Mobility and land use in the Greater Khorasan Civilization: Isotopic approaches (87Sr/86Sr, δ18O) on human populations from southern Central Asia
Sonja Kroll, Julio Bendezu-Sarmiento, Johanna Lhuillier, Élise Luneau, Kai Kaniuth, Mike Teufer, Samariddin Mustafakulov, Mutalib Khasanov, Natalia Vinogradova, Nona Avanesova, et al.

To cite this version:
Sonja Kroll, Julio Bendezu-Sarmiento, Johanna Lhuillier, Élise Luneau, Kai Kaniuth, et al.. Mobility and land use in the Greater Khorasan Civilization: Isotopic approaches (87Sr/86Sr, δ18O) on human populations from southern Central Asia. Journal of Archaeological Science: Reports, 2022, 46, pp.103622. 10.1016/j.jasrep.2022.103622. hal-03850084

HAL Id: hal-03850084
https://hal.science/hal-03850084
Submitted on 1 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Mobility and land use in the Greater Khorasan Civilization: isotopic approaches \( ^{87}\text{Sr}/^{86}\text{Sr}, \delta^{18}\text{O} \) on human populations from southern Central Asia

Sonja Kroll\(^1,2\), Julio Bendezu-Sarmiento\(^3\), Johanna Lhuillier\(^4\), Élise Luneau\(^5\), Kai Kaniuth\(^6\), Mike Teufer\(^6\), Samariddin Mustafakulov\(^7\), Mutalib Khasanov\(^8\), Natalia Vinogradova\(^9\), Nona Avanesova\(^10\), Denis Fiorillo\(^1\), Margareta Tengberg\(^1\), Arash Sharifi\(^11,12\), Céline Bon\(^3\), Delphine Bosch\(^13\), Marjan Mashkour\(^1\)

1 Archéozoologie, Archéobotanique, Sociétés, Pratiques et Environnements (AASPE), Muséum national d'Histoire naturelle, CNRS, Paris, France
2 University of Bern, Institute for Archaeological Science, Department for Near Eastern Archaeology, Bern, Switzerland
3 Laboratoire Eco-anthropologie (UMR 7206), CNRS, Muséum National d'Histoire Naturelle, Université de Paris, Paris, France
4 CNRS, Lyon 2 University, Archéorient (UMR 5133), Maison de l'Orient et de la Méditerranée, Lyon, France
5 German Archaeological Institute, Eurasien Abteilung, Berlin, Germany
6 Ludwig-Maximilian-University, Institute for Near Eastern Archaeology, Munich, Germany
7 Afrasiab Museum Samarkand, Uzbekistan
8 National Center of Archaeology, Uzbekistan Academy of Sciences, Samarkand, Uzbekistan
9 Institute of Oriental Studies, RAS, Moscow, Russia
10 Samarkand State University, Department of Archaeology, Samarkand, Uzbekistan
11 BETA Analytic-Isobar Science, Research and Development Department, Miami, USA
12 Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, USA
13 Géosciences Montpellier, CNRS et Université de Montpellier (UMR 5243), Montpellier, France

Abstract: The question of mobility of Bronze Age societies in southern Central Asia is a lively subject for discussion and remains a key aspect for understanding past human life. Central Asia represents a region where mobility and migration had a deep impact on the development of cultural communities. Surrounded by the great empires of the ancient Near East, it exhibited a high ethnic and genetic diversity. In this paper we present a regional study for southern Central Asia of isotopic analyses of \(^{87}\text{Sr}/^{86}\text{Sr}\) and \(\delta^{18}\text{O}\) of human samples from several Bronze Age sites in southern Turkmenistan (Ulug Depe), south-central Uzbekistan (Dzharkutan, Sapallitepa, Tilla Bulak, Bustan and Bashman 1) and southern Tajikistan (Saridzhar, Gelot and Darnaichi). The three geographical zones manifest different patterns of mobility. The analysis of the Ulug Depe people demonstrates a high rate of immigration during the early periods (EBA) and a tendency for permanent residence. The later periods (MBA) are marked by a decrease in immigration and mobility, indicating a more extensive use of the surrounding landscape. Dzharkutan people displayed a different and complex pattern of mobility and subsistence,
with frequent movements during individual lifetime within a limited area. The other sites in the Surkhan Darya Valley and southern Tajikistan indicate active mobility in which individuals migrated within a wide area of southern Central Asia.

Keywords: $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ isotopes, southern Central Asia, Greater Khorasan Civilization (GKC), human mobility and land use

Authors contribution:
Sonja Kroll: data curation, formal analysis, investigation, methodology, project administration, conceptualization, visualization, writing – original draft, review and editing
Julio Bendezu-Sarmiento: excavator, provision of samples, project administration, funding acquisition, conceptualization, writing – review and editing
Johanna Lhuillier: excavator, provision of samples, conceptualization, writing – review and editing
Élise Luneau: excavator, provision of samples, conceptualization, writing – review and editing
Kai Kaniuth: excavator, provision of samples, conceptualization, writing – review and editing
Mike Teufer: excavator, provision of samples
Samariddin Mustafakulov: excavator, provision of samples
Mutalib Khasanov: excavator, provision of samples
Natalia Vinogradova: excavator, provision of samples
Nona Avanesova: excavator, provision of samples
Denis Fiorillo: technical lab support
Arash Sharifi: data evaluation and map generation, writing – review and editing
Margareta Tengberg: supervision botany, provision of samples, conceptualization, writing – review and editing
and editing
Céline Bon: supervision paleogenetic, conceptualization, writing – review and editing
Delphine Bosch: supervision geochemistry, conceptualization, writing – review and editing
Marjan Mashkour: overall supervision, provision of samples, project administration, funding acquisition, conceptualization, writing – review and editing

Fundings:
The isotopic analyses were kindly funded by the LIA HAOMA – CNRS Project, the Nestlé Foundation (Grant N° SJ866-17), the Shelby White and Leon Levy Program for Archaeological Publication, and the INSU-MITI-ILIADE project. Travelling and accommodation costs of the first author were liberally funded by the French Archaeological delegation in Afghanistan (DAFA).
1. Introduction

During the Middle and Late Bronze Age, the emergence of complex societies is observed in southern Central Asia. With the rise of the Greater Khorasan Civilization (hereafter GKC\textsuperscript{1}, ca. 2400–1500 BCE, e.g., Lyonnet, Dubova 2021) major transformations led to deep cultural and economic shifts. Archaeological remains evidence the establishment of intensive trade networks and long-distance interactions (cf. e.g., Hiebert 1994; Possehl 2007; Frachetti, Rouse 2012). The location between harsh deserts and high mountain ranges was a natural passage since Neolithic periods (Thomalsky et al. 2013), which later developed into the Silk Road (historical Great Khorasan Road, cf. e.g., De la Vaissière 2002; Wilkinson 2014). Due to the prevailing climatic conditions, structural migrations such as pastoralism or nomadism to access natural and economic resources, were always essential subsistence strategies of the communities who settled in this region (e.g., Mashkour 2013; Spengler et al. 2014).

Hence, the impact of migration and of changes in land use and territorial management remains a matter of ongoing discussions among scientists (cf. e.g., Biscione 1976; Vinogradova, Kuz’mina 1996; Kohl 2007; Cattani 2008; Salvatori 2008; Frachetti 2011, 2012; Lamberg-Karlovsky 2013; Luneau 2014, 2019; Rouse, Cerasetti 2018). In this context analyses of isotopes such as strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and oxygen ($\delta^{18}\text{O}$) are today a common and powerful tool for a better understanding of interactions and exchange of past populations. This study takes a first step in exploring human mobility in southern Central Asia presenting isotopic analyses of a main corpus of samples from Ulug Depe in Turkmenistan and Dzharkutan in Uzbekistan, both sites belonging to the first urban centers in the region during the 3\textsuperscript{rd} and 2\textsuperscript{nd} mill. BCE. The results will be compared with single samples from other Bronze Age sites, such as Sapallitepa, Tilla Bulak and Bustan in southern Uzbekistan, Bashman 1 in central Uzbekistan, and Saridzhar and the nearby graveyards Gelot and Darnaichi in southern Tajikistan (fig. 1). The following discussion is based on the first analysis of human material from southern Central Asia. We are aware that the data at our disposal cannot yet produce statistically reliable results; however, since no isotopic studies on residential mobility have previously been conducted on populations in southern Central Asia, this study will provide a first biogeochemical data set of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes and an initial idea of the dynamics during the Bronze Age.

\textsuperscript{1} Biscione, Vahdati 2021, also called Oxus Civilization or Bactria-Margiana Archaeological Complex (BMAC) cf. e.g., Hiebert 1994; Sarianidi 2005; Francfort 2009; Lamberg-Karlovsky 2013; Teufer 2015; Salvatori 2016.
Fig. 1 Topographic map of the studied region with the investigated sites including symbols of the analysed material after https://maps-for-free.com/

2. Context

2.1. Archaeological Background

Ulug Depe and Dzharkutan delivered the major part of the human material in this study. Ulug Depe is located in southern Turkmenistan in the northern submontane plains of the Kopet Dagh Mountains, 175 km south-east of the capital Ashgabat at 288 m a.s.l. (cf. e.g., Lecomte 2007a, 2011, 2013; Bendezu-Sarmiento 2013; Bendezu-Sarmiento, Lhuillier 2016, 2019). In ancient times, Ulug Depe was situated adjacent to the Kelet River, which traverses the Kopet Dagh in the direction of Nishapur and presents a natural pass through the mountains (Lecomte 2013). Already in the Chalcolithic period, the first social changes towards a more centralized system are evidenced. The construction of a fortification wall, as well as the separation of craft areas and the beginning of irrigated agriculture, reflects the changing nature of property and territorial management, as well as a certain social
differentiation (Lecomte 2011). With the appearance of the GKC, Ulug Depe had a period of particular prosperity. Impressive public monuments, such as the remains of high terraces were discovered (Lecomte 2011; Bendezu-Sarmiento, Lhuillier 2019). Numerous finds of gold, lapis lazuli, carnelian and alabaster reflect widespread connections to the Indus Valley and the Iranian Plateau (Bendezu-Sarmiento, Lhuillier 2016: 527 figs. 4–6).

The situation in Dzharkutan is different: at the end of the 3rd mill. BCE the Sapalli culture, a local variant of the GKC, arose in northern Bactria and several new settlements such as Dzharkutan, Sapallitepa, Bustan, Molali, and Tilla Bulak developed in the Surkhan Darya Valley (fig. 1) (Askarov, Abdullaev 1983; Shirinov 2002; Huff et al. 2001, Huff, Teufer 2010; Bendezu-Sarmiento, Mustafakulov 2013; Kaniuth 2021). The establishment of these new settlements has been associated with an increased mobility of the populations (e.g., Frachetti 2011, 2012; Bendezu-Sarmiento, Mustafakulov 2013). The Surkhan Darya Valley is located in southern Uzbekistan, ca. 50 km north of the district capital Termez, at an altitude around 350 m a.s.l. Dzharkutan with a size of about 40–50 ha is the biggest site in the Surkan Darya Valley, including several mounds with traces of occupation, a citadel with a palace, a temple and large necropolises (Shirinov 2002; Huff et al. 2010; Bendezu-Sarmiento, Mustafakulov 2013). Artifacts, mainly pottery influenced by the Andronovo Culture from the steppes were discovered in Dzharkutan, reflecting dynamic interactions with the related farmer-breeder culture from the Pamir foothills of southwestern Tajikistan, the so called Vakhsh culture (Luneau et al. 2013, 2017).

There is considerable uncertainty regarding the regional cohesion and territorial hegemony of the GKC. In particular throughout south/western Tajikistan, researchers have documented numerous instances of mixed cultural remains that include next to GKC-type materials also materials described as "local" (Vakhsh) as well as related to the "steppe" (Andronovo, Federo) (e.g., Rouse 2020, Teufer 2021, Vinogradova 2021). Our sampling thus includes several other sites in addition to the GKC-related centres of Ulug Depe and Dzharkutan. The nearby site of Sapallitepa and the cemetery of Bustan help round out the picture of GKC-related sites in southern Uzbekistan, while the cemeteries of Gelot/Darnachi and the Saridzhar settlement in Tajikistan represent a complex intersection with communities in the upper Yakh-Su River Valley (Teufer 2018, et al. 2014). Likewise, the samples from Bashman 1 in central Uzbekistan will help establish baselines of communication between the GKC and Andronovo related communities (e.g., Luneau 2017).

2.2. Chronological and anthropological context
The human material analysed in this study was collected by different archaeological expeditions during the last decades and often the local possibilities as well as availability and preservation of the material limited the selection. Hence, it was not possible to present a representative sample of all sexes and age groups. Nevertheless, the remains of 32 human individuals from eight sites in southern Central Asia were used for the present study: eleven individuals from Ulug Depe, eleven from Dzharkutan, two from Sapallitepa, one from Bustan, two from Gelot/Darnaichi, three from Saridzhar and two from Bashman 1 (cf. tab. 1 and 4). In Ulug Depe four burials (2 men, 1 undetermined adult, 1 child) date to the Early Bronze Age (EBA, Namazga IV (NMG IV), ca. 2800–2500 BCE), two burials (1 woman, 1 child) date to the transition from the Early to the Middle Bronze Age (EBA–MBA, NMG IV–V) and five burials (1 man, 1 woman, 2 undetermined adults, 1 child) to the later phase of the Middle Bronze Age (MBA (NMG V), ca. 2200–1900 BCE, cf. also Bendezu-Sarmiento 2013). The Ulug group consisted of three men, two women, three undetermined adults and three children.

The eleven individuals from Dzharkutan date between 2100 and 1700 BCE, corresponding to the transition from the MBA to the LBA and the LBA (NMG V–VI, NMG VI; cf. also Bendezu-Sarmiento, Mustafkulov 2013). A young woman and one undetermined adult dated back to the end of the 3rd/beginning of the 2nd mill. BC (MBA/LBA), nine individuals (1 man, 4 women, 3 undetermined adults, 1 child) dated back to the LBA, ca. 1900 and 1700 BC. In a total the group consists of five women, one man, four undetermined adults and one child.

The two individuals from nearby Sapallitepa coincides with the earliest phase of the LBA (Askarov 1973). Sapallitepa is located about 40 km southwest of Dzharkutan, close to the northern bank of the Amu Darya River. The hills of Bustan are located 5 km south of Dzharkutan and dates to the final phase of the Bronze Age (Avanesova 2016). The graveyards of Gelot/Darnaichi and the neighboured settlement Saridzhar are located on the banks of the Yakh-Su River in southern Tajikistan (Teufer, Vinogradova 2010; Teufer 2014; Lombardo et al. 2014, Vinogradova, Kutimov 2018). The two burials from Gelot/Darnaichi belong to the so called Pjandzh culture and date between 2450 and 1900 cal. BCE (Teufer 2018, et al. 2014), while the three individuals from Saridzhar date between 1700 and 1500 BCE (Teufer 2014). The two individuals from Bashman 1 are culturally related to the Andronovo tribes and date to ca. 1600–1400 BCE. The site is located in central Uzbekistan in the northern range of the Nuratau Mountains (Luneau personal communication).²

The choice of human material was made mainly on the basis of the in-situ conservation of the burials after excavation, since a large part of the burials were looted in the past. Teeth were removed as a priority according to their maxillo-mandibular state of preservation. The lower or upper molars (preferably M2 and M3) were selected if possible. The high variety of teeth used for this study makes

² Corresponding tables for chronology can be found in Teufer 2018: 77-78, Bendezu-Sarmiento, Lhuillier 2019: 99 fig. 1 and Lyonnet, Dubova 2021: 8 tab.1.
inter-individual comparisons difficult as the teeth evolve in different stages of life (cf. Knipper 2004: 602 fig. 6; Hillson 2005). In this study mainly molars (M3) were analysed, which represent a later stage of child- and teenager years. The human bone material consisted mainly of ribs, vertebrae and phalanges. Their remodelling rate depends on the particular bone and can vary between 5 and 30 years (cf. Tütken 2010: 35 fig. 2). Long-bones as femurs, tibias and cranium have slow remodelling rates of 20 to 30 years, whereas ribs and pelvic bones have faster turnover rates of 5 to 10 years (cf. e.g., Knipper 2004: 610–615; Tütken 2010: 35). The detailed description of the methods used for the anthropological determination of gender and age can be found in Bendezu-Sarmiento 2013.

Table 1: Simplified comparative chronology of the sites according to the analysed human remains

<table>
<thead>
<tr>
<th>Period</th>
<th>approximate date cal. BCE</th>
<th>Phase</th>
<th>Kopet Dagh Mountains</th>
<th>Surkhan Darya Valley</th>
<th>Yakh-Su Valley</th>
<th>Nuratau Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Bronze Age</td>
<td>2000-1600</td>
<td>NMG VI</td>
<td>bustan</td>
<td>Saridzhar</td>
<td>Bashman 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>sapallitepa</td>
<td>geli/-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>tilla bulak</td>
<td>gelot/-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>dharkutan</td>
<td>daarnaichi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle Bronze Age</td>
<td>2400-2000</td>
<td>NMG V</td>
<td>ulug depe</td>
<td>dharkutan</td>
<td>gelot/-</td>
<td>daarnaichi</td>
</tr>
<tr>
<td>Early Bronze Age</td>
<td>2800-2400</td>
<td>NMG IV</td>
<td>ulug depe</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3. Ecological and geo-chemical realities

One of the main issues of the present study was the description of the distribution of $^{87}$Sr/$^{86}$Sr isotopes in southern Central Asia. The general concept of mobility studies is based on the comparison of the biogenic signature of an individual with the so called isolandscape (cf. Evans et al. 2010, Bowen 2012, Maurer et al. 2012). Isolandsapes record the spatial distribution of the local isotopic composition of environmentally bioavailable $^{87}$Sr/$^{86}$Sr.

All the sites analysed here are located along the northern foothills of Kopet Dagh Mountains, the eastern foothills of Kugitang Mountains and the southern foothills of the Khodzhasartes Mountains (fig. 2). The Kopet Dagh submontane region is formed from alluvial fan deposits and younger Quaternary loess deposits (Fet, Atamuradov 1994; Atamuradov et al. 1999). The Surkhan Darya Valley is covered by layers of clayish and sandy loess, underneath a thick layer of continental deposits mainly consists of sedimentary rocks (sandstone and aleurolite) with sporadic volcanic outcrops (Mukin 1997; Kaniuth 2021). Also, the Yakh-Su River Valley is covered by deep loess deposits, which are up to 200 m thick (Teuffer 2014). The geological formation of Turkmenian cretaceous rocks and carbonates in the
Amu Darya Basin provided $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.7078 and 0.7084 (Meisel et al. 1995; Zheng et al. 2011), while Caspian Sea deposits resulted in $^{87}\text{Sr}/^{86}\text{Sr}$ ranges around 0.7081 (Clauer et al. 2000).

The climate in Ulug Depe is similar to that of the Karakum Desert, a forbidding environment, tempered through the influence of the Kopet Dagh Mountains (Tengberg 2013). The average annual temperature is 16°C, with a maximum of 48°C and a minimum of -26°C; the annual precipitation is around 220 mm, permitting the cultivation of cereals, grapes, vegetables and fruits without irrigation.

The Central Karakum lies directly northward of the Kopet Dagh submontane plains. Characteristic vegetation types are open steppes dominated by shrub species in the piedmont region and open scrub woodlands followed by juniper forests in the Kopet Dagh Mountains (Fet, Atamuradov 1994, 1999; Moore et al. 1994; Miller 1999, 2003; Tengberg 2013). The climate in Dzharkutan is characterized by seasonal rainfalls in winter and early spring resulting in an early and short growing season. From May to October the climate is dry and hot. Average annual precipitation is 200–240 mm; the mean annual temperature is +16.8°C. Wide areas are covered by a xeric savanna ecosystem, dominated by wild pistachio trees (Mukin 1997). The hot and arid climate results in rather high $\delta^{18}O$ averages of modern precipitation around -5.1‰ (VSMOW) in Ulug Depe and -4.2‰ (VSMOW) in Dzharkutan (after the
OIPC, www.waterisoptopes.org). Analyses of Callovian carbonates from the Caspian Sea resulted in δ18O ranges between 0‰ and -5.5‰ (VPDB, after Zheng et al. 2011).

3. Material and Methods

3.1. Isotopic applications and their problems

Isotope analysis is a reliable method for tracking human and animal origins and mobility at a lifetime scale (cf. e.g., Price et al. 2002, 2004; Tütken 2003; Knipper 2004; Ventresca Miller, Makarewicz 2018). The ratio of strontium 87Sr/86Sr depends on water sources and the geological formation with which the water has interacted. Strontium is dissolved out of rocks by the groundwater, permeating through rivers and other water sources into soils and plants. It enters the body through drinking and eating and is incorporated without substantial fractionation into the hydroxyapatite of hard tissues like bones and teeth, often referred to as biogenic strontium (e.g., Tütken 2003; Bentley 2006). The water and food ingested by an organism is thus directly connected to the nature of the geological substrates (Faure 1986; Faure, Mensing 2005). Moreover, tooth enamel is synthesized during childhood and remains static. Therefore, the isotopic ratio of tooth enamel reflects the environment in which the organism evolved during the first years of its life. Bones undergo continuous modification during the whole life and isotopes reflect the situation of the last years before death. Differences between bones and teeth, therefore, provide evidence for changes and the mobility of humans and animals during their lifetime (Price et al. 2002; Bentley 2006; Burton, Price 2013).

The ratio of oxygen 18O/16O (δ18O) in mammals reflects the sources of incorporated water, such as drinking water and the water in edible plants (e.g., Balasse et al. 2002, 2009). The values reflect the composition of local meteoric water, derived from precipitation as rain, snow, or atmospheric moisture. The oxygen composition varies with different factors such as humidity, temperature, rain shadow effects, altitude, latitude and distance from the sea (Longinelli 1984; White et al. 1998, 2004). It can be evidence of local water sources and climate conditions in which an individual grew up and is, therefore, another indicator for the origins and movements of humans and animals (Budd et al. 2004; Millard et al. 2004; White et al. 2004; Bentley, Knipper 2005). The oxygen signal of an individual is not only impacted by the surrounding habitat but also by several physiological factors, such as individual metabolism and water intake, body temperature, or heat loss mechanisms (Makarewicz, Pederzani 2017, Ventresca Miller 2018). Moreover, culturally related manners as the intake of brewed, fermented, or cooked beverages can affect the δ18O ratios (Brettell et al. 2012; Royer et al. 2017), as well as weaning can have an impact on the δ18O ratio in body tissues (White et al. 2004). Additionally,
seasonal variations have to be taken into account. The mineralization of body tissues generally covers a period of several years and might be impacted by seasonal changes through time. Central Asia is dominated by a dry, hot and arid vegetation, groundwater sources like springs, wells, rivers, or lakes may have been seasonal and differ over time. Furthermore, many regions in the world as e.g., tropical zones have similar δ¹⁸O values, ranging from approximately -2.0 to -8.0 (VSMOW), so that a distinction of these regions is difficult (Bowen et al. 2005, Sjögren, Price 2012). Therefore, δ¹⁸O results will be taken only for the interpretation of inter-individual variations.

Diagenesis can have a critical impact on the isotopic composition of human remains. Bones, but especially tooth dentine are very sensible to diagenesis – the ability of isotopes to penetrate from the surrounding milieu into the material. Decay processes as well as bone density, temperature and humidity/aridity can strongly modify the original isotopic composition (e.g., Behrensmeyer 1978; Budd et al. 2000; Denys 2002; Hedges 2002; Hoppe et al. 2003; Tütken 2003, 2010; Maurer et al. 2012). Depending on the conservation of the material, diagenetic effects, especially of recent, well-preserved material, can be more or less completely eliminated by careful mechanical ablation of the topmost layers of the bone compacta followed by a specific leaching treatment with NaOCl and NaOH or acetic acid solutions (Hedges 2002: 322; Hoppe et al. 2003: 25–26; Tütken 2003: 217). Carbonized plant remains also strongly undergo diagenetic changes. Although exogenous strontium does not replace all biogenic strontium and is removable through leaching with strong acid (Fiorentino et al. 2014; Styring et al. 2019), potential diagenetic alterations always have to be taken into account when interpreting isotopic data. The strong homogeneity of ⁸⁷Sr/⁸⁶Sr results of Ulug Depe bones attracts attention, as all of them fall within a very narrow strontium range. It may be feared that these results are caused by contamination through diagenetic processes. Although the assessment of the diagenetic effect on the ⁸⁷Sr/⁸⁶Sr ratios through measuring the concentration of the elements was not performed on the samples, Ulug Depe bones were in very good conditions and leaching with strong acid should have removed the diagenetic impact for isotopic measurements. Moreover, both chemical extractions and measurements were conducted in multiple sessions over a period of two years with each session incorporating samples of different material, species and origins. Therefore, systematic mistakes within the analytical process can be excluded and the results will be considered as reliable.

### 3.2. Reference material

For the determination of the bioavailable local ⁸⁷Sr/⁸⁶Sr ranges in this study material of nine rodents (Mus spec.), two carnivores (Canis familiaris, Panthera spec.), eleven samples of barley (Hordeum vulgare), three samples of wheat (Triticum aestivum), two tamarisks (Tamaris spec.), one juniper
(Juniperus spec.) and one willow (Salix spec.) were analysed (cf. tab. 2 and Mashkour 2013; Tengberg 2013, et al. 2020). Rodents, such as mice, have a natural lifespan of around 2–3 years and form territorial family clans. Hence, their bone compositions can be considered as representative of the surrounding environment and deliver reliable information about the bioavailable strontium (e.g., Knipper 2004; Bentley et al. 2004). When only human material was available as it was the case in Bashman 1, tooth dentine was analysed. Primary dentine is particularly susceptible to diagenetic alterations and represents the bioavailable strontium of the environment rather than the biogenic signal of the individual (cf. e.g., Gerling 2015). Plants were used in form of carbonized grains and charred wood from Bronze and Iron Age layers (Tengberg 2013, et al. 2020). In general, all reference samples were collected during the excavations, and we avoided using modern material because of possible complications with the influence of fertilizers or imported animal feed (Böhlke, Horan 2000; Bentley, Knipper 2005; Maurer et al. 2012).

3.3. **Applied laboratory methods**

Analyses were conducted on bone compacta, tooth enamel and primary tooth dentine. All steps were performed in a sterile atmosphere, tools were cleaned with ethanol and in the ultrasonic bath. Bones were cleaned of dirt with a toothbrush and a diamond drill. The sampling was proceeded with a micro saw followed by careful crushing with an agate mortar and pestle. Teeth were cleaned with a toothbrush and a diamond drill, enamel and dentine sampling was undertaken with a diamond drill. Charred plants were mechanically cleaned of sand and dust with a needle and tweezers under the microscope. After crushing and the treatment with 6 M HCl for 24 hours after Styring et al. (2019), the samples were transformed into ash in a ceramic beaker at 750°C for 12 hours. The residues were solved in 1 ml 13 M HNO₃ in the Ultrasonic bath followed by the evaporation of the acid solution on a hot plate (100⁰C) overnight.

The extraction of strontium was performed with 10–15 mg tooth enamel and 20–25 mg bone compacta/tooth dentine. The leaching procedure to remove the diagenetic strontium was undertaken with 7% acetic acid in an ultrasonic bath (45⁰C) for 30 minutes followed by several rinsing steps with ultrapure H₂O Milli-Q®, changing the solution every 10 minutes until it became clear (only enamel and bones were leached, dentine was only rinsed in water). The samples were dried overnight. The cleaned, leached and oven dried samples were transferred to a clean Teflon beaker and dissolved in 1 ml 13 M HNO₃ in the Ultrasonic bath at 65°C. Acid was evaporated on a hot plate at 100°C and samples were dissolved in 2 ml 2 M HNO₃. Strontium was extracted through a Teflon column using “Sr-Eichrom” resin (Pin et al. 1994) after the following protocol: columns were washed 6 times alternately with 5 ml
6 M HCl and 0.05 M HNO₃ followed by the conditioning step with 3 ml 2 M HNO₃. After uploading the samples, the elimination of other elements was performed with 2 ml 2 M HNO₃, 3 ml 7 M HNO₃ and 0.5 ml 3 M HNO₃. The extraction of strontium was accomplished with 4 ml 0.05 M HNO₃. The lab work of the strontium extraction was carried out in the clean isotope laboratory of the Geoscience Montpellier (CNRS – University of Montpellier). The measurements were realized using a Thermo Scientific MC-ICP-MS (MultiCollector-Inductively Coupled Plasma Mass Spectrometer) Neptune Plus at the AETE-ISO Platform from the OSU-OREME (Montpellier). To assess the reproducibility and accuracy of the isotopic ratios, standards were repeatedly run every five samples. All ratios were normalized using a value of 0.1194 for the $^{88}\text{Sr}/^{86}\text{Sr}$ ratio. The standard average values were 0.710243 ± 6 (±2σ, n = 20) for the NBS987 Sr standard.

For the preparation of structural carbonate for the oxygen analyses, because of the state of preservation varying amounts of mechanically cleaned bone compacta were required: Ulug bones 10–15 mg; Dzharkutan, Gelot/Darnaichi, Saridzhar, and Bashman1 bones 20–30 mg. The required amount of tooth enamel was 5–10 mg. The purification was performed following the protocol of Balasse et al. (2002). To remove the diagenetic carbonate, bone samples were treated with NaOCl (2–3%) for 24–48 hours at room temperature, stirred every 4–6 hours. After rinsing (4–5 times with H₂O Milli-Q®), 1 M acetic acid was added to the bone powder for 1 hour at room temperature, stirred every 20 minutes. Teeth enamel samples were treated with 1 M HCl for 4 hours, stirred every 30 minutes. After rinsing (4–5 times with H₂O Milli-Q®), all samples were dried at 50–70°C for 24–36 hours until all water was thoroughly evaporated. The lab work was carried out in the Cosmochemistry Lab of the Mass Spectrometry Service at the National Museum of Natural History (SSMIM) in Paris. The analyses were performed using a Thermo Scientific Mass-spectrometer DeltaV-Advantage with a Kiel IV automated processor. Oxygen ratios are reported compared to the Vienna Pee Dee Belemnite standard (VPDB) using δ notation. Uncertainties (1σ) for δ¹⁸O were 0.06‰, the measurements are expressed relative to the standard in parts per thousand (‰).

4. Results

4.1. Determination of the local $^{87}\text{Sr}/^{86}\text{Sr}$ ranges

Several methods exist for the calculation of local $^{87}\text{Sr}/^{86}\text{Sr}$ signals to get the most reliable results (e.g., Grupe et al. 1997; Price et al. 2002, 2004; Bentley et al. 2004; Knipper 2004). In order to compare our results with already published data, we followed Price et al. (2002) by expanding the mean value with
The itemized results of the faunal and botanical references, including the calculated local $^{87}\text{Sr}/^{86}\text{Sr}$ ranges, are listed in table 2; the two human dentine results can be found in table 3; all $^{87}\text{Sr}/^{86}\text{Sr}$ ranges are shown in fig. 3.

The bio-available local $^{87}\text{Sr}/^{86}\text{Sr}$ range of Ulug Depe was determined using three samples of rodents and two of carnivores (Mashkour 2013), supplemented by four samples of barley, supposed to be grown locally, one sample of juniper wood, a mountainous species, and one sample of tamarisk, with a high variety of adaptation, but in this region mainly growing along rivers and in the plain (Tengberg et al. 2020). The ratios ranged between 0.707885 and 0.708045 with an average of 0.707964 ($\pm$ 0.000045), resulting in a local $^{87}\text{Sr}/^{86}\text{Sr}$ range for Ulug Depe of 0.707874 – 0.708054 ($\pm 2\sigma$, n = 11).

For the bio-available local $^{87}\text{Sr}/^{86}\text{Sr}$ range of Dzharkutan, two samples of rodents, five botanical samples and two human dentine samples were analysed (Mashkour et al. 2016; Tengberg 2013; Tengberg et al. 2020). The plants were three samples of barley, most probably locally grown; one sample of willow, riverine and probably also locally grown; and one sample of tamarisk. The ratios ranged between 0.708191 and 0.708356 with an average of 0.708273 ($\pm$ 0.000062), resulting in a local $^{87}\text{Sr}/^{86}\text{Sr}$ range for Dzharkutan of 0.708149 – 0.708397 ($\pm 2\sigma$, n = 9).

To get a better idea of the surrounding situations, further faunal samples were added from Tilla Bulak, a small village 25 km west of Dzharkutan, dating around 2000–1750 BCE (Kaniuth 2016).
Seven samples of barley and wheat were analysed (Peters in Kaniuth 2009, 89–91): the ratios ranged between 0.708930 and 0.708968 with an average of 0.708948 (± 0.000015), resulting in a narrow, but significantly different local $^{87}\text{Sr}/^{86}\text{Sr}$ range of $0.708918 – 0.708978$ (±2σ, n = 7).

The two human individuals from Bashman 1 were tested for their dentine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The results were close to each other (0.709297 and 0.709343), giving an impression of the strontium distribution in this region. The enamel ratio of the child was also close to the two dentine ratios; as it was a young child (below 7 years) and the analysed tooth a molar (formation not finished within this age), the child was added to the calculation to get the widest possible description of local strontium distribution. Then, the ratios ranged between 0.709297 and 0.709445 with an average of 0.709362 (± 0.000062), resulting in a local $^{87}\text{Sr}/^{86}\text{Sr}$ signal of $0.709238 – 0.709485$ (±2σ, n = 3).

Several analyses of rodents were included as further references: these do not provide reliable local $^{87}\text{Sr}/^{86}\text{Sr}$ signals, but serve as indicators for the isotopic distribution of the archaeological sites. Hence, the bone material of one rodent from Sangir-tepe, of one from Erkurgan (Mashkour et al. 2016) and of two from Geoktchik Depe (Mashkour 1998) were analysed. Geoktchik Depe is located in the Dehistan Plain, in southwestern Turkmenistan, adjacent to the Caspian Sea, which is today an arid and flat region (Lecomte 2005, 2007b). The two rodents from Geoktchik Depe showed completely different $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, resulting in a wide range of $0.708102 – 0.709616$ (±2σ, n = 2). The rodent from Sangir-tepe displayed a similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.709224 (± 0.000006), while that from Erkurgan a ratio of 0.708273 (± 0.000003) closer to those from Ulug Depe and Dzharkutan.

Table 2 $^{87}\text{Sr}/^{86}\text{Sr}$ results of botanical and faunal references and calculation of the local signals
<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Name of sample</th>
<th>#Ref</th>
<th>Period</th>
<th>Material</th>
<th>Mean ±1σ Local 87Sr/86Sr ±2σ</th>
<th>Mean ±1σ (n=34) Local 87Sr/86Sr ±2σ</th>
<th>Mean ±1σ Local 87Sr/86Sr range ±2σ (±0.001)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ulug Depe</strong></td>
<td>Mus spec.</td>
<td>R-CH. 1</td>
<td>Chantier 1</td>
<td>MBA</td>
<td>bone fragm.</td>
<td>0.707922 ± 0.06</td>
<td>0.707954 ± 0.00045</td>
<td>0.707874 - 0.708054</td>
</tr>
<tr>
<td></td>
<td>Mus spec.</td>
<td>R-CH. 5</td>
<td>Chantier 5</td>
<td>MBA</td>
<td>bone fragm.</td>
<td>0.707885 ± 0.04</td>
<td>0.708008 ± 0.05</td>
<td>0.707961 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Mus spec.</td>
<td>R-CH. 16</td>
<td>Chantier 16</td>
<td>MIA</td>
<td>bone fragm.</td>
<td>0.707972 ± 0.07</td>
<td>0.709908 ± 0.05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Canis fam.</td>
<td>SK16-18</td>
<td>Chantier 5; 2007</td>
<td>EBA/MBA</td>
<td>bone fragm.</td>
<td>0.707908 ± 0.05</td>
<td>0.707961 ± 0.03</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Panthera spec.</td>
<td>SK16-25</td>
<td>Chantier 5; 2004</td>
<td>MBA</td>
<td>bone fragm.</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Tamris spec.</td>
<td>SK18-01</td>
<td>Chantier 1 Est</td>
<td>MBA</td>
<td>charred wood</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Juniperus spec.</td>
<td>SK18-02</td>
<td>Chantier 8, US 830</td>
<td>MBA</td>
<td>charred wood</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-03-1</td>
<td>Chantier 5, US 502</td>
<td>MBA</td>
<td>charred seed</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-03-2</td>
<td>Chantier 5, US 502</td>
<td>MBA</td>
<td>charred seed</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-04</td>
<td>Chantier 1 Est</td>
<td>MBA</td>
<td>charred seed</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-05</td>
<td>Chantier 8, US 830</td>
<td>MBA</td>
<td>charred seed</td>
<td>0.707961 ± 0.03</td>
<td>0.708016 ± 0.04</td>
<td>0.708045 ± 0.03</td>
</tr>
<tr>
<td><strong>Dzharkutan</strong></td>
<td>Mus spec.</td>
<td>R-DZH 1066</td>
<td>Sep. 1066</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.708201 ± 0.05</td>
<td>0.708217 ± 0.000062</td>
<td>0.708149 - 0.708379</td>
</tr>
<tr>
<td></td>
<td>Mus spec.</td>
<td>R-DZH 2012</td>
<td>Excavation 2012</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.708204 ± 0.03</td>
<td>0.708217 ± 0.000062</td>
<td>0.708149 - 0.708379</td>
</tr>
<tr>
<td></td>
<td>Tamris spec.</td>
<td>SK18-86</td>
<td>Chantier 7, US 708</td>
<td>EIA</td>
<td>charred wood</td>
<td>0.708312 ± 0.09</td>
<td>0.708312 ± 0.09</td>
<td>0.708312 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Salix spec.</td>
<td>SK18-07</td>
<td>Chantier 7, US 704</td>
<td>LBA</td>
<td>charred wood</td>
<td>0.708191 ± 0.04</td>
<td>0.708191 ± 0.04</td>
<td>0.708191 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-09-1</td>
<td>Chantier 7, US 704</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708258 ± 0.06</td>
<td>0.708258 ± 0.06</td>
<td>0.708258 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-09-2</td>
<td>Chantier 7, US 704</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708259 ± 0.07</td>
<td>0.708259 ± 0.07</td>
<td>0.708259 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-10</td>
<td>Chantier 7, US 708</td>
<td>EIA</td>
<td>charred wood</td>
<td>0.708259 ± 0.07</td>
<td>0.708259 ± 0.07</td>
<td>0.708259 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>Homo s.p.</td>
<td>DZH 1049</td>
<td>DZH-2011 Sep1049</td>
<td>LBA</td>
<td>tooth dentine</td>
<td>0.708301 ± 0.05</td>
<td>0.708301 ± 0.05</td>
<td>0.708301 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>Homo s.p.</td>
<td>DZH 1051</td>
<td>DZH-2011 Sep1051</td>
<td>LBA</td>
<td>tooth dentine</td>
<td>0.708467 ± 0.000501</td>
<td>0.708467 ± 0.000501</td>
<td>0.707466 - 0.709469 (0.707467 - 0.709467)</td>
</tr>
<tr>
<td><strong>Tilla Bulak</strong></td>
<td>Triticum aest.</td>
<td>SK18-76</td>
<td>TB10-KF-541</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708965 ± 0.03</td>
<td>0.708965 ± 0.03</td>
<td>0.708965 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Triticum aest.</td>
<td>SK18-77</td>
<td>TB10-KF-701</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708933 ± 0.13</td>
<td>0.708933 ± 0.13</td>
<td>0.708933 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>Triticum aest.</td>
<td>SK18-80</td>
<td>TB10-KF-935</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708959 ± 0.06</td>
<td>0.708959 ± 0.06</td>
<td>0.708959 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-75</td>
<td>TB10-KF-626</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708969 ± 0.08</td>
<td>0.708969 ± 0.08</td>
<td>0.708969 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-78</td>
<td>TB10-KF-890</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708944 ± 0.04</td>
<td>0.708944 ± 0.04</td>
<td>0.708944 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-79</td>
<td>TB10-KF-919</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.70893 ± 0.11</td>
<td>0.70893 ± 0.11</td>
<td>0.70893 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>Hordeum vulg.</td>
<td>SK18-81</td>
<td>TB10-KF-937</td>
<td>LBA</td>
<td>charred seed</td>
<td>0.708937 ± 0.07</td>
<td>0.708937 ± 0.07</td>
<td>0.708937 ± 0.07</td>
</tr>
<tr>
<td><strong>Geoktkhik Depe</strong></td>
<td>Mus spec.</td>
<td>SK18-28</td>
<td>IA</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.709237 ± 0.04</td>
<td>0.70859 ± 0.000379</td>
<td>0.708102 - 0.709616</td>
</tr>
<tr>
<td></td>
<td>Mus spec.</td>
<td>SK18-115</td>
<td>IA</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.70848 ± 0.11</td>
<td>0.70848 ± 0.11</td>
<td>0.70848 ± 0.11</td>
</tr>
<tr>
<td><strong>Erkurgan</strong></td>
<td>Mus spec.</td>
<td>SK18-31</td>
<td>BA</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.708273 ± 0.03</td>
<td>0.708273 ± 0.03</td>
<td>0.708273 ± 0.03</td>
</tr>
<tr>
<td><strong>Sangir-tepe</strong></td>
<td>Mus spec.</td>
<td>SK18-32</td>
<td>ST-04 .St delta 3 pit</td>
<td>LBA</td>
<td>bone fragm.</td>
<td>0.709224 ± 0.06</td>
<td>0.709362 ± 0.000062</td>
<td>0.709238 - 0.709485</td>
</tr>
<tr>
<td><strong>Bashman 1</strong></td>
<td>Homo s.p.</td>
<td>SK18-119</td>
<td>LBA</td>
<td>tooth dentine</td>
<td>0.709297 ± 0.05</td>
<td>0.709297 ± 0.05</td>
<td>0.709297 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Homo s.p.</td>
<td>SK18-120</td>
<td>LBA</td>
<td>tooth dentine</td>
<td>0.70943 ± 0.05</td>
<td>0.70943 ± 0.05</td>
<td>0.70943 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Homo s.p.</td>
<td>SK18-120</td>
<td>LBA</td>
<td>tooth enamel</td>
<td>0.709445 ± 0.07</td>
<td>0.709445 ± 0.07</td>
<td>0.709445 ± 0.07</td>
<td></td>
</tr>
</tbody>
</table>
The calculated local signals of the single sites were resultful within the available references and are well distinguishable at a micro-regional scale (cf. fig. 3). The calculated strontium signal of the whole region was calculated resulting in a range of $0.707466 - 0.709469$ ($\pm 2\sigma$, $n = 34$).

### 4.2. Interpolation on an interregional scale

The geographic regions of southern Central Asia comprise a large area with very diverse geological conditions, making interregional comparisons difficult. But the obtained local signals are sufficiently distinctive for a first evaluation on an interregional scale. The background strontium isotope values for the region were reconstructed by interpolating the data for the geological units using the kriging method. The strontium isotope values of the geological units with references can be found in the supplementary. Although the accuracy of this reconstruction is limited by the available data and their locations, higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (~0.70800–0.70850) are seen to the north of Dzharkutan while lower values (~0.70605–0.70700) were observed near Ulug Depe (fig. 4).

![Fig. 4: Strontium isotope values of the geological units. Blue stars denote the isotopic values of Caspian Sea water. Values in red and green denote the local mean values obtained on rodents (Mus sp.) and barley (Hordeum vulg.) respectively.](image)

### 4.3. Human $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ results

The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ results of all human samples from Ulug Depe, Dzharkutan, Sapallitepa, Bustan, Bashman 1, Gelot/Darnaichi and Saridzhar are listed in table 3 and presented in figures 5, 6 and 7 (the individuals from Bashman 1 were only tested for strontium, and are therefore not in figs. 6 and 7). A preliminary cluster analysis of Ulug Depe and Dzharkutan individuals provided two distinguishable clusters with several outliers. Hence the sites can be considered as capable of being differentiated. A
Levene test confirmed that there was no homogeneity of variances between the sites (F = 2.16, p < 0.02). But since the small sample number made statistical analyses unreliable, we desisted from further calculations. Moreover, the deviations of the individual results were negligibly small, when plotting them on the figures the error bars were overlapped by the applied symbols so that the symbols in figures 5, 6 and 7 encompass the error margins at 2σ level for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and 1σ level for $\delta^{18}\text{O}$ ratios.

![Diagram](image)

**Fig. 5:** $^{87}\text{Sr}/^{86}\text{Sr}$ results of humans and references showing the variation between samples from the same individual. Tooth enamel samples are plotted with the sign of the particular gender as well as the colour of the date, bone samples are plotted as dentine samples as X. Dashed boxes mark the determined local ranges, the yellow boxes mark the calculated regional range (dark ±1σ, light ±2σ). Abbreviations: ULG Ulug Depe, DZH Dzharkutan, TB Tilla Bulak, SD Sangir-tepe, EK Erkurgan.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of all samples from Ulug Depe ranged between 0.707864 and 0.709960, $\delta^{18}\text{O}$ ratios were between -6.9‰ and -2.4‰ (VPDB). Bone $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranged between 0.707864 and 0.7097948 with a mean of 0.707893 (± 0.000026, n = 11), $\delta^{18}\text{O}$ bone ratios ranged between -5.3‰ and -2.4‰ and showed a mean of -3.7‰ (± 0.97, n = 11). Tooth enamel $^{87}\text{Sr}/^{86}\text{Sr}$ ranged between 0.707819 and 0.709960 and showed a mean of 0.708156 (± 0.000605, n = 11), while $\delta^{18}\text{O}$ ranged between -6.9‰ and -3.2‰ with a mean of -4.4‰ (± 1.08, n = 11). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of all samples from Dzharkutan ranged between 0.708052 and 0.709200, $\delta^{18}\text{O}$ ratios of all samples ranged from -
6.9‰ to -3.8‰ (V-PDB). The $^{87}$Sr/$^{86}$Sr ratio of human bones ranged between 0.708160 and 0.708474 and showed a mean of 0.708352 ($\pm$ 0.000081, n = 9), bones $\delta^{18}$O ranged between -6.5‰ and -4.8‰ and showed a mean of -5.6‰ ($\pm$ 0.52, n = 9). Tooth enamel $^{87}$Sr/$^{86}$Sr ratios ranged between 0.708052 and 0.709200 and showed a mean of 0.708267 ($\pm$ 0.000316, n = 11), while enamel $\delta^{18}$O ranged between -6.9‰ and -5.0‰ with a mean of -6.2‰ ($\pm$ 0.49, n = 11). The bone sample of burial 20 from Sapallitepa provided an $^{87}$Sr/$^{86}$Sr ratio of 0.708418 ($\pm$ 0.000006), while enamel $^{87}$Sr/$^{86}$Sr ratio of burial 8 was 0.709030 ($\pm$ 0.000026). The single bone sample from Bostan had an $^{87}$Sr/$^{86}$Sr ratio of 0.707893 ($\pm$ 0.000007), $\delta^{18}$O was -5.7‰. The five individuals from Gelot/Darnaichi and Saridzhar range in the $^{87}$Sr/$^{86}$Sr ratio between 0.708616 and 0.709374 ($\pm$ 0.000241‰), $\delta^{18}$O ratios ranged between -2.8‰ and -7.8‰ ($\pm$ 1.4‰). The two individuals from Bashman 1 showed in their $^{87}$Sr/$^{86}$Sr enamel ratios two very different results. The $^{87}$Sr/$^{86}$Sr enamel ratio of the adults was 0.710410 ($\pm$ 0.000040), the child provided an $^{87}$Sr/$^{86}$Sr enamel ratio of 0.709445 ($\pm$ 0.000007). The preparation of structural carbonate was not sufficient for all individuals; therefore, oxygen values are not available for one sample from Sapallitepa and all samples from Bashman 1.

Fig. 6: Human $\delta^{18}$O results out of apatite of bones and teeth with intra-individual variations: minus mark the bone samples, geometric signs mark tooth enamel samples (M3: full coloured, M n.d: striped). Coloured lines mark the averages, dashed boxes the averages $\pm 1\sigma$. 
<table>
<thead>
<tr>
<th>Site</th>
<th>Name of sample</th>
<th>#Ref</th>
<th>Period</th>
<th>Age in years / sex</th>
<th>Material</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (last digits)</th>
<th>$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)</th>
<th>Material</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (last digits)</th>
<th>$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulug Depe</td>
<td>ULG01-Sep53</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/m</td>
<td>M</td>
<td>0.708488 ± 0.08 -4.3 ± 0.05</td>
<td>phalanx</td>
<td>0.707918 ± 0.03 -5.3 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG01-Sep54</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/m</td>
<td>M</td>
<td>0.707856 ± 0.04 -5.0 ± 0.02</td>
<td>rib</td>
<td>0.707800 ± 0.06 -4.0 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG53-Sep55</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/m</td>
<td>M</td>
<td>0.708247 ± 0.03 -4.0 ± 0.04</td>
<td>rib</td>
<td>0.707948 ± 0.04 -4.9 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG56-Sep56</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/m</td>
<td>M</td>
<td>0.709960 ± 0.04 -3.4 ± 0.05</td>
<td>rib</td>
<td>0.707921 ± 0.07 -3.2 ± 0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG6-Sep57</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/m</td>
<td>M</td>
<td>0.708601 ± 0.05 -6.9 ± 0.02</td>
<td>bone fragm.</td>
<td>0.707864 ± 0.05 -4.8 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG6-Sep61</td>
<td>EBA</td>
<td>21-28</td>
<td>21-28/m</td>
<td>I</td>
<td>0.707826 ± 0.08 -3.4 ± 0.03</td>
<td>bone fragm.</td>
<td>0.707873 ± 0.04 -3.3 ± 0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG6-Sep62</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/f</td>
<td>M</td>
<td>0.707859 ± 0.06 -4.5 ± 0.02</td>
<td>phalanx</td>
<td>0.707886 ± 0.06 -2.5 ± 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG6-Sep66</td>
<td>EBA</td>
<td>&gt;40</td>
<td>40/f</td>
<td>M</td>
<td>0.707880 ± 0.04 -4.0 ± 0.04</td>
<td>bone fragm.</td>
<td>0.707894 ± 0.05 -2.8 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulug Depe</td>
<td>ULG6-Sep61</td>
<td>EBA</td>
<td>21-28</td>
<td>21-28/m</td>
<td>I</td>
<td>0.707826 ± 0.08 -3.4 ± 0.03</td>
<td>bone fragm.</td>
<td>0.707873 ± 0.04 -3.3 ± 0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Abbreviations: f: female; m: male; n.d.: not determined; M: Molar, C: Canin.
1σ: Standard deviation
2σ: Standard error of the mean
EBA: Early Bronze Age
ULG: Ulug Depe
DZH: Dzharkutan
Bashman: Bashman 1
Saridzhar: Saridzhar 1
Gelot: Gelot 1
Darnaichi: Darnaichi 1
Ulug Depe: Ulug Depe 1
Darnaichi: Darnaichi 2

Table 4: Material and results of $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ of human and animals from southern Central Asia.
5. Discussion

The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ results from Ulug Depe suggest that all the analysed individuals lived their last years in Ulug Depe or the surrounding area (figs. 5, 7), due to the fact that all bone samples fell within very narrow ranges. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel indicate that the EBA was a period of high immigration. None of the three analysed adult enamel $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are in the local range of Ulug Depe. Burial 56 did not even lie within the calculated strontium signal of southern Central Asia, indicating a more distant origin (figs. 5, 7). Interestingly, especially the five individuals from the GKC (MBA) showed a distinct homogeneity in the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ ratios. The $\delta^{18}\text{O}$ ratios of all Ulug humans ranged between $-6.9\%$ and $-2.4\%$ with a range of $4.5\%$ (enamel: $3.6\%$; bones: $2.5\%$) and average of $-4.0\%$ ($\pm 1.0\%$ $n = 22$) (fig. 6), suggesting a generally hot and arid climate in this region during the Bronze Age (Longinelli 1984; White et al. 2004). Especially, the small inter-individual variations of the bone samples indicate that people ingested water from particular water sources and not from multiple sources spread across the landscape (single site between $0.5$ and $3\%$ after White et al. 2004; Lightfoot, O’Connell 2016). The higher tooth enamel range evidences that the water sources of people’s origin/childhood varied a bit more (fig. 6).
Fig. 7: Scatterplot correlation of $\delta^{18}$O vs. $^{87}$Sr/$^{86}$Sr ratios of all analysed individuals. Abbr.: E stands for enamel, B for bones, ULG for Ulug Depe, DZH for Dzharkutan, G./D. for Gelot/Darnaichi. Dashed boxes mark the $\delta^{18}$O mean value out of human samples ±1σ in combination with the calculated local $^{87}$Sr/$^{86}$Sr signals (±2σ). Big yellow boxes mark the inter-regional $^{87}$Sr/$^{86}$Sr signal (dark ±1σ, light ±2σ).

When comparing the distribution of $^{87}$Sr/$^{86}$Sr and $\delta^{18}$O of bones and teeth from Dzharkutan individuals, two clusters are clearly visible: the bones form a cluster on the upper limit of the local $^{87}$Sr/$^{86}$Sr and on the lower limit of the local $\delta^{18}$O range, and the teeth on the opposite limits of the local ranges (figs. 5, 6). Both clusters are only partly in the determined local ranges, but as a group they fit well together. None of the Dzharkutan individuals (except DZH 1019) lie outside these clusters or in other local ranges (figs. 5, 7), demonstrating a homogeneous group of people. The $\delta^{18}$O ratios ranged between -6.9‰ and -4.8‰ with a range of 2.1‰ and an average of -5.9‰ (± 0.7‰, n = 20). The results are lower than in Ulug Depe (fig. 6), suggesting a more moderate climate. The inter-individual variations are even smaller than in Ulug Depe, indicating that the people buried in Dzharkutan also ingested water from particular water sources and not from multiple sources across the valley. The surrounding landscape of Dzharkutan was characterized by the flood plains of the Sherabad, Surkhan Darya, and Amu Darya rivers and their tributary streams. Hence, the signals of Dzharkutan people could be expected to display more variety. The small intervals between the individuals, however, suggest little mobility. Interestingly, the clusters of teeth and bones indicate a complex pattern of mobility or
subsistence of Dzharkutan’s people with movement between the place of birth/childhood and
residence during later lifetime in a limited area. The individuals date to the transition from MBA to the
LBA and to the LBA, and the results show a certain continuity over this time period. But the real cause
for this unusual pattern of movements of the people from Dzharkutan remains unexplained, until more
results can be evaluated.

Special patterns in terms of biological criteria such as age, sex and the archaeologically
indicated social position of the individuals, are only weakly reflected in the small sample size. The
“foreigners” from Ulug Depe were two men and one not determined adult from the EBA (ULG 53, 55,
56), and one woman from the EBA/MBA (ULG 92). It is not clear if the degree of mobility is connected
to the social position or gender of the people. The two men, who were buried in complex burial
constructions after the prevailing burial traditions of the EBA with rich grave inventories, were both
non-locals. Conspicuous, but comparable female burials are missing. In Dzharkutan, the selection of
samples excluded specific interpretations in terms of gender or the archaeologically indicated social
position, since only one man was part of the test series. This one man (DZH 999) did not differ in the
$^{87}$Sr/$^{86}$Sr and δ^{18}O results. Furthermore, the only very rich grave of a young woman (DZH 1051) did not
show any differences to the group. Hence, whether there is a pattern in the mobility caused by gender
or social position cannot be recognised in the present evidence.

Concerning the question of migration and the movements of single individuals between
populations, the correlation of strontium and oxygen seems to point to the fact that the origins of
some of our non-locals are quite clear and inter-regional connections really existed. The enamel
$^{87}$Sr/$^{86}$Sr and δ^{18}O results of Burial no. 1019 from Dzharkutan and Burial no. 8 from Sapallitepa fit
perfectly within the cluster of Gelot/Darnaichi and Saridzhar people (fig. 7), demonstrating that with
the exchange of material (cf. Luneau 2013) also individuals moved. The $^{87}$Sr/$^{86}$Sr and δ^{18}O ratios of
Gelot/Darnaichi and Saridzhar individuals highlight a homogeneous group of people (fig. 7). It is
conspicuous, however, that all analysed bone samples fell in the same range but only two of four tooth
enamel samples. The results suggest that immigration also played an important role during the Bronze
Age in southern Tajikistan (cf. Kroll et al. forthcoming). Moreover, the adult individual from Bashman
1 is noticeable, as it fell together with ULG 56 outside the calculated regional signal, suggesting an
external origin of this individual too (fig. 5). Bashman 1 is located south of the Syr Darya which marks
the northern border of the GKC and an area inhabited by both—the GKC groups and Andronovo groups
– in the first half of the 2nd mill. BCE. Isotopic studies from the northern communities, where nomadic
pastoralism is argued to be a reason for the spread of the Andronovo culture, did not provide evidence
for long distance migration (Ventresca Miller et al. 2017). Although providing a contrasting image, our
results are provisional but, nevertheless the high variation in the results suggests active mobility
among the inhabitants of southern Central Asia during the Bronze Ages.
6. Conclusion

The present study has provided a first biogeochemical dataset of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes from southern Central Asia and has enabled the initial evaluation of the isotopic distribution on a micro-regional scale. The analyses of $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ isotopes on human material indicate that the populations in Ulug Depe and Dzharkutan were mainly sedentary with an intensive use of the surrounding landscape. The results revealed Ulug Depe during the early periods (EBA, EBA–MBA) with a high rate of immigration, four of six analysed individuals from these time periods did not fall within the local range. Remarkably, the individuals from the GKC phase showed little mobility and almost no immigration. Although this represents a time period of great changes, powerful empires and widespread networks, it seems the inhabitants of Ulug Depe and Dzharkutan remained local. The mobility pattern of Dzharkutan people was different; analyses displayed homogeneous clusters on the upper and lower limit of the local ranges. The results suggest complex patterns of mobility or subsistence, where movements between a person’s place of birth/childhood and residence were a regular feature, observable throughout the centuries. The isotopic results of the other sites in the Surkhan Darya Valley and southern Tajikistan indicate active mobility and corroborate the known exchange of artifacts and technologies. However, the limited number of samples provides only a glimpse of the complex dynamics during Bronze Age in southern Central Asia and further studies are necessary to confirm or broaden the obtained insights.

Acknowledgements We address our first acknowledgments to the Mission archéologique Franco-Ouzbèke Protohistoire (MAFOuz-P), the Mission archéologique franco-turkmène (MAFTur), the French Ministry of Foreign Affairs (MEAE), the French embassies in Turkmenistan and Uzbekistan, the French Archaeological Delegation in Afghanistan (DAFA), the Turkmenistan Directorate for the Protection, Study and Conservation of Historical and Cultural Heritage, the Directorate of the Archaeological Park of Abiwerd (Turkmenistan), the German Archaeological Institute’s missions in Tajikistan and Uzbekistan (with funding provided by the DFG, German Research Foundation, project number 392943887), and the Munich University mission to Tilla Bulak (with funding provided by the Gerda Henkel Foundation). Their support has made the excavations possible, upon which the present work is based. Additionally, we would like to thank the Mission Archéologique Franco–Ouzbèke de Sogdiane (MAFOUZ-Sogdiane) and the Archaeological Institute of Samarkand for authorizing the use of comparative samples. Moreover, we are grateful to the Laboratory AASPE UMR 7209 of the Museum National d’Histoire Naturelle in Paris and the Laboratory of Geoscience in Montpellier for hosting our project. Finally, special thanks should be addressed to the reviewers for their inspiring and constructive comments and to Prof. Michael Roaf for his personal review and the English editing.
References


Askarov AA (1973) Sapallitepa. FAN, Tashkent.


Behrensmeyer AK (1978) Taphonomic and ecologic information from bone weathering. Paleobiology 4, pp 150-162.

Bendezu-Sarmiento J, Lhuillier J (2019) Habitat and Occupancy during the Bronze Age in Central Asia. Recent work at the sites of Ulug-depe (Turkmenistan) and Dzharkutan (Uzbekistan), Urban Cultures of Central Asia from the Bronze Age to the Karakhanids, Harrassowitz Verlag Wiesbaden & Harrassowitz.


https://doi.org/10.1007/s001260100156


White CD, Spence MW, Stuart-Williams HLQ, Schwarcz HP (1998) Oxygen isotopes and the
identification of geographical origins: The Valley of Oaxaca versus the Valley of Teotihuacan.
JAS 25(7), pp 643-655.

https://doi.org/10.1007/s12182-011-0155-8