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Journal of Archaeological Science 35 (2008) 1265–1280

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

Hunter-gatherer mobility strategies and resource use based on strontium isotope ($^{87}Sr/^{86}Sr$) analysis: a case study from Middle Holocene Lake Baikal, Siberia

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Received 3 April 2007; received in revised form 14 September 2007; accepted 15 September 2007

Abstract

In order to test the previously formulated hypotheses regarding mobility and resource procurement strategies practiced by Middle Holocene Glazkovo foragers in the Baikal region of Siberia, stable strontium isotope ($^{87}Sr/^{86}Sr$) analysis was applied to human remains from the Bronze Age Khuzhir-Nuge XIV cemetery. The main goal was to differentiate between two alternative models: one based on resource acquisition within a relatively large territorial range encompassing most of the Cis-Baikal area, and the other involving a smaller annual range mainly confined to specific micro-regions. A secondary goal was to explore inter-individual variability in strontium ratios, and potential sociocultural correlates. Interpretation of the human data involved assessment of the biologically available strontium isotope ratios, tissue biology, trophic level effect, species-specific Sr-catchment, composition of human diet, sharing of resources, and mobility-related technology. The results indicate a considerable degree of intra- and inter-individual variability in strontium isotope ratios and long-term foraging territories focusing on the west coast of Lake Baikal but including other parts of the Baikal region.

Keywords: Lake Baikal; Siberia; Middle Holocene; Hunter-gatherers; Strontium isotopes; Mobility patterns; Resource use; Bone and tooth chemistry

1. Introduction

The goal of this study is to test hypotheses about the nature of mobility and food procurement strategies practiced by middle Holocene Glazkovo hunter-gatherers from the Baikal region in Siberia. More specifically, we previously suggested two alternative models (Weber et al., 2002:278):

1. Regular travel to exploit a variety of food resources within a relatively large annual range encompassing much of the Cis-Baikal region; or
2. Limited travel to food resources in relatively small annual territories confined to specific micro-regions of the Cis-Baikal area.

These two models were developed primarily on the basis of stable carbon and nitrogen isotope analysis of human bone from a number of skeletal samples representing Neolithic and Bronze Age foragers of the Cis-Baikal region (Katzenberg and Weber, 1999; Weber et al., 2002). The second goal is to examine mobility patterns of individuals within a single

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0305-4403/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2007.09.002

cemetery sample for insights into intra-population variability and, if possible, to make inferences about such important aspects of hunter-gatherer adaptations as social structure and organization of subsistence activities.

Our approach employs the method of strontium isotope ratio analysis ($^{87}Sr/^{86}Sr$) which, as demonstrated through our own pilot study (Weber et al., 2003) and a number of other analyses (e.g., Beard and Johnson, 2000; Bentley et al., 2003; Ezzo et al., 1997; Ezzo and Price, 2002; Grupe et al., 1997,1999; Knudson et al., 2004; Price et al., 1994a,b,2000,2002; Tafuri et al., 2006), has the potential to address these goals from a new perspective. In this study, strontium isotope analysis is applied to a sample of human remains excavated from the large Bronze Age cemetery of Khuzhir-Nuge XIV (hereafter referred to as KN XIV) located on the northwestern shore of Lake Baikal (Fig. 1) and dating approximately to the period between ~4650 and 3950 cal. BP (Weber et al., 2005).

In order to put this study in perspective, we offer an overview of the culture historical and the terminological conventions used in the paper. The study operates within the model developed in previous publications (Link, 1999; Weber, 1995; Weber et al., 2002), revised most recently by Weber et al. and summarized in Table 1.

The model explicitly stipulates discontinuity in the development of mortuary traditions which were very likely accompanied by a major redefinition of the region's hunter-gatherer adaptations taking place during the Middle Neolithic period (Weber et al., 2005). In Siberian archaeology the advent of the Neolithic and Bronze Age is defined exclusively on the basis of technological criteria involving the appearance of pottery, the bow and arrow, stone grinding and copper and bronze objects, respectively. Cis-Baikal encompasses the northwest coast of Lake Baikal and the upper sections of the Angara and Lena river drainages immediately west and north of the lake (approximately between 52° and 58° N and 101° and 110° E). The Little Sea, or the Ol'khon area, is a microregion along the mid-part of the northwestern coast of Lake Baikal and includes Ol'khon island itself, the mainland across from it, and the shallow part of the lake between them (Fig. 1).

2. Strontium isotope analysis: hunter-gatherer mobility strategies

A key to more detailed examination of prehistoric hunter-gatherer mobility and food procurement strategies is the identification of mobility behaviour at the level of the individual, as group mobility is partly a function of aggregated individual patterns. Until recently, such an approach in archaeology was not possible. However, with the pioneering work of Ericson (1985, 1989), strontium isotopes ($^{87}Sr/^{86}Sr$) preserved in bone were shown to reflect the geological background of the individual. Furthermore, a comparison of strontium isotope ratios in hard tissues formed at different ages within an individual's lifetime provides information on long-term mobility patterns (e.g., Sealy et al., 1995).

Since, as mentioned earlier, archaeological applications of the strontium isotope ratio analysis are becoming more frequent and several comprehensive accounts of strontium isotope geochemistry, systematics and laboratory methods have been published recently (e.g., Bentley, 2006; Hodell et al., 2004; Price et al., 2002), here we will discuss only a few aspects that are directly relevant to this particular study.

To date, most of the archaeological applications of strontium isotopes have addressed questions of residential migration among food producers (early farmers, peasants and pastoralists). Typically, these studies attempt to identify recent immigrants into an otherwise sedentary community based on the comparison between $^{87}Sr/^{86}Sr$ documented in first molars and bones (e.g., Bentley et al., 2003, 2004; Ezzo et al., 1997; Ezzo and Price, 2002; Knudson et al., 2004; Price et al., 1994a,b,1998,2000,2001; Schweissing and Grupe, 2003). In these cases, most of the lifetime residents of the local population would have accessed the same range of resources for much of their lifespan, thus making their $^{87}Sr/^{86}Sr$ relatively uniform both at the inter- and intra-individual level. Immigrants, provided they came from a region with sufficiently different geochemical characteristics, have been identified by $^{87}Sr/^{86}Sr$ in bone samples varying from the tooth signature or the mean adult bone ratio by at least two standard deviations (e.g., Grupe et al., 1997). An alternative measure of local $^{87}Sr/^{86}Sr$ is based on analysis of biologically available strontium using bones or teeth from local fauna with relatively small home ranges (Bentley et al., 2004; Price et al., 2002).

Application of the strontium isotope technique to explore mobility and food procurement strategies among hunter-gatherers is still rather novel (Tafuri et al., 2006; Weber et al., 2003). In our case, the goal is to explore mobility patterns for individuals with a potentially high degree of mobility already built into their adaptive strategies and subsisting off a relatively large territory in a complex environment that is characterized by marked seasonality and both temporal and spatial variability in the distribution of food resources (Weber, 2003). Because the overall context of this research setting differs from the previous applications of the strontium isotope methodology, a dedicated approach is required.

The teeth and bones of humans and other animals incorporate strontium signatures from the diet during the time these hard tissues are undergoing mineralization. Each tooth crown develops during a specific time interval which is largely under genetic control (Avery, 1992; Hillson, 1996). For example, the crown of each of the three permanent molars represents approximately 3–4 years of developmental time: M1, birth to ~3–4 years; M2, between ~2–3 years and ~7–8 years; and M3, between ~7–10 years and ~12–16 years (Avery, 1992). Thus, the composition of each tooth crown reflects the strontium isotopes ingested during those time intervals. Consequently, if movement occurs to an area with different geochemical characteristics, it will be reflected in variable strontium isotope ratios in the tissues. Thus, by comparing the composition of an individual's enamel from teeth formed at different life stages, it is possible to track mobility from infancy to late childhood. Strontium isotopes have been shown to serve this purpose very well (e.g., Beard and Johnson, 2000; Montgomery et al., 2000).

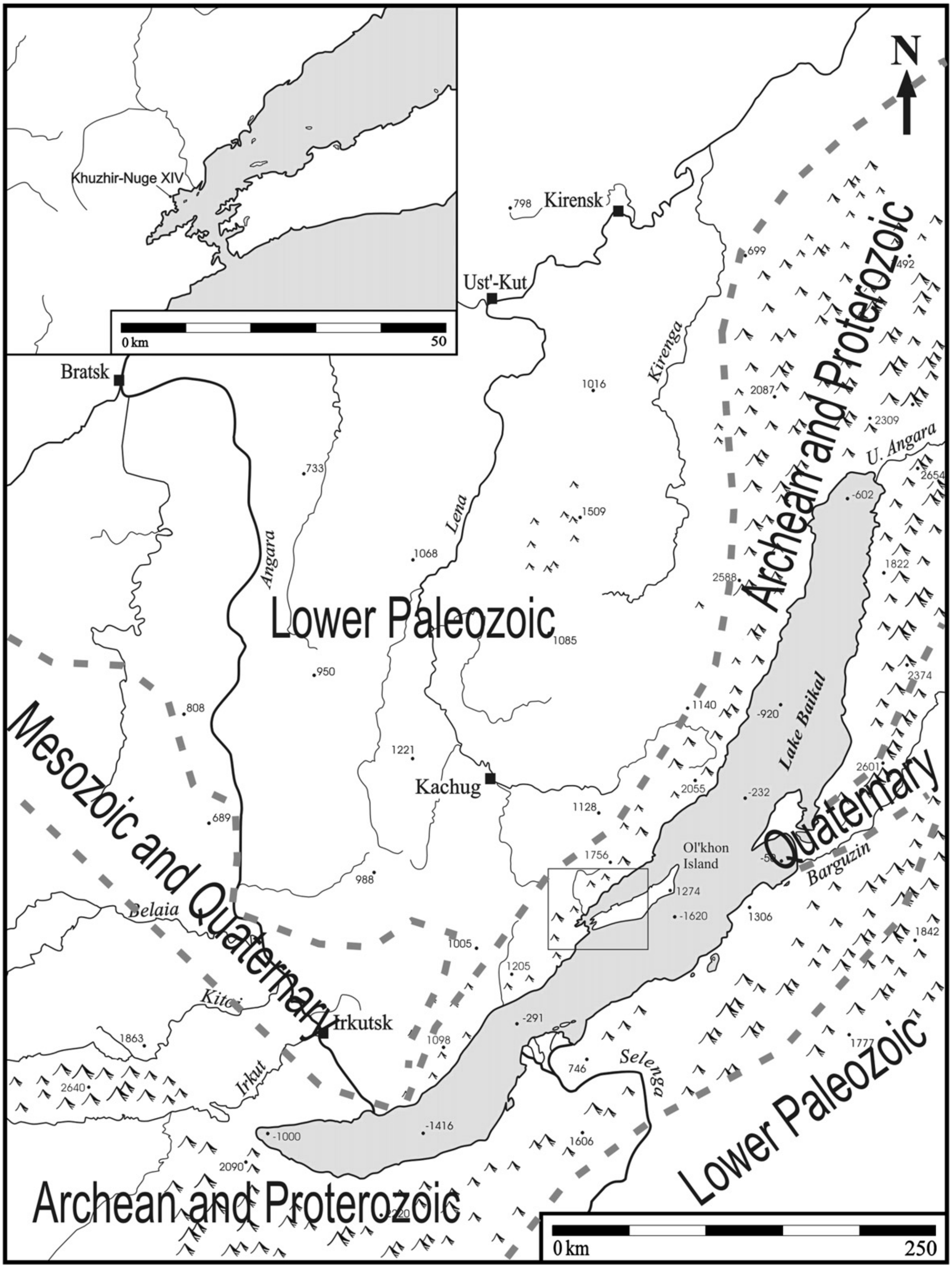

Fig. 1. Map of Cis-Baikal.

Whereas tooth enamel is metabolically inert after the tissue has matured, bone stays biologically active after completing its growth in length. Bone is continuously remodelled throughout life in response to factors such as activity, age, diet, and disease (Sandford, 1993). Although remodelling rates differ in cancellous and cortical bone (∼25%/year and ∼2–3%/year, respectively; Ortner and Putschar, 1985), the strontium isotopic signature of a bone sample will reflect resources accessed during the last 10–20 years of a person's life.

Table 1

Period	Mortuary tradition(s)	Angara, S. Baikal Cal BP	Upper Lena Cal BP	Little Sea Cal BP
Late Mesolithic	n/a	8800–8000	8800–8000	8800–8000
Early Neolithic	Kitoi and other	8000–7000/6800	8000–7200	8000–7200
Middle Neolithic	Hiatus	7000/6800–6000/5800	7200–6000/5800	7000/6800–6000/5800
Late Neolithic	Isakovo, Serovo, tightly flexed	6000/5800–5200	6000/5800–5200/5000	6000/5800–5200/5000
Bronze Age	Tightly flexed, Glazkovo	5200/5000–4000	5200/5000–3400	5200/5000–4000

To assess the feasibility of the strontium technique for the study of hunter-gatherer mobility strategies in the Cis-Baikal, a pilot project was carried out (Weber et al., 2003). Enamel samples from the first, second, and third molar, and bone from the midshaft of the femur for six individuals from the Bronze Age cemetery at KN XIV in the Ol'khon area on Lake Baikal were analyzed. In addition, bone samples from the local suslik (ground squirrel), Baikal seal, and omul' (an abundant Baikal fish) were also examined as part of the environmental comparative framework. This study revealed a few important patterns. First, it demonstrated that the variability in $^{87}Sr/^{86}Sr$ between different teeth or between teeth and bone of the same individual can be quite substantial. Second, different lifetime patterns represented by the sequence of M1, M2, M3 and bone values were observed. And third, these early data suggested that this particular group of hunter-gatherers had their long-term procurement ranges likely based within the Ol'khon region, that is relatively close to their cemetery (Weber et al., 2003). At the methodological level the results suggested that the geological diversity in the Cis-Baikal region was sufficient for a broader application of the technique to address some of the specific questions about mobility and procurement strategies of the region's middle Holocene foragers. The current study tests all KN XIV individuals with sufficient number of molars and femur fragments available for examination and expands assessment of the biologically available $^{87}Sr/^{86}Sr$ in the Cis-Baikal region.

3. Materials and laboratory procedures

3.1. The Khuzhir-Nuge XIV cemetery

The KN XIV cemetery is located on the west coast of the Little Sea (in Russian: *Maloe more*) micro-region of the Lake Baikal basin, near the southern end of Ol'khon Island and c. 3 km southwest of the mouth of the Sarma River (Fig. 1; 53°04′58″ N, 106°48′21″ E). It occupies the southeast slope of a hill rising from a shallow bay. With 79 graves and a total of 89 individuals unearthed, KN XIV is the largest Bronze Age hunter-gatherer cemetery ever excavated in the entire Cis-Baikal region (Weber et al., 2007). All the graves were only c. 30–60 cm deep sub-rectangular pits filled with rocks and loamy sand, and covered by surface structures built of stone slabs still visible on the surface prior to archaeological excavation. Most graves contained single inhumations, seven were double, and two were triple interments.

The north–south orientation of Grave 7 is consistent with the Late Neolithic Serovo culture of the Ol'khon region, while all the other graves show clear similarities with the mortuary tradition of the Bronze Age Glazkovo culture (Goriunova and Khlobystin, 1992; Goriunova, 1997, 2002; Goriunova et al., 2004; Kharinskii and Sosnovskaia, 2000; Komarova and Sher, 1992; Konopatskii, 1982). The most diagnostic Glazkovo characteristics include the generally west–east orientation of the burials and such grave goods as copper or bronze objects (rings, knives, needles, and bracelets), kaolinite beads, and rings and discs made of white nephrite or calcite. A recent analysis of approximately 80 ^{14}C dates indicates that the KN XIV cemetery was used continuously by Glazkovo peoples for a maximum of 700 years between ~4650 and 3950 cal. BP but the majority of the burials (70%) date to between ~4450 and 4250 cal. BP (Weber et al., 2005). Since the analysis did not reveal any obvious temporal trends in mortuary attributes, it seems to be justified to treat the cemetery, with the exception of the much earlier Grave 7, as one analytical unit (McKenzie, 2006; Weber et al., 2005).

In addition to 20 adult individuals for which all three molars and a femur sample were available, 5 subadult burials with only M1 and M2 crowns completed were included too (Table 2). For the latter individuals (Burials 16, 35.2, 37.2, 39 and 45) the M3 was either not yet formed, or still forming. Partly developed crowns were not examined because such crowns are incompletely mineralized and this could have affected the isotope ratios. The data obtained for the individuals tested in the pilot study are used in the present analysis. In total, our data set represents 25 individuals of which one dates to the Late Neolithic Serovo culture (B. 7) and the remaining 24 are associated with the Bronze Age Glazkovo.

3.2. Preparation of human tooth enamel and bone samples

Enamel samples were obtained using a diamond cutting disk (NTI Diamond disc, Interflex-double sided, 8 mm diameter, thickness 0.15 mm) fitted to a Dremel tool. An attempt was made to use a standardized sampling location within the lower half of the crown just above the cementum–enamel junction. This allowed us to use teeth even with considerable wear. For each individual tooth, either the buccal or lingual side of the crown was used, depending on the quality and the amount of enamel present. Due to the sometimes extremely oblique wear pattern, for maxillary molars the crown height was often highest on the buccal side and for mandibular molars on the lingual side. The same side was chosen on each of the molars from an individual whenever possible. Both the mesial and distal sides of the crown were avoided, as enamel tends to

Table 2
Khuzhir-Nuge XIV, summary of archaeological information for the examined individuals

No.	Grave no.	Master ID	Teeth analyzed	Bone	Age	Sex	Relative age	Mortuary tradition	Lab. no.	^{14}C age BP	Collagen yield
1	7	K14_1997.007	36, 37, 38[b]	Femur	25–35	PM	Late Neolithic	Serovo	TO-06862	5110 ± 270	0.04
2	10	K14_1997.010[a]	36, 37, 38	Femur	20–25	–[c]	Bronze Age	Glazkovo	TO-07834	3530 ± 60	0.60
3	11	K14_1997.011[a]	36, 17, 18	Femur	35–50	M	Bronze Age	Glazkovo	TO-06864	3910 ± 60	10.30
4	12	K14_1997.012[a]	36, 37, 38	Femur	25–35	–[c]	Bronze Age	Glazkovo	TO-07835	3700 ± 70	1.70
5	14	K14_1997.014[a]	36, 27, 28	Femur	35–50	PM	Bronze Age	Glazkovo	TO-06865	3580 ± 60	0.70
6	15	K14_1997.015[a]	36, 37, 38	Femur	25–35	M	Bronze Age	Glazkovo	TO-06866	3960 ± 60	1.70
7	16	K14_1997.016	36, 37	Femur	7–9	–[c]	Bronze Age	Glazkovo	TO-07836	3860 ± 60	2.50
8	19	K14_1997.019[a]	36, 37, 38	Femur	35–50	F	Bronze Age	Glazkovo	TO-07837	4300 ± 60	0.70
9	27	K14_1998.027.01	36, 37, 38	Femur	35–50	M	Bronze Age	Glazkovo	TO-08485	4060 ± 120	0.70
10	35	K14_1998.035.01	36, 37, 28	Femur	18–20	PM	Bronze Age	Glazkovo	TO-09381	4030 ± 70	4.70
11	35	K14_1998.035.02	46, 37	Femur	8–10	–[c]	Bronze Age	Glazkovo	TO-09382	3770 ± 140	0.30
12	36	K14_1998.036.01	36, 37, 18	Femur	35–50	–[c]	Bronze Age	Glazkovo	TO-09383	3930 ± 90	0.20
13	37	K14_1998.037.02	36, 37	Femur	14–17	–[c]	Bronze Age	Glazkovo	TO-09386	3540 ± 60	0.90
14	38	K14_1998.038	26, 37, 38/48?	Femur	35–50	M	Bronze Age	Glazkovo	TO-09387	4200 ± 90	1.10
15	39	K14_1998.039	36, 37	Femur	9–11	–[c]	Bronze Age	Glazkovo	TO-09388	3930 ± 100	1.70
16	44	K14_1999.044	36, 37, 18	Femur	35–50	M	Bronze Age	Glazkovo	TO-09391	4120 ± 180	0.30
17	45	K14_1999.045	36, 37	Femur	8–10	–[c]	Bronze Age	Glazkovo	TO-11546	4820 ± 90	1.90
18	46	K14_1999.046	36, 37, 18	Femur	25–35	M	Bronze Age	Glazkovo	TO-09393R	3910 ± 70	0.40
19	51	K14_1999.051	36, 37, 38	Femur	18–20	M	Bronze Age	Glazkovo	TO-09397	3950 ± 150	0.30
20	55	K14_1999.055	36, 17, 18	Femur	35–50	PM	Bronze Age	Glazkovo	TO-09401	4540 ± 150	0.40
21	57	K14_1999.057.02	26, 27, 38	Femur	35–50	PM	Bronze Age	Glazkovo	TO-09403	4080 ± 550	0.10
22	59	K14_1999.059.02	36, 37, 28	Femur	18–20	M	Bronze Age	Glazkovo	TO-09407	3670 ± 50	2.20
23	63	K14_2000.063	26, 27, 28	Femur	16–18	–[c]	Bronze Age	Glazkovo	TO-09412	3150 ± 70	0.50
24	64	K14_2000.064	36, 37, 38	Femur	25–35	M	Bronze Age	Glazkovo	TO-11545	3740 ± 60	1.30
25	77	K14_2000.077	36, 37, 38	Femur	12–15	–[c]	Bronze Age	Glazkovo	TO-09424	3450 ± 50	1.00

Master_ID: cemetery name in abbreviated form, excavation year, grave number, and the individual number when more than one interment was present. Age: years of age at death. Sex: M, male; PM, probable male; F, female; PF, probable female.
[a] Individuals were part of the pilot study (Weber et al., 2003).
[b] Coding according to the FDI system.
[c] Undetermined or individual unobservable for condition.

be lost during life at the contact points with adjacent teeth, resulting in gradual formation of interproximal wear facets.

Next, the outermost enamel with any discolouration or attached deposits of calculus or sediment was removed and any adhering dentine from the inner layer of enamel was similarly removed. This was accomplished using the same diamond cutting disc and its flat side to scrape gently material away in thin layers. The progress of this mechanical cleaning procedure was repeatedly checked with a seven-fold magnification hand lens using mainly the colour difference between enamel and dentine for guidance. The prepared sections of enamel were weighed on a microbalance. Enamel samples of approximately 20–30 mg were submitted for strontium chemical separation procedures although for some crowns with a more advanced stage of wear the amount of obtained enamel was less.

The midshaft of the human femur was chosen as the standardized sampling locus for bone samples. In order to facilitate inter-individual comparison of bone strontium isotope data the use of other long bones (which may have different remodelling rates) in cases where the femur was not available or not suitable was avoided. Given the general susceptibility of bone to ionic exchange with the burial environment, an important advantage of using the femur is its relatively thick cortex. This enables one to obtain a sample from the core of the cortical bone by removing mechanically both the inner and outer layer of cortex with a Dremel tool and diamond cutting disc (NTI Diamond disc, Superflex-double sided, 22 mm diameter, thickness 0.15 mm). Additional cleaning of sample surfaces and decontamination procedures applied to bone samples are included in the description of the strontium chemical separation protocol.

3.3. Environmental samples and their preparation

In order to assess biologically available strontium, faunal specimens were collected from each of the three Cis-Baikal micro-regions (Tables 3 and 4) and, if possible, from the vicinity of known archaeological sites. Terrestrial species such as roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), and moose (*Alces alces*) as well as several fish species and the lake Baikal seal (*Phoca sibirica*) were included in analysis. All of these animals are known to have been procured by prehistoric and historic hunter-gatherer groups in the region (Katzenberg and Weber, 1999; Weber et al., 2002). Guided by the concepts of strontium catchment and time averaging of isotope ratios in bone, we attempted to sample species from different trophic levels, with home ranges of different size, and with diverse feeding and migratory behaviour. Unfortunately, due to various practical considerations, it was not always possible to replicate the same species selection for each of the three basins. While most of the samples are modern,

Table 3
Strontium stable isotope ratios for terrestrial fauna from the Baikal region

Sample no.	Species	Region	Source	$^{87}Sr/^{86}Sr$	2s error
1998.238	Ground squirrel	Baikal, Little Sea, mainland	Sarma Canyon, entrance	0.74330	0.000030
2000.230	Ground squirrel	Baikal, Little Sea, Ol'khon	Shara-Nur Lake	0.71220	0.000027
1997.059	Ground squirrel	Baikal, Little Sea, mainland	Khuzhir-Nuge cove	0.71373[a]	0.000019
1997.068	Ground squirrel	Baikal, Little Sea, mainland	Khuzhir-Nuge cove	0.71329[a]	0.000019
2000.229	Ground squirrel	Baikal, Little Sea, mainland	Khuzhir-Nuge cove	0.71254	0.000037
1991.054	Moose (p)	Baikal, Little Sea, mainland	Tudugu	0.73142	0.000018
1993.151	Moose (p)	Baikal, Little Sea, mainland	Sagan-Zaba	0.71502	0.000022
1991.104	Red deer (p)	Baikal, Little Sea, Ol'khon	Shamanskii Mys	0.71176	0.000013
1991.108	Red deer (p)	Baikal, Little Sea, Ol'khon	Shamanskii Mys	0.71218	0.000009
1991.109	Roe deer (p)	Baikal, Little Sea, Ol'khon	Shamanskii Mys	0.71163	0.000051
2002.390	Red deer	Baikal, Southwest coast	Kultuk	0.70958	0.000031
2001.691	Red fox	Baikal, Northwest coast	Bolshie Koty	0.70994	0.000060
2003.704	Wolf (p)	Upper Angara valley	Lokomotiv-Raisovet Grave 8	0.71035	0.000013
2002.417	Ground squirrel	Middle Angara valley, East	Ida River	0.70906	0.000050
2001.671	Hare	Middle Angara valley, East	Batchai	0.70889	0.000026
2002.383	Hare	Middle Angara valley, East	Ida River	0.70973	0.000013
2002.384	Hare	Middle Angara valley, East	Ida River	0.70973	0.000011
2001.697	Moose	Middle Angara valley, East	Batchai	0.70974	0.000017
2001.669	Mouse	Middle Angara valley, East	Batchai	0.70917	0.000015
2002.419	Red fox	Middle Angara valley, East	Ida River	0.70907	0.000035
2002.423	Roe deer	Middle Angara valley, East	Ida River	0.70933	0.000012
2002.427	Roe deer	Middle Angara valley, East	Ida River	0.70909	0.000014
2002.429	Roe deer	Middle Angara valley, East	Ida River	0.70963	0.000018
2002.396	Ground squirrel	Middle Angara valley, West	Belaia River	0.71128	0.000018
2002.397	Ground squirrel	Middle Angara valley, West	Belaia River	0.71082	0.000029
1993.079	Red deer (p)	Middle Angara valley, West	Belaia River, Gorelyi Les	0.71183	0.000022
1993.081	Red deer (p)	Middle Angara valley, West	Belaia River, Gorelyi Les	0.71066	0.000018
1993.094	Red deer (p)	Middle Angara valley, West	Belaia River, Gorelyi Les	0.71680	0.000022
2001.757	Bear	Middle Angara valley	Bratsk	0.71073	0.000032
2001.777	Moose	Middle Angara valley	Bratsk	0.70991	0.000025
2001.760	Red deer	Middle Angara valley	Bratsk	0.70957	0.000045
2001.773	Red deer	Middle Angara valley	Bratsk	0.70920	0.000029
2001.774	Red deer	Middle Angara valley	Bratsk	0.70913	0.000025
1991.013	Dog (p)	Upper Lena valley	Obkhoi	0.70969	0.000015
2002.360	Lynx	Upper Lena valley		0.71097	0.000039
2002.361	Lynx	Upper Lena valley		0.71027	0.000062
2002.358	Mouse	Upper Lena valley		0.70882	0.000017
2002.362	Red fox	Upper Lena valley		0.70927	0.000016
2002.364	Roe deer	Upper Lena valley		0.70950	0.000013
2002.366	Roe deer	Upper Lena valley		0.71092	0.000084
2002.370	Roe deer	Upper Lena valley		0.71056	0.000052

(p) indicates prehistoric specimen.
[a] TIMS analysis.

several prehistoric specimens for some terrestrial species were also tested. Provenance was recorded when available. The age of fish specimens was generally unknown, although an effort was made to collect only adult individuals and their length (an approximate measure of age) was documented. Laboratory processing of animal samples followed the protocol used for the human bone specimens.

3.4. Strontium chemical separation and mass spectrometry

Bone samples were weighed into 1.5 ml polypropylene centrifuge tubes and sonicated for 15 min in Millipore water (MQ) and then in 5% acetic acid for 15 min. After an overnight leaching in 5% acetic acid, the acid was removed and samples were rinsed with MQ prior to transfer to clean microwave vials. After adding a known amount of ^{87}Rb-^{84}Sr spike, the samples were digested in a microwave oven in 4 ml of 16 N HNO_3 and 1 ml of ~10 N HCl. Digested samples were transferred to a clean Teflon vial and dried overnight on a hot plate (80 °C). Dried samples were dissolved in 3 ml of 0.75 N HCl and centrifuged at 5000 rpm for 10 min prior to loading onto columns. Columns were rinsed with 3 × 1 ml of 0.75 N HCl, 3 × 1 ml of 2.5 N HCl and washed with 17 ml of 2.5 N HCl. Samples of 5 ml of 2.5 N HCl containing the purified Sr each were collected into Teflon vials with an added drop of H_3PO_4 and then left to dry overnight on a hot plate (80 °C).

Purified strontium samples were submitted for mass spectrometry analysis, using thermal ionization mass spectrometry (TIMS) for the specimens examined in the pilot study, but shifting to solution mode multi-collector inductively coupled

Table 4
Strontium stable isotope ratios for aquatic fauna from the Baikal region

Sample no.	Species	Region	Source	$^{87}Sr/^{86}Sr$	2s error
1998.013	Baikal sturgeon	Baikal	n/a	0.70818	0.000013
1998.014	Baikal sturgeon	Baikal	n/a	0.70857	0.000015
1997.111	Omul'	Baikal	n/a	0.70852[a]	0.000023
1997.113	Omul'	Baikal	n/a	0.70851[a]	0.000019
1997.114	Omul'	Baikal	n/a	0.70855[a]	0.000018
1993.098	Seal	Baikal	n/a	0.70857[a]	0.000016
1993.100	Seal	Baikal	n/a	0.70858[a]	0.000019
1993.101	Seal	Baikal	n/a	0.70858[a]	0.000020
2000.546	Northern pike	Baikal	Little Sea	0.70985	0.000025
2000.547	Northern pike	Baikal	Little Sea	0.71141	0.000018
2001.707	Northern pike	Baikal	Little Sea	0.72829	0.000016
2002.307	Black grayling	Upper Angara	Irkutsk	0.70878	0.000034
2002.308	Black grayling	Upper Angara	Irkutsk	0.70900	0.000032
2002.309	Black grayling	Upper Angara	Irkutsk	0.70880	0.000019
2002.449	Burbot	Middle Angara, East	Ida River	0.70824	0.000029
2002.450	Burbot	Middle Angara, East	Ida River	0.70813	0.000022
2002.451	Burbot	Middle Angara, East	Ida River	0.70879	0.000018
2002.444	Prussian carp	Middle Angara, East	Ida River	0.70856	0.000031
2002.445	Prussian carp	Middle Angara, East	Ida River	0.70831	0.000020
2002.452	Prussian carp	Middle Angara, East	Ida River	0.70811	0.000022
2002.406	Dace	Middle Angara, West	Belaia River	0.71004	0.000034
2002.409	Dace	Middle Angara, West	Belaia River	0.71137	0.000029
2002.410	Dace	Middle Angara, West	Belaia River	0.70928	0.000031
2002.400	Perch	Middle Angara, West	Belaia River	0.70907	0.000023
2002.401	Perch	Middle Angara, West	Belaia River	0.70983	0.000030
2002.403	Perch	Middle Angara, West	Belaia River	0.70951	0.000021
2001.765	Arctic grayling	Middle Angara	Bratsk	0.70880	0.000023
2001.766	Arctic grayling	Middle Angara	Bratsk	0.70888	0.000027
2001.767	Arctic grayling	Middle Angara	Bratsk	0.70968	0.000039
2002.354	Dace	Upper Lena	n/a	0.70888	0.000019
2002.356	Dace	Upper Lena	n/a	0.70881	0.000018
2002.357	Dace	Upper Lena	n/a	0.70882	0.000014
2002.342	Perch	Upper Lena	n/a	0.70895	0.000021
2002.343	Perch	Upper Lena	n/a	0.70895	0.000015
2002.344	Perch	Upper Lena	n/a	0.70895	0.000017
2002.345	Roach	Upper Lena	n/a	0.70881	0.000013
2002.346	Roach	Upper Lena	n/a	0.70887	0.000016
2002.347	Roach	Upper Lena	n/a	0.70889	0.000018

[a] TIMS analysis.

plasma mass spectrometry (MC-ICP-MS) when it became available. The latter measurement is a much faster procedure that allowed for analysis of up to 30 samples in a single day. For the pilot study, mass analysis was performed with a Micromass Sector 54 9-collector mass spectrometer operating in multidynamic mode. For solution mode MC-ICP-MS, the purified strontium was dissolved in 2% HNO_3 and then diluted appropriately to avoid detector overload. The diluted sample was introduced into the ICP unit via a desolvating nebulizing system (DSN-100 from Nu Instruments Inc.) and strontium isotope data were obtained in static, multicollection mode using six Faraday collectors. For each sample, data acquisition consisted of 40 individual measurements. All ratios were calculated relative to the NIST SRM987 strontium isotopic standard using a value of 0.710245. External reproducibility of the standard was 0.710194 (SD 0.000033) and 0.710242 (SD 0.000041) for the TIMS and MC-ICP-MS analyses, respectively.

For several specimens, replicate Sr isotope analyses were performed and these exhibit differences between 0.00004 and 0.00087 (Table 5). The larger discrepancies between replicate analyses (e.g. sample 1997.193) are attributed to a small degree of isotopic inhomogeneity within the sample; however, even the largest discrepancy is an order of magnitude lower than the overall Sr isotope variation exhibited by the entire data set and hence does not exert an important influence on the interpretations being presented. While all results are presented in Tables 3–5, the means were calculated for the purpose of graphic presentation and further interpretation of the data. All samples were processed and analyzed by the Radiogenic Isotope Facility, Department of Earth and Atmospheric Sciences, University of Alberta, under the joint direction of R.A. Creaser and A. Simonetti.

4. Factors affecting $^{87}Sr/^{86}Sr$ in human tissues

Some of the frequently discussed variables affecting $^{87}Sr/^{86}Sr$ in human tissues include the geological structures and biologically available strontium, tissue biology, trophic

Table 5
Khuzhir-Nuge XIV, human strontium stable isotope ratios

Burial	Master ID	Sample no.	Sample type	$^{87}Sr/^{86}Sr$	2s error
B.7	K14_1997.007	1997.197	M1	0.70940	0.000052
B.7	K14_1997.007	1997.211	M2	0.71075	0.000023
B.7	K14_1997.007	1997.220	M3	0.70906	0.000015
B.7	K14_1997.007	1997.407	Femur	0.70888	0.000014
B.10[a]	K14_1997.010	1997.189	M1	0.71006	0.000019
B.10[a]	K14_1997.010	1997.212	M2	0.71041	0.000020
B.10[a]	K14_1997.010	1997.223	M3	0.71002	0.000019
B.10	K14_1997.010	1997.223 (r)	M3	0.70989	0.000020
B.10[a]	K14_1997.010	1997.200	Femur	0.70958	0.000013
B.10	K14_1997.010	1997.200 (r)	Femur	0.71013	0.000020
B.10	K14_1997.010	1997.412	Femur	0.71022	0.000015
B.11[a]	K14_1997.011	1997.190	M1	0.71349	0.000019
B.11[a]	K14_1997.011	1997.213	M2	0.71295	0.000016
B.11[a]	K14_1997.011	1997.224	M3	0.71318	0.000020
B.11	K14_1997.011	1997.224 (r)	M3	0.71322	0.000019
B.11[a]	K14_1997.011	1997.201	Femur	0.71109	0.000026
B.12[a]	K14_1997.012	1997.191	M1	0.71554	0.000016
B.12[a]	K14_1997.012	1997.214	M2	0.71640	0.000018
B.12[a]	K14_1997.012	1997.225	M3	0.71285	0.000020
B.12	K14_1997.012	1997.225 (r)	M3	0.71329	0.000019
B.12[a]	K14_1997.012	1997.202	Femur	0.70981	0.000042
B.12	K14_1997.012	1997.202 (r)	Femur	0.71068	0.000035
B.12	K14_1997.012	1997.408	Femur	0.70983	0.000016
B.14[a]	K14_1997.014	1997.192	M1	0.71344	0.000017
B.14[a]	K14_1997.014	1997.215	M2	0.71364	0.000015
B.14[a]	K14_1997.014	1997.226	M3	0.71227	0.000016
B.14[a]	K14_1997.014	1997.203	Femur	0.71140	0.000037
B.15[a]	K14_1997.015	1997.193	M1	0.71389	0.000019
B.15[a]	K14_1997.015	1997.193 (r)	M1	0.71316	0.000019
B.15[a]	K14_1997.015	1997.216	M2	0.71190	0.000021
B.15[a]	K14_1997.015	1997.227	M3	0.71170	0.000019
B.15[a]	K14_1997.015	1997.204	Femur	0.71129	0.000043
B.16	K14_1997.016	1997.194	M1	0.71451	0.000026
B.16	K14_1997.016	1997.217	M2	0.71320	0.000026
B.16	K14_1997.016	2003.584	Femur	0.71096	0.000026
B.19[a]	K14_1997.019	1997.196	M1	0.72126	0.000019
B.19[a]	K14_1997.019	1997.219	M2	0.71709	0.000023
B.19[a]	K14_1997.019	1997.229	M3	0.71161	0.000020
B.19[a]	K14_1997.019	1997.206	Femur	0.71085	0.000023
B.27-1	K14_1998.027.01	1998.331	M1	0.70997	0.000017
B.27-1	K14_1998.027.01	1998.330	M2	0.70976	0.000026
B.27-1	K14_1998.027.01	1998.332	M3	0.70982	0.000018
B.27-1	K14_1998.027.01	1998.304	Femur	0.71037	0.000013
B.35-1	K14_1998.035.01	1998.354	M1	0.71112	0.000027
B.35-1	K14_1998.035.01	1998.355	M2	0.71080	0.000023
B.35-1	K14_1998.035.01	1998.356	M3	0.71063	0.000012
B.35-1	K14_1998.035.01	1998.312	Femur	0.71012	0.000019
B.35-1	K14_1998.035.01	1998.391	Femur	0.71004	0.000020
B.35-1	K14_1998.035.01	2001.597	Femur	0.71012	0.000016
B.35-2	K14_1998.035.02	1998.358	M1	0.71157	0.000033
B.35-2	K14_1998.035.02	1998.359	M2	0.71054	0.000031
B.35-2	K14_1998.035.02	2003.597	Femur	0.71036	0.000027
B.36-1	K14_1998.036.01	1998.362	M1	0.71146	0.000028
B.36-1	K14_1998.036.01	1998.363	M2	0.71393	0.000018
B.36-1	K14_1998.036.01	1998.364	M3	0.71125	0.000015
B.36-1	K14_1998.036.01	1998.318	Femur	0.71063	0.000014
B.37-2	K14_1998.037.02	1998.372	M1	0.71091	0.000030
B.37-2	K14_1998.037.02	1998.373	M2	0.71276	0.000031
B.37-2	K14_1998.037.02	1998.321	Femur	0.70993	0.000013
B.38	K14_1998.038	1998.376	M1	0.71103	0.000027
B.38	K14_1998.038	1998.377	M2	0.71064	0.000027
B.38	K14_1998.038	1998.378	M3	0.71153	0.000015
B.38	K14_1998.038	1998.322	Femur	0.71005	0.000019
B.39	K14_1998.039	1998.379	M1	0.71196	0.000017
B.39	K14_1998.039	1998.380	M2	0.71334	0.000051
B.39	K14_1998.039	2003.591	Femur	0.71066	0.000022
B.44	K14_1999.044	1999.163	M1	0.71288	0.000059
B.44	K14_1999.044	1999.164	M2	0.71179	0.000022
B.44	K14_1999.044	1999.165	M3	0.71186	0.000018
B.44	K14_1999.044	1999.179	Femur	0.71129	0.000015
B.45	K14_1999.045	1999.156	M1	0.71507	0.000039
B.45	K14_1999.045	1999.157	M2	0.71292	0.000022
B.45	K14_1999.045	2003.623	Femur	0.71056	0.000021
B.46	K14_1999.046	1999.129	M1	0.71040	0.000042
B.46	K14_1999.046	1999.130	M2	0.71014	0.000016
B.46	K14_1999.046	1999.131	M3	0.70997	0.000017
B.46	K14_1999.046	1999.127	Femur	0.71012	0.000015
B.51	K14_1999.051	1999.134	M1	0.71109	0.000022
B.51	K14_1999.051	1999.135	M2	0.71397	0.000021
B.51	K14_1999.051	1999.136	M3	0.71226	0.000015
B.51	K14_1999.051	1999.137	Femur	0.71014	0.000017
B.55	K14_1999.055	1999.140	M1	0.71196	0.000018
B.55	K14_1999.055	1999.141	M2	0.71166	0.000019
B.55	K14_1999.055	1999.142	M3	0.71183	0.000015
B.55	K14_1999.055	1999.139	Femur	0.71152	0.000012
B.57-2	K14_1999.057.02	2001.644	M1	0.71046	0.000035
B.57-2	K14_1999.057.02	2001.645	M2	0.71347	0.000016
B.57-2	K14_1999.057.02	2001.646	M3	0.71302	0.000018
B.57-2	K14_1999.057.02	1999.175	Femur	0.71096	0.000018
B.59-2	K14_1999.059.02	1999.172	M1	0.71375	0.000024
B.59-2	K14_1999.059.02	1999.173	M2	0.71197	0.000020
B.59-2	K14_1999.059.02	2001.637	M3	0.71147	0.000018
B.59-2	K14_1999.059.02	1999.185	Femur	0.71040	0.000018
B.63	K14_2000.063	2000.141	M1	0.71606	0.000023
B.63	K14_2000.063	2000.142	M2	0.71305	0.000014
B.63	K14_2000.063	2000.143	M3	0.71460	0.000018
B.63	K14_2000.063	2000.144	Femur	0.71138	0.000017
B.64	K14_2000.064	2000.126	M1	0.71679	0.000030
B.64	K14_2000.064	2000.127	M2	0.71201	0.000017
B.64	K14_2000.064	2000.128	M3	0.71598	0.000019
B.64	K14_2000.064	2003.616	Femur	0.71064	0.000033
B.77	K14_2000.077	2000.166	M1	0.70966	0.000022
B.77	K14_2000.077	2000.167	M2	0.70949	0.000022
B.77	K14_2000.077	2000.168	M3	0.71032	0.000016
B.77	K14_2000.077	2000.530	Femur	0.70969	0.000017

(r) indicates repeat analysis.
[a] Results published first by Weber et al. (2003) using the TIMS analysis.

level effect, dietary preferences, and migratory behaviour all contributing to Sr-catchment (cf. Bentley and Knipper, 2005; Bentley, 2006; Price et al., 2002). Factors directly relevant to this study are discussed below.

4.1. Geological framework of Cis-Baikal

The study region can be subdivided into three major zones (Fig. 1). The area along the west coast of the lake, which includes the Primorskii and Baikalskii mountain ranges, is expected to be characterized by relatively high $^{87}Sr/^{86}Sr$ (~0.720–0.735) due to the presence of Archean and Proterozoic granites (Galazii, 1993). Similar bedrock occurs around the southwestern shores of Lake Baikal and part of the western drainage basin of the Angara River adjacent to the Eastern

Sayan Mountains. The upper section of the Angara River flows through Mesozoic and Quaternary deposits, with expected $^{87}Sr/^{86}Sr$ in the range of 0.705–0.710. The upper Lena watershed, part of the Central Siberian Plateau, is dominated by Cambrian and Precambrian limestones for which $^{87}Sr/^{86}Sr$ ratios of around 0.709 have been reported (Huh et al., 1994). The overall $^{87}Sr/^{86}Sr$ for Lake Baikal water is reported as 0.7085 (Kenison Falkner et al., 1992) and 0.70893 for the upper Lena (Huh et al., 1998). These main geological zones within Cis-Baikal show considerable overlap with the three main archaeological micro-regions: (1) the Baikal basin including the Ol'khon area; (2) the drainage of the upper and middle Angara River; and (3) the upper Lena River basin.

4.2. Biologically available strontium isotope ratios in Cis-Baikal

While the three geological zones mentioned above constitute a useful general framework of reference, the biologically available strontium isotope ratios in various animals provide more direct guidelines and models for analysis and interpretation of the human data (Bentley and Knipper, 2005; Hodell et al., 2004; Price et al., 2002). Because the middle Holocene foragers used terrestrial as well as aquatic resources (Katzenberg and Weber, 1999), our study involved materials representing both ecosystems (Tables 3 and 4). On the regional scale the terrestrial samples display a wide range of strontium isotope ratios and a few interesting patterns can be observed. First, the size of the animal Sr-catchment and proximity to geological formations with high $^{87}Sr/^{86}Sr$ appear to be the main factors controlling $^{87}Sr/^{86}Sr$ in terrestrial animals. For example, the specimens from the Little Sea micro-region produced the most variable, including the highest, $^{87}Sr/^{86}Sr$ ratios. Furthermore, animals with very small Sr-catchment (suslik, mouse) clearly have more variable $^{87}Sr/^{86}Sr$ than the animals with large catchments (red deer, roe deer) even in the areas where the background geological $^{87}Sr/^{86}Sr$ is quite uniform and low (e.g., on the upper Lena). The lowest $^{87}Sr/^{86}Sr$ (0.70882) was recorded for a mouse in the upper Lena basin and the highest (0.74330) for a suslik found near the entrance to the Sarma Canyon in the Little Sea area. The large herbivores also seem to conform to this pattern: in the Little Sea area, the moose, whose procurement range is relatively small, produced $^{87}Sr/^{86}Sr$ much more variable than found in the roe deer which is known for its very long treks. And last, the Angara valley evinced some additional spatial differences between the areas to the east and to the west of the river. While sample sizes in both cases are small, the specimens from the east feature lower mean and are less variable (mean 0.70934, SD 0.000332, $n = 10$) compared to the area to the west (mean 0.71228, SD 0.002569, $n = 5$).

The overall variability for the aquatic specimens is limited, with the exception of $^{87}Sr/^{86}Sr$ for three pike specimens from the Little Sea region (Table 4). In this micro-region the pike with the highest $^{87}Sr/^{86}Sr$ of all aquatic samples came from the same area as the highest result for the suslik. Perch and dace are the only two fishes that were analyzed for both the Lena and Angara Rivers with the mean values of 0.70884 and 0.71023, respectively. The differences observed in the strontium isotope ratios clearly show that these two river systems have somewhat different geochemical characteristics. Apart from this, the fish data also suggest that the east side of the Angara valley (mean 0.70836, SD 0.000332, $n = 10$) differs from the west side (mean 0.70985, SD 0.002569, $n = 5$) in terms of $^{87}Sr/^{86}Sr$, a pattern visible also in the data obtained for the terrestrial species.

Overall, these data demonstrate that in Cis-Baikal the biologically available $^{87}Sr/^{86}Sr$ is sufficiently variable to be useful for archaeological applications. These differences consider not only the terrestrial ecosystem, but also the aquatic. The Little Sea area on Lake Baikal is clearly distinguishable from the rest of Cis-Baikal with its much higher on average $^{87}Sr/^{86}Sr$ and also, rather unexpectedly, much more variable values on the intra- and inter-species levels compared to the rest of Cis-Baikal. Interestingly, biologically available strontium in the eastern and western parts of the Angara drainage appears to be distinguishable too. The upper Lena, however, turned out to be similar to the eastern part of the Angara valley.

4.3. Glazkovo diet

Paleodiet reconstruction based on stable carbon and nitrogen isotopes has focused on human bone and a combination of terrestrial and aquatic animal species thought to have been exploited by hunter-gatherer groups in Cis-Baikal. To date only one plant sample has been analyzed: pine nuts with $\delta^{13}C$ of $-22.7‰$ (Lam, 1994). However, there are no known C_4 plants in the region so it has been assumed that plant foods in the diet would result in $\delta^{13}C$ typical of C_3 plants (averaging $-25‰$) and less enriched $\delta^{15}N$ values. Ethnographic information on other boreal forest peoples in both Canada and Siberia indicates an emphasis on animal foods with some contributions from seasonally available berries (Alekseenko, 1999; Asch, 1981; Helm, 1981). Many of the same faunal samples analyzed for $^{87}Sr/^{86}Sr$ are also being analyzed for stable isotopes of carbon and nitrogen, and some have been reported previously (Katzenberg and Weber, 1999; Weber et al., 2002).

The available carbon and nitrogen stable isotope data suggest that all Neolithic as well as Bronze Age hunter-gatherer groups in Cis-Baikal had a diet distinctly dominated by meat over plant foods (Katzenberg and Weber, 1999; Weber et al., 2002). The meat component included herbivores, various fishes, and seal—the last food item available on a seasonal basis to the groups residing on the shores of Lake Baikal including the Little Sea micro-region. The same data imply that intra-populational variability in diet composition was limited and that in the Little Sea area the lagoon fishes (pike, perch, dace, and roach) contributed most to the overall catch. It appears that the pelagic omul', the most abundant commercial fish during the historical times, did not play a significant role in Neolithic and Bronze Age fishing—a notion supported also by the faunal assemblages (Losey et al., in press).

As mentioned earlier, strontium in human body tissues derives from three sources: animal and plant foods, and drinking water. Overall strontium concentrations in organisms decrease with increasing trophic levels due to the preferred uptake of calcium over strontium across biological membranes (biopurification). Because strontium tends to accumulate in the hard tissues, when a human diet is predominantly based on meat, the other sources of strontium, namely plants and water, could theoretically contribute most of the strontium to the diet. It seems to follow then, that due to the relatively minimal contribution of plants to the diet of these groups, strontium stable isotope signatures as measured in bone or tooth enamel were affected most by water, next by aquatic foods which may include consumption of small bones, and lastly by herbivore meat. This supposition, however, will have to remain conjectural until mathematical models are developed to account better for these very complex processes. The situation is further complicated by the fact that while $^{87}Sr/^{86}Sr$ of the Lake Baikal water appears to be similar to the Angara and upper Lena Rivers and also to the bedrock formations underlying most of these two micro-regions, some of the smaller rivers flowing into Lake Baikal clearly have much elevated values consistent with the geological formations of the mountains enveloping the lake (Huh and Edmond, 1997).

Since addressing the concerns mentioned in this section requires dedicated geochemical research, the main resulting guideline for our study is that the strong aquatic component of the Glazkovo diet would result in lower and perhaps less variable $^{87}Sr/^{86}Sr$ in human samples. In turn, more terrestrial herbivore meat from species inhabiting the Little Sea area and the drainage basins of its small rivers may result in higher and perhaps more variable $^{87}Sr/^{86}Sr$. Both patterns find direct support in our environmental samples (Tables 3 and 4).

4.4. Food sharing

Food sharing is an important element of any hunter-gatherer adaptive strategy. Through this behaviour, individuals can incorporate strontium into their bodies from parts of the territory that they themselves have never visited. At this point it is useful to bring into our discussion the concepts of logistical and residential mobility—the two ideal models of hunter-gatherer movement across landscape *sensu* Binford (1980). Sharing, of course, is the principal idea underlying the logistical model. This should not, of course, be construed as if the groups following the residential model of mobility do not share their food. In the logistical model a task group travels on behalf of some social unit into more distant locations in pursuit of prey or other resources. While the individuals of such logistic parties will consume resources encountered during travelling, the ultimate goal of the trip is to bring collected food back to the main camp for sharing with the rest of the group. The implication of this would be that at least some of the geochemical differences in inter-individual signatures possibly resulting from such trips repeated on a long-term basis would be eventually masked by sharing. While sharing patterns were likely the same within the entire Glazkovo regional community, the procurement ranges of the smaller social units did not have to be. Therefore the variability visible in $^{87}Sr/^{86}Sr$ more likely reflects the differences in the size and location of procurement ranges used by these smaller social units. However, if we were able to define these social units based on some other independent criteria and assuming that such a unit operated within a well defined procurement range, then the presence of even relatively minor inter-individual variability may be viewed as indicative of the employment of logistical mobility.

The matter would evidently look much different for groups whose procurement was organized according to the residential model in which the entire social unit moves as a whole from one resource patch to another. It is clear that in this particular case not only the inter-individual variability in $^{87}Sr/^{86}Sr$ should be lower, due to both sharing and mobility pattern, but the degree of intra-individual variability between the teeth and bone samples is also expected to be minimal. In sum, the strontium isotope method offers some promise with regard to the identification of mobility patterns functioning in hunter-gatherer groups.

4.5. Availability of mobility-related technology

The last source of potential variability to consider regards the environmental and cultural factors affecting the ability of Glazkovo people to travel across Cis-Baikal. In most northern environments travel is much easier in winter than during the warm seasons. Similarly, in Cis-Baikal the rivers flowing through the dense taiga may impede travel in summer, but facilitate winter movement when they are frozen. The winter factor would be less important for the upper section of the Angara and the Little Sea both featuring steppe or parkland vegetation. The lake, normally frozen for about three to four months only, would also make travel along its mountainous coast less troublesome. While it is useful to mention these environmental factors, their role in the investigated processes is relatively easy to take into account because they affected mobility of each smaller Glazkovo social unit in the same way.

The role of two potentially important cultural variables, however, is less clear. They regard availability of water craft and domestication of reindeer. While there is no direct archaeological support (e.g., paddles) for the use of boats during the entire Cis-Baikal Neolithic and Bronze Age, a few indirect lines of evidence suggest that water craft could have been available already during the Early Neolithic. These clues include the familiarity with birch bark technology and the use of sinkers, likely in fishing, both documented already for the Early Neolithic, as well as petroglyphs depicting boats dating perhaps to the Bronze Age (Goriunova and Novikov, 2004).

The question of reindeer domestication and use for transportation is equally, if not more, ambiguous. Traditionally, based on ethnohistorical data, Russian scholars believe that domestication of reindeer occurred in Siberia very late, certainly not during the prehistoric times. However, there is no apparent reason why this animal—relatively docile, of high endurance, and relatively easy to feed, thus of high utility to hunter-gatherers—could not be domesticated much earlier than commonly believed. The fact that zooarchaeological research in the entire Siberia remains in a nascent stage offers no help here, but at least does not contradict this hypothesis either. Possibly, the strontium isotope approach may reveal dimensions of hunter-gatherer mobility in Cis-Baikal that cannot be explained in any other way than by invoking domestic use of this animal.

The possible employment of both technologies has important implications for the overall potential foraging range. Obviously, they would have facilitated access to a much larger procurement range and distant resource patches within the same or even less time. Likewise, they would have altered the dynamics of any foraging trip because of their impact on transporting loads of both resources and people. In sum, if employed on a significant scale these two agents should lead to reduction of variability in strontium signatures at all levels (i.e., intra- and inter-individual, and inter-group) that would otherwise result from other factors.

5. Results and discussion

Using the interpretive framework presented above, we can now examine the human $^{87}Sr/^{86}Sr$ data from the KN XIV cemetery to address our main research questions. Given the period of use of the KN XIV, our strontium isotope data pertain to several generations of Glazkovo foragers, and as such reflect both spatial and temporal aspects of land use and mobility patterns. Because of space considerations, the following discussion focuses primarily on examination of the most general points. Furthermore, due to the rather small samples sizes available for the various units of analysis, we employ mostly a qualitative approach; however, we frequently refer to descriptive statistics which, for the human samples, are presented in Table 6.

Table 6
Khuzhir-Nuge XIV, descriptive statistics for human strontium stable isotope ratios grouped by intra-individual distribution patterns (adults only)

Descriptive statistic	M1	M2	M3	Femur
Pattern 1				
Mean	0.71040	0.71055	0.71023	0.70990
SD	0.000712	0.000273	0.000919	0.000607
Range	0.00172	0.00066	0.00248	0.00148
Minimum	0.70940	0.71014	0.70906	0.70888
Maximum	0.71112	0.71080	0.71153	0.71037
Count	5	5	5	5
Pattern 2a				
Mean	0.71512	0.71341	0.71348	0.71046
SD	0.001462	0.001814	0.001816	0.000557
Range	0.00335	0.00443	0.00452	0.00129
Minimum	0.71344	0.71197	0.71147	0.71011
Maximum	0.71679	0.71640	0.71598	0.71140
Count	5	5	5	5
Pattern 2b				
Mean	0.71100	0.71379	0.71218	0.71048
SD	0.000507	0.000275	0.000886	0.000704
Range	0.00100	0.00049	0.00177	0.00124
Minimum	0.71046	0.71347	0.71125	0.71005
Maximum	0.71146	0.71397	0.71302	0.71129
Count	3	3	3	3
Pattern 3				
Mean	0.71127	0.71097	0.71129	0.71103
SD	0.001797	0.001636	0.001532	0.000369
Range	0.00383	0.00346	0.00338	0.00086
Minimum	0.70966	0.70949	0.70982	0.71066
Maximum	0.71349	0.71295	0.71320	0.71152
Count	4	4	4	4
Pattern 4				
Mean	0.71589	0.71359	0.71172	0.71096
SD	0.004662	0.003028	0.000127	0.000329
Range	0.00838	0.00530	0.00025	0.00066
Minimum	0.71288	0.71179	0.71161	0.71063
Maximum	0.72126	0.71709	0.71186	0.71129
Count	3	3	3	3

5.1. General patterns

The fact that most of the human $^{87}Sr/^{86}Sr$ values fall within the lower half of the 0.710–0.715 range (Fig. 2), when the terrestrial environmental signatures along the west coast of Lake Baikal belong to the upper half and some are much higher (Table 3), could mean that resources from the lake (water, fishes, and seal; Table 4) contributed significantly to the human $^{87}Sr/^{86}Sr$ values. However, the inland region behind the Primorskii Range (mostly the upper Lena basin, but also the eastern half of the Angara valley) is characterized by similarly low strontium isotope ratios. Therefore, in this particular area, relying on strontium isotope ratios alone it is not possible to differentiate between aquatic resources from the lake on the one hand, and terrestrial resources from the upper Lena or Angara on the other. Nevertheless, as mentioned earlier, the carbon and nitrogen stable isotope data for the KN XIV and other Little Sea cemeteries confirm the substantial contribution of local aquatic foods.

Another issue that needs to be addressed is the overall convergence of all strontium isotope values with first molars and bone specimens displaying highest and lowest variability, respectively (Fig. 2). It is important to reiterate that bone, because of its continuous remodelling during life, reflects on average more time than all enamel from a tooth crown. Naturally, the overall variability for such samples is greatly reduced which could partly explain the similarity and convergence of the bone strontium isotope ratios. However, an equally relevant possibility is the overall susceptibility of bone to diagenetic alteration which would result in a gradual equilibration of $^{87}Sr/^{86}Sr$ in the bones with those of the surrounding burial matrix, specifically the soluble fraction (Bentley, 2006). The fact that the overall bedrock values in the area of the KN XIV cemetery are much higher would appear to counter this argument (cf. suslik values; Table 3). Comparative human $^{87}Sr/^{86}Sr$ data from the other micro-regions of Cis-Baikal will greatly assist in more conclusive assessment of both of these matters. For now, in the remainder of our study we assume that the bone values provide generally legitimate behavioural information (Ezzo et al., 2003).

One more conspicuous trend displayed by the entire data set is that the variability range for all molar samples is about three times greater than for the bone samples (Fig. 2). This may suggest quite different principles shaping subadult and adult mobility, however, the shorter time intervals involved

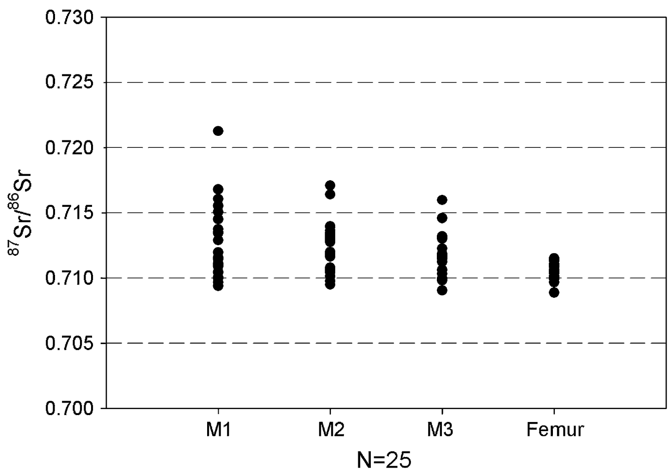

Fig. 2. Khuzhir-Nuge XIV, strontium stable isotope ratios grouped by specimen type.

in the formation of tooth enamel or difference in dietary intake, particularly for M1, may also account for this pattern.

In Fig. 3 the adult individuals have been arranged according to the observed patterning of the intra-individual $^{87}Sr/^{86}Sr$ values. The individual from Grave 7, the single Serovo burial, is shown on the left side of the graph separately from the Glazkovo individuals. Although classification of a few cases is somewhat arbitrary (e.g., B. 14 in Pattern 2a), examination of this data set reveals four distinct types of intra-individual variability for the adult Glazkovo individuals:

Pattern 1 Relatively similar isotope ratios for all four samples (3 teeth and 1 bone) were found in four individuals (B. 10, 35.1, 38, and 46). Interestingly, the clustering of the strontium signatures available for each individual in this group occurs towards the lower portion of the entire variability range documented for the KN XIV community.

Pattern 2 Quite different results for each of the examined specimens were produced for a group of eight individuals. This pattern can be further divided into two additional trends: (a) in five burials (No. 12, 14, 59.2, 63, and 64) the values for M1, and in a few cases also for M2, are much higher than the values recorded for the femur; and (b) in the remaining three individuals M1 values are very close to the femora but M2s and M3s are much different (i.e., higher).

Pattern 3 In this group of results, observed in four individuals (B. 11, 27.1, 55, and 77), all three molars give fairly similar ratios, but the bone sample yields a different value, either higher or lower than the teeth data.

Pattern 4 Documented in three individuals (B. 15, 19, and 44), is characterized by a deviating value only for M1. Burial 19 shows also a very different value for M2.

With this summary description of the variability in strontium signatures for the KN XIV community we can now proceed to the interpretation of the identified patterns. Pattern 1 seems to represent individuals whose lifetime procurement ranges did not undergo any substantial changes in terms of access to the biologically available strontium as evidenced by the homogenous values for all four samples examined. The observed clustering also suggests that these procurement ranges were relatively stable in terms of geographic location and perhaps also in size. These inferences are based on the expectation that if the procurement ranges at different life stages of these people differed in location and size, their strontium signatures should also vary due to the geological diversity of

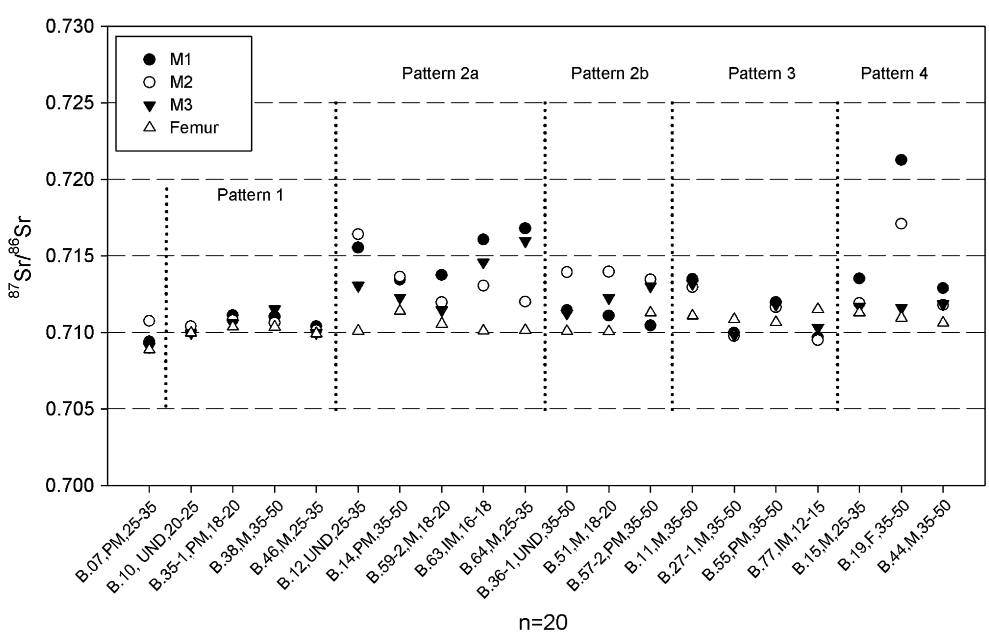

Fig. 3. Khuzhir-Nuge XIV, strontium stable isotope ratios grouped by distribution patterns. The labels for the 'x' axis provide information about the burial number as well as the sex and age. Abbreviations: B, burial; M, male; PM, probable male; F, female; UND, undeterminable; IM, immature.

the Baikal region. The $^{87}Sr/^{86}Sr$ signatures of these individuals belong, as mentioned above, to the lower end of the KN XIV variability range and they are also quite consistent with most of the terrestrial and aquatic animal samples for which Cis-Baikal averages are around 0.711 and 0.709, respectively (Tables 3 and 4). With the mean of 0.71771 (SD 0.010778, $n = 10$), the terrestrial animals from the Little Sea micro-region are the only territorial group of environmental samples that is inconsistent with the humans from Pattern 1. Based on this, it appears that procurement ranges of Pattern 1 individuals were either quite large encompassing territories outside of the Little Sea, namely the Angara and upper Lena valleys, or that they were actually located entirely outside of the Little Sea. However, if the latter was the case, the question arises why these people were buried at KN XIV. It seems more plausible that these persons were born outside of the Little Sea and active more or less equally in the entire Cis-Baikal and perhaps even beyond or, at least, that the Little Sea was not the only area of their long term residence and procurement behaviour. Despite this, their societal ties with the Little Sea Glazkovo community must have been strong enough to warrant their interment according to the mortuary protocol common to this micro-region. Another possibility is that while Pattern 1 persons lived their lives in the Little Sea area, their Sr-catchment was dominated by the aquatic resources of this micro-region.

Pattern 2, characterized by conspicuous intra-individual heterogeneity of $^{87}Sr/^{86}Sr$ ratios for each individual in this group, clearly reflects different lifetime trends in procurement ranges both with regards to location and size. In geochemical terms Pattern 2 appears to correspond to substantial changes to procurement ranges over the lifetime as well as access to resources with different biologically available strontium signatures. Because the enamel samples from each molar include a full year at the minimum, the observed variation cannot be attributed to seasonal differences in resource use but rather involved extended periods of time spent in various areas of Cis-Baikal.

The generally high values for the molars, however gradually decreasing for each next tooth, suggest that Pattern 2a individuals were born in the Little Sea area and spent much of their childhood years there, but with adulthood approaching their procurement ranges increasingly matched those from Pattern 1. The individuals belonging to Pattern 2b clearly could not have been born or have spent their earliest childhood in the same area as Pattern 2a people, that is, if we are correct in our interpretation, not in the Little Sea area. However, as soon as the stage in life marked by the formation of M2 enamel, procurement ranges of both groups were likely quite compatible with each other in terms of their size, location and amount of time these people lived there. Based on the available evidence, our best conjecture at the moment is that Pattern 2b people were born and spent much of their early childhood either in the Angara valley or on the upper Lena.

Pattern 3, found in four individuals, is interesting, but somewhat difficult to interpret. The clustering of the molar values suggests that during this stage of their lives (0–15 years old), procurement ranges of these individuals were quite stable in size and location. Two of these persons might have been based in the Little Sea area (B. 11 and 55), while the other two (B. 27.1 and 77) probably lived elsewhere. By the age represented by the femur samples their procurement ranges essentially matched the rest of the adult segment of the KN XIV community. Since the three adult individuals in this group were assessed to be up to 50 years old (y.o.), it is not possible to ascertain when in their lifetime this change occurred. The fourth person (12–15 y.o.) likely moved to the Little Sea area not long before death. The difference in time interval represented by tooth enamel and femur samples further corroborates, in our opinion, this interpretation. Namely, the total time represented by all three molars together is similar to that of the bone tissue, yet the cluster of the tooth values in each case differs from the femur value.

Pattern 4 is what has often been used in the literature as an indicator of migration from a place of birth to a different region where the individual died. Recall, however, that these studies examined sedentary farming communities rather than inherently mobile hunter-gatherers and that only M1 (or another similarly early forming tooth) and adult bone specimens (usually femur fragments) were analyzed. In our case the interpretation is not equally straightforward because the variability in $^{87}Sr/^{86}Sr$ values may result from the changes in the location and size of the procurement range, the latter assumed to be negligible factor in the studies of farming communities. Since M1 and M2 values for Burial 19 are clearly the highest within the entire data set, including the group of individuals considered to be born within the Little Sea area (Pattern 2a) this person's homeland was likely elsewhere than in any of the three micro-regions discussed in our study. An alternative explanation perhaps is that only the individuals with the highest M1 values, e.g. above 0.715 were born within the Little Sea area, while the rest are all immigrants from elsewhere. The other two individuals from Pattern 4 (B. 15 and 44) are somewhat ambiguous in that their M1 values do not differ as much from the other results; both perhaps should rather be classified as Pattern 2a.

The last matter to address here is the procurement range of the subadult segment (<15 y.o.) of the KN XIV community. In addition to the subadult life histories represented by the molar signatures of all the adults examined in this study, we also have five young individuals for whom only M1, M2, and femur samples were analyzed (Fig. 4). One more subadult has already been discussed together with the adults because all three molars were available for testing. In this case, Burial 77 (12–15 y.o.; Fig. 3) was classified as Pattern 3 due to its femur $^{87}Sr/^{86}Sr$ differing from the cluster of the molar values and closely resembling the distribution for Burial 27.1.

Even though these additional subadults only have three $^{87}Sr/^{86}Sr$ results, their intra-individual variability falls within the range observed for the adults (Fig. 3). More specifically, the results vary roughly between 0.710 and 0.715 for the femur and M1 samples, respectively. It thus seems quite likely that if all four results were available, these five individuals could easily be classified within one of the identified distribution patterns. For example, Burials 16 and 45 would belong to Pattern 2a, Burial 35.2 to Pattern 1, and Burials 37.2 and 39

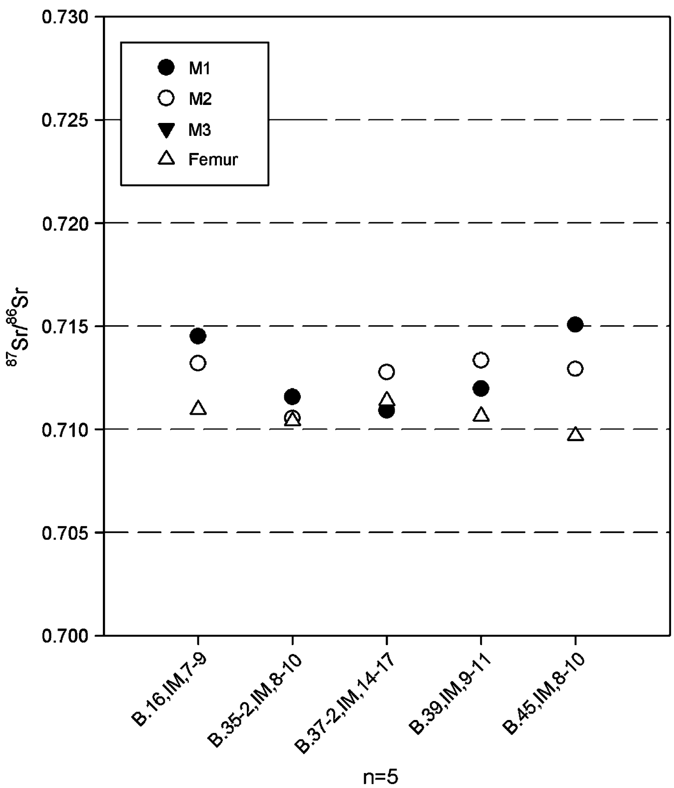

Fig. 4. Khuzhir-Nuge XIV, strontium stable isotope ratios for subadult individuals (see Fig. 3 for the explanation of abbreviations).

would likely fit within Pattern 2b. Furthermore, M1 and M2 values are more variable than the femur values—a pattern which is also consistent with the trend observed for the adults. Two individuals appear to be indigenous to the Little Sea area (B. 16 and 45), whereas the other three may be considered to be born elsewhere (B. 35.2, 37.2, and 39). In sum then, these subadults are fully explicable in terms of the model developed for the adults.

5.2. Temporal patterns

Examination of chronological differences in mobility patterns within our KN XIV cemetery population involves comparison between the only Late Neolithic Serovo individual from Grave 7 and the remainder of the examined burials which all represent the Bronze Age Glazkovo culture. Grave 7 stands out from the rest of the graves not only on typological grounds but also based on its radiocarbon date which implies that it is older than the Glazkovo graves by c. 1000 years (Table 2). While it may be argued that in general Burial 7 (25–35 y.o. probable male) fits well with Pattern 1 or some individuals from Pattern 3 (B. 77), it clearly stands out from the rest of the examined sample due to its very low $^{87}Sr/^{86}Sr$ results. The bone value is by far the lowest of all results available for KN XIV, the M1 and M3 values are the second and third lowest overall, and the M2 signature, the highest for this individual, still falls within the lower end of the variability range for the entire data set.

Comparison with our comparative animal data (Tables 3 and 4) reveals that the $^{87}Sr/^{86}Sr$ values for this Serovo individual are most consistent with almost exclusive consumption of resources with low strontium signature (around 0.709). Such values are found in both terrestrial and aquatic resources from the east part of the Angara and upper Lena drainage, as well as aquatic resources of Lake Baikal. Interestingly, the carbon and nitrogen stable isotope results for this individual (M.A. Katzenberg, personal communication) are quite consistent with those obtained for the Late Neolithic and Bronze Age burials from the Angara and upper Lena valleys (Katzenberg and Weber, 1999; Weber et al., 2002). This invites two possible explanations: one invoking a very large procurement range encompassing perhaps the entire Cis-Baikal and another suggesting that this individual was a very recent immigrant to the Little Sea micro-region. In the face of the evidence at hand, we find the latter scenario more plausible. Further assessment of the significance of this observation is beyond the goals of this study and will be undertaken elsewhere when comparative $^{87}Sr/^{86}Sr$ data from the other parts of Cis-Baikal become available.

6. Summary and conclusion

This study allows the following general observations:

1. The long-term procurement ranges of the individuals buried at KN XIV likely included territories outside of the immediate vicinity of the Little Sea micro-region perhaps reaching as far as the Angara or the upper Lena valleys;
2. The substantial amount of inter-individual variability suggests that procurement was organized on principles more consistent with the logistical model rather than the residential model as suggested earlier by Weber et al. (2002).
3. The community under investigation integrated individuals born and raised not only within the Little Sea area, but also in the valleys of the Angara and upper Lena and even beyond (e.g., B. 19?). Interestingly, roughly at least half of the examined Glazkovo sample appears to be born outside of this micro-region.
4. $^{87}Sr/^{86}Sr$ measured in the majority of the human teeth are higher, sometimes considerably, than the values documented for the aquatic foods suggesting that resources with high $^{87}Sr/^{86}Sr$ values must have contributed significantly to the overall dietary intake of these individuals. At present, terrestrial herbivores along the west coast of the lake including the Little Sea micro-region and perhaps the water of some of its smaller rivers, are the only food items within the entire Cis-Baikal that meet this requirement.
5. It appears that water craft, if known to the Glazkovo people, were not used on an extensive scale and the notion of reindeer domestication as early as during the Bronze Age does not find support in our data.
6. Finally, our study also reveals a distinct difference in procurement ranges between the Late Neolithic Serovo individual from Grave 7 and the Bronze Age Glazkovo people.

Since the application of the strontium isotope method to prehistoric hunter-gatherers is still in its early stage both in terms of empirical research and theoretical reflection, our paper should be viewed primarily as an exploration of the utility of this new line of investigation and as a pursuit of effective analytical and interpretive methods. Consequently, the approach presented here as well as the findings listed above need to be considered not only as tentative but also as potentially useful avenues for further research. The fact that several of the specific inferences about the nature of Glazkovo hunter-gatherer adaptation already appear to be supported by a few other entirely independent studies seems to demonstrate that application of the strontium isotope method to prehistoric hunter-gatherers offers much new promise. Overall, the data show that the strontium isotope method can contribute a number of important insights into prehistoric hunter-gatherer mobility, subsistence and social structure otherwise not available via examination of any other category of archaeological materials. It is clear, however, that in order to further the interpretation of strontium data, human comparative samples from the other areas of Cis-Baikal are needed.

Acknowledgements

The authors would like to thank Kelly Nixon, Stacey Hagen, Guangcheng Chen, and Jaime Donnelly (Radiogenic Isotope Facility, Department of Earth and Atmospheric Sciences, University of Alberta) for valuable advice and assistance with the strontium isotope analyses; Dr Sandra-Garvie-Lok for use of laboratory facilities during sample preparation at the University of Alberta, and Julija Keleçević for assistance with bone sample preparation. This research is part of the Baikal Archaeology Project based at the University of Alberta and funded by the Major Collaborative Research Initiatives grant No. 421-2000-1000 from the Social Sciences and Humanities Research Council of Canada. Additional financial support from the Canadian Circumpolar Institute is gratefully acknowledged.

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