Freshwater reservoir effects in Cis-Baikal: an overview

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Abstract

This paper summarises research on freshwater reservoir effects (FRE) in the Baikal region and their impact on the radiocarbon dating of human remains. Varying relationships are seen between human $\delta^{13}C$ and $\delta^{15}N$ and ^{14}C offsets in paired human-terrestrial mammal radiocarbon dates from the same graves in the different microregions of Cis-Baikal. In the Upper Lena microregion the FRE may also vary through time. These differences can be related in some cases to different isotopic ecologies, and in others to the presence of different old carbon reservoirs. Some areas requiring further research are highlighted, and the use of other proxies ($\delta^{2}H$, $\delta^{34}S$) for assessing the dietary contributions of freshwater resources are considered. A case study from the Early Neolithic cemetery of Shamanka II is used to illustrate the marked effects of changes in dietary catchment over an individual's life history, with bone and tooth dates from the same individual differing by 385 ^{14}C yr.

Introduction

Since first introduced by Willard Libby in the 1940s, the ability to provide chronometric dates has revolutionised archaeology, with an especially profound effect on prehistoric archaeology (Bronk Ramsey 2008; Wood 2015). Its first application in the Baikal region involved conventional ^{14}C dating of a number of Neolithic to Early Bronze Age burials (Mamonova and Sulerzhitskii 1989), which called into question the established culture-historical sequence (Okladnikov 1950). The next major development was the advent and widespread use of AMS ^{14}C dating, allowing the analysis of much smaller samples (Weber et al. 2006; 2010). In addition to providing a broad sense of the ordering of 'cultures' and their timespans, the increased precision of ^{14}C dating, especially when combined with Bayesian modelling, provides the opportunity for increasingly fine-grained temporal resolution, enabling prehistory to be treated more as history. But in order to achieve this potential, it is essential that dates are accurate as well as precise. The most recent development is the realisation that all radiocarbon determinations on prehistoric human skeletal remains from the Baikal region are subject to a freshwater reservoir effect.

While the impact of the marine reservoir effect (MRE) on radiocarbon dates is very well known, an appreciation of the freshwater reservoir effect (FRE) has grown more slowly (Cook et al. 1991). Yet the FRE can be as large or larger than the general ocean reservoir offset of ca. 400 ^{14}C years. Both introduce carbon that is older compared to the atmospheric reservoir, and so can make a substantial difference to radiocarbon dates on human remains or on other organisms either originating or consuming foods from marine or freshwater ecosystems. The importance of the FRE has come into sharp focus at Lake Baikal, where an offset of ca. 800 ^{14}C years has been observed between herbivores and Baikal's endemic freshwater seal (the nerpa, *Pusa sibirica*) from the same levels at the archaeological site of Sagan-Zaba II (Nomokonova et al. 2013). In this paper, we summarise previously published research on the FRE in Lake Baikal and its surrounding river systems, highlighting the importance of developing correction equations for radiocarbon dates made on prehistoric humans in the region. Taking a life history approach to a single individual from the Early Neolithic (EN) site of Shamanka II, we present an example illustrating the impact on radiocarbon dates of changing diets from youth to older adulthood, with concomitant differences in isotopic ecology and carbon reservoirs. The use of stable sulphur isotopes ($\delta^{34}S$) as another proxy for the consumption of aquatic resources is also briefly explored.

Sources of freshwater reservoir effects

The sources of old carbon in freshwater systems are considerably more varied and complex than those in marine systems, which are reasonably well understood, with an online worldwide database available to estimate departures (expressed as ΔR) from the global ocean offset of ca. 400 ^{14}C yrs (http://calib.org/marine/) (Reimer and Reimer 2001). The MRE is mostly based on the residence time of dissolved CO_2 in the water itself. At the ocean surface this is fairly consistent (the aforementioned 400 ^{14}C yrs), but can be regionally affected by upwelling, bringing much 'older' water to the surface, and locally by freshwater inputs (e.g., at the mouths of large rivers) (Alves et al. 2018). The mechanism, however, remains the same. This is not the case with freshwater reservoir effects, to which residence time makes usually only a small contribution, given the much greater interface between atmospheric CO_2 relative to water volume in most lakes. Despite its status as the world's deepest and largest freshwater lake by volume, water residence time in Lake Baikal is calculated to have been on the order of only 377 years (Khozov 1963: 28), partly due to the rapid mixing of surface and deep water (Hohmann et al. 1997; Peeters et al. 1997). Residence time is even less of an issue for constantly flowing rivers, with the notable exception of water entering from groundwater and aquifers (Kalin 2000). Other sources of old carbon include 'dead' carbon from dissolved carbonate rock (Philippsen and Heinemeier 2013; Keaveney and Reimer 2012) or in methane hydrate gasses released from deep lake sediments and volcanic vents (Kalmychkov et al. 2006; Prokopenko and Williams 2004), old CO_2 from glacial meltwater (Hendy and Hall 2006; Osipov and Khlystov 2010), and organic carbon released from peat and permafrost during periods of climate warming (Gustafsson et al. 2011).

Freshwater reservoir correction equations

The standard approach to characterising reservoir effects (whether marine or freshwater) is to undertake paired radiocarbon dating of the material of interest (thought to be subject to an 'old carbon' reservoir effect) and a directly associated terrestrial sample drawing on the atmospheric carbon reservoir (e.g., Cook et al. 2001; Olsen et al. 2010; Schulting et al. 2014; Wood et al. 2013). A regression equation is then created based on linear (or conceivably non-linear) correlations between the observed offset in ^{14}C years for the paired dates and one or more human stable isotope measurements—usually $\delta^{13}C$ and $\delta^{15}N$, though other isotope systems are briefly considered below. These serve as proxies for the amount of freshwater resources in the diet of that individual, and hence the extent of the freshwater reservoir offset. The FRE correction is considered 'successful' to the extent that: 1) stable isotope values can accurately estimate the proportional contribution of freshwater resources in an individual's diet; and 2) the FRE/s from which the resources derived show the same apparent ^{14}C age. This latter is a crucial point, since fish might be taken from different stretches of rivers or lakes, with similar stable isotope values but subject to different carbon reservoir ages (cf. Fernandes et al. 2016). Both this and any imprecision in the estimation of the contribution of freshwater resources will lead to 'noise' in the regression equation. Because of these, and potentially other factors, it is not always possible to construct useful reservoir correction equations (cf. Higham et al. 2010).

In the case of Cis-Baikal, we have over the course of the last five years undertaken 53 such paired datings, in some cases involving duplicate ^{14}C measurements on the same burials, so that the actual number of dates involved is more than 106 (Bronk Ramsey et al. 2014; Schulting et al. 2014; 2015; 2018). Multiple dates on the same individuals are combined in OxCal using the *R_combine* function (cf. Ward and Wilson 1978), with the resulting averaged date used for comparison with its terrestrial pairing. The terrestrial samples in all cases are either unmodified marmot (*Marmota* sp.; probably *M. sibirica*) incisors or perforated red deer (*Cervus elaphus*) canines. While the marmot incisors are unmodified, they are found—often in large numbers—placed over the skeleton in a manner indicating that they were attached to clothing worn by the deceased. The difference in terrestrial species used in our paired dating programme relates to their presence, sometimes in large numbers, in the EN graves and their complete absence in LN and EBA graves. On the other hand, red deer canines occur in graves of all periods. Given the relative fragility and easy accessibility of these teeth, we would not expect curation over a period of more than a decade or so, a comparable timeframe to that of carbon turnover in adult bone collagen (Hedges et al. 2007). There is no suggestion that the diets of either species incorporated riverine or lacustrine foods that themselves might be subject to reservoir effects, as might be the case for other species. For example, while less common as burial inclusions in Cis-Baikal, beaver remains (*Castor fiber*) are sometimes found, but as their diets may include some aquatic vegetation (Nolet et al. 1995), they would not provide an ideal pairing.

Reservoir corrections in the microregions of Cis-Baikal

The reservoir correction equations that have been developed for Cis-Baikal are summarised in Table 1. Correlation coefficients (r^2 values), measuring the strength of the relationship (i.e., its predictive power) between human stable isotope values ($\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$) and ^{14}C offsets range from 0.21 to 0.86. In other words, the equations account for approximately 20% to 85% of the variation in ^{14}C offsets between paired human and terrestrial mammal dates. Low predictive power is found with the use of $\delta^{13}C$ only, although as noted below, even this can be of some use. Note that in all cases the error terms associated with the radiocarbon determinations are increased proportionally to the additional uncertainty in the regression equation, denoted by 'S', the standard deviation of the model's residuals (i.e., the difference between the predicted human date using the equation and the actual measured date) (Table 1).

An overall correction for Cis-Baikal, excluding the Upper Lena, explains ca. 67% of the ^{14}C offsets in 31 paired dates. This excludes young child 2–4 years old, likely subject to a nursing effect (Water-Rist et al. 2011) and therefore having a different relationship between their $\delta^{15}N$ value and ^{14}C offset (Schulting et al. 2014). While this general equation is useful, it was apparent that there were different relationships between human $\delta^{13}C$ and $\delta^{15}N$ values and human-terrestrial mammal ^{14}C offsets on a microregional level. Thus, separate regression equations for SW Baikal/Angara and the Little Sea microregions show markedly greater predictive power than that for Cis-Baikal as a whole, with r^2 values of 0.728 and 0.859, respectively (eq. 3 and 5 in Table 1), with that for the Little Sea being the most successful equation obtained thus far for Cis-Baikal. At present, we assume that Lake Baikal acts as a single reservoir, so that the different equations for these two microregions relate more to their isotope ecology than to differences in old carbon. The shallower waters of the Little Sea, for example, are more ^{13}C-enriched, and so fish caught there are on average higher in $\delta^{13}C$ than in many other parts of the lake (Ogawa et al. 2000; Yoshii 1999; Yoshii et al. 1999).

Source	*Regression formula*	r^2	*p*	*n*	*S*
1/ Cis-Baikal $\delta^{13}C$ (Schulting et al. 2014)	$1180.3+50.5(\delta^{13}C)$	0.208	0.008	33	142.1
2/ Cis-Baikal $\delta^{15}N$ (Schulting et al. 2014)	$-732.76+76.63(\delta^{15}N)$	0.672	0.000	31	85.5
3/ SW Baikal/Angara (Schulting et al. 2014)	$-1388.85+125.45(\delta^{15}N)$	0.728	0.000	15	64.1
4/ Shamanka (SW Baikal) (Schulting et al. 2018)	$-3338.00-246.26 (\delta^{13}C)+10.57(\delta^{2}H)$	0.603	0.016	10	146.0
5/ Little Sea (Schulting et al. 2014)	$-3329.54-125.60(\delta^{13}C)+95.11(\delta^{15}N)$	0.859	0.000	16	51.8
6/ Upper Lena (Schulting et al. 2015)	$-7364.19-402.40(\delta^{13}C)$	0.490	0.016	11	183.6
7/ Upper Lena, EBA sites	$-4289.89-211.19(\delta^{13}C)+45.38(\delta^{15}N)$	0.840	0.030	6	40.3

only (Schulting et al. 2015)					
8/ Adjusted error range (Weber et al. 2016a)	$\sqrt{(\mathrm{s.d.})^2 + S^2}$				

Table 1. Regression equations for FRE corrections on radiocarbon dates from Cis-Baikal and its microregions. Adjusted error range (eq. 8) is calculated using the ± error term associated with the ^{14}C measurement ('s.d.') and the standard deviation of the model's residuals ('S').

Therefore, the regression equation for the Little Sea makes use of both δ^{13}C and δ^{15}N, while for both Cis-Baikal as a whole and for the SW Baikal/Angara microregion only δ^{15}N makes a significant contribution to the model. Nevertheless, the question of whether ^{14}C offsets may differ across the lake is certainly worth further investigation. Indeed, the possibility of this has been suggested by radiocarbon dating programmes undertaken on palaeoenvironmental cores from different parts of the lake, with a reservoir effect of ca. 1200 yrs for the Academician Ridge (Watanabe et al. 2009) north of the Little Sea, and of ca. 500 yrs for the Bugeldeika Saddle across from the Selenga River delta (Nara et al. 2010). However, these reservoirs will not necessarily translate directly into the aquatic biosphere; hence the need for additional research.

With its headwaters in the Baikal Mountains on the west side of the central part of Lake Baikal, the Upper Lena River has no connection to the lake itself (Figure 1). Relatively little archaeological excavation has been undertaken in this microregion, so that an initial investigation of its FRE was based on only 11 paired dates, with the resulting regression equation providing a moderate r^2 value of 0.49. There also appears to be a significantly higher ^{14}C offset here than in Baikal, of up to 1000 years (Schulting et al. 2015). Interestingly, the regression equation for the Upper Lena as a whole was based on δ^{13}C results alone, with δ^{15}N making no significant contribution. This was initially surprising, since the small number of measurements available for modern fish in the Upper Lena are not ^{13}C-enriched like the inshore fishes of Lake Baikal, and instead are ^{13}C-depleted (by ca. 3‰) relative to modern terrestrial mammals from the microregion (Katzenberg et al. 1999; Schulting et al. 2015; Weber et al. 2011). The river's fish are significantly higher in δ^{15}N (by ca. 5‰) than the region's terrestrial herbivores, so that this isotope should be a better predictor of fish consumption, and hence of the ^{14}C offset. The explanation for why this is not the case may lie in the sources of ^{13}C- and ^{14}C-depleted carbon along certain stretches of the river and its tributaries. A plausible candidate is highly biolabile terrestrial (hence ^{13}C-depleted) organic matter from unevenly distributed peat bogs and/or patches of melting permafrost along the watershed. All fish would be ^{15}N-enriched relative to terrestrial herbivores, but their ^{14}C ages would differ based on their proximity to these spatially variable sources of old carbon entering the river. This would become progressively diluted further downstream from particular locations, and so could lead to linked variation in δ^{13}C and in ^{14}C in fish populations between different stretches of the river (cf. Philippsen and Heinemeier 2013).

Further complicating Upper Lena's FRE is the finding that a group of six paired dates from the Early Bronze Age cemeteries of Makrushino and Ust'-Iamnaia show a much stronger correlation (r^2 = 0.840), in this case based on both δ^{13}C and δ^{15}N (eq. 7 in Table 1). At present it is unclear whether this in fact reflects a temporal shift in the FRE, or whether it relates to the southern stretch of the river along which these EBA sites concentrated, with the EN cemeteries of Turuka and the LN cemetery of Zakuta lying over 200 km downriver to the north (see Figure 1) (Schulting et al. 2015). A temporal shift is certainly possible, particularly if the source of old carbon were melting permafrost, present in the catchment (Bezrukova et al. 2014), which would increase during warm periods, such as pertained 9.3–6.4 ka cal BP (Tarasov et al. 2007; Watanabe et al. 2009). The four pairs of dates from this earlier group show larger offsets on average than the EBA sites: 750 vs. 430 ^{14}C years. A single Late Mesolithic/EN paired date from the site of Popovskii Lug 2 on the southern Lena shows a much larger offset of ca. 900 ^{14}C years, more in keeping with those of the northern sites. However, there are currently too few results from the Upper Lena to adequately address the possibility of both spatial and temporal variability in reservoir offsets and their complex interplay. With new research being undertaken on the LN/EBA cemetery at Verkholensk (White et al., 2020), and with new fieldwork underway as part of the Baikal Archaeological Project, we hope to be in a position soon to address these matters using additional paired dates.

Correcting for the FRE not only provides a more robust chronology for Cis-Baikal's prehistoric hunter-gatherers (Weber et al. 2016a), but can also be used to explore connections between microregions with varying ^{14}C offsets. An example is provided by the Upper Lena and Little Sea microregions, separated by some 65 km (further in terms of real travel distance), and between which δ^{13}C and δ^{15}N results have previously suggested a connection (Katzenberg et al. 2012; Scharlotta and Weber 2014; Weber and Goriunova 2013; Weber et al. 2011). Stable nitrogen isotope values from EBA individuals in the Little Sea present a bimodal distribution, from which have been inferred Game-Fish-Seal (GFS) and Game-Fish (GF) dietary patterns. The δ^{15}N values for the GF diet (i.e., < 13.3‰) in the Little Sea are comparable to those found in the EBA of the Upper Lena. Furthermore, strontium isotope (^{87}Sr/^{86}Sr) results from the Little Sea EBA cemetery of Khuzhir-Nuge XIV found that all those individuals consistent with a local origin had GFS diets, while those identified as non-local exhibited both dietary patterns (Scharlotta and Weber 2014; Weber and Goriunova 2013; Weber et al. 2011). But the very different reservoir correction equations for the two regions raise a question over this scenario. If individuals moving from the Upper Lena to the Little Sea in childhood retained sufficient δ^{13}C and δ^{15}N signals from the former upon dying and being buried in the latter microregion, then they should also exhibit a higher reservoir effect, typical of the Upper Lena (cf. White et al. 2020). Yet the individuals with GF diets show a significantly lower ^{14}C offset than the 'locals' with GFS diets, as well as very different relationships with δ^{13}C and δ^{15}N between the two microregions (Figures 3 and 4). As mentioned above, new research is underway on the Upper Lena that should shed further light on this complex relationship.

A river too far: dealing with reservoirs not represented

Obviously, the regression equations developed for Cis-Baikal make certain assumptions regarding the use of broadly local aquatic resources by human communities. The importance of this is emphasised by the different equations for the microregions presented in Table 1. The Upper Lena in particular appears to have a substantially higher old carbon reservoir than estimated for Lake Baikal (Schulting et al. 2015). Thus, for example, an individual moving from the Upper Lena to the Little Sea would present considerable difficulties in terms of knowing which microregional regression equation to apply, especially as we would not necessarily be able to detect an individual's mobility either archaeologically (in terms of mortuary treatment) or isotopically. While in this case, there are some clear differences in $\delta^{13}C$ and $\delta^{15}N$ values between the two microregions, they would become progressively obscured over time assuming that the individual adopted the new 'Little Sea diet'—and note that there is significant isotopic variability within that microregion, given the presence of the two broad dietary patterns noted above (Katzenberg et al. 2012; Weber and Goriunova 2013; White et al. 2020). In an even more distant connection, it is possible that three Late Neolithic individuals from Ulan-Khada on the Little Sea originated from the Angara microregion based on their stable isotope values, which would imply that the Angara reservoir correction should be used rather than that for the Little Sea—the difference in the resulting determinations being on the order of 100 to 200 ^{14}C years (White et al. 2020).

The situation of course would be exacerbated if individuals died and were buried in a Cis-Baikal cemetery following a recent move from another watershed entirely, one not represented in our paired dating programme, and with a significantly different old carbon reservoir, and/or with a different isotope ecology, since it is the human stable isotope results that are entered into the regression equation. This is very likely to be the case with the Selenga River microregion in Trans-Baikal. Recent $\delta^{13}C$ and $\delta^{15}N$ analyses on human remains from the large, multi-period cemetery at Fofanovo suggest that this microregion's isotope ecology is distinct from those of Cis-Baikal (White et al., submitted). Unlike the Angara River, which flows out of Lake Baikal and so for a long stretch consists predominantly of the lake's waters, the Selenga is by far the lake's single largest inflowing river, and so has a very different catchment and hence very probably a different reservoir offset. Human communities would have had access to a combination of fish entering the Selenga from Lake Baikal during spawning runs (mostly the omul', *Coregonus migratorius*), and the river's own autochthonous fish populations. No terrestrial materials for paired datings are as yet available from Fofanovo, so that the radiocarbon dates on human bone from the site reported in White et al. (submitted) have provisionally been corrected for the freshwater reservoir offset using the regression equation for Cis-Baikal (eq. 2 from Table 1). This is not ideal, but reasonable given the presence of fish from Lake Baikal—and hence exhibiting the lake's reservoir offset—in the lower Selenga.

A case study from the large EN cemetery of Shamanka II provides a striking illustration of the effects of individual mobility on both diet and reservoir offsets. Shamanka II is located on a thin peninsula stretching into the shallow Kultuk Bay (*Kultukskii Zaliv*) encompassing the southwest end of Lake Baikal, with a number of small inflowing rivers nearby. The dominant reservoir here is assumed to be that of the lake. Paired human-terrestrial mammal dates from this site contributed to the regression equation for the SW Baikal/Angara microregion (Bronk Ramsey et al. 2014; Schulting et al. 2014), while a follow-on study explored the use of $\delta^{2}H$ in providing additional information on estimating the trophic level of human consumers (Schulting et al. 2018). Grave 42 held the remains of two adult females, one (42.01) 40–45 years old, and the other (42.02) 50+ years old (Figure 5). Burial 42.01 provided a radiocarbon determination of 6386 ± 34 BP (OxA-26192), while 42.02 yielded a considerably older date of 6792 ± 35 BP (OxA-24774). Although the burials were clearly successive (Figure 5), such a large difference was unexpected. A second determination was therefore made on 42.02 using a different skeletal element, giving a very similar result of 6821 ± 35 BP (OxA-26193). The two dates for this individual can be combined to 6807 ± 25 BP (Table 2). Weber et al. (2016b: 243) discuss the wide divergence in the dating of the two individuals in this grave, and also note Burial 42.02's anomalously low $\delta^{15}N$ value of 10.4‰. This was measured multiple times, on collagen meeting all quality control criteria (DeNiro 1985; van Klinken 1999). To put this into perspective, this value is 4.75 standard deviations below the mean of 14.8 ± 0.9‰ for 99 adults at Shamanka II. Combined with a relatively low $\delta^{13}C$ value of –17.7‰, this suggests a predominantly, though not entirely, terrestrial diet.

A series of sequential samples of the first (M1) and third (M3) molars were taken from Burial 42.02 for $\delta^{13}C$ and $\delta^{15}N$ analyses to trace this individual's early dietary life history (for details on sample preparation and analysis, see Scharlotta et al. submitted). In total, 15 samples were taken from the M1, and 11 from the M3. In order to attain the weight required for radiocarbon dating, seven sequential M1 and five M3 samples were combined, reflecting an average of diet over approximately ages of 4–6 and 16–18 years, respectively. The sequential stable isotope measurements are provided in Appendix 1. The results show a small difference between the mean $\delta^{13}C$ value of the combined molar samples and the duplicate bone measurements of ca. +1.1‰, but far more striking is the $\delta^{15}N$ tooth-bone difference of +5.8‰. This must reflect a very different diet in childhood and adolescence from that of the last decade or more of this individual's life (probably on the order of two-three decades given the slowing of bone turnover in older individuals (Hedges et al. 2007)). This is confirmed by the radiocarbon determinations on the M1 and M3, which can be combined to 7165 ± 24 BP (χ^2, df=1, T=2.4(5%, 3.8)), 358 ^{14}C years older than the duplicate dates on adult bone combining to 6807 ± 25 BP (χ^2, df=1, T=0.3(5%, 3.8)) (Table 2). This is a striking difference for determinations made on the same individual, one that requires further discussion.

Applying the SW Baikal/Angara FRE regression equation to the combined tooth dates makes them younger than the combined bone dates by 285 ^{14}C years. However, while the low bone $\delta^{15}N$ value of 10.4‰ is consistent with a largely terrestrial diet, the $\delta^{13}C$ value of –17.7‰ strongly suggests some continued consumption of lake fish, some of which do have relatively low $\delta^{15}N$ values of ca. 8‰ (Katzenberg et al. 2012). But applying the SW Baikal/Angara FRE regression equation to the combined bone dates (eq. 3 in Table 1) results in a correction of ca. –80 years, i.e., the date becomes *older*. There is no known mechanism for this; therefore, we instead apply the Cis-Baikal correction using only the $\delta^{13}C$ value (eq. 1 in Table 1). This has a large uncertainty, and so is generally avoided; in this case, however, it does bring the dates for the bone and teeth in line (Table 2; Figure 6). It is possible that this is coincidental, in that the woman's adulthood diet is isotopically unusual for Cis-Baikal, and so she must have have spent much of her adult life in another location entirely, one that is not currently represented by our FRE equations. That said, at present, only the waters of Lake Baikal have been shown to have ^{13}C-enriched fishes, and so some contribution from them is plausible. So, while this is best seen as an heuristic exercise, it is worth noting that not only do they overlap, but the mean FRE-corrected dates are nearly identical at 7418 cal BP and 7433 cal BP for the combined bone and tooth dates, respectively (Figure 6).

In sum, the stable isotope values for the teeth of the elderly woman in Burial 42.02 are consistent with those of other individuals at Shamanka II, indicating the significant consumption of fish from the lake, resulting in a correspondingly high FRE. It is likely, then, that she spent her childhood and adolesence with the Shamanka community. At some point in adulthood she either changed diets radically, or, more likely, moved to another area before returning to Shamanka II not long before her death. Her grave may have been somehow marked, or perhaps it was encountered during the digging of the grave for Burial

42.01 many centuries later. The re-use of graves is not uncommon in the Early Neolithic Kitoi mortuary tradition (Weber, submitted), though this is the largest time gap found so far: 670 years between the mean dates, with 42.02 belonging to Phase 1 and 42.01 to Phase 2 (Weber et al. 2016b). This implies that their co-location in the same grave cut was coincidental, in the sense that—in contrast to what we generally assume to have been the case for most multiple burials—there is unlikely to have been any 'real' relationship between the two women.

Burial	*Lab code*	*^{14}C yr*	±	*^{14}C offset*	*FRE ^{14}C yr*	*FRE ±*	*δ^{13}C*	*δ^{15}N*	*FRE-corrected cal BP*	
Burial 42.01	OxA-26192	6386	34	482	5921	73	−16.6	14.8	6940	6564
Burial 42.02	OxA-24774	6792	35	288	6533	146	−17.6	10.5	7677	7165
Burial 42.02	OxA-26193	6821	35	297	6495	146	−17.8	10.3	7668	7030
combined	OxA-24774, 26193	6807	25	292	6514	104	−17.7	10.4	7591	7249
Burial 42.02, M1	OxA-V-2727-18	7201	33	647	6520	72	−16.4	16.5	7567	7294
Burial 42.02, M3	OxA-V-2727-19	7129	33	546	6523	72	−16.7	15.9	7568	7306
combined	OxA-V-2727-18, 19	7165	24	597	6522	51	−16.6	16.2	7560	7321

Table 2. Radiocarbon dates for Shamanka II Early Neolithic burials 42.01 and 42.02 (SHA_2004.042.01 and 42.02). The ^{14}C offsets are calculated with the general Cis-Baikal regression equation using only δ^{13}C (eq. 1 in Table 1) for the 42.02 bone dates, and the SW Baikal/Angara regression equation using only δ^{15}N (eq. 3) for the 42.01 bone date and the 42.02 tooth dates (see text for discussion of why this is necessary).

Adding other isotopes to the equation

A pilot study at the large EN cemetery of Shamanka II explored the use of stable hydrogen isotopes (δ^{2}H, alternatively designated δD) in the construction of regression equations. While more commonly used as an environmental proxy, δ^{2}H also reflects trophic level and so should aid in estimating the contribution of fish to an individual's diet (Birchall et al. 2005; Reynard and Hedges 2008; van der Sluis et al. 2019). A strong positive correlation was found between δ^{15}N and δ^{2}H, confirming the latter's usefulness as a proxy for trophic level (eq. 4 in Table 1). Moreover, δ^{2}H was found to slightly outperform δ^{15}N when combined with δ^{13}C in a regression model as a predictor of the observed ^{14}C offsets between human and terrestrial mammal dates (Schulting et al. 2018). The resulting model, with an r^2 value of 0.60, performs less well than the equation for the SW Baikal/Angara microregion proposed earlier (Schulting et al. 2014), arguably at least partly as a result of the more limited isotopic variability at Shamanka II. Given its importance as a large EN cemetery and some of the interesting diachronic dietary patterns already identified (Weber et al. 2016b), further paired datings from the site will be undertaken. Because it also acts as an environmental proxy, δ^{2}H may be useful in detecting outliers from different regions in a cemetery.

Sulphur isotopes (δ^{34}S) have the potential to differentiate between freshwater and terrestrial resources (Petersen and Fry 1987), but until recently archaeological applications have been relatively few and have yielded mixed results. While in some cases freshwater and terrestrial ecosystems clearly differ in δ^{34}S, in others they do not (Drucker et al. 2018; Privat et al. 2007; Webb et al. 2017). Unfortunately, Lake Baikal seems to fall into the latter category: a pilot study found no difference (Student's *t*-test, $t = 0.758$, $p = 0.456$) between mean $\delta^{34}S$ values on bone collagen for archaeological red and roe deer (6.6 ± 1.3‰, n = 16) and archaeological seals (6.2 ± 1.2‰, n = 9) from Lake Baikal (see Appendix 2 for measurement details). The human values are in the same range (6.5 ± 1.1‰, n = 35), with no significant differences between red/roe deer, seals, and humans (ANOVA, $F = 0.328$, $p = 0.722$) (Figure 6).

A new pilot study currently underway will explore the measurement of $\delta^{15}N$ in single amino acids for further refining trophic level relationships (cf. Naito et al. 2010; 2013; Strying et al. 2010; Webb et al. 2013).

Conclusions

This overview has presented recent work on freshwater reservoir correction equations for Middle Holocene archaeology of Cis-Baikal. The importance of developing separate equations for different microregions is emphasised, particularly for those as yet poorly represented (the Upper Lena) and even more so for those not yet represented at all (the Selenga). Additional research on the sources of the FRE as it affects the aquatic biosphere is also required; these may vary temporally as well as spatially, and may themselves hold useful palaeoenvironmental information. Of other isotopic proxies for the proportion of fish and seals in the diet, $\delta^{2}H$ seems to hold some potential, while $\delta^{34}S$ does not, at least not for the Lake Baikal itself. Whether separate river systems (e.g., the Upper Lena and the Selenga) will be more suitable is yet to be determined.

While research on the FRE of the Lake Baikal region is still in its early stages, it has already made a substantial impact on our understanding of hunter-gatherer adaptations, allowing us to address a range of questions at a level of chronological resolution (or at least accuracy) not previously possible. We can now define better the chronological parameters of all relevant culture historical units (periods and mortuary traditions), facilitating a consideration of the tempo of cultural change and a better understanding of the transitions between archaeologically defined cultures. We are also increasingly able to assess diachronic trends within and between micro-regions (Weber et al. 2016a, 2016b; submitted) as well as the temporal patterns of cemetery use (Bronk Ramsey et al. submitted; Weber et al. 2016a, 2016b;).

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Figures and Tables

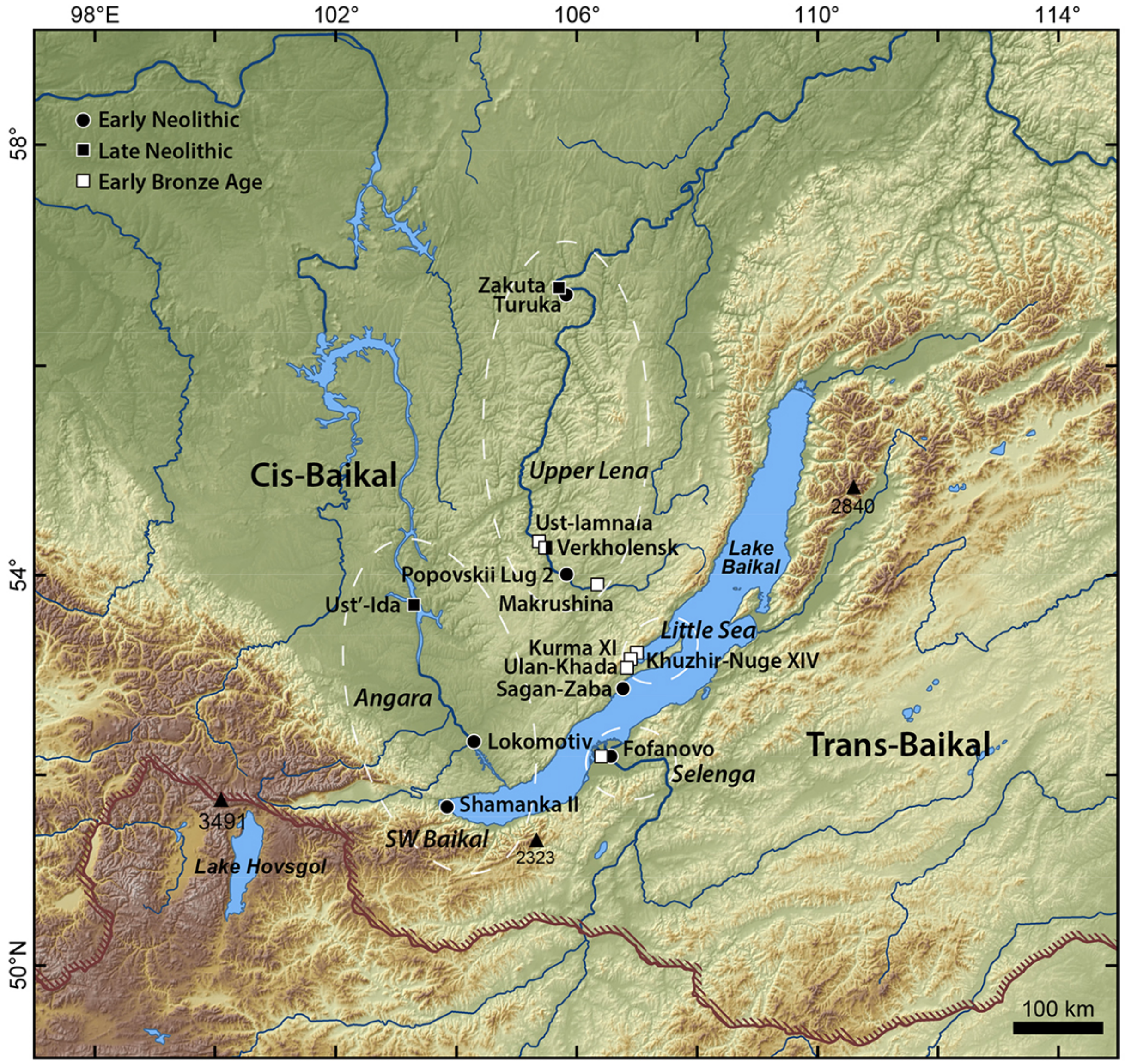

Figure 1. Map of the Baikal region showing its microregions and key sites mentioned in the text. Basemap by Christian Leipe, Freie Univeristät Berlin. Topography is based on elevation Shuttle Radar Topography Mission (SRTM) v4.1 data (Jarvis et al., 2008).

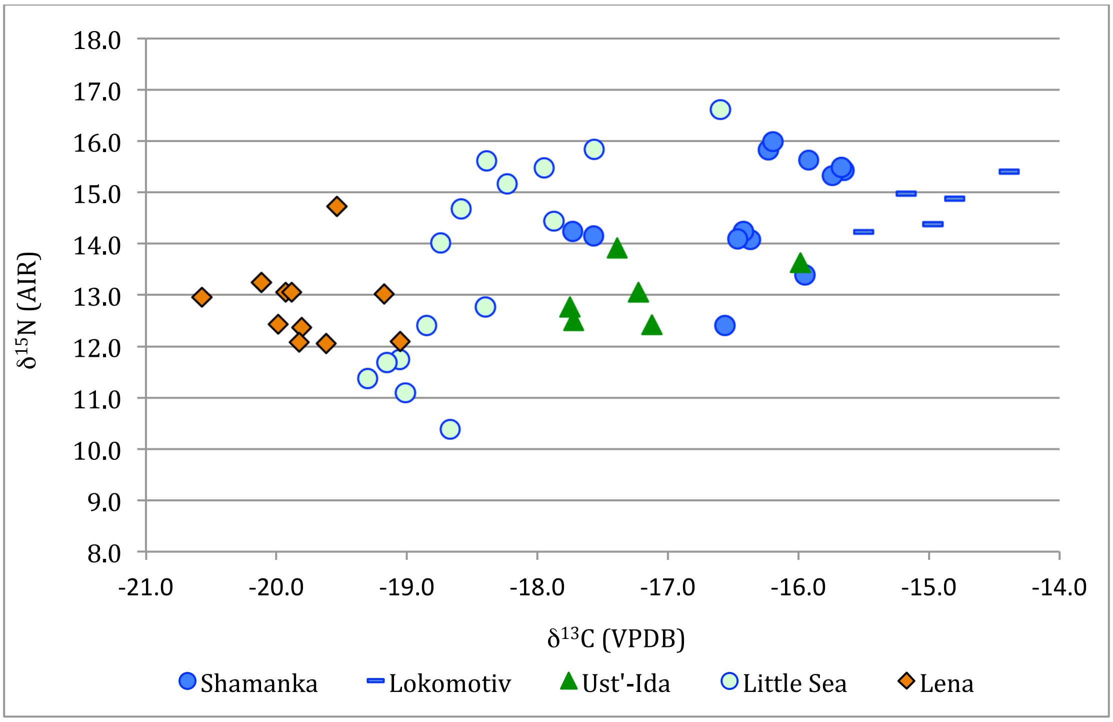

Figure 2. Post-weaning age human $\delta^{13}C$ and $\delta^{15}N$ results used in paired dating, showing variability between sites and microregions (sources: Schulting et al. 2014; 2015; 2018).

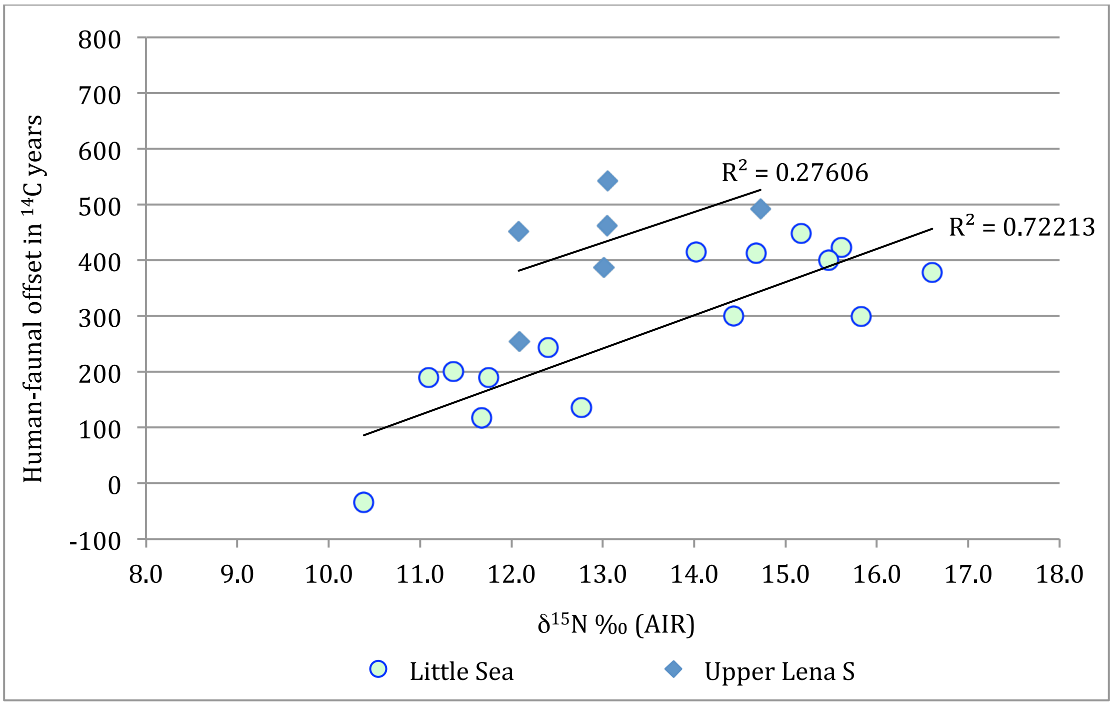

Figure 3. Comparison of regression lines for $\delta^{15}N$ and human-terrestrial fauna ^{14}C offsets between the Little Sea and Upper Lena microregions.

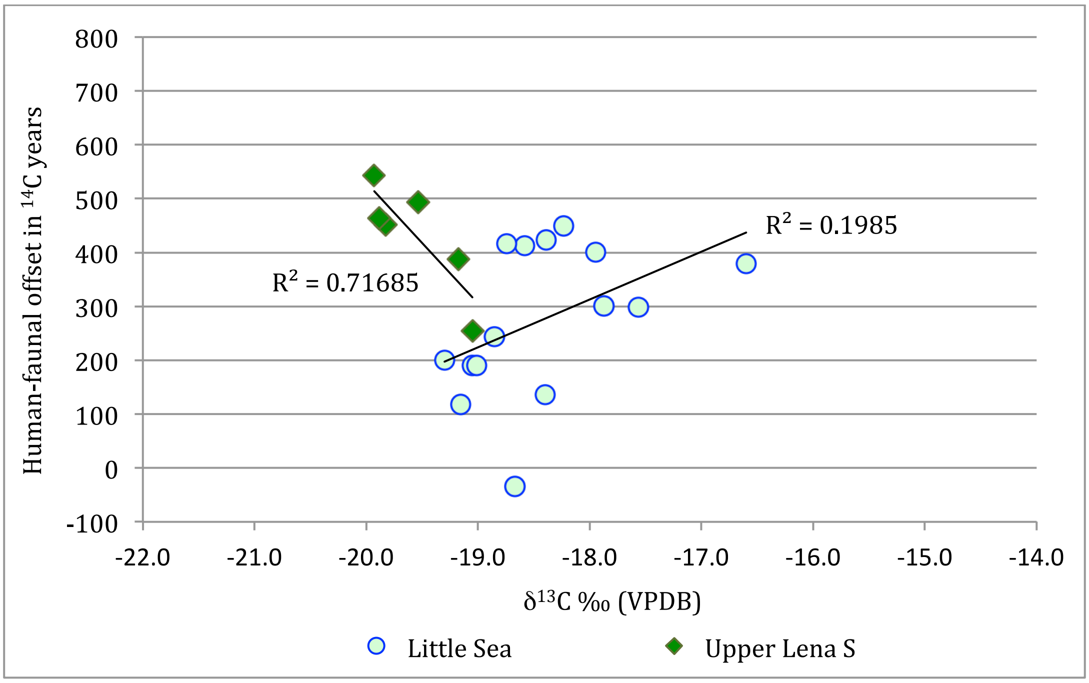

Figure 4. Comparison of regression lines for δ^{13}C and human-terrestrial fauna ^{14}C offsets between the Little Sea and Upper Lena microregions.

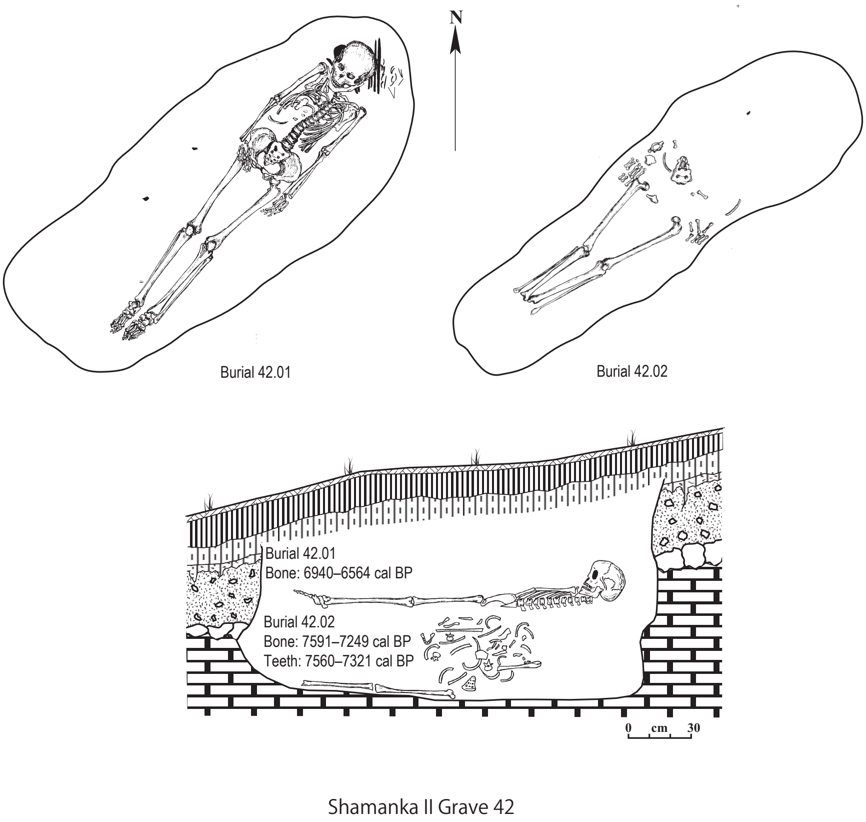

Figure 5. Shamanka II, Grave 42 plan and section (created by Natalia Kasprishina and Andrei Tiutrin, Irkutsk)

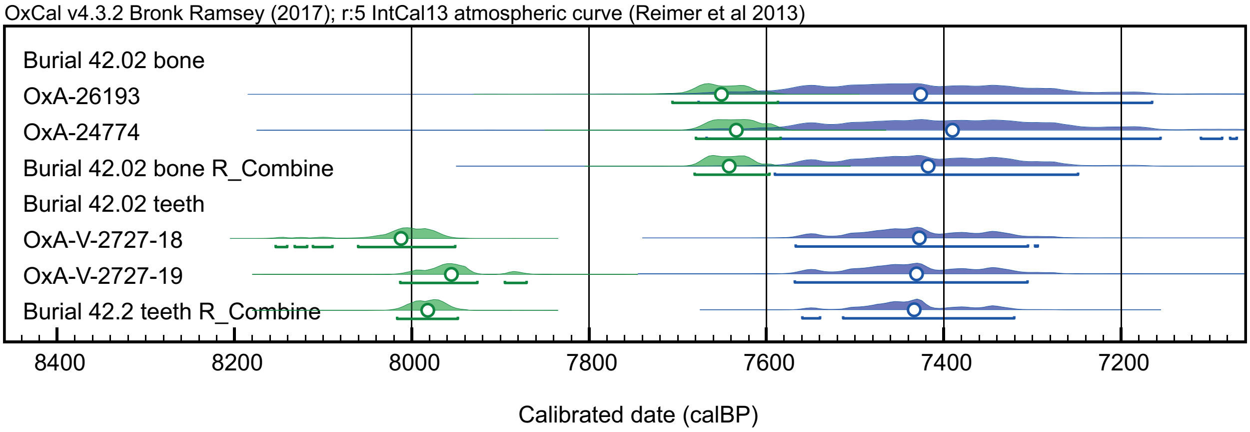

Figure 6. OxCal plot of the uncorrected (green) and FRE-corrected (blue) dates on bone and teeth for Burial 42.02, Shamanka II. Circles show mean date.

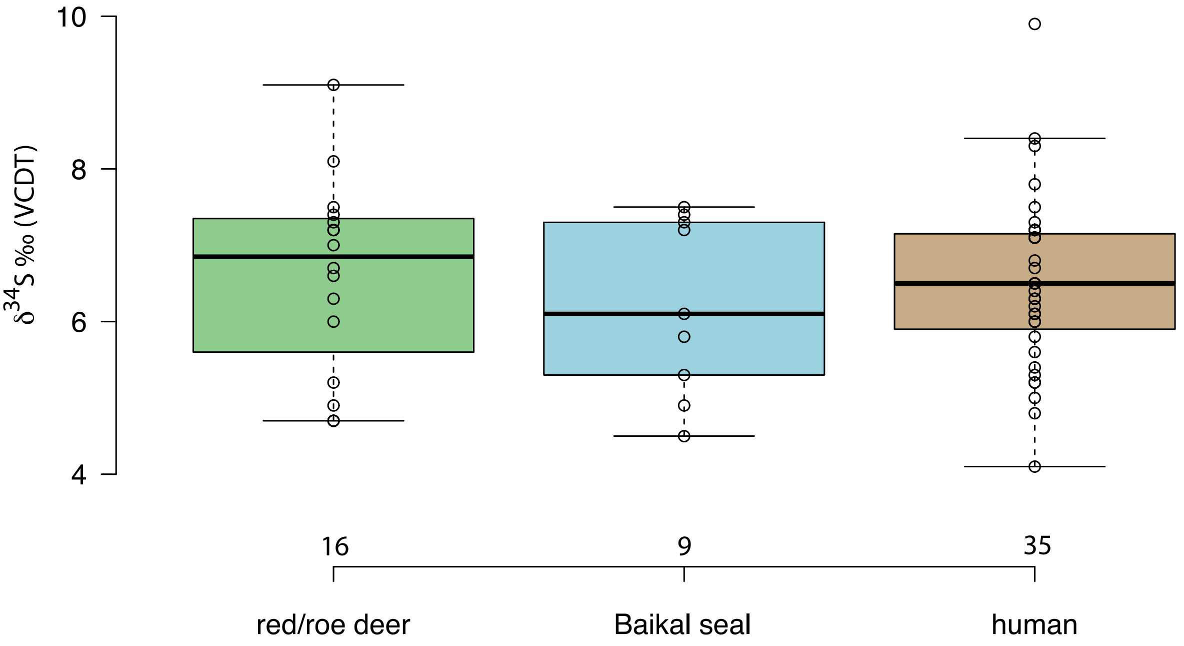

Figure 7. Boxplot of $\delta^{34}S$ results on faunal and human bone collagen from Cis-Baikal.

Appendix 1. Sequential dentine analysis (I. Scharlotta)

For details on sample preparation and analysis of sequential dentine samples, see Scharlotta et al. (submitted).

Sample	*δ^{13}C (‰)*	*δ^{15}N (‰)*	*%C*	*%N*	*C:N*
first molar M1	*VPDB*	*AIR*			
H 2004.022-1	−17.2	17.0	43.2	15.3	3.3
H 2004.022-2	−17.1	15.7	42.8	15.1	3.3
H 2004.022-3	−16.9	15.9	42.1	15.0	3.3
H 2004.022-4*	−16.6	16.1	42.8	15.2	3.3
H 2004.022-5*	−16.5	16.4	42.8	15.2	3.3
H 2004.022-6*	−17.2	16.2	42.8	15.2	3.3
H 2004.022-7*	−17.1	15.9	42.2	14.9	3.3
H 2004.022-8*	−17.2	16.2	42.5	15.1	3.3
H 2004.022-9*	−17.3	16.4	42.6	15.0	3.3
H 2004.022-10*	−17.9	16.4	42.0	14.9	3.3
H 2004.022-11	−18.1	16.3	42.8	15.0	3.3
H 2004.022-12	−18.2	16.1	42.0	14.7	3.3
H 2004.022-13	−17.8	15.9	–	14.8	
H 2004.022-14	−17.4	16.6	42.1	14.7	3.3
H 2004.022-15	−16.7	17.0	42.5	14.6	3.4
third molar M3					
H 2004.023-16	−16.3	15.9	42.6	15.3	3.3
H 2004.023-17	−16.0	16.2	42.5	15.3	3.2
H 2004.023-18*	−16.5	16.4	42.9	15.5	3.2
H 2004.023-19*	−17.3	14.8	41.6	14.8	3.3
H 2004.023-20*	−17.5	15.4	43.2	15.2	3.3
H 2004.023-21*	−17.2	15.7	42.9	15.3	3.3
H 2004.023-22*	−16.5	14.8	42.2	15.0	3.3
H 2004.023-23	−15.7	15.6	42.2	15.1	3.3
H 2004.023-24	−15.4	16.1	42.0	14.9	3.3
H 2004.023-25	−14.9	17.0	42.4	15.2	3.3
H 2004.023-26	−15.4	16.4	42.0	15.0	3.3

Table A1.1. Stable carbon and nitrogen isotope results and associated collagen quality data for sequential sampling of dentine for first and third molars of Grave 42.02 from Shamanka II. Starred samples refer to those from which remaining collagen was combined for radiocarbon dating.

Tooth	*δ^{13}C*	*±*	*δ^{15}N*	*±*	*n*
M1	-17.3	0.5	16.2	0.4	15
M3	-16.2	0.9	15.8	0.7	11
M1*	-17.1	0.5	16.2	0.2	7
M3*	-17.0	0.5	15.4	0.7	5

Table A1.2. Summary of dentine δ^{13}C and δ^{15}N sequential sampling results for first and third molars of Grave 42.02 from Shamanka II. Starred samples refer to those from which remaining collagen was combined for radiocarbon dating.

There is a significant difference between the total series of $\delta^{13}C$ samples for the two teeth (Mann-Whitney U-test, $Z = 2.78$, $p = 0.005$), but not those of the pooled subsample selected for ^{14}C dating ($Z = 0.00$, $p = 1.00$) (Table A1.2). The reverse holds for $\delta^{15}N$ values, which do not differ significantly overall (heteroscedastic *t*-test, $t = 1.68$, $p = 0.114$), but do between the pooled ^{14}C subsamples, with the M1 and M3 exhibiting mean values of 16.2 ± 0.2‰ and 15.4 ± 0.7‰, respectively (heteroscedastic *t*-test, $t = 2.64$, $p = 0.046$). That these values differ slightly from those obtained on the pooled samples themselves (Table 2) is likely due to the variable contributions by weight of collagen from the individual sequential samples, so that taking a straight average is an inappropriate way of characterising the pooled mean.

It can also be noted that, although they can be successfully combined (see main text), the date for the M1 is 72 ^{14}C yr older than that for the M3, in the direction that is consistent with higher (hence more aquatic) $\delta^{13}C$ and $\delta^{15}N$ values of the M1. While there is limited variation in both isotope values for the M1 (with the exception of the clear decrease between the first and second subsamples, reflecting the weaning process; Figure A1.1), there is considerable fluctuation in the $\delta^{15}N$ values in the M3, suggesting sub-annual fluctuations in the amount/kinds of high-trophic-level resources (presumably fish) consumed. There is only limited correlation with $\delta^{13}C$ values (Figure A1.2).

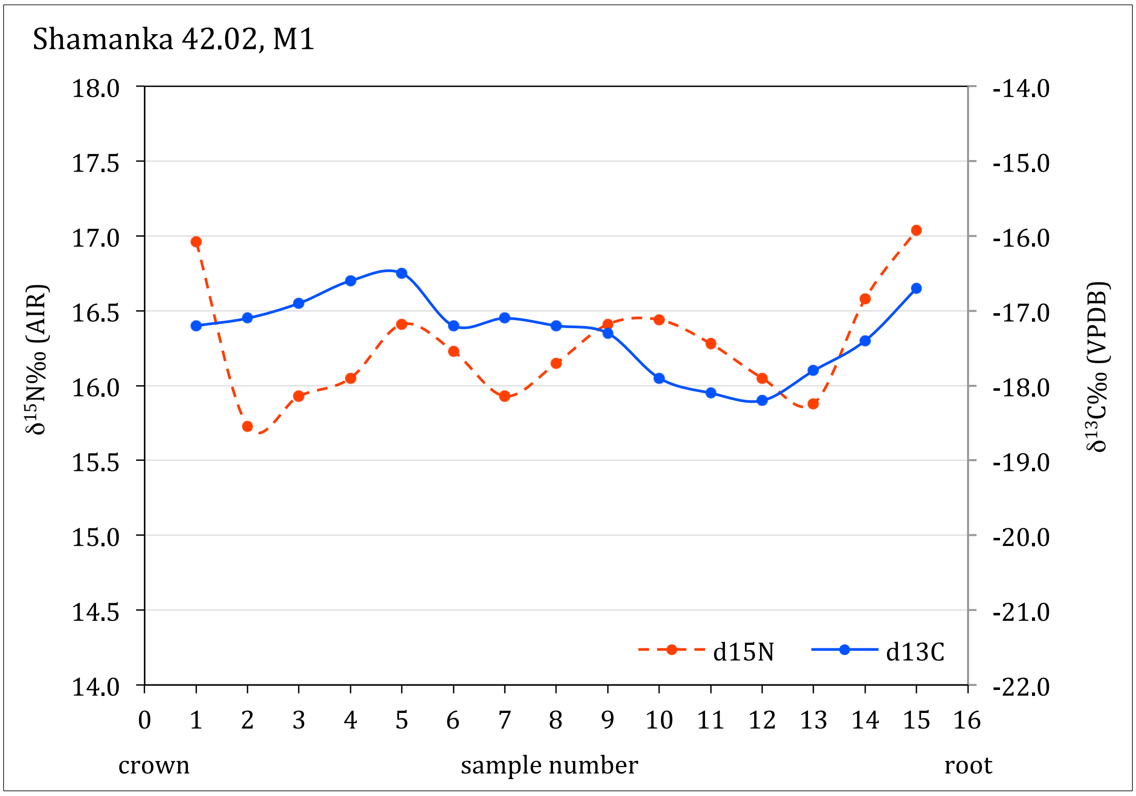

Figure A1.1. Plot of sequential $\delta^{13}C$ and $\delta^{15}N$ results for the M1 of Grave 42.02. The weaning process is reflected in the sharp drop between the first and second $\delta^{15}N$ values. Remaining collagen from samples 4-10 was pooled for ^{14}C dating.

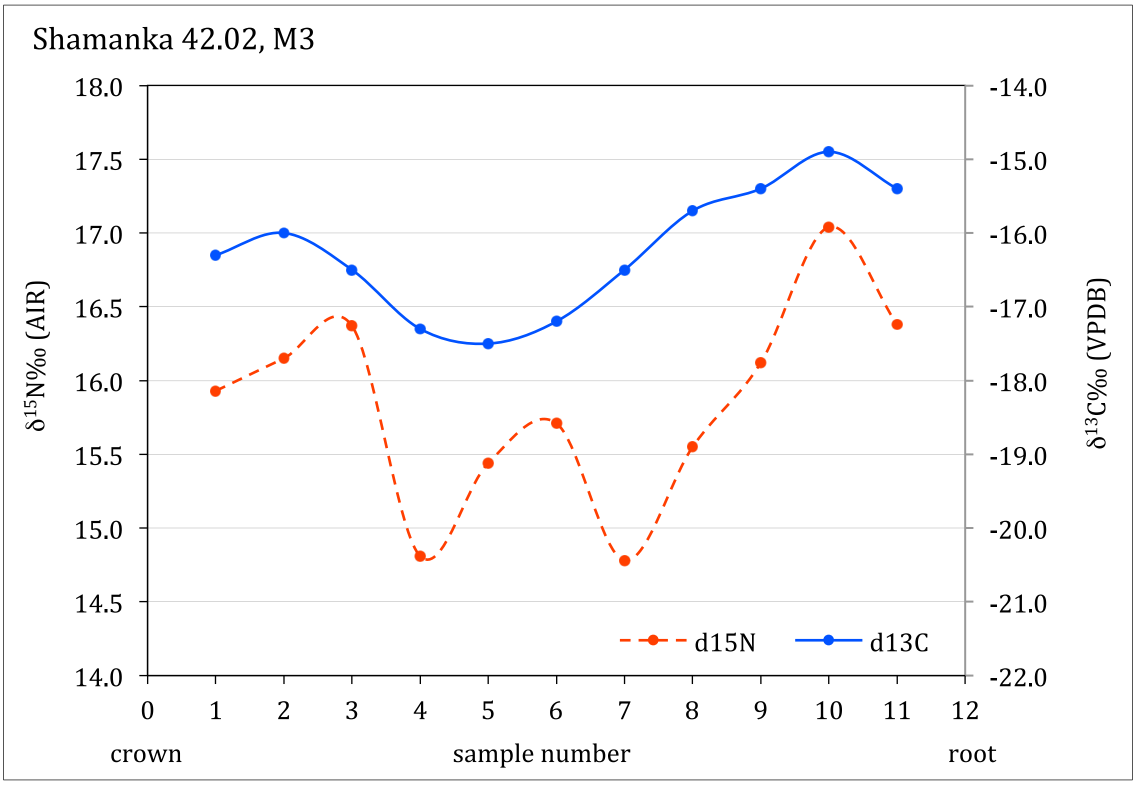

Figure A1.2. Plot of sequential $\delta^{13}C$ and $\delta^{15}N$ results for the M3 of Grave 42.02. Remaining collagen from samples 3-7 was pooled for ^{14}C dating.

Appendix 2. Stable sulphur isotope analysis (M. Richards)

Sulphur isotope measurements were made on bone collagen extracted following the methods outlined in Richards and Hedges (1999) and Brown et al. (1988). Approximately 500mg of whole bone pieces were surface cleaned and were then demineralised in 0.5M HCl for several days at 4°C. Demineralised organic residues were gelatinised at 72°C for 48h and then filtered in a 5-8 μm filter (Ezee filter, Elkay Laboratories, Ltd., U.K.). The resulting solution was further filtered by ultrafiltration to isolate the >30kDa fraction. Finally, the material was lyophilized (freeze-dried) and weighed into Eppendorf tubes.

Sulphur isotope measurement was undertaken using approximately 10mg of extracted bone collagen (Nehlich and Richards 2009). The bone collagen was combusted with additional V_2O_5 and a pulse of oxygen to ensure complete combustion. The resulting gases SO and SO_2 were analysed in a HeKaTech EuroVector coupled to a Delta V plus (ThermoFinnigan, Bremen, Germany). The inorganic international standards NBS127 ($\delta^{34}S$ +20.3‰), IAEA S1 (-0.3‰), S2 (+21.5‰) and SO-5 (+0.15‰) and two organic standards NIST1577b bovine liver (+7.5‰) and IVA casein protein (+6.3‰) were analysed daily. The precision of the sulphur isotope results of the archaeological bone collagen is better than ±0.6‰ (Nehlich and Richards 2009). Values are reported relative to the international standard VCDT (Vienna Canyon Diablo Troilite) (Coplen and Krouse 1998).

Group	*$\delta^{34}S$*	*±*	*C:S*	*±*	*n*
Red/roe deer	6.6	1.3	179.4	16.3	16
Baikal seal	6.2	1.2	152.6	22.3	9
Humans	6.5	1.1	196.8	34.6	35

Table A2.1. Summary of $\delta^{34}S$ results on archaeological deer, seals and humans from Cis-Baikal.

Additional References

Brown, T.A., Nelson, D.E. and Southon, J.R. 1988. Improved collagen extraction by modified Longin method. *Radiocarbon* 30: 171-177.

Coplen, T.B. and Krouse, H.R. 1998. Sulphur isotope data consistency improved. *Nature* 392: 32.

Nehlich, O. and Richards, M.P. 2009. Establishing collagen quality criteria for sulphur isotope analysis of archaeological bone collagen. *Archaeological and Anthropological Sciences* 1(1): 59–75.

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