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Pastoralist Mobility in Bronze Age Landscapes of Northern Kazakhstan: $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ Analyses of Human Dentition from Bestamak and Lisakovsk

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ABSTRACT

The role of migration and mobility of people across the steppe has often been cited as key to Bronze Age developments across Eurasia, including the emergence of complex societies in the steppe and the spread of material culture. The central Eurasian steppe (CES) is a focal point for the investigation of the shifting nature of pastoral societies because of the clear transition in archaeological patterning that occurred from the Middle (MBA) to Late Bronze Age (LBA). The spread of LBA (1700–1400 cal BC) Andronovo cultural materials found across wide swaths of the steppe provide indirect evidence for broad scale interactions, but the degree to which people moved across the landscape remains poorly understood. This study takes a first step into documenting human movement during these critical periods through strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotopic analyses of tooth enamel recovered from human individuals buried in the cemeteries of Bestamak (MBA) and Lisakovsk (LBA) in northern Kazakhstan. Strontium isotope results, referenced against the distribution of contemporary bioavailable strontium in the vicinity of both sites, suggest local communities engaged in small-scale mobility with limited ranges. Reduced strontium and oxygen isotopic variation visible in humans from Lisakovsk suggests mobility decreased from the Middle to Late Bronze Age likely indicative of a shift in resource and landscape use over time.

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Human mobility; Sintashta; Andronovo; Eurasian steppe; Bronze Age; bioavailable strontium; stable isotopes; landscape use

Introduction

The Eurasian steppe was an important crossroad for the transmission of domesticates, technologies, and ideas throughout the Bronze and Iron Ages (Ventresca Miller and Makarewicz forthcoming; Boyle, Renfrew, and Levine 2002; Koryakova and Epimakhov 2007; Hanks and Linduff 2009; Frachetti 2012; Doonan et al. 2014; Brosseder 2015; Honeychurch 2015). During this dynamic period, plant cultivars, ceramic motifs, and bronze ornaments spread across this vast region and were used, repurposed, and recontextualized in spatially disparate and culturally diverse communities. However, it remains unclear if technologies and cultural material were transferred across the steppe through trade, transmitted as part of mobile pastoral interactions, or associated with other forms of social interaction (Tkacheva 1999; Grigory'ev 2000; Kuz'mina 2007; Koryakova and Epimakhov 2007; Tkacheva and Tkachev 2008). Moreover, research focusing on human migrations and broad temporal scales has muted our understanding of mobility at the local level. Our investigation is an early attempt to identify scalar patterns of human movement and clarify the impact of mobility on the transmission of goods.

In north central Eurasia, a clear shift in settlement patterns during the mid-second millennium cal BC points towards a reconfiguration in the spatial extent of interaction networks suggestive of a change in the scale of human mobility at this time. The extent of Sintashta and Petrovka culture areas during the Middle Bronze Age (MBA) spanned the southern Urals and a portion of northern Kazakhstan (Figure 1). During the MBA (2100–1700 cal BC), populations were living in nucleated settlements thought to support large aggregated populations consisting of between 200 and 700 individuals (Gening, Zdanovich, and Gening 1992; Grigor'yev 2000; Anthony 2007; Kohl 2007; Koryakova and Epimakhov 2007; Hanks 2009). MBA settlements were planned, with multiple stages of construction, and featured enclosures frequently interpreted as defensive fortifications (Zdanovich 1995; Zdanovich and Batanina 2002; Zdanovich and Zdanovich 2002). Subsequent Late Bronze Age (LBA; 1700–1400 cal BC) settlements of the Andronovo culture

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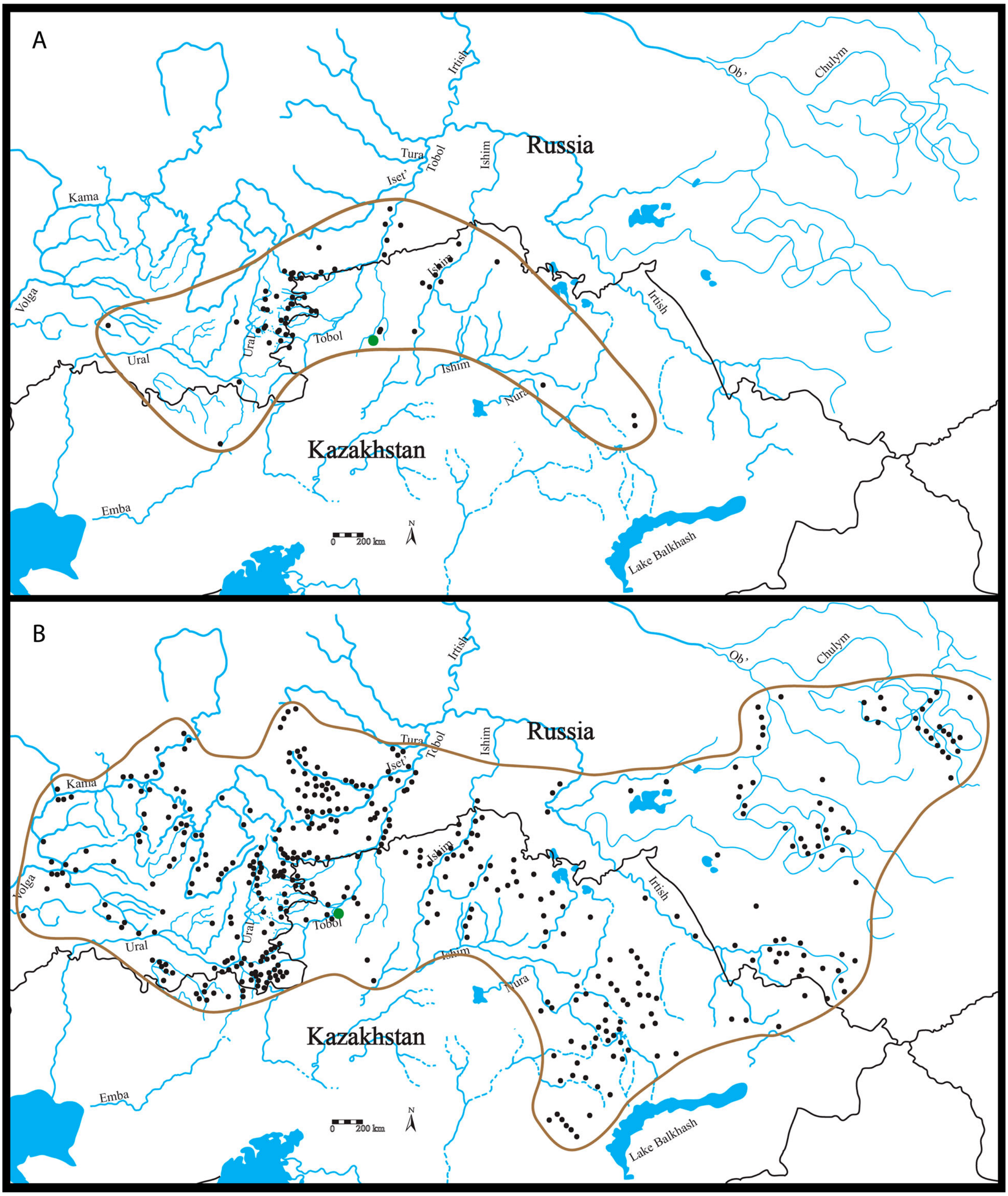

Figure 1. Maps of north central Eurasia, A) with Middle Bronze Age Sintashta and Petrovka sites – Bestamak identified, B) with Late Bronze Age Andronovo sites – Lisakovsk identified.

typically consisted of less than twenty pithouses, lacked enclosures and organised planning, and supported much smaller communities (Kuz'mina 2007, 36–38). The spread of Andronovo cultural materials extended across the whole of Kazakhstan while Sintashta and Petrovka sites were limited to the southeastern portion of the Ural Mountains (Figure 1).

The spread of cultural materials during the LBA has been interpreted as the result of migration, colonisation, and the intensification of long-distance mobility associated with the emergence of nomadic pastoralism (Tkacheva 1999; Grigory'ev 2000; Kuz'mina 2007; Koryakova and Epimakhov 2007; Tkacheva and Tkachev 2008). Migrations across the steppe have been posited as the impetus for the transformation of archaeological cultures and scholars have focused heavily on craniometric techniques to support these theories (Alekseev and Gokhman 1984; Hemphill and Mallory 2004, 207; Kozintsev 2009). Recent genomic evidence from Eurasia suggests that genetic variation is evident between Bronze Age populations and, while there is some disagreement regarding shared ancestry, research suggests long-distance migrations may have impacted the structure of Eurasian steppe populations (Allentoft et al. 2015; Haak et al. 2015). According to Allentoft et al., early Bronze Age (EBA) Afanasievo groups (Altai-Sayan-Minusinsk region) are genetically indistinguishable from Yamnaya culture (far west of the Urals), suggesting an eastward expansion of populations across the steppe (2015). They found that both the Afanasievo and Yamnaya groups are genetically distinct from later Sintashta (MBA) and Andronovo (LBA) groups (Allentoft et al. 2015). The authors propose that Sintashta (Trans-Urals) and Late-Neolithic Corded Ware (Eastern Europe) populations shared a common ancestry or that Sintashta populations derived from an eastward migration of Corded Ware peoples into the steppe (Allentoft et al. 2015). In contrast, work by Haak *et al.* suggests that Corded Ware people traced approximately ¾ of their ancestry to Yamnaya populations, but are unrelated to Sintashta groups (2015). This relationship was the result of westward migrations of Yamnaya pastoralists during the Late Neolithic (Haak et al. 2015). While genetic evidence has not clarified ancestry in the region, direct studies of human mobility within steppe populations have the potential to elucidate human interactions.

Mobility and migration in the Eurasian steppe has also been previously examined through stable isotopic analyses of human remains (Haverkort et al. 2008; Bernbeck et al. 2011; Lillie et al. 2012; Gerling et al. 2012; Weber and Goriunova 2013). For example, the link between mobility and culture change was investigated across several micro-regions using $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ isotopes (Gerling 2015) and indicated that for the nearby Altai region horses had greater mobility than humans (Bernbeck et al. 2011; Gerling 2015). However, the absence of isotopic reference data have severely constrained interpretations of mobility across the steppe zone, resulting in determinations of human mobility such as 'limited' or 'non-detectable' (Gerling 2015, 284).

Here, we seek to resolve some of these issues and examine mobility at the community scale through the analysis of oxygen and strontium isotopic analyses of tooth enamel recovered from humans interred at the MBA site of Bestamak and LBA site of Lisakovsk in northern Kazakhstan. The settlement pattern and material cultural record suggest that the Middle to Late Bronze Age transition was characterised by increased human mobility, but this has yet to be independently tested in the human remains themselves. In order to better understand the scale of landscape use by Bronze Age groups, we built isotopic reference sets describing the distribution of local bioavailable strontium and characterising oxygen isotope variation in modern drinking water.

Figure 2. The locations of the Bestamak and Lisakovsk sites in northern Kazakhstan.

Central Eurasian Steppe (Northern Kazakhstan)

The sites of Bestamak (MBA) and Lisakovsk (LBA) are cemeteries located in north central Kazakhstan, bordering the Russian Federation, and situated in Kostanay Oblast' (administrative region) (Figure 2). Bestamak is located along the right bank of the Buruktal River, just north of one of its main tributaries the Shiili stream, while the cemetery and settlements associated with Lisakovsk are located along the Tobol River. Both cemeteries have been almost completely excavated, with approximately 60 Bronze Age burials identified at Bestamak and 233 burials at Lisakovsk (Logvin and Shevnina 2004, 2008; Kalieva and Logvin 2009; Logvin et al. 2009; Usmanova 2013). Skeletal collections include a large number of well-preserved individuals from securely dated contexts recovered from Bestamak ($n = 60$; 2039–1639 cal BC) and Lisakovsk ($n = 88$; 1860–1680 cal BC) (Panyushkina et al. 2008; Logvin and Ševnina 2013). The sites are located in similar steppe environments and share similar topography, vegetation, and climate.

The geology within the vicinity of the two archaeological sites under study is similar, with Cenozoic period geological formations encompassing the area around and between the two sites (Figure 3). Quaternary alluvial deposits are present along the Tobol and

Ubagan Rivers, which are bounded by Neogenic and Paleogenic soils and outcrops. Estimated strontium values for soils and plants from Cenozoic geological formations, which encompass Neogenic, Paleogenic and Quaternary deposits, range from 0.709 to 0.711 (Asch 2005; Voerkelius et al. 2010). On a pan-regional scale, the study areas are bounded by geological formations with a great deal of variation. The Ural Mountains to the west are characterised by Paleozoic period outcrops (with varied $^{87}Sr/^{86}Sr$ values), while the areas to the east and south of the Urals consist of Mesozoic and Cenozoic sediments. Varied geologic strata are also found east of the Ishim River, with $^{87}Sr/^{86}Sr$ values similar to those in the Urals. As the study area is bounded topographically to the west and east, our discussion will focus on the potential mobility of humans across these zones.

The local hydrology, in particular river recharge sources, is different for each site. The MBA site of Bestamak is located on the right bank of the Buruktal River, just north of where the Shiili stream enters as a tributary. The Shiili is a small seasonal stream, while the Buruktal is slightly larger and continues to flow in the summer months. The Buruktal is one of the main tributaries of the Ubagan River which is just north of the Bestamak site. The Ubagan originates in Shiili Lake and flows through a chain of salt lakes in the Turgay depression (Zakharov and Udris 1971). The Shiili stream originates in the marshy lowlands to the southwest of the site, while the Buruktal River originates with two unnamed tributaries in the marshy lowlands southeast of the study area. Overall, the Tobol-Turgay river basin is the poorest in Kazakhstan in terms of water resources. Numerous small lakes and ponds are present in the study area, yet many are shallow and saline, drying up in the summer months (UNDPKAZ 07 2004, 18).

The LBA site of Lisakovsk is located on high bluff outcrops above the Tobol River, which originates in the eastern slopes of the southern portion of the Ural Mountains (Zakharov and Udris 1971). The headwaters of the Tobol River consist of several named (Kairakty, Sasyksai, Kokpekty, Bozbie) and unnamed streams (Zakharov and Udris 1971). The river flows north through Kazakhstan and portions of southern Russia, parallel to the Ural Mountains. Water flow in the Tobol is almost exclusively derived from snowmelt and is characterised by alternating low and high water years (UNDPKAZ 07 2004). As discussed above, multiple small lakes and ponds were identified in the study area, yet many of these are shallow and have varied levels of salinity, leading many to dry up in the summer months (UNDPKAZ 07 2004).

The climate of the central Eurasian steppe during the Bronze Age is understudied. The steppe and forest-steppe regions are greatly affected by continental climate shifts, which cause drastic spatial variation in seasonal conditions (Coupland 1992). Across west Siberia and Kazakhstan, climate change has been reconstructed based on pollen, lake levels, and soil data (Kremenetski 1997; Kremenetski, Tarasov, and Cherkinsky 1997a, 1997b; Stobbe et al. 2015, 2016). In the proximity of the study areas, two paleoclimate studies have been undertaken with varied results and interpretations. The first lake core from the steppe region was recovered from Mokhovoe Lake located in Kostanay Oblast' between the Tobol and Ubagan Rivers (Kremenetski, Tarasov, and Cherkinsky 1997a, 1997b). A hiatus in sediment deposition dating from 2500 to 900 cal BC which encompasses the Bronze Age has been interpreted as a period of aridity and continental climate (Kremenetski, Tarasov, and Cherkinsky 1997a). However, a lack of sedimentation does not preserve pollen, making inferences about climate and vegetation difficult to discern. The general absence of paleoclimate data for this region challenges attempts to clearly define climate conditions for the Bronze Age (Stobbe et al. 2016). Recent palynological and sedimentological evidence from the southern Urals suggest that the climate was relatively humid from 2400 to 1570 cal BC, similar to the modern period, with evidence for slight expansion of the forests after 2050 cal BC (Stobbe et al. 2015). Steppe degradation was evident locally, based on an increase in Cheopodiacea and Plantago, and attributed to zoo-anthropogenic factors and drought (Stobbe et al. 2015).

Isotopic Approaches to Human Mobility

Strontium and oxygen isotopes of tooth enamel have been used to identify movement of humans in prehistory (Bentley and Knipper 2005; Evans, Chenery, and Fitzpatrick 2006; 2012; Giblin 2009; Chenery et al. 2010; Gerling 2015; Gerling et al. 2012). The use of stable isotope analysis to trace the mobility of humans depends on two main principles. First, the natural abundance of different isotopes in food and drink varies systematically according to natural environments which are passed on to consumers. Second, tracking mobility depends on the identification and appropriate characterisation of the spatial distribution of isotopic signatures through which people move (West et al. 2006; Bowen et al. 2009, 2014; Bowen 2010; Bataille and Bowen 2012; Bataille, Laffoon, and Bowen 2012).

Bedrock $^{87}Sr/^{86}Sr$ is the ultimate source of strontium in soils and surface waters, yet these can differ substantially due to variation in weathering rates (Capo, Stewart, and Chadwick 1998; Stewart, Capo, and Chadwick 1998). The main components of strontium in plants are soil, precipitation, and atmospheric dust, with soil being the major contributor as it has the greatest Sr concentration (Åberg 1995). Therefore, local food sources such as plants have $^{87}Sr/^{86}Sr$ values that can be traced back to the geology of the locality where they were grown. The local strontium composition of

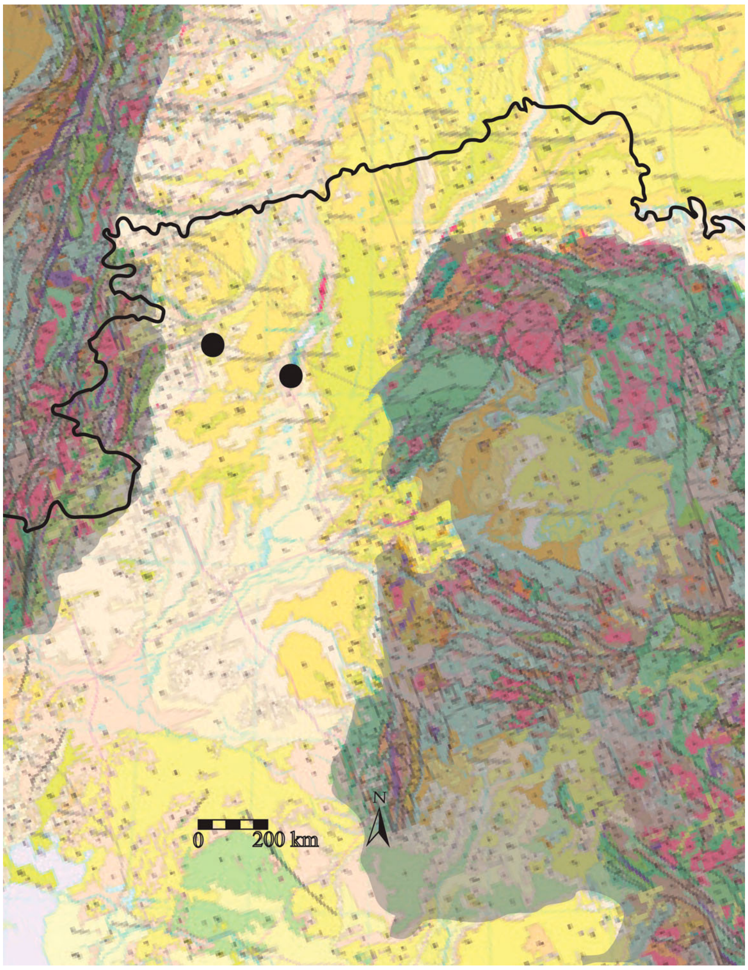

Figure 3. Broad geological variation in north central Eurasia with locations of sites (green) surrounded by 15 km radii study areas (constructed based on Asch 2005).

plants, animals, and water ingested by humans and animals is thus reflected in skeletal tissues where strontium (Sr) substitutes for calcium (Ca) during bone and tooth mineralisation (Graustein 1989). There is negligible metabolic fractionation of strontium isotopes and variation in $^{87}Sr/^{86}Sr$ that occurs as it is passed along the food chain is corrected during analysis for conventionally measured and reported values (Steiger and Jäger 1977; Knudson et al. 2010; Slovak and Paytan 2012). Strontium isotope analysis is therefore an attractive method for the purposes of establishing the mobility of human and animals in ancient environments (Ericson 1985, 1989; Bentley 2006). Several approaches have been used to define local range of bioavailable $^{87}Sr/^{86}Sr$ in studies of mobility. These include direct measurements of bedrock, soils, plants and water collected from modern landscapes, as well as measurements of archaeological skeletal tissues from wild or domesticated animal taxa with small home ranges (Hoppe et al. 1999; Price, Burton, and Bentley 2002; Montgomery, Evans, and Cooper 2007; Hodell et al. 2004; Giblin et al. 2013). The $^{87}Sr/^{86}Sr$ ratios of soil and precipitation are reflected in plants (Graustein 1989; Åberg 1995), which are consumed by and passed on to animals and humans (Ericson 1985; Beard and Johnson 2000). Due to the lack of published $^{87}Sr/^{86}Sr$ ratios for the Eurasian steppe, this study included an assessment of locally bioavailable $^{87}Sr/^{86}Sr$ through the direct measurement of modern plants from a 15 km radius around each site. Isotopic reference sets were constructed for the sites using $^{87}Sr/^{86}Sr$ of plant specimens linked to digitised geologic maps. Human values were further compared to pan-regional geologic maps (Asch 2005; Petrov et al. 2016), broad bioavailable $^{87}Sr/^{86}Sr$ data (Voerkelius et al. 2010), and human $^{87}Sr/^{86}Sr$ values from across the steppe (Gerling 2015).

The oxygen isotopic composition of tooth enamel carbonate directly reflects the $\delta^{18}O$ of body water (Iacumin et al. 1996; Daux et al. 2008; Chenery et al. 2012). The oxygen isotopic composition of body water is influenced by atmospheric oxygen, food, and imbibed water (Longinelli 1984; Luz, Kolodny, and Horowitz 1984; Luz and Kolodny 1985; Levinson, Luz, and Kolodny 1987). The $\delta^{18}O$ values of meteroic water are influenced by continental positions, precipitation amount, altitude, and temperature (Dansgaard 1964; Gat 1996). In the steppe region, there is strong seasonality in the oxygen isotopic composition of meteoric water $\delta^{18}O$ values (Tsujimura et al. 2007;

Yamanaka et al. 2007). The isotopic composition of drinking water obtained from open water sources including rivers, lakes, springs, and wells is influenced by the $\delta^{18}O$ values of local meteoric water, groundwater, lake depth, and aridity (Gat 1995, 1996; Gibson et al. 2002, 2008). Waters in evaporative surface water systems, such as lakes, are generally enriched in ^{18}O relative to precipitation (Gat 1995, 1996; Gibson et al. 2002, 2008). Evaporative effects on the $\delta^{18}O$ composition of lakes are influenced by geographical extent and lake depth, as well as salinity (Gat 1995; Gibson, Birks, and Edwards 2008). Water in shallow lakes may exhibit a wider range of oxygen isotope values due to seasonal shifts in precipitation and temperature, while water in deeper lakes frequently exhibit more stable $\delta^{18}O$ values (Gat 1995; Gibson, Birks, and Edwards 2008). River water is largely derived from precipitation falling in upstream catchments, but also receives water from a variety of isotopically distinct sources including localised precipitation, glacial meltwater, tributaries, groundwater, and surface runoff (Gibson et al. 2002; Halder et al. 2015).

Materials and Methods

Human Dentition from Bestamak and Lisakovsk

Human dentition was collected from previously excavated cemeteries and included permanent first and second molars. Teeth were selected from individuals recovered from the sites of Bestamak (MBA) ($n = 13$) and Lisakovsk (LBA) ($n = 5$) (Supplementary Data 1). The first molar begins to calcify at birth and complete crown mineralisation occurs by 2.5–3 years of age, while the second molar begins to calcify at 2.5–3 years and mineralisation of the crown is complete by 7–8 years of age (Nelson and Ash 2010). Bulk samples were removed from each tooth crown. This approach integrates the oxygen isotopic inputs recorded in teeth over the entire duration of tooth formation, which extends over several years for most teeth. Dental calculus and dirt were removed from teeth using a scalpel and were ultrasonically cleaned in ultra-pure water (deionised water). Teeth were dried overnight and a thin outer surface of the enamel was removed using a Dremel® fitted with a medium grain diamond drill bit (1 mm). Enamel samples were drilled from clean locations and the resulting enamel powder was collected on sheets of weighing paper and placed in a 1.5 mL Eppendorf tube. Enamel samples were treated with 0.1M acetic acid, mixed with a vortex and left to soak for 4 h. Samples were then rinsed with deionised water, mixed, and centrifuged a total of 5 times. On the final rinse the water was removed, samples were placed in the freezer until frozen, and then samples were placed in the freeze dryer overnight. Carbonate samples were tested for $\delta^{18}O$ and $\delta^{13}C$ at the Leibniz-Laboratory for Radiometric Dating and Isotope Research at the Christian Albrechts University of Kiel. Carbonates were tested using a Finnigan MAT 253 connected with a Kiel IV carbonate device. Isotopic values are reported in conventional delta (δ) notation as the per mil (‰) deviation from Vienna Peedee Belemnite (VPDB). Precision for $\delta^{18}O$ and $\delta^{13}C$ samples was <±0.07‰ and <±0.04‰, respectively.

Enamel samples for strontium isotopes were removed by separating a small slice along the entire vertical extent of the tooth crown with a circular diamond edged dental saw. Sliced samples were ultrasonically cleaned in ultra-pure water (deionised water) and dried at room temperature. Radiogenic strontium isotope analysis was conducted at the clean laboratory of the GEOMAR Helmholtz-Centre for Ocean Research Kiel. Samples were weighed into clean Teflon beakers and dissolved in 8 M HNO_3 and H_2O_2, evaporated to dryness, re-dissolved in 8 M HNO_3 and finally loaded on chromatographic columns filled with Eichrom strontium-specific resin. Strontium was separated from the sample matrix by washing the column with 8 M HNO_3 and eluted using 0.05 M HNO_3. After separation, the solutions were dried, followed by heating with a mixture of concentrated HNO_3 and H_2O_2. Radiogenic $^{87}Sr/^{86}Sr$ ratios were measured using multi collector inductively coupled plasma mass spectrometry (MC-ICP-MS). Machine precision was 0.00002 or better (1σ standard deviation).

Modern Plant Sample Collection and Preparation

Modern plants were sampled at three locations within a 15 km radius of the centre of each archaeological site. These provide an initial assessment of the distribution of strontium isotopes within each of the geologic zones present (Supplementary Data 1). Plant samples were collected from units measuring 1 m^2 and two examples of each plant species was collected. Plant collection plots at Bestamak ($n = 37$) and Lisakovsk ($n = 43$), were dispersed across the landscape to capture the diverse vegetation communities present in the region (Ventresca Miller et al. forthcoming). Of these, a select number of plots were chosen for strontium isotope analyses (5008, 5016, 5038, 5050, 5066, 5080) from areas with varied geologic strata (Supplementary Data 2). Modern plant samples were washed with ultra-pure water (deionised water) to eliminate superficial contaminants including soil or dung and then oven dried at 60°C. Plants from each unit were subsampled, across all species and functional groups, and homogenised. Homogenised samples included a combination of grasses and flowering non-woody species (Supplementary Data 2). Samples were crushed using a mortar and pestle, and ashed at 650°C for 9 h in covered porcelain crucibles. Strontium isotope analysis of human tooth enamel and modern plant samples was conducted at the *GEOMAR* Helmholtz Centre for Ocean Research Kiel as described above.

Water Sample Collection and Preparation

The movement of ancient humans and animals is frequently identified by referencing bioapatite $\delta^{18}O$ values to the oxygen isotopic distribution of modern precipitation, tap water, groundwater, and surface water values (Eckardt et al. 2009; Leach et al. 2009; Knudson 2009; Scherer, de Carteret, and Newman 2015). Direct comparison of bioapatite $\delta^{18}O$ values from ancient human skeletal remains with modern precipitation is not advisable, as this practice does not account for temporal disparity in climate conditions that influence both meteoric $\delta^{18}O$ values and their distribution across the landscape (Pollard et al. 2011). However, measurement of modern environmental water can reveal the primary factors defining the distribution of oxygen isotopes in local hydrological systems (e.g. Ventresca Miller 2018). Water samples were collected at multiple locations within a 15 km radius around each site. At the site of Bestamak, water samples were collected from the Buruktal and Ubagan Rivers, as well as the Shiili stream (Supplementary Data 3). In the vicinity of Lisakovsk, samples were collected from multiple locations along the Tobol River, from several lakes (Sasyksor, Aksukol', Kozha, Karasor) and from a single rainfall event (Supplementary Data 3). All water samples were collected over a month long period during August (2014) when temperatures ranged from 10° to 38°C with a mean temperature of 24°C (Lawrimore 2016). The impact of sampling surface waters in the summer may result in higher $\delta^{18}O$ values as well as more variation in values between shallow lakes and large rivers. Water samples were collected using 2 ml glass collection vials with Teflon tops and wrapped in Parafilm. Samples were kept in a cool location and out of direct sunlight to prevent evaporation. Two samples were collected from each location to test for evaporative effects. Water samples were analyzed at the Leibniz–Laboratory for Radiometric Dating and Isotope Research at the Christian Albrechts University of Kiel. Water was tested using a continuous flow Finnigan Delta^{plus}XL connected to a GasBench II (continuous flow interface) and equipped with a CTC Combi PAL Autosampler. Isotopic values are reported in conventional delta (δ) notation as the per mil (‰) deviation from Vienna Standard Mean Ocean Water (VSMOW). Analytical precision for the $\delta^{18}O$ of water is <±0.06‰.

Results

Bioavailable $^{87}Sr/^{86}Sr$

The two sites are located in similar geological substrates dating to the Cenozoic period and the $^{87}Sr/^{86}Sr$ ratios of isotopic reference materials (plants) are within the range of predicted values (Figure 3). At the site of Bestamak, homogenised plant samples ($n = 3$) exhibited an average $^{87}Sr/^{86}Sr$ value of 0.7097 (range 0.7095–0.7099), while homogenised plants ($n = 3$) from the site of Lisakovsk have an average $^{87}Sr/^{86}Sr$ value of 0.7094 (range 0.7093–0.7096) (Figure 4). These strontium isotope values contrast with predicted values for diverse geological substrates of the Ural Mountains that lie approximately 100 km to the east (predicted values ranging from 0.7070 to 0.7090 and 0.7110 to 0.7800) (c.f. Voerkelius et al. 2010). Similar $^{87}Sr/^{86}Sr$ values are predicted for areas east of the Ishim River, with estimated strontium ratios well outside of the range exhibited at the two study areas (predicted values ranging from 0.7070 to 0.7090 and 0.7110 to 0.7800) (c.f. Voerkelius et al. 2010).

Archaeological Human $^{87}Sr/^{86}Sr$ Values

Human $^{87}Sr/^{86}Sr$ ratios from the MBA site of Bestamak ($n = 13$) range from 0.7091 to 0.7097, with an average of 0.7095 (Figure 5). Two individuals (B3570 and B3529) lie outside the range of local bioavailable strontium as measured in plants, exhibiting $^{87}Sr/^{86}Sr$ values of 0.70912 and 0.70916 respectively. Human $^{87}Sr/^{86}Sr$ ratios from Lisakovsk ($n = 5$) exhibit an average value of 0.7093 (0.7092–0.7096) (Figure 6). Humans from Lisakovsk also exhibit relatively homogenous $^{87}Sr/^{86}Sr$ ratios ranging from 0.7092 to 0.7096 and fall within the range of local bioavailable strontium.

$\delta^{18}O$ in Contemporary Local Rivers, Streams, and Lakes

Modern surface waters exhibit a broad range of $\delta^{18}O$ values at each site. Rivers and streams local to Bestamak exhibit $\delta^{18}O$ values ranging from 0.5 to −11.0‰ (Figure 7). The Shiili stream (0.5‰) and the Buruktal River (−3.5‰) were enriched by 10.5 and 6.5‰ in ^{18}O relative to the Ubagan River which had an average value of −10.0‰, derived from 8 samples sites ranging from −9.0 to −11.0‰. The combination of the location of the Shiili and Buruktal in lowland basins (117masl) receiving ^{18}O enriched precipitation due to altitude effects and evaporative enrichment effects caused by seasonal drying would explain the higher $\delta^{18}O$ values of both these waterways. In contrast, the Ubagan River originates in Shiili Lake and flows through a chain of salt lakes in the Turgay depression. The source areas of these waters likely receive ^{18}O depleted precipitation and are constantly flowing due to recharge from snowmelt.

Water sources around Lisakovsk are equally varied in their oxygen isotopic composition and a total of

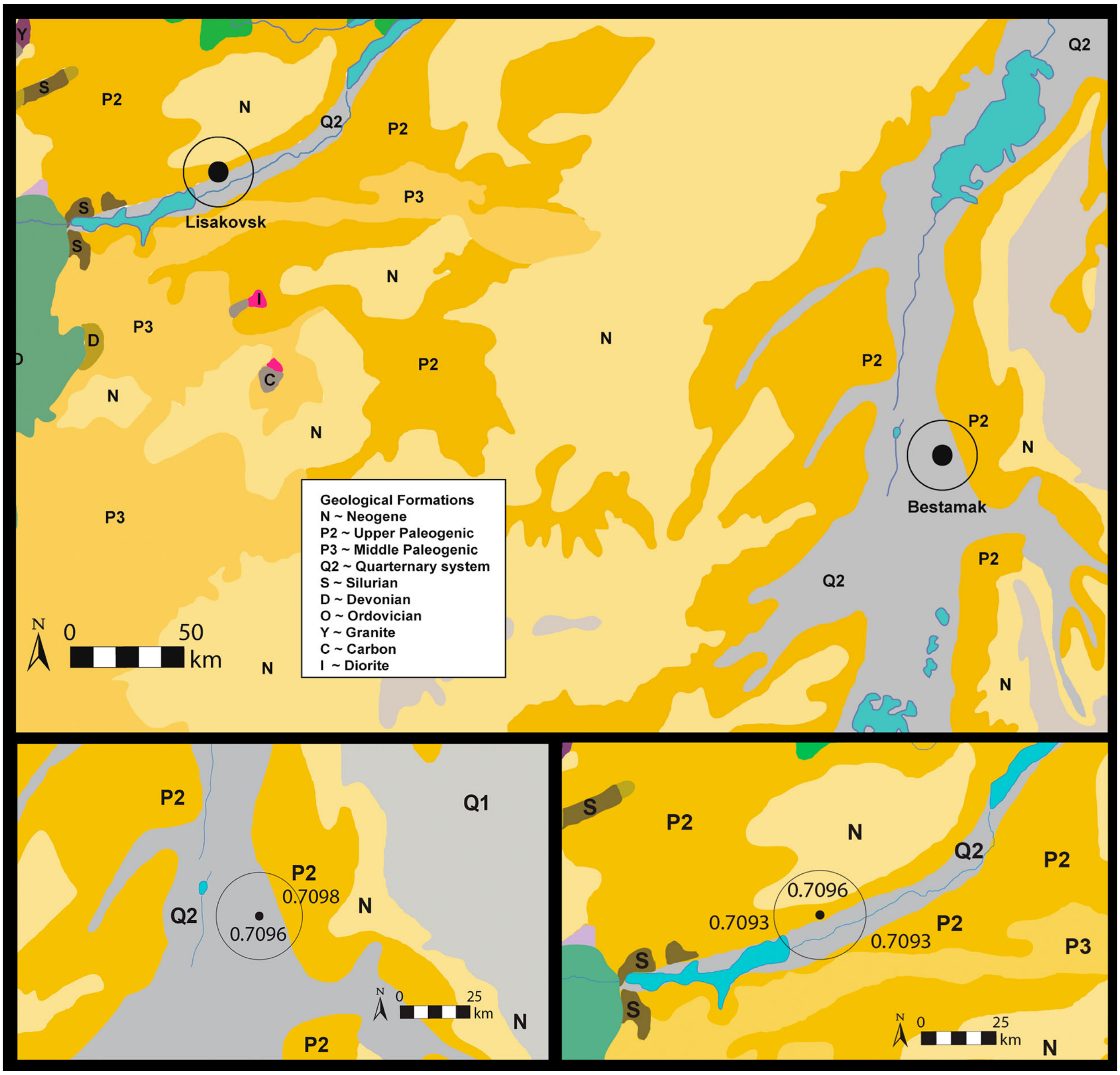

Figure 4. Geological strata and measured bioavailable $^{87}Sr/^{86}Sr$ values in the vicinity of Bestamak (bottom left) and Lisakovsk (bottom right).

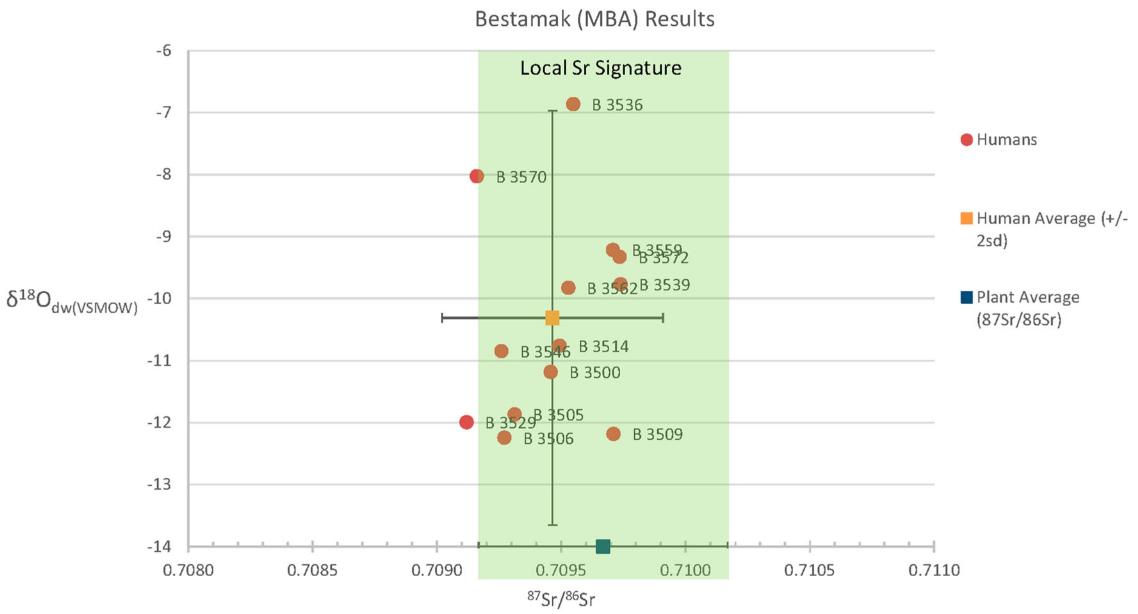

Figure 5. Human $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values for Bestamak.

Figure 6. Human $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values for Lisakovsk.

20 samples range in $\delta^{18}O$ from −2.0 to −11.2‰ (Figure 8). A range of average values was evident between Lake Sasykor (−4.3‰), Lake Aksukol' (−2.2‰), Lake Kozha (−4.1‰), and Lake Karasor (−8.1‰), yet all were enriched in ^{18}O relative to Tobol River values (−10.8 to −11.2‰). A single precipitation sample was also collected from this site with a value of −7.0‰. Lake waters are enriched in ^{18}O relative to the Tobol River, suggesting that many are shallow, affected by evaporation, or have high salinity levels. In contrast, the Tobol River is depleted by 2.9 to 10.8‰ in ^{18}O relative to lakes reflecting the contribution of snowmelt and large highland catchment area (UNDPKAZ 07 2004).

Human $\delta^{18}O$

Oxygen isotope values for humans at the two sites are discussed both in terms of measured values ($\delta^{18}O_{c(VPDB)}$) and values transformed to drinking water ($\delta^{18}O_{dw(VSMOW)}$) to explore human mobility relative to local oxygen isotope reference sets. Observed human enamel values were transformed to reflect carbonate $\delta^{18}O_{c(VSMOW)}$ (Coplen, Kendal, and Hopple 1983), converted from $\delta^{18}O_{c(VSMOW)}$ to phosphate $\delta^{18}O_{p(VSMOW)}$ (Iacumin et al. 1996), and finally transformed to drinking water $\delta^{18}O_{dw(VSMOW)}$ values (Daux et al. 2008, regression equation 6). Transformed values are calculated as a rough heuristic

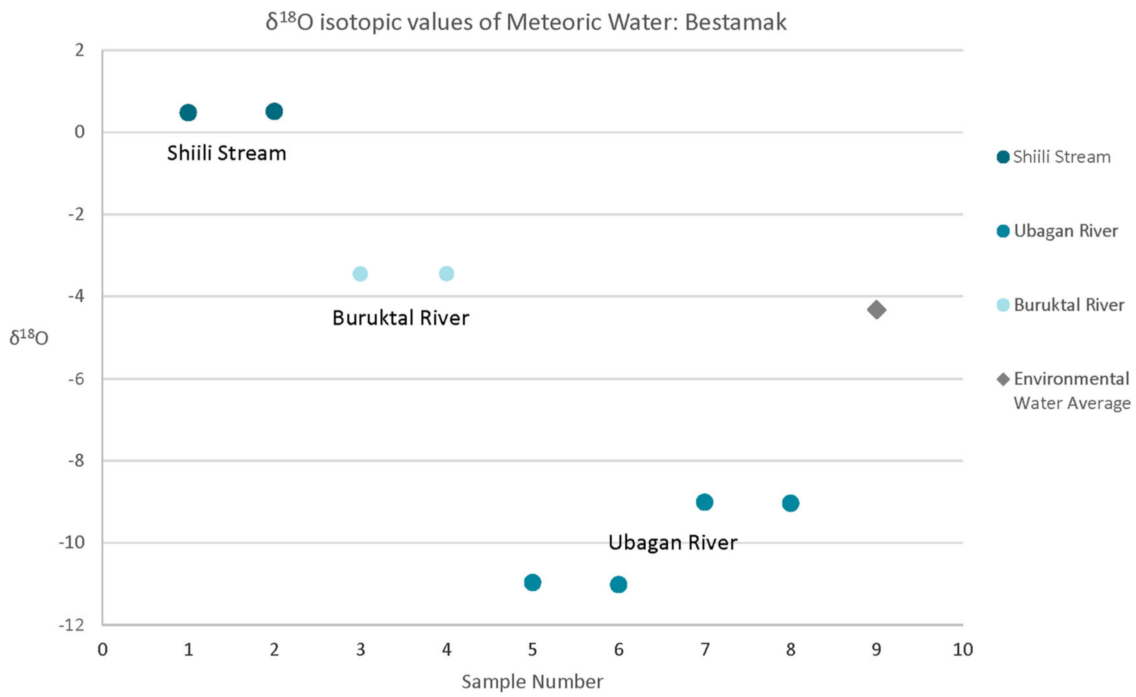

Figure 7. $\delta^{18}O$ values of meteoric water at Bestamak.

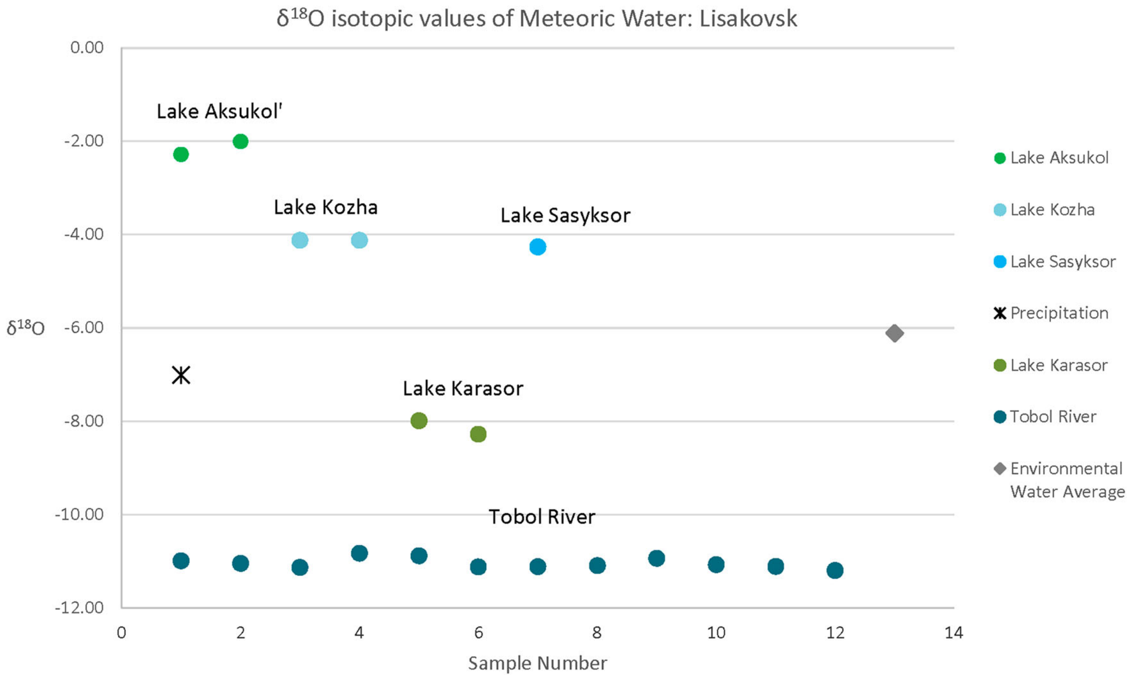

Figure 8. $\delta^{18}O$ values of meteoric water at Lisakovsk.

device to refine our understanding of oxygen isotope variability in the region. The study of local drinking water sources, in addition to archaeological samples, allows for a discussion of observed and expected drinking water values for each site. Human $\delta^{18}O_{c(VPDB)}$ values for the site of Bestamak range from −4.3 to −7.7‰, with an average value of −6.5‰ and when transformed to $\delta^{18}O_{dw(VSMOW)}$ values ranged from −6.8 to −12.2‰, with an average of −10.3‰. The average human $\delta^{18}O_{c(VPDB)}$ value for the site of Lisakovsk was −7.2‰ (ranging from −6.6 to −7.8‰), and when transformed to $\delta^{18}O_{dw(VSMOW)}$ had an average value of −11.3‰ (ranging from −10.4 to −12.3‰).

Discussion

Human Mobility Based on $^{87}Sr/^{86}Sr$ Values

The strontium isotopic analysis of a subset of the Bestamak (MBA) burial community indicates the presence of two individuals that exhibited $^{87}Sr/^{86}Sr$ values outside of the range established for this site (15% of individuals sampled). While these individuals were not 'local' to the study area examined from this site, identifying origin points of these individuals is difficult due to the lack of environmental strontium isotope data from the region. Comparatively, all individuals sampled from the Lisakovsk (LBA) burial group exhibited $^{87}Sr/^{86}Sr$ values within the range of locally bioavailable strontium values. All individuals from both sites, even non-local individuals from Bestamak, likely originated between the Ural Mountains and the eastern bank of the Ishim River, where Cenozoic period formations have $^{87}Sr/^{86}Sr$ values, both predicted and measured, ranging from 0.7090 to 0.7110. It is unlikely that individuals moved to or from far western or eastern areas that have significantly different geologic substrates and associated isotope ratios. These results indicate a shift in mobility strategies during the Bronze Age, with more diverse origins of individuals from the earlier period (MBA) than the later period (LBA).

Human Mobility Based on $\delta^{18}O$ Values

The oxygen isotopic values of prehistoric individuals from northern Kazakhstan provide evidence of shifting landscape use by local communities from the Middle to Late Bronze Age. The wide differences in the range of $\delta^{18}O$ values expressed in Bestamak and Lisakovsk humans suggests variation in the oxygen isotopic composition of local drinking water sources or scale of landscape use. Average variation in human $\delta^{18}O$ values from a single location have been determined to range from 0.5 to 3‰ (Lightfoot and O'Connell 2016; Daux et al. 2008; Ehleringer et al. 2008; White, Longstaffe, and Law 2004). However, a wide range of values in $\delta^{18}O$ isotopic reference sets for the areas studied, ranging from 0.5 to −11.0‰ and −2.0 to −11.2‰, suggest that in strongly seasonal environments such as the steppe there may be more variation in the range of human $\delta^{18}O$ values.

Bestamak (MBA) humans have a wide range in oxygen isotope values (5.4‰) indicating that humans ingested water from multiple sources across the landscape. High variation in the $\delta^{18}O$ values of contemporary potable rivers and streams in the site vicinity may explain the wide range of inter-individual $\delta^{18}O$ values and suggest that the local landscape was used extensively. The average human $\delta^{18}O_{dw(VSMOW)}$ value was −10.3‰, which corresponds to the average value for the Ubagan River of −10.0‰, which is not directly adjacent to the site. This further suggests that individuals moved across the landscape, sourcing drinking water from multiple locations.

At Lisakovsk, the low range of variation in $\delta^{18}O$ values between individuals (1.9‰), combined with a wide range of $\delta^{18}O$ values in contemporary potable rivers and lakes in the vicinity of the site suggest that humans ingested water from a single source, or multiple sources with similar $\delta^{18}O$ values. The average human $\delta^{18}O_{dw(VSMOW)}$ value of −11.3‰ roughly corresponds to the observed $\delta^{18}O$ values of the modern Tobol River (−10.8 to −11.2‰) which flows next to the site, suggesting that this could have been the main drinking water source for Lisakovsk humans. One caveat is the possibility that rivers in the region, such as the Tobol, may have homogenous $\delta^{18}O$ values over long distances making evidence for mobility undetectable. Pastoral communities may have stayed within the vicinity of large rivers such as the Tobol, a constant source of potable water, as they moved their herds across the landscape.

Bronze Age Mobility

The strontium and oxygen isotopic results from Bestamak (MBA) and Lisakovsk (LBA) suggest that pastoral groups in northern Kazakhstan engaged in small-scale movements that remained largely local to settlement sites. At the same time, these data hint at slight differences between MBA and LBA mobility patterns based on the presence of a few non-local strontium values observed in individuals from Bestamak. Furthermore, these isotopic results suggest that groups did not migrate long distances from west of the Urals or east of the Ishim River. If this is the case, pan-regional population movements were not an impetus for complex social developments during either of these periods. Alternatively, we need to focus on interpretations of social complexity that contextualise how pastoral populations navigated their social and environmental landscapes to establish complex social configurations.

Conclusion

The isotopic results presented here are the first to directly explore human mobility in the central Eurasian steppe. At Bestamak during the MBA, human groups remained largely local to the settlement, exploiting multiple resource areas within the landscape. There is also evidence of sporadic intra-regional movement at the site for several individuals. In contrast, mobility at Lisakovsk appears to have been very small scale in nature, although additional samples would better support this interpretation. A shift in patterns of landscape use from the MBA to LBA indicates that individuals were more mobile in the earlier period when large settlements dominated the southern Urals region. Our findings are in direct contrast to archaeological models claiming that increased mobility, often associated with nomadic pastoralism, was the impetus behind the spread of Andronovo materials across Kazakhstan during the LBA. Further, contrary to genomic evidence, our results suggest that if long-distance migratory events were occurring during the Bronze Age, they did not impact the communities under study. Bronze Age groups in the region appear to have been exploiting resources at the local and regional level rather than at pan-regional scales across the steppe.

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