 km of the KN XIV cemetery which did not have such elevated $^{87}Sr/^{86}Sr$ values. From these data it became clear that an approach using a combination of different methods or regional dietary mixing models would likely be necessary to reconstruct any patterns of movement within this group.

Trying to identify a local range from sediments and samples in proximity to the KN XIV cemetery for a local/non-local boundary, or determining statistical outliers from this range of values and attributing them provenance to another region was not feasible (Fig. 3). The primary inference from these data is some filtering or homogenizing effect produced with age with $^{87}Sr/^{86}Sr$ values ranging for M1 (0.70940–0.72126), M2 (0.70949–0.71709), M3 (0.70906–0.71598), and femurs (0.70888–0.71152) (Haverkort et al., 2008: Fig. 2). As individuals grow older, a smaller range of strontium values are exhibited; possibly due to differences in weaning, sub-adult foraging strategies, or some other cultural pattern of differential subsistence; for example if adults practiced a more limited or refined subsistence strategy with fewer targets or inputs contributing to dietary makeup. Further analysis of the human results indicated four different patterns of $^{87}Sr/^{86}Sr$ values between different skeletal elements (Fig. 4), and so inferred different patterns of mobility through life (Haverkort et al., 2008: Fig. 3). The patterns indicated that in addition to patterns of changing subsistence

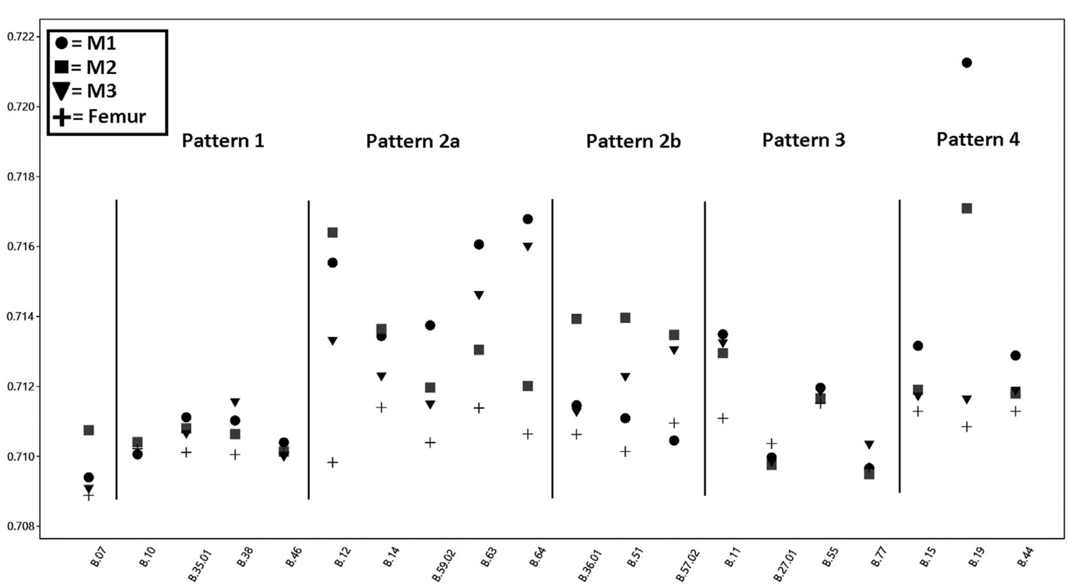

Fig. 4. $^{87}Sr/^{86}Sr$ values from Khuzhir-Nuge XIV grouped by distribution patterns, following Haverkort et al., 2008.

through life, some individuals were more mobile than others, and were moving across the landscape at different points in their lives. This intriguing complexity spawned increased interest in the technical aspect of analyses and further incorporation of the individual life history approach (Zvelebil and Weber, 2013), to examine potential areas for improvement that could help to clarify these patterns of EBA behavior in Cis-Baikal.

9. Individual life histories

In order to address questions beyond whether or not individuals were locally born, or where migrants were coming from, additional data is needed. The individual life history approach is a good framework for reconstructing patterns of mobility rather than migration, as the focus is to understand the entire life story of every individual (Zvelebil and Weber, 2013). Expanding the number of skeletal elements involved is the most direct way to learn more about an individual. Each tooth holds information on the biogeochemical interactions for a different period of sub-adulthood; bone represents a time-averaging of the final years of life, producing four data points for each individual. In order to differentiate the KN XIV population using this approach, individuals were separated out by the relationship between the $^{87}Sr/^{86}Sr$ data at each point (M1, M2, M3, and femur) for every individual. This yielded a series of different patterns that better explained the high strontium variability noted earlier, and suggested relevant patterns in mobility and foraging behavior (Haverkort et al., 2010; Haverkort et al., 2008). Parsing out provenance or tying patterns of behavior using the geologic and faunal reference materials proved elusive as samples such as mice and *suslik*, which are not anticipated to contribute greatly to the dietary intake of subarctic residents, provided the clearest evidence of geographically discrete areas of high and low $^{87}Sr/^{86}Sr$ values.

Regional clustering of high $^{87}Sr/^{86}Sr$ (Sarma Delta) and low $^{87}Sr/^{86}Sr$ (Upper Lena) zones suggested that differential patterns of population movement might be involved in producing the different behavioral patterns observed. Anecdotally, regional archaeologists had often assumed that there were significant linkages and likely cultural interactions between the Angara and Little Sea micro-regions. Regional population densities inferred from cemetery size/distribution as well as similarities in the mortuary traditions suggested direct cultural interactions. However, none of the individuals from KN XIV could be clearly identified as having spent their childhood on the Angara, moved, and been buried in the Little Sea (Scharlotta and Weber, 2014). The addition of stable isotope dietary information did help to explain important resources and whether individuals were foraging in food chains different from their local area (Weber and Goriunova, 2013; Weber et al., 2016; Weber et al., 2011).

10. Regional mapping

Given the difficulties encountered during early phases of research, it was clear that a greater emphasis would be needed on expanding the biogeochemical reference map as well as explore additional techniques that could add layers to these data. Improvements on reference sampling can greatly improve the efficacy of a technique, allowing researchers to build comparative maps of the biogeochemical environment. Refined maps provide a better understanding of the local environmental variability and allow outliers to be identified with greater confidence. Effective provenance analysis can be conducted for the development of patterns of residential mobility as long as suitable matches for different "local" populations or areas are available. However, consideration needs to be given to what materials are being used as reference samples as different plants and animals represent different catchment areas, or the territorial range that sustains them and will be reflected in their geochemical makeup. Herbivores tend to have smaller ranges than do predators, though migratory animals will have comparatively larger ranges, making species with limited home ranges the preferred options. Geologic maps can look promising (e.g., Fig. 1), but geochemical analysis of samples that can accurately reflect an area is necessary to understand the extent of biogeochemical variability.

In spite of relatively simple distributions of dominant geologically-aged regions, these regions represent a variety of different geologic formations and rock types, as well as a complex history of erosion and deposition for sediments that will produce bioavailable strontium. Humans and other animals do not eat rocks directly, but interact with them through biogeochemical pathways. Chemical processes break down the rocks into soils that support plants and impart a biologically accessible fraction of the initial rock formation through water leaching and nutrient uptake for plants. Fish impart water from their environment and have a direct, although dilute, means of directly accessing the rock/soil isotopic and elemental environment of these watercourses. Plants are slightly more complex as their roots reach to different depths (i.e., soil strata and related geological exposures) and can either contribute directly to food resources for humans, contribute indirectly by providing food for animals that human eat, or even more indirectly (particularly relevant for trees) by contributing their constituent elements to the soils in which plants directly consumed by humans or prey species will grow.

The distribution of biologically-available $^{87}Sr/^{86}Sr$ values shows a great deal of variation throughout the region as evidenced by faunal samples from multiple micro-regions in Cis-Baikal (Haverkort et al., 2008; Scharlotta and Weber, 2014; Weber et al., 2003). Efforts to improve the comparison map and reference sample database, and thus, the overall provenance potential of this region, focused on collecting environmental samples (plant and water) samples (Fig. 5). Additional faunal samples were sought as well, yet as in previous efforts, provided an important but biased overview of different micro-regions based on accessibility, fauna present, and ground visibility (Scharlotta and Weber, 2014). Based on the complexity of this map, it was not likely to be possible to determine provenance for individuals without using complex mixing models informed by detailed dietary information, or a secondary isotopic or elemental link to provenance.

The dominant geologic formations roughly correspond with cultural micro-regions (Fig. 1); however, the biologically available strontium values (Fig. 5) vary widely, overlap greatly in their ranges, and do not support neat separations between regions (Scharlotta and Weber, 2014). Conducting a secondary analysis using trace elemental data, internally standardized to make disparate materials comparable and analyzed using multi-variate statistics, did not clarify the situation (Scharlotta and Weber, 2014). Breaking the $^{87}Sr/^{86}Sr$ data into arbitrary sub-groups (e.g., 0.708–0.710, 0.710–0.712, etc.) and examining the trace elemental data within these subset, it proved possible to effectively separate out all the reference materials into their cultural micro-regions. This was a key step in efforts to refine the $^{87}Sr/^{86}Sr$ analysis for mobility studies as it became possible to discriminate isotopically similar regions within cultural relevant micro-regions of Cis-Baikal.

11. Human samples

Converting data for the 49 elements collected (Li, Na, Mg, Al, P, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ta, Au, Tl, Pb, Th, and U) to ratios using an internal standard made faunal and human materials could be compared directly to the plant and water reference samples. Experiments comparing faunal materials of known provenance with the $^{87}Sr/^{86}Sr$ sub-groups for each micro-region.

proved successful, correctly classifying the faunal samples to the geochemical groups reflecting their origins (Scharlotta, 2012). The success of provenancing faunal materials supporting the hypothesis that human provenance could be reconstructed. The question then was to what extent the analytical methods employed could be refined to produce data that would potentially represent smaller time scales and so

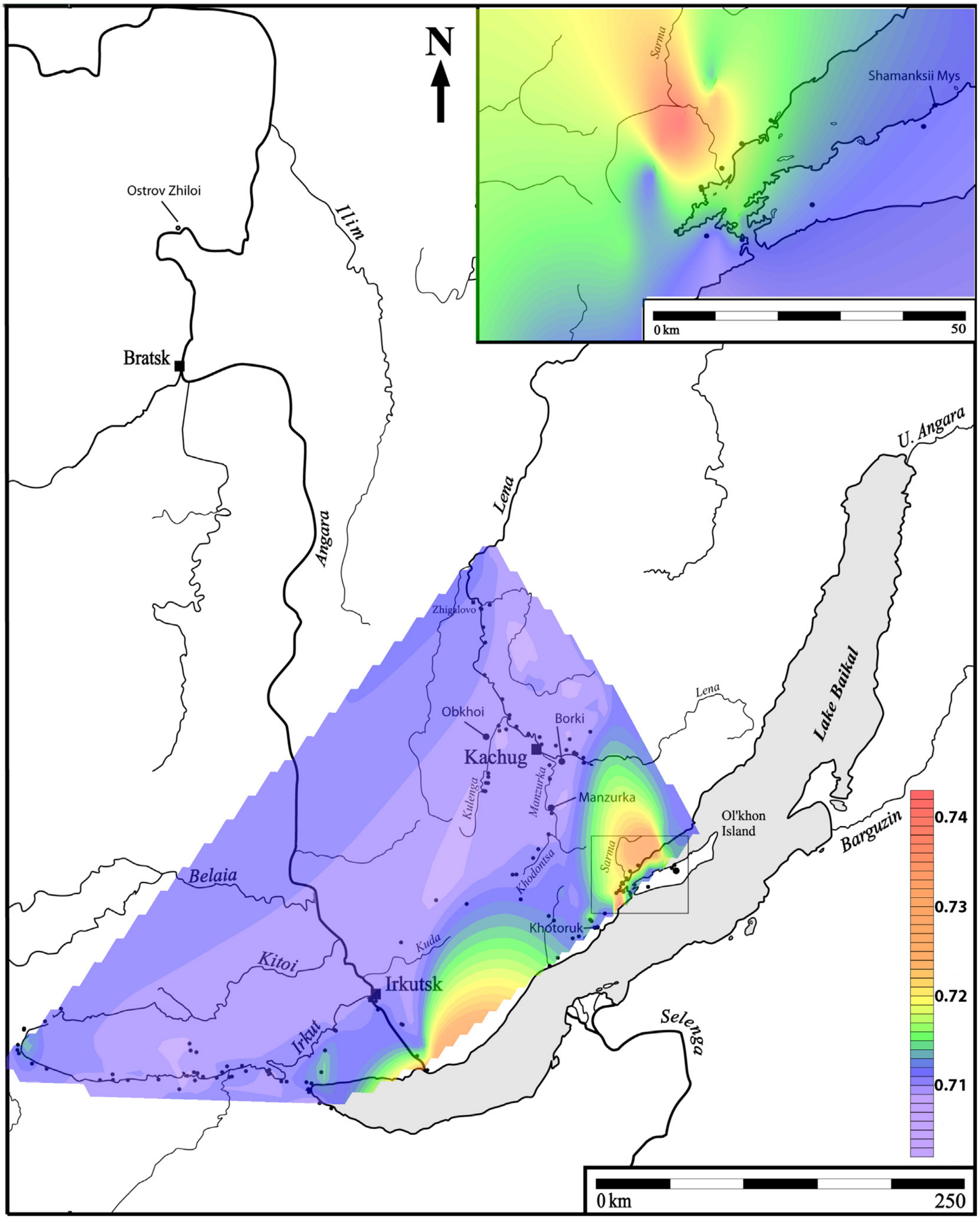

Fig. 5. Gradient map of $^{87}Sr/^{86}Sr$ isotopic distributions throughout the Cis-Baikal region and locations of environmental (water and plant) sampling sites (Scharlotta and Weber, 2014).

provide greater insight in the provenance of the individual during as many points during their life as possible.

11.1. Tooth micro-sampling

Experiments were conducted to determine the feasible scale for generating additional data from each tooth using laser ablation (LA) (Scharlotta, 2012; Scharlotta et al., 2011). Laser ablation MC-ICP-MS as an alternative means of producing $^{87}Sr/^{86}Sr$ data than using either TIMS or solution-mode(SM) MC-ICP-MS had been proposed fairly early on in BAP research for both the reduced destructive impact to individual samples and as a potential means of expanding the data potential of each human molar analyzed. The process of conducting LA for $^{87}Sr/^{86}Sr$ by MC-ICP-MS and for trace elemental values using a quadrupole ICP-MS was also much simpler than the laboratory preparations necessary to extract and purify $^{87}Sr/^{86}Sr$ solutions and maintain separate aliquots for trace elemental analysis.

At the time, there was an unsolved problem in terms of accurately reproducing $^{87}Sr/^{86}Sr$ data for human materials using laser ablation, a problem that would eventually be identified as an isobaric interference occurring as a result of the ablation process that could be modified using post-hoc correction equations and with modification to the equipment tuning (Lewis et al., 2014; Müller and Anczkiewicz, 2016; Scharlotta et al., 2011; Simonetti et al., 2008; Woodhead et al., 2005).

Based on the results of laser experimentation, the growth rate of human molars, mineralization rate, and body-averaging or time-delays, it seems as though the current maximum effective scale for human molars is around 6 sampling sites equally spaced from crown to cingulum on teeth with minimal wear, and 3–4 for worn teeth (Scharlotta and Weber, 2014). Each data point was classified by micro-regional group before trying to figure out the more precise area. Some samples were very similar to reference materials and likely spent considerable time in a specified area, while others likely moved throughout and between micro-regions (Scharlotta and Weber, 2014).

11.2. Bone micro-sampling

Bone is comprised of calcium hydroxyapatite, similar to tooth enamel, but has a different structure and density making tooth enamel more durable than bones during life and within the burial environment. Much evidence has been produced to suggest a degree of caution and heavy laboratory cleaning procedures to ensure that strontium and other chemical data produced from skeletal tissues are representative of activities during life and not simply diagenetic overprinting from the burial environment (Bell, 1990; Budd et al., 2000; Copeland et al., 2010; DeNiro and Hastorf, 1985; Hedges, 2002; Knudson et al., 2012; Koch et al., 1997; Kohn et al., 1999; Maurer et al., 2011; Nelson et al., 1986; Nielsen-Marsh and Hedges, 1999; Nielsen-Marsh and Hedges, 2000a; Nielsen-Marsh and Hedges, 2000b; Price et al., 1992; Smith et al., 2007; Snoeck et al., 2015).

Bone is more challenging than teeth as a source of finer resolution data that remains intact as the likelihood of alteration is higher, as are the number of specific factors that can be involved in the diagenetic alteration of skeletal materials. Luckily, currently known diagenetic processes follow predictable patterns of intrusion and destruction (e.g., Jans, 2008; Jans et al., 2004; Smith et al., 2007; Trueman et al., 2008). To an extent, individual osteons within long bones are enclosed chemical environments, largely shut off from the outside world (and burial environment) until breached by physical or microbial action. This made it possible to locate resistant micro-structural components within osteons that yielded laser ablation analytical data on par with purified solutions (Fig. 6; Scharlotta et al., 2013).

This was hugely important because long bones hold the record of adult life and can inform researchers on the last 10–15 years of life rather than simply the death and burial environment.

The level of precision for averaged LA analyses is lower than the internal reproducibility on standards using TIMS or SM-MC-ICP-MS on standardized materials, but similar to the disparities observed for human samples from Cis-Baikal that were resampled and/or analyzed using multiple methods (Haverkort et al., 2008; Scharlotta et al., 2013; Scharlotta and Weber, 2014). If LA confers a lower average level of precision, then researchers must consider the variability in bioavailable strontium sources to determine if LA can provide adequate analytical data for their needs. Alternatively, intra-individual and intra-sample heterogeneity is increasingly observed as a likely source of variability in analytical data. Internal $^{87}Sr/^{86}Sr$ heterogeneity will not be observable if materials are homogenized and analyzed only a single time making LA appear less reliable for sake of an abundance of data. In areas with complex and heterogeneous distributions of bioavailable strontium (e.g., Cis-Baikal), geographical movements within or between micro-regions will only be clearly evidenced by substantial shifts in $^{87}Sr/^{86}Sr$ values.

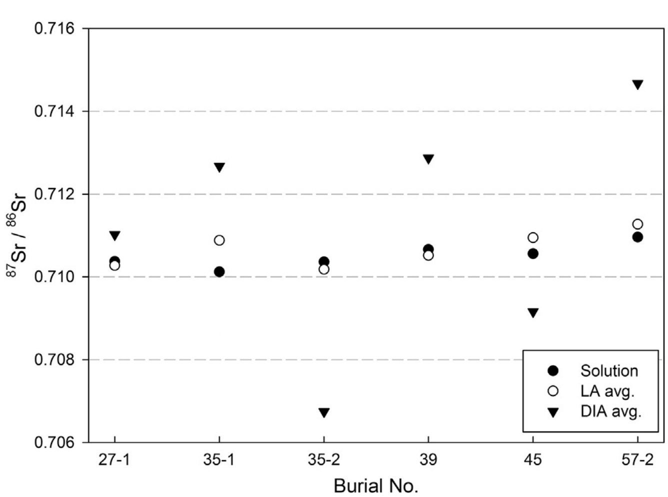

Fig. 6. Solution-mode and laser-ablation $^{87}Sr/^{86}Sr$ ratios compared with diagenetically-impacted portions of bone (Scharlotta et al., 2013).

The generally low strontium concentrations for Cis-Baikal samples used for LA-MC-ICP-MS $^{87}Sr/^{86}Sr$ analysis required a minimum beam size of ~80 μm, roughly the radius of a full osteon, to produce signal strength comparable to SM-MC-ICP-MS of bone powders from the same samples (Scharlotta et al., 2013). Advantages of using LA averaging include the opportunity for testing internal reproducibility by sampling multiple intact osteons, demonstrating the resilience of the crystalline matrix, and intentionally sampling diagenetically altered portions of bone for comparison with known degradation processes and with the burial environment. Samples from regions/populations with higher strontium concentrations, for example as a result of higher plant consumption, can likely produce stable $^{87}Sr/^{86}Sr$ data with smaller LA beam sizes.

Luckily, trace elemental analysis was more effective and could produce 5–10 data points from within a single osteon and verified by replicating the analysis on multiple intact osteons (Fig. 7; Scharlotta et al., 2013). Using 5 data points for each osteon, multiple movement events during adult life can be observed, helping to explain patterns of adult behavior and how they ultimately came to be buried in the Little Sea micro-region. Used in concert with tooth micro-sampling for individuals with all 3 molars and intact long bones, we can conservatively generate 12 data points for the first 20 years of life and an additional 5 for the last 10–15 years before death. For good quality samples, this could be expanded to close to 30 total data points, though would potentially cause issues of comparability with more degraded samples from the region.

12. Conclusions

We have seen in the progression of scientific archaeological techniques applied, that increased accuracy and precision are only beneficial if they can help to answer specific research questions that involve a finer scale of analysis. There is often a gap or lag time between the advancement of techniques determining what is possible and researchers asking questions that are both realistic and innovative to make good use of the analytical data. Early biogeochemical studies were very clear as to what type of mobility or migration was being demonstrated by their data. However, at this point it is no longer clear what exactly researchers are dealing with. Aspects of migration can involve multiple steps, but generally refer to major geographic shifts that last years, decades, or the remainder of an individual's life. Migrations involve a combination of physical and social elements including kinship and information

Fig. 7. Example of laser ablation analysis within a single osteon.

availability that go beyond the straightforward action of moving between a series of geographical locations. Migration, more broadly is a population level concept that is difficult to apply to individuals or small groups as evidence for movement over great distances may not correlate with additional variables related to migration. The conflation of migration and mobility is problematic. Researchers trying to reconstruct the movement of a population in/out of a region, or the changing population membership through recruitment outside of the region have the necessary tools at hand. Researchers reconstructing a series of movements for an individual during their lifetime, or group level patterning from multiple individuals may not benefit from the technologies and conceptual framework associated with migration. The concern is that researchers are attempting to address questions of mobility without stopping to consider if their methods and explanations truly operate at a suitable scale for what they hope to achieve.

Discussions of mobility during life are not possible without microsampled data. Using multiple skeletal elements is a good start, but limits the data to four events or periods of possible limited scale, or fewer long-distance migration events. Generating 15–30 points for diet and provenance for an individual's life presents an enhanced dataset with which to discuss actual specific movement events as well as mobility and subsistence patterns. If researchers do not need this level of detail, or are asking questions of migration or residential or social mobility, then explicit terminology would great aid the clarity of the study and reader's ability to determine if the methods support the conclusions. For researchers discussing hunter-gatherers or any other population suspected of frequent or erratic patterns of movement during life, it is crucial to explain their terminology and employ methods that can generate data with sufficient resolution to truly address whether or not a given pattern of behavior can best be explained as a specific type of mobility or if other factors may be involved.

The work of the BAP with skeletal materials from the Cis-Baikal region have provided an encapsulated look at the progression of technology applied in the field of biogeochemistry and attempts to study prehistoric patterns of mobility. A number of key improvements have highlighted the importance of matching analytical techniques with the research goals of the project to ensure that valuable data are not missed in the process. The resultant resolution for behavioral patterns reconstructed using the individual life history approach has provided invaluable insight into Early Bronze Age hunter-gatherer populations and provided a framework that can be applied to other populations and regions of the world.

Acknowledgments

This research is based on the works produced by the Baikal (now Baikal-Hokkaido) Archaeology Project based at the University of Alberta and funded by two Major Collaborative Research Initiative Grants Nos. 412-2000-1000 and 412-2005-1004 awarded by the Social Sciences and Humanities Research Council of Canada. Special thanks go to all researchers, support staff, graduate and undergraduate students associated with the Baikal Archaeology Project since the 1990s. Finally, and most importantly, this research would not have been possible without the continuous support of Irkutsk State University in Russia and our numerous Russian friends who never hesitated to help our project in the most generous and imaginative ways.

References

Anthony, D.W., 1990. Migration in archaeology: the baby and the bathwater. Am. Anthropol. 92, 895–914.
Anthony, D.W., 1992. The bath refilled: migration in archaeology again. Am. Anthropol. 94, 174–176.
Anthony, D.W., 1997. Prehistoric migration as a social process. In: Chapman, J., Hamerow, H. (Eds.), Migrations and Invasions in Archaeological Explanation. Archaeopress, Oxford, pp. 21–32.
Avery, J.K., 1992. Essentials of Oral Histology and Embryology — A Clinical Approach. Mosby-Year Book, Inc., St. Louis.
Balasse, M., Ambrose, S.H., Smith, A.B., Price, T.D., 2002. The seasonal mobility model for prehistoric herders in the south-western Cape of South Africa assessed by isotopic analysis of sheep tooth enamel. J. Archaeol. Sci. 29, 917–932.
Bell, L.S., 1990. Paleopathology and diagenesis; a SEM evaluation of structural changes using backscattered electron imaging. J. Archaeol. Sci. 17, 86–102.
Bentley, R.A., Knipper, C., 2005. Geographical patterns in biologically available strontium, carbon and oxygen isotope signatures in prehistoric SW Germany. Archaeometry 47, 629–644.
Bentley, R.A., Price, T.D., Luning, J., Gronenborn, D., Wahl, J., Fullagar, P.D., 2002. Prehistoric migration in Europe: strontium isotope analysis of early Neolithic skeletons. Curr. Anthropol. 43, 799–804.
Bentley, R.A., Krause, R., Price, T.D., Kaufmann, B., 2003. Human mobility at the early Neolithic settlement of Vaihingen, Germany: evidence from strontium isotope analysis. Archaeometry 45, 471–486.
Bettinger, R.L., 1991. Hunter-Gatherers: Archaeological and Evolutionary Theory. Plenum Press, New York.
Bettinger, R.L., 2009. Hunter-Gatherer Foraging: Five Simple Models. Eliot Werner Publications, Inc., Clinton Corners.
Binford, L., 1980. Willow smoke and dogs' tails: hunter-gatherer settlement systems and archaeological site formation. Am. Antiq. 45, 4–20.
Britton, K., Grimes, V., Dau, J., Richards, M.P., 2009. Reconstructing faunal migrations using intra-tooth sampling and strontium and oxygen isotope analyses: a case study of modern caribou (*Rangifer tarandus granti*). J. Archaeol. Sci. 36, 1163–1172.
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. Hum. Evol. 61, 176–185.
Budd, P., Montgomery, J., Barreiro, B., Thomas, R.G., 2000. Differential diagenesis of strontium in archaeological human dental tissues. Appl. Geochem. 15, 687–694.
Buikstra, J.E., Price, T.D., Wright, L.E., Burton, J.H., 2004. Tombs from the Copan acropolis: a life history approach. Understanding early classic Copan, pp. 191–212.
Burton, J.H., Price, T.D., Cahue, L., Wright, L.E., 2003. The use of barium and strontium abundances in human skeletal tissues to determine their geographic origins. Int. J. Osteoarchaeol. 13, 88–95.
Chapman, J., Dolukhanov, P.M., 1992. The baby and the bathwater: pulling the plug on migrations. Am. Anthropol. 94, 169–174.
Comar, C.L., Wasserman, R.H., 1964. Strontium. In: Comar, C.L., Bronner, F. (Eds.), Mineral Metabolism. Academic Press, New York, pp. 523–572.
Comar, C.L., Russell, R.S., Wasserman, R.H., 1957. Strontium–calcium movement from soil to man. Science 126, 485–492.
Copeland, S.R., Sponheimer, M., Lee-Thorp, J.A., Le Roux, P.J., De Ruiter, D.J., Richards, M.P., 2010. Strontium isotope ratios in fossil teeth from South Africa: assessing laser ablation MC-ICP-MS analysis and the extent of diagenesis. J. Archaeol. Sci. 37, 1437–1446.
DeNiro, M.J., Hastorf, C.A., 1985. Alteration of and ratios of plant matter during the initial stages of diagenesis: studies utilizing archaeological specimens from Peru. Geochim. Cosmochim. Acta 49, 97–115.
Dolphin, A.E., Kang, D., Goodman, A.H., Amarasiriwardena, D., 2003. Microspatial analyses of intra- and intertooth variations in the distribution of trace elements. Am. J. Phys. Anthropol. Suppl. 36, 90.
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. Anthropol. 128, 878–888.
Dolphin, A., Dundas, S.H., Kosler, J., Tvinnereim, H.M., Geffen, A.J., 2012. A comparison of techniques for measuring the trace element content of human teeth: laser ablation ICP-MS versus solution ICP-MS of micromilled enamel. Int. J. Anal. Bioanal. Chem. 189–195.
Dolphin, A.E., Teeter, M.A., White, C.D., Longstaffe, F.J., 2016. Limiting the impact of destructive analytical techniques through sequential microspatial sampling of the enamel from single teeth. J. Archaeol. Sci. 5, 537–541.
Elias, R.W., Hirao, Y., Patterson, C.C., 1982. The circumvention of the natural biopurification of calcium along nutrient pathways by atmospheric inputs of industrial lead. Geochim. Cosmochim. Acta 46, 2561–2580.
Ericson, J.E., 1985. Strontium isotope characterization in the study of prehistoric human ecology. J. Hum. Evol. 14, 503–514.
Ericson, J.E., 1989. Some problems and potentials for strontium isotope analysis for human and animal ecology. In: Rundel, P.W., Nagy, K.A. (Eds.), Stable Isotopes in Ecological Research. Springer Verlag, New York, pp. 252–259.
Evans, J., Montgomery, J., Wildman, G., Boulton, N., 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. J. Geol. Soc. 167, 1–4.
Ezzo, J.A., Johnson, C.M., Price, T.D., 1997. Analytical perspective on prehistoric migration: a case study from east-central Arizona. J. Archaeol. Sci. 24, 447–466.
Farell, J., Amarasiriwardena, D., Goodman, A.H., Arriaza, B., 2013. Bioimaging of trace metals in ancient Chilean mummies and contemporary Egyptian teeth by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Microchem. J. 106, 340–346.
Gosz, J.R., Brookins, D.G., Moore, D.I., 1983. Using strontium isotope ratios to estimate inputs into ecosystems. Bioscience 33, 23–30.
Grupe, G., Herrmann, B., 1988. Trace Elements in Environmental History. Springer Science & Business Media, Berlin.
Grupe, G., Price, T.D., Schröter, P., Söllner, F., Johnson, C.M., Beard, B.L., 1997. Mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains. Appl. Geochem. 12, 517–525.
Haverkort, C.M., Weber, A.W., Katzenberg, M.A., Goriunova, O.I., Simonetti, A., Creaser, R.A., 2008. Hunter-gatherer mobility strategies and resource use based on strontium

isotope ($^{87}Sr/^{86}Sr$) analysis: a case study from Middle Holocene Lake Baikal, Siberia. J. Archaeol. Sci. 35, 1265–1280.
Haverkort, C.M., Bazaliiski, V.I., Savel'ev, N.A., 2010. Identifying hunter-gatherer mobility patterns using strontium isotopes. In: Weber, A.W., Katzenberg, M.A., Schurr, T.G. (Eds.), Prehistoric Hunter-Gatherers of the Baikal Region, Siberia: Bioarchaeological Studies of Past Lifeways. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp. 217–239.
Hedges, R.E.M., 2002. Bone diagenesis: an overview of processes. Archaeometry 44, 319–328.
Hillson, S., 1996. Dental Anthropology. Cambridge University Press.
Hodell, D.A., Quinn, R.L., Brenner, M., Kamenov, G., 2004. Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: a tool for tracking ancient human migration. J. Archaeol. Sci. 31, 585–601.
Hoppe, K.A., Koch, P.L., Furutani, T.T., 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int. J. Osteoarchaeol. 13, 20–28.
Ives, J.W., 1990. A Theory of Northern Athapaskan Prehistory. University of Calgary Press, Calgary.
Ives, J.W., 1998. Developmental processes in the pre-contact history of Athapaskan, Algonquian and Numic kin systems. In: Godelier, M., Trautmann, T.R., Tjon Sie Fat, F. (Eds.), Transformations of Kinship, the Round Table: Dravidian, Iroquois and Crow-Omaha Kinship Systems. Smithsonian Institution Press, Washington and London, pp. 94–139.
Jans, M.M.E., 2008. Microbial bioerosion of bone — a review. In: Wisshak, M., Tapanila, L. (Eds.), Current Developments in Bioerosion. Springer-Verlag, Heidelberg, pp. 397–413.
Jans, M.M.E., Nielsen-Marsh, C.M., Smith, C., Collins, M.J., Kars, H., 2004. Characterisation of microbial attack on archaeological bone. J. Archaeol. Sci. 33, 87–95.
Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the globe Version 4. (available from the CGIAR-CSI SRTM 90 m Database (http://srtm.csi.cgiar.org)).
Kang, D., Amarasiriwardena, D., Goodman, A.H., 2004. Application of laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) to investigate trace metal spatial distributions in human tooth enamel and dentine growth layers and pulp. Anal. Bioanal. Chem. 378, 1608–1615.
Katzenberg, M.A., Weber, A.W., 1999. Stable isotope ecology and palaeodiet in the Lake Baikal region of Siberia. J. Archaeol. Sci. 26, 651–659.
Kelly, R., 1992. Mobility/sedentism: concepts, archaeological measures, and effects. Annu. Rev. Anthropol. 21, 43–66.
Kelly, R., 1995. The Foraging Spectrum. Smithsonian Institute Press, Washington D.C.
Knudson, K.J., 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. Anthropol. 132, 25–39.
Knudson, K.J., Price, T.D., Buikstra, J.E., Blom, D.E., 2004. The use of strontium isotope analysis to investigate Tiwanaku migration and mortuary ritual in Bolivia and Peru. Archaeometry 46, 5–18.
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. Archaeol. Sci. 32, 903–913.
Knudson, K.J., Pestle, W.J., Torres-Rouff, C., Pimentel, G., 2012. Assessing the life history of an Andean traveller through biogeochemistry: stable and radiogenic isotope analyses of archaeological human remains from Northern Chile. Int. J. Osteoarchaeol. 22, 435–451.
Koch, P.L., Halliday, A.N., Walter, L.N., Stearley, R.F., Huston, T.J., Smith, G.R., 1992. Sr isotopic composition of hydroxyapatite from recent and fossil salmon: the record of lifetime migration and diagenesis. Earth Planet. Sci. Lett. 108, 277–287.
Koch, P.L., Tuross, N., Fogel, M.L., 1997. The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite. J. Archaeol. Sci. 24, 417–429.
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.
Kusaka, S., Ando, A., Nakano, T., Yumoto, T., Ishimaru, E., Yoneda, M., Hyodo, F., Katayama, K., 2009. A strontium isotope analysis on the relationship between ritual tooth ablation and migration among the Jomon people in Japan. J. Archaeol. Sci. 36, 2289–2297.
Laffoon, J.E., Davies, G.R., Hoogland, M.L., Hofman, C.L., 2012. Spatial variation of biologically available strontium isotopes ($^{87}Sr/^{86}Sr$) in an archipelagic setting: a case study from the Caribbean. J. Archaeol. Sci. 39, 2371–2384.
Lam, Y.M., 1994. Isotopic evidence for change in dietary patterns during the Baikal Neolithic. Curr. Anthropol. 35, 185–190.
Lee, E.S., 1966. A Theory of Migration. Demography 3, 47–57.
Lewis, J., Coath, C., Pike, A., 2014. An improved protocol for $^{87}Sr/^{86}Sr$ by laser ablation multi-collector inductively coupled plasma mass spectrometry using oxide reduction and a customised plasma interface. Chem. Geol. 390, 173–181.
Lightfoot, E., 2008. Movement, Mobility and Migration. Archaeological Review from Cambridge 23, p. 2.
Likins, R.C., McCann, H.G., Posner, A.S., Scott, D.B., 1960. Comparative fixation of calcium and strontium by synthetic hydroxyapatite. J. Biol. Chem. 235, 2152–2156.
Manning, P., 2005. Migration in World History. Routledge, New York.
Maurer, A.F., Gerard, M., Person, A., Barrientos, I., del Carmen Ruiz, P., Darras, V., Durlet, C., Zeitoun, V., Renard, M., Faugère, B., 2011. Intra-skeletal variability in trace elemental content of Precolumbian Chupicuaro human bones: the record of post-mortem alteration and a tool for palaeodietary reconstruction. J. Archaeol. Sci. 38, 1784–1797.
Montgomery, J., Evans, J.A., 2006. Immigrants on the Isle of Lewis — combining traditional funerary and modern isotope evidence to investigate social differentiation, migration and dietary change in the Outer Hebrides of Scotland. In: Gowland, R., Knüsel, C. (Eds.), The Social Archaeology of Funerary Remains. Oxbow, Oxford, pp. 122–142.
Montgomery, J., Evans, J.A., Horstwood, M.S.A., 2010. Evidence for long-term averaging of strontium in bovine enamel using TIMS and LA-MC-ICP-MS strontium isotope intra-molar profiles. Environ. Archaeol. 15, 32–42.
Müller, W., Anczkiewicz, R., 2016. Accuracy of laser-ablation (LA)-MC-ICPMS Sr isotope analysis of (bio) apatite—a problem reassessed. J. Anal. At. Spectrom. 31, 259–269.
Müller, W., Fricke, H., Halliday, A.N., McCulloch, M.T., Wartho, J.-A., 2003. Origin and migration of the Alpine Iceman. Science 302, 862–866.
Nelson, D.A., Sauer, N.J., 1984. An evaluation of postdepositional changes in the trace element content of human bone. Am. Antiq. 49, 141–147.
Nelson, B.K., Deniro, M.J., Schoeninger, M.J., De Paolo, D.J., Hare, P.E., 1986. Effects of diagenesis on strontium, carbon, nitrogen and oxygen concentration and isotopic composition of bone. Geochim. Cosmochim. Acta 50, 1941–1949.
Nicholas, G.P., 2007. Prehistoric hunter-gatherers in wetland environments: mobility/sedentism and aspects of socio-political organisation. In: Lillie, M., Ellis, S. (Eds.), Wetland Archaeology and Environments: Regional Issues, Global Perspectives. Oxbow Books, Oxford, pp. 245–257.
Nielsen-Marsh, C.M., Hedges, R.E.M., 1999. Bone porosity and the use of mercury intrusion porosimetry in bone diagenesis studies. Archaeometry 41, 165–174.
Nielsen-Marsh, C.M., Hedges, R.E.M., 2000a. Patterns of diagenesis in bone I: the effects of site environments. J. Archaeol. Sci. 27, 1139–1150.
Nielsen-Marsh, C.M., Hedges, R.E.M., 2000b. Patterns of diagenesis in bone II: effects of acetic acid treatment and removal of diagenetic CO^{2-3}. J. Archaeol. Sci. 27, 1151–1159.
Parfitt, A.M., 1979. The quantum concept of bone remodeling and turnover. Implications for the pathogenesis of osteoporosis. Calcif. Tissue Int. 28, 1–5.
Price, T.D., 1989. The Chemistry of Prehistoric Bone. Cambridge University Press, Cambridge.
Price, T.D., Blitz, J., Burton, J., Ezzo, J.A., 1992. Diagenesis in prehistoric bone: problems and solutions. J. Archaeol. Sci. 19, 513–529.
Price, T.D., Grupe, G., Schröter, P., 1994a. Reconstruction of migration patterns in the Bell Beaker period by stable strontium isotope analysis. Appl. Geochem. 9, 413–417.
Price, T.D., Johnson, C.M., Ezzo, J.A., Ericson, J.E., Burton, J.H., 1994b. Residential mobility in the Prehistoric Southwest United States: a preliminary study using strontium isotope analysis. J. Archaeol. Sci. 21, 315–330.
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.
Ravenstein, E.G., 1885. The laws of migration. J. Stat. Soc. Lond. 48, 167–235.
Ravenstein, E.G., 1889. The laws of migration. J. R. Stat. Soc. 52, 241–305.
Richards, M.P., Harvati, K., Grimes, V., Smith, C., Smith, T., Hublin, J.-J., 2008. Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. J. Archaeol. Sci. 35, 1251–1256.
Rosenthal, H.L., Chochrane, O.A., Eves, M.M., 1972. Strontium content of mammalian bone, diet and excreta. Environ. Res. 5, 182–191.
Scharlotta, I., 2012. Geochemical Analysis of Human Mobility: Studying Hunter-Gatherer Mobility using Isotopic and Trace Elemental Analysis. Lambert Academic Publishing, Saarbrucken, Germany.
Scharlotta, I., Weber, A.W., 2014. Mobility of middle Holocene foragers in the Cis-Baikal region, Siberia: individual life history approach, strontium ratios, rare earth and trace elements. Quat. Int. 348, 37–65.
Scharlotta, I., DuFrane, S.A., Weber, A.W., Goriunova, O.I., Creaser, R.A., 2011. Assessing hunter-gatherer mobility in Cis-Baikal, Siberia using LA-ICP-MS: methodological corrections for laser interactions with calcium phosphate matrices and the potential for integrated LA-ICP-MS sampling of archaeological skeletal materials. In: Black, S.E. (Ed.), Laser Ablation: Effects and Applications. Nova Publishers, pp. 45–98.
Scharlotta, I., Goriunova, O.I., Weber, A.W., 2013. Micro-sampling of human bones for mobility studies: diagenetic impacts and potentials for elemental and isotopic research. J. Archaeol. Sci. 40, 4509–4527.
Schroeder, H.A., Nason, A.P., Tipton, I.H., 1972. Essential metals in man: strontium and barium. J. Chronic Dis. 25, 491–517.
Schweissing, M.M., Grupe, G., 2003. Stable strontium isotopes in human teeth and bone: a key to migration events of the late Roman period in Bavaria. J. Archaeol. Sci. 30, 1373–1383.
Sealy, J.C., 1989. Reconstruction of Later Stone Age Diets in the South-western Cape, South Africa: Evaluation and Application of Five Isotopic and Trace Element Techniques. University of Capetown, Capetown, South Africa.
Sealy, J.C., Sillen, A., 1988. Sr and Sr/Ca in marine and terrestrial foodwebs in the south-western Cape, South Africa. J. Archaeol. Sci. 15, 425–438.
Sealy, J., Armstrong, R., Schire, C., 1995. Beyond lifetime averages: tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons. Antiquity 69, 290–300.
Sillen, A., Kavanagh, M., 1982. Strontium and paleodietary research: a review. Am. J. Phys. Anthropol. 25, 67–90.
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.
Smith, C., Nielsen-Marsh, C.M., Jans, M.M.E., Collins, M.J., 2007. Bone diagenesis in the European Holocene I: patterns and mechanisms. J. Archaeol. Sci. 34, 1485–1493.
Snoeck, C., Lee-Thorp, J., Schulting, R., Jong, J., Debouge, W., Mattielli, N., 2015. Calcined bone provides a reliable substrate for strontium isotope ratios as shown by an enrichment experiment. Rapid Commun. Mass Spectrom. 29, 107–114.
Tafuri, M.A., Bentley, R.A., Manzi, G., di Lernia, S., 2006. Mobility and kinship in the prehistoric Sahara: strontium isotope analysis of Holocene human skeletons from the Acacus Mts. (southwestern Libya). J. Anthropol. Archaeol. 25, 390–402.
Trueman, C.N., Privat, K., Field, J., 2008. Why do crystallinity values fail to predict the extent of diagenetic alteration of bone mineral? Palaeogeogr. Palaeoclimatol. Palaeoecol. 266, 160–167.

Turner, B.L., Kamenov, G.D., Kingston, J.D., Armelagos, G.J., 2009. Insights into immigration and social class at Machu Picchu, Peru based on oxygen, strontium, and lead isotopic analysis. J. Archaeol. Sci. 36, 317–332.
Tushingham, S., 2009. The Development of Intensive Foraging Systems in Northwestern California. University of California, Davis.
Weber, A.W., Bettinger, R.L., 2010. Middle Holocene hunter-gatherers of Cis-Baikal, Siberia: an overview for the new century. J. Anthropol. Archaeol. 29, 491–506.
Weber, A.W., Goriunova, O.I., 2013. Hunter-gatherer migrations, mobility and social relations: a case study from the Early Bronze Age Baikal region, Siberia. In: Weber, A.W., Zvelebil, M. (Eds.), Human Bioarchaeology: Group Identity and Individual Life Histories. Journal of Anthropological Archaeology, special issue, pp. 330–346.
Weber, A.W., Link, D.W., Katzenberg, M.A., 2002. Hunter-gatherer culture change and continuity in the Middle Holocene of the Cis-Baikal, Siberia. J. Anthropol. Archaeol. 21, 230–299.
Weber, A.W., Creaser, R.A., Goriunova, O.I., Haverkort, C.M., 2003. Strontium isotope tracers in enamel of permanent human molars provide new insights into prehistoric hunter-gatherer procurement and mobility patterns: a pilot study of a Middle Holocene group from Cis-Baikal. In: Weber, A.W., McKenzie, H. (Eds.), Prehistoric Foragers of the Cis-Baikal, Siberia, Proceedings of the First Conference of the Baikal Archaeology Project. Canadian Circumpolar Institute Press, Edmonton, pp. 133–153.
Weber, A.W., Katzenberg, M.A., Schurr, T.G., 2010. Prehistoric Hunter-Gatherers of the Baikal Region, Siberia: Bioarchaeological Studies of Past Life Ways. University of Pennsylvania Museum of Archaeology and Anthropology, Pennsylvania.
Weber, A.W., White, D., Bazaliiskii, V.I., Goriunova, O.I., Savel'ev, N.A., Anne Katzenberg, M., 2011. Hunter-gatherer foraging ranges, migrations, and travel in the middle Holocene Baikal region of Siberia: insights from carbon and nitrogen stable isotope signatures. J. Anthropol. Archaeol. 30, 523–548.
Weber, A.W., Schulting, R., Bronk Ramsey, C., Bazaliiskii, V.I., 2016. Biogeochemical data from the Shamanka II Early Neolithic cemetery on southwest Baikal: chronological and dietary patterns. Quat. Int. 290–291.
Woodburn, J., 1982. Egalitarian societies. Man 17, 431–451.
Woodhead, J.D., Swearer, S., Hergt, J., Maas, R., 2005. In situ Sr-isotope analysis of carbonates by LA-MC-ICP-MS: interference corrections, high spatial resolution and an example from otolith studies. J. Anal. At. Spectrom. 20, 22–27.
Zvelebil, M., Weber, A.W., 2013. Human bioarchaeology: group identity and individual life histories. 32, 275–279.