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

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

✉ Marjan Mashkour

marjan.mashkour@mnhn.fr

Directrice adjointe de l'UMR 7209 (AASPE)

Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environnements

CNRS (Centre national de Recherche Scientifique) et MNHN (Muséum national d'Histoire naturelle)

Case postale 56

55 rue Buffon

75005 Paris - 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,

51 with frequent movements during individual lifetime within a limited area. The other sites in the  
52 Surkhan Darya Valley and southern Tajikistan indicate active mobility in which individuals migrated  
53 within a wide area of southern Central Asia.

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

59

60

61 **Authors contribution:**

62 Sonja Kroll: data curation, formal analysis, investigation, methodology, project administration,  
63 conceptualization, visualization, writing – original draft, review and editing

64 Julio Bendezu-Sarmiento: excavator, provision of samples, project administration, funding  
65 acquisition, conceptualization, writing – review and editing

66 Johanna Lhuillier: excavator, provision of samples, conceptualization, writing – review and editing

67 Élise Luneau: excavator, provision of samples, conceptualization, writing – review and editing

68 Kai Kaniuth: excavator, provision of samples, conceptualization, writing – review and editing

69 Mike Teufer: excavator, provision of samples

70 Samariddin Mustafakulov: excavator, provision of samples

71 Mutalib Khasanov: excavator, provision of samples

72 Natalia Vinogradova: excavator, provision of samples

73 Nona Avanesova: excavator, provision of samples

74 Denis Fiorillo: technical lab support

75 Arash Sharifi: data evaluation and map generation, writing – review and editing

76 Margareta Tengberg: supervision botany, provision of samples, conceptualization, writing – review  
77 and editing

78 Céline Bon: supervision paleogenetic, conceptualization, writing – review and editing

79 Delphine Bosch: supervision geochemistry, conceptualization, writing – review and editing

80 Marjan Mashkour: overall supervision, provision of samples, project administration, funding  
81 acquisition, conceptualization, writing – review and editing

82

83

84

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## 91 **1. Introduction**

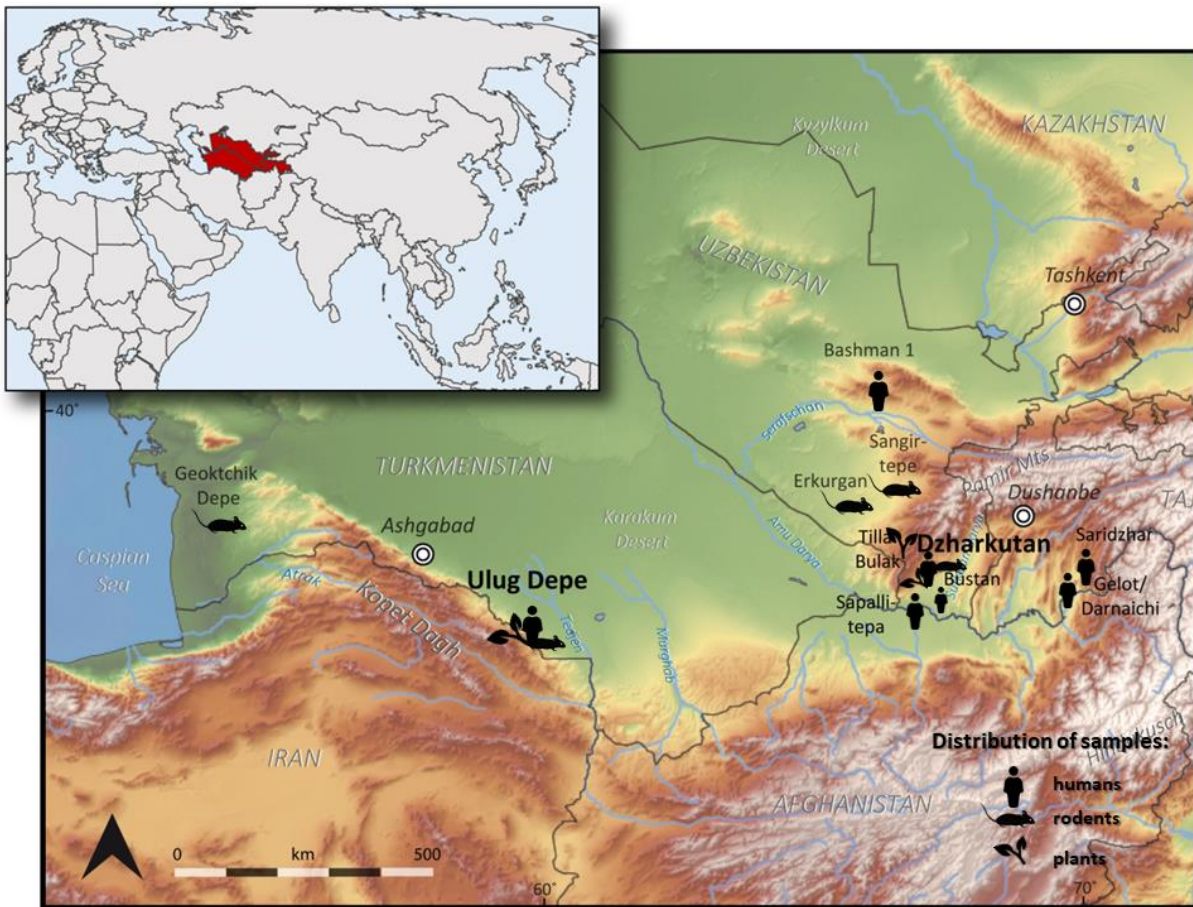
92

93 During the Middle and Late Bronze Age, the emergence of complex societies is observed in southern  
94 Central Asia. With the rise of the Greater Khorasan Civilization (hereafter GKC<sup>1</sup>, ca. 2400–1500 BCE,  
95 e.g., [Lyonnet, Dubova 2021](#)) major transformations led to deep cultural and economic shifts.  
96 Archaeological remains evidence the establishment of intensive trade networks and long-distance  
97 interactions (cf. e.g., [Hiebert 1994](#); [Possehl 2007](#); [Frachetti, Rouse 2012](#)). The location between harsh  
98 deserts and high mountain ranges was a natural passage since Neolithic periods ([Thomalsky et al.](#)  
99 [2013](#)), which later developed into the Silk Road (historical *Great Khorasan Road*, cf. e.g., [De la Vaissière](#)  
100 [2002](#); [Wilkinson 2014](#)). Due to the prevailing climatic conditions, structural migrations such as  
101 pastoralism or nomadism to access natural and economic resources, were always essential subsistence  
102 strategies of the communities who settled in this region (e.g., [Mashkour 2013](#); [Spengler et al. 2014](#)).  
103 Hence, the impact of migration and of changes in land use and territorial management remains a  
104 matter of ongoing discussions among scientists (cf. e.g., [Biscione 1976](#); [Vinogradova, Kuz'mina 1996](#);  
105 [Kohl 2007](#); [Cattani 2008](#); [Salvatori 2008](#); [Frachetti 2011, 2012](#); [Lamberg-Karlovsky 2013](#); [Luneau 2014,](#)  
106 [2019](#); [Rouse, Cerasetti 2018](#)). In this context analyses of isotopes such as strontium (<sup>87</sup>Sr/<sup>86</sup>Sr) and  
107 oxygen ( $\delta^{18}\text{O}$ ) are today a common and powerful tool for a better understanding of interactions and  
108 exchange of past populations. This study takes a first step in exploring human mobility in southern  
109 Central Asia presenting isotopic analyses of a main corpus of samples from Ulug Depe in Turkmenistan  
110 and Dzharkutan in Uzbekistan, both sites belonging to the first urban centers in the region during the  
111 3<sup>rd</sup> and 2<sup>nd</sup> mill. BCE. The results will be compared with single samples from other Bronze Age sites,  
112 such as Sapallitepa, Tilla Bulak and Bustan in southern Uzbekistan, Bashman 1 in central Uzbekistan,  
113 and Saridzhar and the nearby graveyards Gelot and Darnaichi in southern Tajikistan ([fig. 1](#)). The  
114 following discussion is based on the first analysis of human material from southern Central Asia. We  
115 are aware that the data at our disposal cannot yet produce statistically reliable results; however, since  
116 no isotopic studies on residential mobility have previously been conducted on populations in southern  
117 Central Asia, this study will provide a first biogeochemical data set of <sup>87</sup>Sr/<sup>86</sup>Sr isotopes and an initial  
118 idea of the dynamics during the Bronze Age.

119

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<sup>1</sup> [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](#).



121

122 **Fig. 1** Topographic map of the studied region with the investigated sites including symbols of the analysed  
 123 material after <https://maps-for-free.com/>  
 124

125

## 126 2. Context

127

### 128 2.1. Archaeological Background

129

130 Ulug Depe and Dzharkutan delivered the major part of the human material in this study. Ulug Depe is  
 131 located in southern Turkmenistan in the northern submontane plains of the Kopet Dagh Mountains,  
 132 175 km south-east of the capital Ashgabat at 288 m a.s.l. (cf. e.g., [Lecomte 2007a, 2011, 2013](#);  
 133 [Bendezu-Sarmiento 2013](#); [Bendezu-Sarmiento, Lhuillier 2016, 2019](#)). In ancient times, Ulug Depe was  
 134 situated adjacent to the Kelet River, which traverses the Kopet Dagh in the direction of Nishapur and  
 135 presents a natural pass through the mountains ([Lecomte 2013](#)). Already in the Chalcolithic period, the  
 136 first social changes towards a more centralized system are evidenced. The construction of a  
 137 fortification wall, as well as the separation of craft areas and the beginning of irrigated agriculture,  
 138 reflects the changing nature of property and territorial management, as well as a certain social

139 differentiation ([Lecomte 2011](#)). With the appearance of the GKC, Ulug Depe had a period of particular  
140 prosperity. Impressive public monuments, such as the remains of high terraces were discovered  
141 ([Lecomte 2011](#); [Bendezu-Sarmiento, Lhuillier 2019](#)). Numerous finds of gold, lapis lazuli, carnelian and  
142 alabaster reflect widespread connections to the Indus Valley and the Iranian Plateau ([Bendezu-](#)  
143 [Sarmiento, Lhuillier 2016: 527 figs. 4–6](#)).

144 The situation in Dzharkutan is different: at the end of the 3<sup>rd</sup> mill. BCE the Sapalli culture, a  
145 local variant of the GKC, arose in northern Bactria and several new settlements such as Dzharkutan,  
146 Sapallitepa, Bustan, Molali, and Tilla Bulak developed in the Surkhan Darya Valley ([fig. 1](#)) ([Askarov,](#)  
147 [Abdullaev 1983](#); [Shirinov 2002](#); [Huff et al. 2001](#), [Huff, Teufer 2010](#); [Bendezu-Sarmiento, Mustafakulov](#)  
148 [2013](#); [Kaniuth 2021](#)). The establishment of these new settlements has been associated with an  
149 increased mobility of the populations (e.g., [Frachetti 2011, 2012](#); [Bendezu-Sarmiento, Mustafakulov](#)  
150 [2013](#)). The Surkhan Darya Valley is located in southern Uzbekistan, ca. 50 km north of the district  
151 capital Termez, at an altitude around 350 m a.s.l. Dzharkutan with a size of about 40–50 ha is the  
152 biggest site in the Shurkan Darya Valley, including several mounds with traces of occupation, a citadel  
153 with a palace, a temple and large necropolises ([Shirinov 2002](#); [Huff et al. 2010](#); [Bendezu-Sarmiento,](#)  
154 [Mustafakulov 2013](#)). Artifacts, mainly pottery influenced by the Andronovo Culture from the steppes  
155 were discovered in Dzharkutan, reflecting dynamic interactions with the related farmer-breeder  
156 culture from the Pamir foothills of southwestern Tajikistan, the so called Vakhsh culture ([Luneau et al.](#)  
157 [2013, 2017](#)).

158 There is considerable uncertainty regarding the regional cohesion and territorial hegemony of  
159 the GKC. In particular throughout south/western Tajikistan, researchers have documented numerous  
160 instances of mixed cultural remains that include next to GKC-type materials also materials described  
161 as "local" (Vakhsh) as well as related to the "steppe" (Andronovo, Federovo) (e.g., [Rouse 2020](#), [Teufer](#)  
162 [2021](#), [Vinogradova 2021](#)). Our sampling thus includes several other sites in addition to the GKC-related  
163 centres of Ulug Depe and Dzharkutan. The nearby site of Sapallitepa and the cemetery of Bustan help  
164 round out the picture of GKC-related sites in southern Uzbekistan, while the cemeteries of  
165 Gelot/Darnachi and the Saridzhar settlement in Tajikistan represent a complex intersection with  
166 communities in the upper Yakh-Su River Valley ([Teufer 2018, et al. 2014](#)). Likewise, the samples from  
167 Bashman 1 in central Uzbekistan will help establish baselines of communication between the GKC and  
168 Andronovo related communities (e.g., [Luneau 2017](#)).

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## 171 **2.2. Chronological and anthropological context**

172

173 The human material analysed in this study was collected by different archaeological expeditions during  
174 the last decades and often the local possibilities as well as availability and preservation of the material  
175 limited the selection. Hence, it was not possible to present a representative sample of all sexes and  
176 age groups. Nevertheless, the remains of 32 human individuals from eight sites in southern Central  
177 Asia were used for the present study: eleven individuals from Ulug Depe, eleven from Dzharkutan, two  
178 from Sapallitepa, one from Bustan, two from Gelot/Darnaichi, three from Saridzhar and two from  
179 Bashman 1 (cf. [tab. 1 and 4](#)). In Ulug Depe four burials (2 men, 1 undetermined adult, 1 child) date to  
180 the Early Bronze Age (EBA, Namazga IV (NMG IV), ca. 2800–2500 BCE), two burials (1 woman, 1 child)  
181 date to the transition from the Early to the Middle Bronze Age (EBA–MBA, NMG IV–V) and five burials  
182 (1 man, 1 woman, 2 undetermined adults, 1 child) to the later phase of the Middle Bronze Age (MBA  
183 (NMG V), ca. 2200–1900 BCE, cf. also [Bendezu-Sarmiento 2013](#)). The Ulug group consisted of three  
184 men, two women, three undetermined adults and three children.

185 The eleven individuals from Dzharkutan date between 2100 and 1700 BCE, corresponding to  
186 the transition from the MBA to the LBA and the LBA (NMG V–VI, NMG VI; cf. also [Bendezu-Sarmiento,](#)  
187 [Mustafakulov 2013](#)). A young woman and one undetermined adult dated back to the end of the  
188 3rd/beginning of the 2nd mill. BC (MBA/LBA), nine individuals (1 man, 4 women, 3 undetermined  
189 adults, 1 child) dated back to the LBA, ca. 1900 and 1700 BC. In a total the group consists of five women,  
190 one man, four undetermined adults and one child.

191 The two individuals from nearby Sapallitepa coincides with the earliest phase of the LBA  
192 ([Askarov 1973](#)). Sapallitepa is located about 40 km southwest of Dzharkutan, close to the northern  
193 bank of the Amu Darya River. The hills of Bustan are located 5 km south of Dzharkutan and dates to  
194 the final phase of the Bronze Age ([Avanesova 2016](#)). The graveyards of Gelot/Darnaichi and the  
195 neighboured settlement Saridzhar are located on the banks of the Yakh-Su River in southern Tajikistan  
196 ([Teufer, Vinogradova 2010; Teufer 2014; Lombardo et al. 2014, Vinogradova, Kutimov 2018](#)). The two  
197 burials from Gelot/Darnaichi belong to the so called Pjandzh culture and date between 2450 and 1900  
198 cal. BCE ([Teufer 2018, et al. 2014](#)), while the three individuals from Saridzhar date between 1700 and  
199 1500 BCE ([Teufer 2014](#)). The two individuals from Bashman 1 are culturally related to the Andronovo  
200 tribes and date to ca. 1600–1400 BCE. The site is located in central Uzbekistan in the northern range  
201 of the Nuratau Mountains ([Luneau personal communication](#)).<sup>2</sup>

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

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<sup>2</sup> 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](#).

206 inter-individual comparisons difficult as the teeth evolve in different stages of life (cf. [Knipper 2004:](#)  
 207 [602 fig. 6;](#) [Hillson 2005](#)). In this study mainly molars (M3) were analysed, which represent a later stage  
 208 of child- and teenager years. The human bone material consisted mainly of ribs, vertebrae and  
 209 phalanges. Their remodelling rate depends on the particular bone and can vary between 5 and 30 years  
 210 (cf. [Tütken 2010: 35 fig. 2](#)). Long-bones as femurs, tibias and cranium have slow remodelling rates of  
 211 20 to 30 years, whereas ribs and pelvic bones have faster turnover rates of 5 to 10 years (cf. e.g.,  
 212 [Knipper 2004: 610–615;](#) [Tütken 2010: 35](#)). The detailed description of the methods used for the  
 213 anthropological determination of gender and age can be found in [Bendezu-Sarmiento 2013](#).

214  
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**Table 1:** Simplified comparative chronology of the sites according to the analysed human remains

<i>Period</i>	<i>approximate date cal. BCE</i>	<i>Phase</i>	<i>Kopet Dagh Mountains</i>	<i>Surkhan Darya Valley</i>	<i>Yakh-Su Valley</i>	<i>Nuratau Range</i>
<b>Late Bronze Age</b>	2000-1600	NMG VI	Ulug Depe	Bustan Sapallitepa Tilla Bulak Dzharkutan	Saridzhar Gelot/ Darnaichi	Bashman 1
			Ulug Depe	Dzharkutan	Gelot/ Darnaichi	
<b>Middle Bronze Age</b>	2400-2000	NMG V	Ulug Depe			
<b>Early Bronze Age</b>	2800-2400	NMG IV	Ulug Depe			

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218

### 219 **2.3. Ecological and geo-chemical realities**

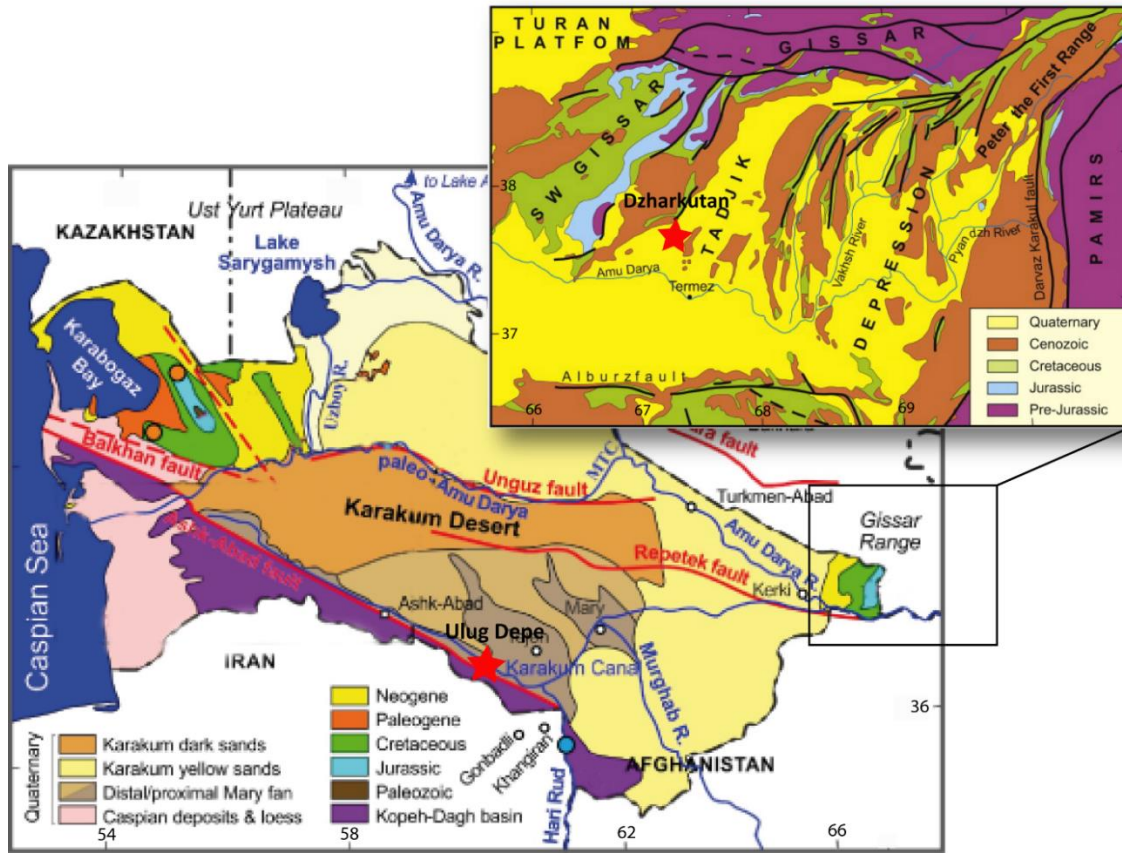
220

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

226 All the sites analysed here are located along the northern foothills of Kopet Dagh Mountains,  
 227 the eastern foothills of Kugitang Mountains and the southern foothills of the Khodzhasartes Mountains  
 228 ([fig. 2](#)). The Kopet Dagh submontane region is formed from alluvial fan deposits and younger  
 229 Quaternary loess deposits ([Fet, Atamuradov 1994;](#) [Atamuradov et al. 1999](#)). The Surkhan Darya Valley  
 230 is covered by layers of clayish and sandy loess, underneath a thick layer of continental deposits mainly  
 231 consists of sedimentary rocks (sandstone and aleurolite) with sporadic volcanic outcrops ([Mukin 1997;](#)  
 232 [Kaniuth 2021](#)). Also, the Yakh-Su River Valley is covered by deep loess deposits, which are up to 200 m  
 233 thick ([Teufer 2014](#)). The geological formation of Turkmenian cretaceous rocks and carbonates in the



234 Amu Darya Basin provided  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between 0.7078 and 0.7084 (Meisel et al. 1995; Zheng et al.  
 235 2011), while Caspian Sea deposits resulted in  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges around 0.7081 (Clauer et al. 2000).



236  
 237 **Fig. 2:** Geological maps of southern Central Asia after Ghassemi et al. 2019: 127 fig. 2 (Turkmenistan) and Sanchez  
 238 de Corral, Thum 2012: 92 fig. 3 (Uzbekistan, Tajikistan)  
 239

240 The climate in Ulug Depe is similar to that of the Karakum Desert, a forbidding environment,  
 241 tempered through the influence of the Kopet Dagh Mountains (Tengberg 2013). The average annual  
 242 temperature is 16°C, with a maximum of 48°C and a minimum of -26°C; the annual precipitation is  
 243 around 220 mm, permitting the cultivation of cereals, grapes, vegetables and fruits without irrigation.  
 244 The Central Karakum lies directly northward of the Kopet Dagh submontane plains. Characteristic  
 245 vegetation types are open steppes dominated by shrub species in the piedmont region and open scrub  
 246 woodlands followed by juniper forests in the Kopet Dagh Mountains (Fet, Atamuradov 1994, 1999;  
 247 Moore et al. 1994; Miller 1999, 2003; Tengberg 2013). The climate in Dzharkutan is characterized by  
 248 seasonal rainfalls in winter and early spring resulting in an early and short growing season. From May  
 249 to October the climate is dry and hot. Average annual precipitation is 200–240 mm; the mean annual  
 250 temperature is +16.8°C. Wide areas are covered by a xeric savanna ecosystem, dominated by wild  
 251 pistachio trees (Mukin 1997). The hot and arid climate results in rather high  $\delta^{18}\text{O}$  averages of modern  
 252 precipitation around -5.1‰ (VSMOW) in Ulug Depe and -4.2‰ (VSMOW) in Dzharkutan (after the

253 OIPC, [www.waterisotopes.org](http://www.waterisotopes.org)). Analyses of Callovian carbonates from the Caspian Sea resulted in  
254  $\delta^{18}\text{O}$  ranges between 0‰ and -5.5‰ (VPDB, after [Zheng et al. 2011](#)).

255

256

### 257 **3. Material and Methods**

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#### 259 **3.1. Isotopic applications and their problems**

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261 Isotope analysis is a reliable method for tracking human and animal origins and mobility at a lifetime  
262 scale (cf. e.g., [Price et al. 2002, 2004](#); [Tütken 2003](#); [Knipper 2004](#); [Ventresca Miller, Makarewicz 2018](#)).

263 The ratio of strontium  $^{87}\text{Sr}/^{86}\text{Sr}$  depends on water sources and the geological formation with which the  
264 water has interacted. Strontium is dissolved out of rocks by the groundwater, permeating through  
265 rivers and other water sources into soils and plants. It enters the body through drinking and eating and  
266 is incorporated without substantial fractionation into the hydroxyapatite of hard tissues like bones and  
267 teeth, often referred to as biogenic strontium (e.g., [Tütken 2003](#); [Bentley 2006](#)). The water and food  
268 ingested by an organism is thus directly connected to the nature of the geological substrates ([Faure  
269 1986](#); [Faure, Mensing 2005](#)). Moreover, tooth enamel is synthesized during childhood and remains  
270 static. Therefore, the isotopic ratio of tooth enamel reflects the environment in which the organism  
271 evolved during the first years of its life. Bones undergo continuous modification during the whole life  
272 and isotopes reflect the situation of the last years before death. Differences between bones and teeth,  
273 therefore, provide evidence for changes and the mobility of humans and animals during their lifetime  
274 ([Price et al. 2002](#); [Bentley 2006](#); [Burton, Price 2013](#)).

275 The ratio of oxygen  $^{18}\text{O}/^{16}\text{O}$  ( $\delta^{18}\text{O}$ ) in mammals reflects the sources of incorporated water, such  
276 as drinking water and the water in edible plants (e.g., [Balasse et al. 2002, 2009](#)). The values reflect the  
277 composition of local meteoric water, derived from precipitation as rain, snow, or atmospheric  
278 moisture. The oxygen composition varies with different factors such as humidity, temperature, rain  
279 shadow effects, altitude, latitude and distance from the sea ([Longinelli 1984](#); [White et al. 1998, 2004](#)).  
280 It can be evidence of local water sources and climate conditions in which an individual grew up and is,  
281 therefore, another indicator for the origins and movements of humans and animals ([Budd et al. 2004](#);  
282 [Millard et al. 2004](#); [White et al. 2004](#); [Bentley, Knipper 2005](#)). The oxygen signal of an individual is not  
283 only impacted by the surrounding habitat but also by several physiological factors, such as individual  
284 metabolism and water intake, body temperature, or heat loss mechanisms ([Makarewicz, Pederzani  
285 2017](#), [Ventresca Miller 2018](#)). Moreover, culturally related manners as the intake of brewed,  
286 fermented, or cooked beverages can affect the  $\delta^{18}\text{O}$  ratios ([Brettell et al. 2012](#); [Royer et al. 2017](#)), as  
287 well as weaning can have an impact on the  $\delta^{18}\text{O}$  ratio in body tissues ([White et al. 2004](#)). Additionally,

288 seasonal variations have to be taken into account. The mineralization of body tissues generally covers  
289 a period of several years and might be impacted by seasonal changes through time. Central Asia is  
290 dominated by a dry, hot and arid vegetation, groundwater sources like springs, wells, rivers, or lakes  
291 may have been seasonal and differ over time. Furthermore, many regions in the world as e.g., tropical  
292 zones have similar  $\delta^{18}\text{O}$  values, ranging from approximately -2.0 to -8.0 (VSMOW), so that a distinction  
293 of these regions is difficult (Bowen et al. 2005, Sjögren, Price 2012). Therefore,  $\delta^{18}\text{O}$  results will be  
294 taken only for the interpretation of inter-individual variations.

295 Diagenesis can have a critical impact on the isotopic composition of human remains. Bones,  
296 but especially tooth dentine are very sensible to diagenesis – the ability of isotopes to penetrate from  
297 the surrounding milieu into the material. Decay processes as well as bone density, temperature and  
298 humidity/aridity can strongly modify the original isotopic composition (e.g., Behrensmeyer 1978; Budd  
299 et al. 2000; Denys 2002; Hedges 2002; Hoppe et al. 2003; Tütken 2003, 2010; Maurer et al. 2012).  
300 Depending on the conservation of the material, diagenetic effects, especially of recent, well-preserved  
301 material, can be more or less completely eliminated by careful mechanical ablation of the topmost  
302 layers of the bone compacta followed by a specific leaching treatment with NaOCl and NaOH or acetic  
303 acid solutions (Hedges 2002: 322; Hoppe et al. 2003: 25–26; Tütken 2003: 217). Carbonized plant  
304 remains also strongly undergo diagenetic changes. Although exogenous strontium does not replace all  
305 biogenic strontium and is removable through leaching with strong acid (Fiorentino et al. 2014; Styring  
306 et al. 2019), potential diagenetic alterations always have to be taken into account when interpreting  
307 isotopic data. The strong homogeneity of  $^{87}\text{Sr}/^{86}\text{Sr}$  results of Ulug Depe bones attracts attention, as all  
308 of them fall within a very narrow strontium range. It may be feared that these results are caused by  
309 contamination through diagenetic processes. Although the assessment of the diagenetic effect on the  
310  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios through measuring the concentration of the elements was not performed on the  
311 samples, Ulug Depe bones were in very good conditions and leaching with strong acid should have  
312 removed the diagenetic impact for isotopic measurements. Moreover, both chemical extractions and  
313 measurements were conducted in multiple sessions over a period of two years with each session  
314 incorporating samples of different material, species and origins. Therefore, systematic mistakes within  
315 the analytical process can be excluded and the results will be considered as reliable.

316

317

### 318 **3.2. Reference material**

319

320 For the determination of the bioavailable local  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges in this study material of nine rodents  
321 (*Mus spec.*), two carnivores (*Canis familiaris*, *Panthera spec.*), eleven samples of barley (*Hordeum*  
322 *vulgare*), three samples of wheat (*Triticum aestivum*), two tamarisks (*Tamaris spec.*), one juniper

323 (*Juniperus spec.*) and one willow (*Salix spec.*) were analysed (cf. [tab. 2](#) and [Mashkour 2013; Tengberg](#)  
324 [2013, et al. 2020](#)). Rodents, such as mice, have a natural lifespan of around 2–3 years and form  
325 territorial family clans. Hence, their bone compositions can be considered as representative of the  
326 surrounding environment and deliver reliable information about the bioavailable strontium (e.g.,  
327 [Knipper 2004; Bentley et al. 2004](#)). When only human material was available as it was the case in  
328 [Bashman 1](#), tooth dentine was analysed. Primary dentine is particularly susceptible to diagenetic  
329 alterations and represents the bioavailable strontium of the environment rather than the biogenic  
330 signal of the individual (cf. e.g., [Gerling 2015](#)). Plants were used in form of carbonized grains and  
331 charred wood from Bronze and Iron Age layers ([Tengberg 2013, et al. 2020](#)). In general, all reference  
332 samples were collected during the excavations, and we avoided using modern material because of  
333 possible complications with the influence of fertilizers or imported animal feed ([Böhlke, Horan 2000;](#)  
334 [Bentley, Knipper 2005; Maurer et al. 2012](#)).

335

336

### 337 **3.3. Applied laboratory methods**

338

339 Analyses were conducted on bone compacta, tooth enamel and primary tooth dentine. All steps were  
340 performed in a sterile atmosphere, tools were cleaned with ethanol and in the ultrasonic bath. Bones  
341 were cleaned of dirt with a toothbrush and a diamond drill. The sampling was proceeded with a micro  
342 saw followed by careful crushing with an agate mortar and pestle. Teeth were cleaned with a  
343 toothbrush and a diamond drill, enamel and dentine sampling was undertaken with a diamond drill.  
344 Charred plants were mechanically cleaned of sand and dust with a needle and tweezers under the  
345 microscope. After crushing and the treatment with 6 M HCl for 24 hours after [Styring et al. \(2019\)](#), the  
346 samples were transformed into ash in a ceramic beaker at 750°C for 12 hours. The residues were solved  
347 in 1 ml 13 M HNO<sub>3</sub> in the Ultrasonic bath followed by the evaporation of the acid solution on a hot  
348 plate (100°C) overnight.

349 The extraction of strontium was performed with 10–15 mg tooth enamel and 20–25 mg bone  
350 compacta/tooth dentine. The leaching procedure to remove the diagenetic strontium was undertaken  
351 with 7% acetic acid in an ultrasonic bath (45°C) for 30 minutes followed by several rinsing steps with  
352 ultrapure H<sub>2</sub>O Milli-Q®, changing the solution every 10 minutes until it became clear (only enamel and  
353 bones were leached, dentine was only rinsed in water). The samples were dried overnight. The  
354 cleaned, leached and oven dried samples were transferred to a clean Teflon beaker and dissolved in 1  
355 ml 13 M HNO<sub>3</sub> in the Ultrasonic bath at 65°C. Acid was evaporated on a hot plate at 100°C and samples  
356 were dissolved in 2 ml 2 M HNO<sub>3</sub>. Strontium was extracted through a Teflon column using “Sr-Eichrom”  
357 resin ([Pin et al. 1994](#)) after the following protocol: columns were washed 6 times alternately with 5 ml

358 6 M HCl and 0.05 M HNO<sub>3</sub> followed by the conditioning step with 3 ml 2 M HNO<sub>3</sub>. After uploading the  
359 samples, the elimination of other elements was performed with 2 ml 2 M HNO<sub>3</sub>, 3 ml 7 M HNO<sub>3</sub> and  
360 0.5 ml 3 M HNO<sub>3</sub>. The extraction of strontium was accomplished with 4 ml 0.05 M HNO<sub>3</sub>. The lab work  
361 of the strontium extraction was carried out in the clean isotope laboratory of the Geoscience  
362 Montpellier (CNRS – University of Montpellier). The measurements were realized using a Thermo  
363 Scientific MC-ICP-MS (MultiCollector-Inductively Coupled Plasma Mass Spectrometer) Neptune Plus at  
364 the AETE-ISO Platform from the OSU-OREME (Montpellier). To assess the reproducibility and accuracy  
365 of the isotopic ratios, standards were repeatedly run every five samples. All ratios were normalized  
366 using a value of 0.1194 for the <sup>88</sup>Sr/<sup>86</sup>Sr ratio. The standard average values were 0.710243 ± 6 (±2σ, n  
367 = 20) for the NBS987 Sr standard.

368 For the preparation of structural carbonate for the oxygen analyses, because of the state of  
369 preservation varying amounts of mechanically cleaned bone compacta were required: Ulug bones 10–  
370 15 mg; Dzharkutan, Gelot/Darnaichi, Saridzhar, and Bashman1 bones 20–30 mg. The required amount  
371 of tooth enamel was 5–10 mg. The purification was performed following the protocol of Balasse et al.  
372 (2002). To remove the diagenetic carbonate, bone samples were treated with NaOCl (2–3%) for 24–48  
373 hours at room temperature, stirred every 4–6 hours. After rinsing (4–5 times with H<sub>2</sub>O Milli-Q®), 1 M  
374 acetic acid was added to the bone powder for 1 hour at room temperature, stirred every 20 minutes.  
375 Teeth enamel samples were treated with 1 M HCl for 4 hours, stirred every 30 minutes. After rinsing  
376 (4–5 times with H<sub>2</sub>O Milli-Q®), all samples were dried at 50–70°C for 24–36 hours until all water was  
377 thoroughly evaporated. The lab work was carried out in the Cosmochemistry Lab of the Mass  
378 Spectrometry Service at the National Museum of Natural History (SSMIM) in Paris. The analyses were  
379 performed using a Thermo Scientific Mass-spectrometer DeltaV-Advantage with a Kiel IV automated  
380 processor. Oxygen ratios are reported compared to the Vienna Pee Dee Belemnite standard (VPDB)  
381 using δ notation. Uncertainties (1σ) for δ<sup>18</sup>O were 0.06‰, the measurements are expressed relative to  
382 the standard in parts per thousand (‰).

383

384

## 385 4. Results

386

### 387 4.1. Determination of the local <sup>87</sup>Sr/<sup>86</sup>Sr ranges

388

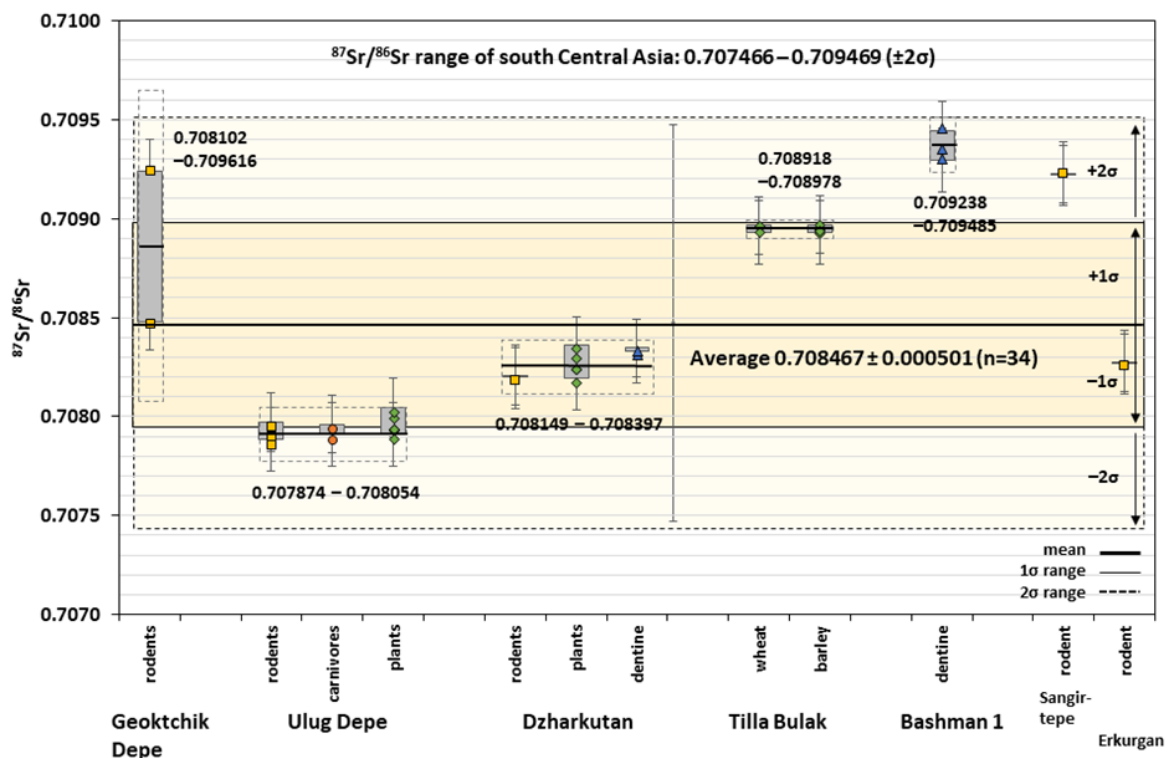
389 Several methods exist for the calculation of local <sup>87</sup>Sr/<sup>86</sup>Sr signals to get the most reliable results (e.g.,  
390 Grupe et al. 1997; Price et al. 2002, 2004; Bentley et al. 2004; Knipper 2004). In order to compare our  
391 results with already published data, we followed Price et al. (2002) by expanding the mean value with

392 2σ. The itemized results of the faunal and botanical references, including the calculated local  $^{87}\text{Sr}/^{86}\text{Sr}$   
 393 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  
 394 are shown in fig. 3.

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

401 For the bio-available local  $^{87}\text{Sr}/^{86}\text{Sr}$  range of Dzharkutan, two samples of rodents, five botanical  
 402 samples and two human dentine samples were analysed (Mashkour et al. 2016; Tengberg 2013;  
 403 Tengberg et al. 2020). The plants were three samples of barley, most probably locally grown; one  
 404 sample of willow, riverine and probably also locally grown; and one sample of tamarisk. The ratios  
 405 ranged between 0.708191 and 0.708356 with an average of 0.708273 ( $\pm 0.000062$ ), resulting in a local  
 406  $^{87}\text{Sr}/^{86}\text{Sr}$  range for Dzharkutan of **0.708149 – 0.708397** ( $\pm 2\sigma$ , n = 9).

407



408  
 409 **Fig. 3:**  $^{87}\text{Sr}/^{86}\text{Sr}$  signals from southern Central Asia; sites are in geographical order from west to east. Dashed  
 410 boxes mark the determined local  $^{87}\text{Sr}/^{86}\text{Sr}$  signals; the yellow box marks the calculated regional range (dark  $\pm 1\sigma$ ,  
 411 light  $\pm 2\sigma$ ).  
 412

413 To get a better idea of the surrounding situations, further faunal samples were added from  
 414 Tilla Bulak, a small village 25 km west of Dzharkutan, dating around 2000–1750 BCE (Kaniuth 2016).

415 Seven samples of barley and wheat were analysed (Peters in Kaniuth 2009, 89–91): the ratios ranged  
416 between 0.708930 and 0.708968 with an average of 0.708948 ( $\pm 0.000015$ ), resulting in a narrow, but  
417 significantly different local  $^{87}\text{Sr}/^{86}\text{Sr}$  range of **0.708918 – 0.708978** ( $\pm 2\sigma$ ,  $n = 7$ ).

418 The two human individuals from Bashman 1 were tested for their dentine  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. The  
419 results were close to each other (0.709297 and 0.709343), giving an impression of the strontium  
420 distribution in this region. The enamel ratio of the child was also close to the two dentine ratios; as it  
421 was a young child (below 7 years) and the analysed tooth a molar (formation not finished within this  
422 age), the child was added to the calculation to get the widest possible description of local strontium  
423 distribution. Then, the ratios ranged between 0.709297 and 0.709445 with an average of 0.709362 ( $\pm$   
424 0.000062), resulting in a local  $^{87}\text{Sr}/^{86}\text{Sr}$  signal of **0.709238 – 0.709485** ( $\pm 2\sigma$ ,  $n = 3$ ).

425 Several analyses of rodents were included as further references: these do not provide reliable  
426 local  $^{87}\text{Sr}/^{86}\text{Sr}$  signals, but serve as indicators for the isotopic distribution of the archaeological sites.  
427 Hence, the bone material of one rodent from Sangir-tepe, of one from Erkurgan (Mashkour et al. 2016)  
428 and of two from Geoktchik Depe (Mashkour 1998) were analysed. Geoktchik Depe is located in the  
429 Dehistan Plain, in southwestern Turkmenistan, adjacent to the Caspian Sea, which is today an arid and  
430 flat region (Lecomte 2005, 2007b). The two rodents from Geoktchik Depe showed completely different  
431  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, resulting in a wide range of **0.708102 – 0.709616** ( $\pm 2\sigma$ ,  $n = 2$ ). The rodent from Sangir-  
432 tepe displayed a similar  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.709224 ( $\pm 0.000006$ ), while that from Erkurgan a ratio of  
433 0.708273 ( $\pm 0.000003$ ) closer to those from Ulug Depe and Dzharkutan.

434

435 **Table 2**  $^{87}\text{Sr}/^{86}\text{Sr}$  results of botanical and faunal references and calculation of the local signals

436

437

Site	Species	Name of sample	#Ref	Period	Material	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (last digits)	Mean $\pm 1\sigma$	Local $^{87}\text{Sr}/^{86}\text{Sr}$ range $\pm 2\sigma$	Mean $\pm 1\sigma$ (n=34)	Local $^{87}\text{Sr}/^{86}\text{Sr}$ range $\pm 2\sigma$ ( $\pm 0.001$ )
Ulug Depe	Mus spec.	R-CH. 1	Chantier 1	MBA	bone fragm.	0.707922 $\pm 06$	0.707954 $\pm 0.000045$	0.707874 - 0.708054	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	R-CH. 5	Chantier 5	MBA	bone fragm.	0.707885 $\pm 04$				
	Mus spec.	R-CH. 16	Chantier 16	MIA	bone fragm.	0.707972 $\pm 07$				
	Canis fam.	SK16-18	Chantier 1; 2007	EBA/MBA	bone fragm.	0.707908 $\pm 05$				
	Panthera spec.	SK16-25	Chantier 5; 2004		bone fragm.	0.707961 $\pm 03$				
	Tamaris spec.	SK18-01	Chantier 1 Est	MBA	charred wood	0.708016 $\pm 04$				
	Juniperus spec.	SK18-02	Chantier 8, US 8350	MIA	charred wood	0.708045 $\pm 03$				
	Hordeum vulg.	SK18-03-1	Chantier 5, US 5012	EBA	charred seeds	0.707955 $\pm 05$				
	Hordeum vulg.	SK18-03-2	Chantier 5, US 5012	EBA	charred seeds	0.70796 $\pm 05$				
	Hordeum vulg.	SK18-04	Chantier 1 Est	MBA	charred seeds	0.707963 $\pm 06$				
Dzharkutan	Hordeum vulg.	SK18-05	Chantier 8, US 8305	MIA	charred seeds	0.707911 $\pm 05$	0.708273 $\pm 0.000062$	0.708149 - 0.708397	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	R-DZH 1066	Sep. 1066	LBA	bone fragm.	0.708201 $\pm 05$				
	Mus spec.	R-DZH 2012	Excavation 2012	LBA	bone fragm.	0.708204 $\pm 03$				
	Tamaris spec.	SK18-86	Chantier 7, US 7018	EIA	charred wood	0.708312 $\pm 09$				
	Salix spec.	SK18-07	Chantier 7, US 7034	LBA	charred wood	0.708191 $\pm 04$				
	Hordeum vulg.	SK18-09-1	Chantier 7, US 7034	LBA	charred seeds	0.708258 $\pm 06$				
	Hordeum vulg.	SK18-09-2	Chantier 7, US 7034	LBA	charred seeds	0.708359 $\pm 06$				
	Hordeum vulg.	SK18-10	Chantier 7, US 7018	EIA	charred seeds	0.708259 $\pm 07$				
	Homo sap.	DZH 1049	DZH-2011 Sep1049	LBA	tooth dentine	0.708330 $\pm 05$				
	Homo sap.	DZH 1051	DZH-2011 Sep1051	LBA	tooth dentine	0.708346 $\pm 05$				
Tilla Bulak	Triticum aest.	SK18-76	TB10-KF-541	LBA	charred seeds	0.708965 $\pm 03$	0.708948 $\pm 0.000015$	0.708918 - 0.708978	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Triticum aest.	SK18-77	TB10-KF-701	LBA	charred seeds	0.708931 $\pm 13$				
	Triticum aest.	SK18-80	TB10-KF-935	LBA	charred seeds	0.708959 $\pm 06$				
	Hordeum vulg.	SK18-75	TB09-KF-626	LBA	charred seeds	0.708968 $\pm 08$				
	Hordeum vulg.	SK18-78	TB10-KF-890	LBA	charred seeds	0.708944 $\pm 04$				
	Hordeum vulg.	SK18-79	TB10-KF-919	LBA	charred seeds	0.70893 $\pm 11$				
	Hordeum vulg.	SK18-81	TB10-KF-937	LBA	charred seeds	0.708937 $\pm 07$				
	Mus spec.	SK18-28		IA	bone fragm.	0.709237 $\pm 04$				
	Mus spec.	SK18-115		IA	bone fragm.	0.70848 $\pm 11$				
	Mus spec.	SK18-31		BA	bone fragm.	0.708273 $\pm 03$				
Geoktchik Depe	Mus spec.	SK18-32	ST-04-03 delta 3 pit	BA	bone fragm.	0.709224 $\pm 06$	0.708859 $\pm 0.000379$	0.708102 - 0.709616	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	SK18-119		LBA	tooth dentine	0.709297 $\pm 05$				
	Homo sap.	SK18-120		LBA	tooth dentine	0.709343 $\pm 05$				
	Homo sap.	SK18-120		LBA	tooth enamel	0.709445 $\pm 07$				
Erkurgan	Mus spec.	SK18-32	ST-04-03 delta 3 pit	BA	bone fragm.	0.709224 $\pm 06$	0.708859 $\pm 0.000379$	0.708102 - 0.709616	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	SK18-119		LBA	tooth dentine	0.709297 $\pm 05$				
Sangir-tepe	Mus spec.	SK18-32	ST-04-03 delta 3 pit	BA	bone fragm.	0.709224 $\pm 06$	0.708859 $\pm 0.000379$	0.708102 - 0.709616	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	SK18-119		LBA	tooth dentine	0.709297 $\pm 05$				
Bashman 1	Mus spec.	SK18-120		LBA	tooth dentine	0.709343 $\pm 05$	0.708859 $\pm 0.000379$	0.708102 - 0.709616	0.708467 $\pm 0.000501$	0.707466 - 0.709469 (0.707467 - 0.709467)
	Mus spec.	SK18-120		LBA	tooth enamel	0.709445 $\pm 07$				



438 The calculated local signals of the single sites were resultful within the available references  
439 and are well distinguishable at a micro-regional scale (cf. fig. 3). The calculated strontium signal of the  
440 whole region was calculated resulting in a range of **0.707466 – 0.709469** ( $\pm 2\sigma$ , n = 34).

441

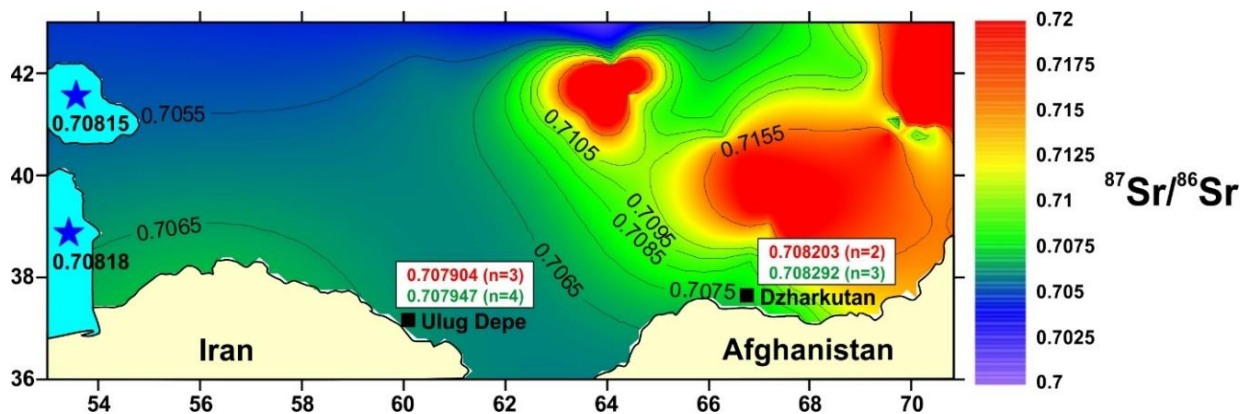
442

## 443 4.2. Interpolation on an interregional scale

444

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

453



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

458

459

460

## 461 4.3. Human $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ results

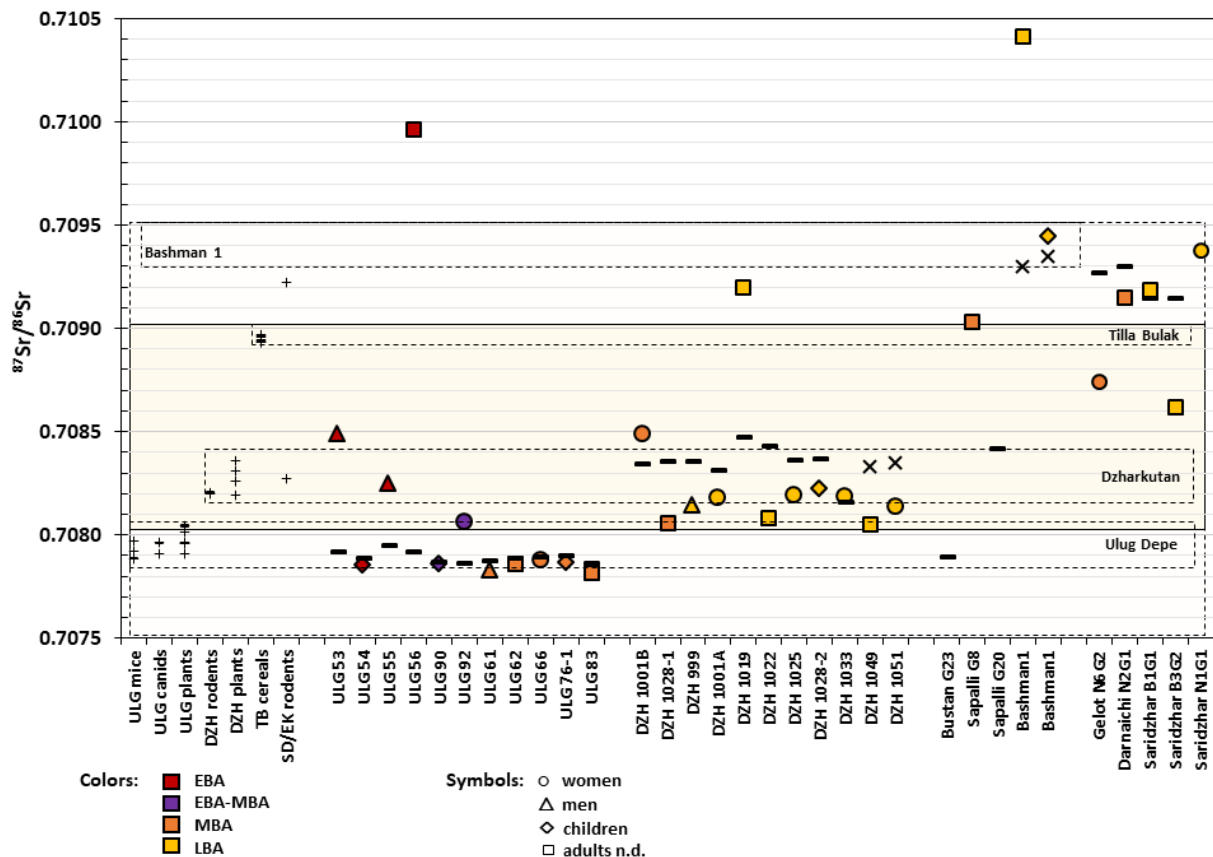
462

463 The  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  results of all human samples from Ulug Depe, Dzharkutan, Sapallitepa, Bustan,  
464 Bashman 1, Gelot/Darnaichi and Saridzhar are listed in table 3 and presented in figures 5, 6 and 7 (the  
465 individuals from Bashman 1 were only tested for strontium, and are therefore not in figs. 6 and 7). A  
466 preliminary cluster analysis of Ulug Depe and Dzharkutan individuals provided two distinguishable  
467 clusters with several outliers. Hence the sites can be considered as capable of being differentiated. A

468 Levene test confirmed that there was no homogeneity of variances between the sites ( $F = 2.16$ ,  $p <$   
 469  $0.02$ ). But since the small sample number made statistical analyses unreliable, we desisted from further  
 470 calculations. Moreover, the deviations of the individual results were negligibly small, when plotting  
 471 them on the figures the error bars were overlapped by the applied symbols so that the symbols in  
 472 figures 5, 6 and 7 encompass the error margins at  $2\sigma$  level for the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and  $1\sigma$  level for  $\delta^{18}\text{O}$   
 473 ratios.

474

475



476

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

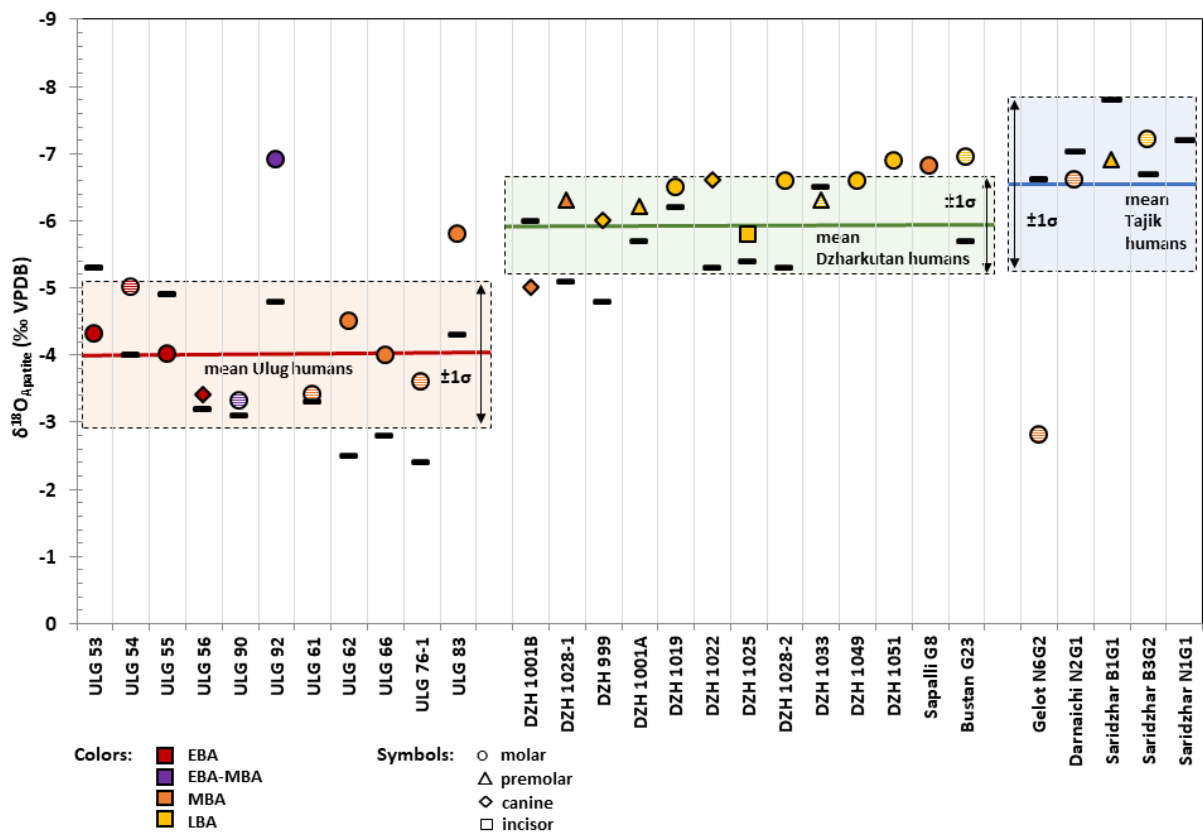
482

483

484 The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of all samples from Ulug Depe ranged between 0.707864 and 0.709960,  
 485  $\delta^{18}\text{O}$  ratios were between  $-6.9\text{‰}$  and  $-2.4\text{‰}$  (VPDB). Bone  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranged between 0.707864  
 486 and 0.707948 with a mean of 0.707893 ( $\pm 0.000026$ ,  $n = 11$ ),  $\delta^{18}\text{O}$  bone ratios ranged between  $-5.3\text{‰}$   
 487 and  $-2.4\text{‰}$  and showed a mean of  $-3.7\text{‰}$  ( $\pm 0.97$ ,  $n = 11$ ). Tooth enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  ranged between  
 488 0.707819 and 0.709960 and showed a mean of 0.708156 ( $\pm 0.000605$ ,  $n = 11$ ), while  $\delta^{18}\text{O}$  ranged  
 489 between  $-6.9\text{‰}$  and  $-3.2\text{‰}$  with a mean of  $-4.4\text{‰}$  ( $\pm 1.08$ ,  $n = 11$ ). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of all samples  
 490 from Dzharkutan ranged between 0.708052 and 0.709200,  $\delta^{18}\text{O}$  ratios of all samples ranged from -

491 6.9‰ to -3.8‰ (V-PDB). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of human bones ranged between 0.708160 and 0.708474  
 492 and showed a mean of 0.708352 ( $\pm 0.000081$ ,  $n = 9$ ), bones  $\delta^{18}\text{O}$  ranged between -6.5‰ and -4.8‰  
 493 and showed a mean of -5.6‰ ( $\pm 0.52$ ,  $n = 9$ ). Tooth enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranged between 0.708052  
 494 and 0.709200 and showed a mean of 0.708267 ( $\pm 0.000316$ ,  $n = 11$ ), while enamel  $\delta^{18}\text{O}$  ranged  
 495 between -6.9‰ and -5.0‰ with a mean of -6.2‰ ( $\pm 0.49$ ,  $n = 11$ ). The bone sample of burial 20 from  
 496 Sapallitepa provided an  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.708418 ( $\pm 0.000006$ ), while enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of burial  
 497 8 was 0.709030 ( $\pm 0.000026$ ). The single bone sample from Bustan had an  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.707893  
 498 ( $\pm 0.000007$ ),  $\delta^{18}\text{O}$  was -5.7‰. The five individuals from Gelot/Darnaichi and Saridzhar range in the  
 499  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio between 0.708616 and 0.709374 ( $\pm 0.000241$ ‰),  $\delta^{18}\text{O}$  ratios ranged between -2.8‰ and  
 500 -7.8‰ ( $\pm 1.4$ ‰). The two individuals from Bashman 1 showed in their  $^{87}\text{Sr}/^{86}\text{Sr}$  enamel ratios two very  
 501 different results. The  $^{87}\text{Sr}/^{86}\text{Sr}$  enamel ratio of the adults was 0.710410 ( $\pm 0.000040$ ), the child provided  
 502 an  $^{87}\text{Sr}/^{86}\text{Sr}$  enamel ratio of 0.709445 ( $\pm 0.000007$ ). The preparation of structural carbonate was not  
 503 sufficient for all individuals; therefore, oxygen values are not available for one sample from Sapallitepa  
 504 and all samples from Bashman 1.

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508 **Fig. 6:** Human  $\delta^{18}\text{O}$  results out of apatite of bones and teeth with intra-individual variations: minus mark the  
 509 bone samples, geometric signs mark tooth enamel samples (M3: full coloured, M n.d: striped). Coloured lines  
 510 mark the averages, dashed boxes the averages  $\pm 1\sigma$ .  
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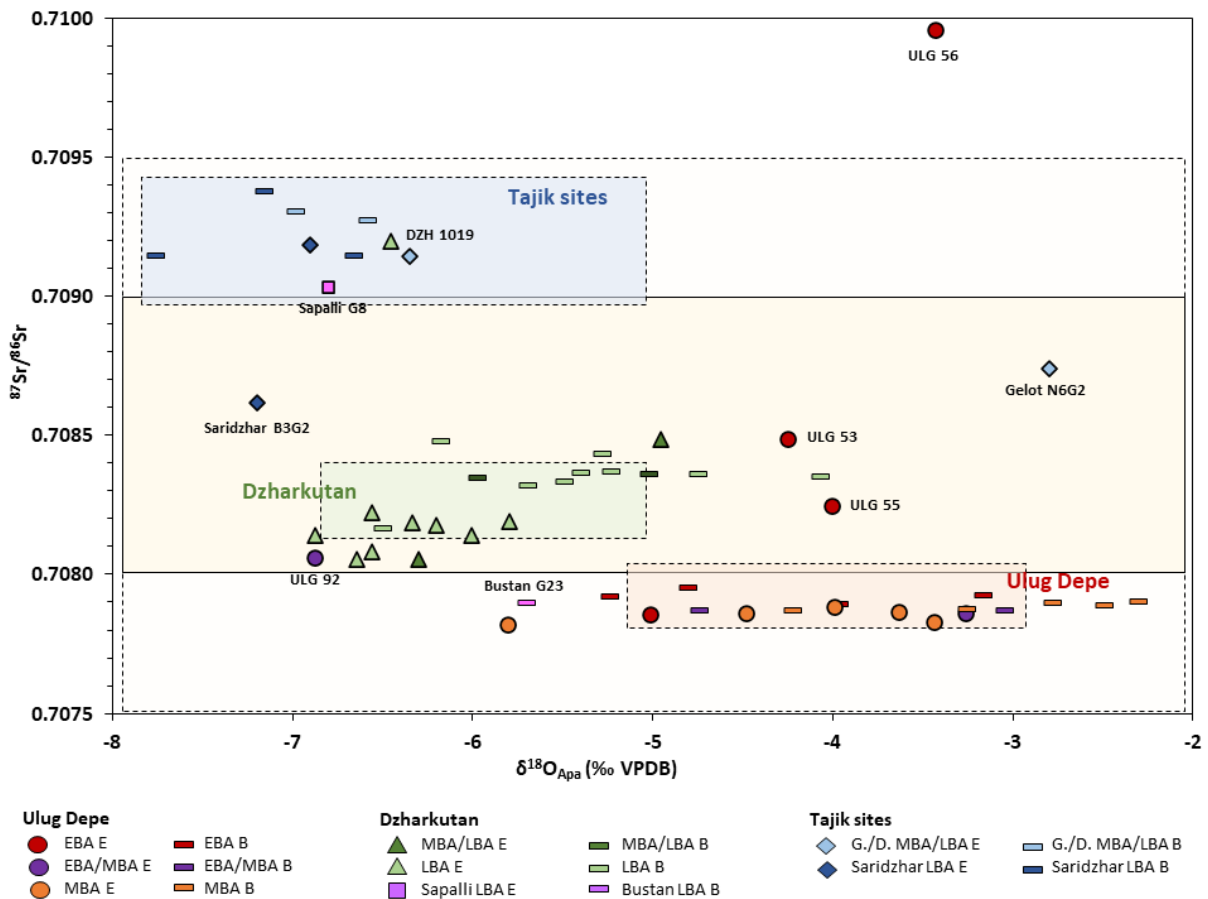
Site	Name of sample	#Ref	Period	Age in years / sex	tooth enamel				bone compacta/tooth dentine					
					Material	<sup>87</sup> Sr/ <sup>86</sup> Sr	2σ (last digits)	δ <sup>18</sup> O <sub>ppm</sub> ‰ (VPDB)	1σ	Material	<sup>87</sup> Sr/ <sup>86</sup> Sr	2σ (last digits)	δ <sup>18</sup> O <sub>ppm</sub> ‰ (VPDB)	1σ
Ulug Depe	ULG 53	ULG01-Sep53	EBA	>40 / m	M3	0.708488	± 08	-4.3	± 0.05	phalanx	0.707918	± 03	-5.3	± 0.01
Ulug Depe	ULG 54	ULG01-Sep54	EBA	1-3 / n.d.	M	0.707856	± 04	-5.0	± 0.02	rib	0.707890	± 06	-4.0	± 0.01
Ulug Depe	ULG 55	ULG05-Sep55	EBA	>40 / m	M3	0.708247	± 03	-4.0	± 0.04	rib	0.707948	± 04	-4.9	± 0.02
Ulug Depe	ULG 56	ULG01-Sep56	EBA	adult / n.d.	C	0.709960	± 04	-3.4	± 0.05	rib	0.707921	± 07	-3.2	± 0.03
Ulug Depe	ULG 90	ULG06-CH17-Sep90	EBA-MBA	ca. 3 / n.d.	M	0.707857	± 04	-3.3	± 0.02	rib	0.707867	± 06	-3.1	± 0.02
Ulug Depe	ULG 92	ULG05-CH17-Sep92	EBA-MBA	>40 / f	M3	0.708061	± 05	-6.9	± 0.02	bone fragm.	0.707864	± 05	-4.8	± 0.02
Ulug Depe	ULG 61	ULG04-Sep61	MBA	21-28 / m	I	0.707826	± 08	-3.4	± 0.03	bone fragm.	0.707873	± 04	-3.3	± 0.03
Ulug Depe	ULG 62	ULG04-Sep62	MBA	adult / n.d.	M3	0.707859	± 06	-4.5	± 0.02	phalanx	0.707886	± 06	-2.5	± 0.04
Ulug Depe	ULG 66	ULG04-CH1Est-Sep66	MBA	>40 / f	M3	0.707880	± 04	-4.0	± 0.04	bone fragm.	0.707894	± 05	-2.8	± 0.02
Ulug Depe	ULG 76-1	ULG04-Sep76-Ind1	MBA	4-6 / n.d.	M	0.707865	± 05	-3.6	± 0.03	vertebra	0.707899	± 04	-2.4	± 0.01
Ulug Depe	ULG 83	ULG05-CH17-Sep83	MBA	adult / n.d.	M3	0.707819	± 06	-5.8	± 0.03	vertebra	0.707865	± 04	-4.3	± 0.02
Dzharkutan	DZH 1001B	DZH-2007 Sep1001B	MBA-LBA	20-29 / f	C	0.708487	± 07	-5.0	± 0.04	bone fragm.	0.708343	± 05	-6.0	± 0.02
Dzharkutan	DZH 1028-1	DZH-2009 Sep1028-1	MBA-LBA	adult / n.d.	PM	0.708055	± 06	-6.3	± 0.03	phalanx	0.708358	± 05	-5.1	± 0.03
Dzharkutan	DZH 999	DZH-2007 Sep999	LBA	20-39 / m	C	0.708142	± 07	-6.0	± 0.03	phalanx	0.708355	± 03	-4.8	± 0.02
Dzharkutan	DZH 1001A	DZH-2007 Sep1001A	LBA	20-29 / f	PM	0.708178	± 08	-6.2	± 0.01	carpal	0.708314	± 05	-5.7	± 0.01
Dzharkutan	DZH 1019	DZH-2008 Sep 1019	LBA	adult / n.d.	M3	0.709200	± 08	-6.5	± 0.07	phalanx	0.708474	± 03	-6.2	± 0.02
Dzharkutan	DZH 1022	DZH-2009 Sep1022	LBA	adult / n.d.	PM	0.708082	± 08	-6.6	± 0.02	rib	0.708430	± 04	-5.3	± 0.03
Dzharkutan	DZH 1025	DZH-2009 Sep1025	LBA	17-40 / f	I	0.708190	± 06	-5.8	± 0.08	bone fragm.	0.708362	± 06	-5.4	± 0.03
Dzharkutan	DZH 1028-2	DZH-2009 Sep1028-2	LBA	child / n.d.	M	0.708223	± 06	-6.6	± 0.07	humerus	0.708368	± 04	-5.3	± 0.02
Dzharkutan	DZH 1033	DZH-2009 Sep1033	LBA	>40 / f	PM	0.708185	± 06	-6.3	± 0.03	rib	0.708160	± 04	-6.5	± 0.03
Dzharkutan	DZH 1049	DZH2011 Sep1049	LBA	adult / n.d.	M3	0.708052	± 04	-6.6	± 0.03	M3 dentine	0.708330	± 05	-5.5	± 0.07
Dzharkutan	DZH 1051	DZH2011 Sep1051	LBA	15-20 / f	M3	0.708138	± 05	-6.9	± 0.07	M3 dentine	0.708346	± 05	-4.1	± 0.06
Sepallitepa	SK17-24	Sep 8 (2) 00-149	LBA	adult / n.d.	M3	0.709030	± 26	-6.8	± 0.03	-	-	-	-	-
Sepallitepa	SAP2	1971 Sep. 20 0027	LBA	adult / n.d.	-	-	-	-	-	bone fragm.	0.708418	± 06	-	-
Bustan	SK17-23	Sep 23 59-30	LBA	adult / n.d.	M1	-	-	-6.9	± 0.04	bone fragm.	0.707893	± 07	-5.7	± 0.04
Gelot	SK17-05	N6 grave 2	MBA-LBA	40 / f	M	0.708739	± 05	-2.8	± 0.05	bone fragm.	0.709270	± 03	-6.6	± 0.04
Damaichi	SK17-13	N2 grave 1	MBA	adult / n.d.	M	0.709147	± 04	-6.5	± 0.03	skull (frontal bone)	0.709302	± 08	-7.0	± 0.04
Saridzhar	SK17-10	B1 grave 1	LBA	adult / n.d.	PM	0.709188	± 09	-6.9	± 0.03	skull (frontal bone)	0.709143	± 05	-7.8	± 0.04
Saridzhar	SK17-11	B3 grave 2	LBA	adult / n.d.	M	0.708616	± 16	-7.2	± 0.04	bone fragm.	0.709143	± 10	-6.7	± 0.02
Saridzhar	SK17-12	N1 grave 1	LBA	adult / n.d.	-	-	-	-	-	bone fragm.	0.709374	± 09	-7.2	± 0.01
Bashman1	SK18-119	2018; GPS 150	LBA	adult / n.d.	M3	0.710410	± 40	-	-	M3 dentine	0.709297	± 05	-	-
Bashman1	SK18-120	2018; GPS 150	LBA	child / n.d.	M	0.709445	± 07	-	-	M dentine	0.709343	± 05	-	-
Ulug Depe	SK18-18	Chantier 1	EBA-MBA	Canis fam.	-	-	-	-	-	Mandibel	0.707908	± 05	-3.0	± 0.07
Ulug Depe	SK18-25	Chantier 5	-	Panthera spec.	-	-	-	-	-	ulna	0.707961	± 03	-1.6	± 0.05

514 \*Abbreviations: f: female; m: male; n.d.: not determined; M: Molar, C: Canine, I: Incisor. "M" or "bone. fragm." stand for samples where the determination was unsure, especially when samples were very little; "adult" stand for individuals where the preservation did not allow a further age determination; "child" stand for children below 14 years, but the preservation also did not allow a further age determination.

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## 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  $-6.9\text{‰}$  and  $-2.4\text{‰}$  with a range of  $4.5\text{‰}$  (enamel:  $3.6\text{‰}$ ; bones:  $2.5\text{‰}$ ) and average of  $-4.0\text{‰}$  ( $\pm 1.0\text{‰}$  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  $3\text{‰}$  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).



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539 **Fig. 7:** Scatterplot correlation of  $\delta^{18}\text{O}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of all analysed individuals. Abbr.: E stands for enamel, B  
 540 for bones, ULG for Ulug Depe, DZH for Dzharkutan, G./D. for Gelot/Darnaichi. Dashed boxes mark the  $\delta^{18}\text{O}$  mean  
 541 value out of human samples  $\pm 1\sigma$  in combination with the calculated local  $^{87}\text{Sr}/^{86}\text{Sr}$  signals ( $\pm 2\sigma$ ). Big yellow boxes  
 542 mark the inter-regional  $^{87}\text{Sr}/^{86}\text{Sr}$  signal (dark  $\pm 1\sigma$ , light  $\pm 2\sigma$ ).  
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When comparing the distribution of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  of bones and teeth from Dzharkutan individuals, two clusters are clearly visible: the bones form a cluster on the upper limit of the local  $^{87}\text{Sr}/^{86}\text{Sr}$  and on the lower limit of the local  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  ratios ranged between  $-6.9\text{‰}$  and  $-4.8\text{‰}$  with a range of  $2.1\text{‰}$  and an average of  $-5.9\text{‰}$  ( $\pm 0.7\text{‰}$ ,  $n = 20$ ). 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

559 subsistence of Dzharkutans' people with movement between the place of birth/childhood and  
560 residence during later lifetime in a limited area. The individuals date to the transition from MBA to the  
561 LBA and to the LBA, and the results show a certain continuity over this time period. But the real cause  
562 for this unusual pattern of movements of the people from Dzharkutan remains unexplained, until more  
563 results can be evaluated.

564 Special patterns in terms of biological criteria such as age, sex and the archaeologically  
565 indicated social position of the individuals, are only weakly reflected in the small sample size. The  
566 "foreigners" from Ulug Depe were two men and one not determined adult from the EBA (ULG 53, 55,  
567 56), and one woman from the EBA/MBA (ULG 92). It is not clear if the degree of mobility is connected  
568 to the social position or gender of the people. The two men, who were buried in complex burial  
569 constructions after the prevailing burial traditions of the EBA with rich grave inventories, were both  
570 non-locals. Conspicuous, but comparable female burials are missing. In Dzharkutan, the selection of  
571 samples excluded specific interpretations in terms of gender or the archaeologically indicated social  
572 position, since only one man was part of the test series. This one man (DZH 999) did not differ in the  
573  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  results. Furthermore, the only very rich grave of a young woman (DZH 1051) did not  
574 show any differences to the group. Hence, whether there is a pattern in the mobility caused by gender  
575 or social position cannot be recognised in the present evidence.

576 Concerning the question of migration and the movements of single individuals between  
577 populations, the correlation of strontium and oxygen seems to point to the fact that the origins of  
578 some of our non-locals are quite clear and inter-regional connections really existed. The enamel  
579  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  results of Burial no. 1019 from Dzharkutan and Burial no. 8 from Sapallitepa fit  
580 perfectly within the cluster of Gelot/Darnaichi and Saridzhar people (fig. 7), demonstrating that with  
581 the exchange of material (cf. [Luneau 2013](#)) also individuals moved. The  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  ratios of  
582 Gelot/Darnaichi and Saridzhar individuals highlight a homogeneous group of people (fig. 7). It is  
583 conspicuous, however, that all analysed bone samples fell in the same range but only two of four tooth  
584 enamel samples. The results suggest that immigration also played an important role during the Bronze  
585 Age in southern Tajikistan (cf. [Kroll et al. forthcoming](#)). Moreover, the adult individual from Bashman  
586 1 is noticeable, as it fell together with ULG 56 outside the calculated regional signal, suggesting an  
587 external origin of this individual too (fig. 5). Bashman 1 is located south of the Syr Darya which marks  
588 the northern border of the GKC and an area inhabited by both– the GKC groups and Andronovo groups  
589 – in the first half of the 2<sup>nd</sup> mill. BCE. Isotopic studies from the northern communities, where nomadic  
590 pastoralism is argued to be a reason for the spread of the Andronovo culture, did not provide evidence  
591 for long distance migration ([Ventresca Miller et al. 2017](#)). Although providing a contrasting image, our  
592 results are provisional but, nevertheless the high variation in the results suggests active mobility  
593 among the inhabitants of southern Central Asia during the Bronze Ages.

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## 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.

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