

# Infant and Child Diet in Neolithic Hunter-Fisher-Gatherers From Cis-Baikal, Siberia: Intra-Long Bone Stable Nitrogen and Carbon Isotope Ratios

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**ABSTRACT** Analysis of stable nitrogen and carbon isotopes ( $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ ) from subadults and adults allows for assessment of age-related dietary changes, including breastfeeding and weaning, and adoption of an adult diet. In one of the first studies of hunter-fisher-gatherer subadults from Eurasia, three Neolithic (8,800–5,200 calBP) mortuary sites from southwestern Siberia are analyzed to evaluate hypothesized differences in weaning age between Early versus Late Neolithic groups. An intra-individual sampling methodology is used to compare bone formed at different ages. Collagen samples ( $n = 143$ ) from three different growth areas of long bones—the proximal metaphysis, diaphysis, and distal metaphysis—were obtained from 49 subadults aged birth to 10 years. In infants (birth to 3 years,  $n =$

23) contrasting the  $\delta^{15}\text{N}$  values of the metaphysis, which contains newer bone, to the  $\delta^{15}\text{N}$  values of the diaphysis, which contains older bone, permits a more precise determination of breastfeeding-weaning status. In Early and Late Neolithic groups breast milk was the major protein source until the age of 2–3 years. However, there are differences in the age of weaning completion and duration: Early Neolithic groups weaned their infants at a later age and over a shorter amount of time. Differences may have affected infant morbidity and mortality, and female fecundity and inter-birth intervals. Stable isotope values in older subadults (4–10 years,  $n = 26$ ) do not differ from adults suggesting the absence of age-based food allocation. *Am J Phys Anthropol* 146:225–241, 2011. © 2011 Wiley-Liss, Inc.

Few hunter-gatherer archaeological sites have a sufficient number of adequately preserved infants and children to reconstruct breastfeeding and weaning practices via isotopic analysis of bone collagen (Schurr and Powell, 2005; Clayton et al., 2006). Large cemeteries in the southwestern region of Lake Baikal, Siberia, Russian Federation (the *Cis-Baikal*), 9,000–5,000 years old, coupled with good preservation of bone, present an opportunity to evaluate the subadult feeding practices of Eurasian hunter-fisher-gatherer groups. This study builds upon that of Weber et al. (2002) who initiated stable isotope analysis of subadults from the *Cis-Baikal* region. Infant feeding patterns can be assessed by examining parameters such as the timing of introduction of complementary foods, the age when breast milk consumption ceased entirely, and the types of complementary foods introduced at different ages (Stuart-Macadam and Dettwyler, 1995). Infant feeding practices influence the size and demographic structure of a population, with longer weaning periods generally resulting in larger inter-birth intervals and fewer total children born (i.e., Dettwyler, 1987; as reviewed by Vitzhum, 1994; Wood, 1994; Ellison, 1995). Based on differences in the demographic structure of two *Cis-Baikal* mortuary sites, Link (1996, 1999) hypothesized that Late Neolithic<sup>1</sup> peo-

ples may have had an earlier age of weaning, which resulted in shorter inter-birth intervals and increased fecundity, compared with Early Neolithic peoples who were argued to be experiencing population stagnation and even decline (also see Lieverse, 2005, 2010). The archaeological record of an approximately 1,000-year discontinuity in the use of formal cemeteries during the seventh millennium BP suggests a shift in how Early Neolithic groups used the land that may be related to smaller population sizes (Weber, 1995; Weber et al., 2002; Weber and McKenzie, 2003; Weber and Bettinger, 2010).

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<sup>1</sup>In Siberia, the term Neolithic refers to the introduction of pottery, the bow and arrow, and stone polishing techniques, not agriculture.

Stable nitrogen isotope ratios<sup>2</sup> ( $\delta^{15}\text{N}$ ) are used to reconstruct infant feeding practices as  $\delta^{15}\text{N}$  enrichment of about three permil (‰) occurs with transfer through higher trophic levels (Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984). Fogel et al. (1989) first reported that breastfeeding infants exhibit a further  $\delta^{15}\text{N}$  trophic shift in comparison with their mothers (see also Millard, 2000; Fuller et al., 2006). Subsequently many researchers have analyzed the  $\delta^{15}\text{N}$  of bone or dentine collagen of infants from archaeological contexts to reconstruct breastfeeding and weaning<sup>3</sup> patterns<sup>4</sup> (Katzenberg and Pfeiffer, 1995; Herring et al., 1998; Dupras et al., 2001; Herrscher, 2003; Schurr and Powell, 2005; Richards et al., 2006; Jay et al., 2008, among many others; see Table 2 in Waters-Rist and Katzenberg 2010). Variation in protein consumption between infancy, childhood, and adolescence, as compared with adulthood, has also been investigated using  $\delta^{15}\text{N}$  (Katzenberg, 1993; White and Schwarcz, 1994; Clayton et al., 2006; Turner et al., 2007; Choy et al., 2010). In addition, stable carbon isotope ratios ( $\delta^{13}\text{C}$ ) have been shown to display a small trophic-level effect of around +1.0‰ (Katzenberg et al., 1993; Fuller et al., 2006) while more negative values (Wright and Schwarcz, 1998, 1999; Richards et al., 2002) may be tracking the introduction of weaning foods. Thus, stable carbon and nitrogen isotopes are an effective way of examining subadult feeding practices.

Eighteenth and nineteenth century ethnographies of central and northern Siberian hunter-gatherer populations, such as the Koryaks and Yakuts, report that breastfeeding continued into and beyond the third year (Krasheninnikov, 1764; Jochelson, 1908). In the Dolgani breastfeeding continued until 4–5 years of age (Popov, 1946). These weaning ages correspond with those of many hunter-gatherer groups listed in the Human Relation Areas Files Database (eHRAF, 2010; also see Ford, 1964; Dettwyler, 1995; Sellen, 2001; Kennedy, 2005). While breastfeeding may have occurred for many years, complementary foods such as fat from terrestrial mam-

mals, fish, and seals, were introduced early in infancy, in some cases as early as three to four months of age. Pre-mastication of tougher food items was a common method of making fish, meat and venison, and fibrous roots and vegetal items, easily digestible for infants. In the *Cis-Baikal* the advent of ceramics in the Early Neolithic and their increased use by the Late Neolithic-Bronze Age may also have been important in the preparation of weaning foods. Once “toddlerhood” has passed in many hunter-gatherers offspring are not considered dependents in need of different food, but assume adult diets (Bird-David, 2005; Hewett and Lamb, 2005). In contrast, in some agricultural populations the diets of children, juveniles, and adolescents are different from adults, particularly in the amount or type of protein (Turner et al., 2007).

We use an intra-long bone sampling method to determine the feeding pattern of subadults from Early Neolithic and Late Neolithic populations of the *Cis-Baikal*. Among the adults from any population there is variability in  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values due to differences in diet and physiology. If we assume that the majority of adult females buried at a mortuary site are the mothers of the subadults also buried there, we can reasonably expect that the amount of isotopic variation in adult females will be replicated in breastfeeding infants. High levels of intra-site  $\delta^{15}\text{N}$  variation can make it difficult to determine the exact feeding status of an infant. For example, if a breastfeeding female has a low  $\delta^{15}\text{N}$  value relative to the rest of the population her infant will also have a low  $\delta^{15}\text{N}$  value relative to other breastfeeding infants, which could be erroneously interpreted to indicate that the infant was not breastfed or was weaned. We must, therefore, be cautious in suggesting infant feeding status when using the position of a single  $\delta^{15}\text{N}$  value above or below the adult female  $\delta^{15}\text{N}$  mean: further consideration of adult female  $\delta^{15}\text{N}$  variation is needed. This article demonstrates a method based on intra-individual sampling of growing long bones that can circumvent this limitation.

Intra-individual sampling, from different mineralized tissues or between different parts of the same anatomical element, has been found to be useful in assessing the diachronic dietary history of individuals (Fizet et al., 1995; Sealy et al., 1995; Cox and Sealy, 1997; Wright and Schwarcz, 1998; Balasse et al., 1999, 2001; Bell et al., 2001; Balasse and Tresset, 2002; Mays et al., 2002; Fuller et al., 2003; Herrscher, 2003; Jørkov et al., 2009). This study compares  $\delta^{15}\text{N}$  values from the metaphyseal area of a growing long bone with those from the diaphysis of the same bone. Growth in length of long bones occurs as osteoid deposited by the growth plate is mineralized at the metaphyses, at the proximal and distal ends of the bone. The long bone shaft, the diaphysis, of the bones examined in this study, is formed in the seventh to eighth week of fetal life (Scheuer and Black, 2000).<sup>5</sup> Subsequently, the diaphyseal area undergoes the comparatively slow processes of appositional growth and remodeling so that any dietary change will be gradually integrated. The diaphyseal isotope signal will reflect dietary behavior from earlier in life. More recent dietary

<sup>2</sup>Stable isotope ratios are reported in the delta ( $\delta$ ) notation, as per thousand (permil ‰), as follows:  $\delta X = [(R^{\text{sample}}/R^{\text{standard}}) - 1] \times 10^3$ . For nitrogen  $X$  is  $^{15}\text{N}$  and  $R^{\text{sample}}$  and  $R^{\text{standard}}$  are the corresponding ratios of heavy to light isotopes ( $^{15}\text{N}/^{14}\text{N}$ ) in the sample and standard, respectively. The standard for  $\delta^{15}\text{N}$  is atmospheric nitrogen (AIR) and the standard for  $\delta^{13}\text{C}$  is Pee Dee Belemnite (PDB).

<sup>3</sup>Following Katzenberg et al. (1996), we use the term “weaning” to indicate the introduction of foods other than breast milk, and the term “complete weaning” or “weaned” to indicate the cessation of breastfeeding.

<sup>4</sup>Protein poor diets have been found to result in  $\delta^{15}\text{N}$  values that do not track a gradual decrease in nursing but rather remained elevated until weaning was complete because milk protein made the largest contribution to  $\delta^{15}\text{N}$  collagen values even when the amount consumed was minimal (Balasse et al., 2001). In the examined *Cis-Baikal* hunter-gatherer groups, protein consumption was relatively high (Katzenberg and Weber, 1999; Weber et al., 2002; Katzenberg et al., 2009, 2010) so this threshold effect should not be manifested.

<sup>5</sup>While there are slight differences in fetal-maternal  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values due to isotope effects that are not well understood, fetal  $\delta^{15}\text{N}$  values are not elevated like those of breastfeeding infants with a full trophic level increase (Millard, 2000; Fuller et al., 2006).

#### Abbreviations

aDNA	ancient DNA
ANCOVA	analysis of covariance
ANOVA	analysis of variance
HRAF	human relation areas files
LOK	Lokomotiv
SHA	Shamanka
UID	Ust'-Ida I

behavior will be recorded in bone collagen from the metaphyses. Schurr (1997, 1998) demonstrated that the metaphyseal area of a growing long bone contains the most recently deposited collagen and therefore can tell us about diet soon before death. In addition, the proximal and distal ends of long bones grow at different rates. For example, in the humerus approximately 80% of longitudinal growth occurs at the proximal metaphysis and 20% occurs at the distal metaphysis (Pritchett, 1991). Thus, the “metaphysis of majority growth” will contain collagen deposited most recently before death, as compared with the “metaphysis of minority growth” which should contain comparatively older collagen. As such, the humeral proximal metaphysis should have a relatively higher  $\delta^{15}\text{N}$  value in breastfeeding infants, and lower  $\delta^{15}\text{N}$  value in weaning infants. Rates of bone growth and turnover will determine how much collagen retained in a particular area was formed during any particular time-period before death (see Hedges et al., 2007 for collagen synthesis during adolescence).

In this article, we demonstrate that intra-long bone sampling permits a more precise determination of the feeding status of infants, and improves reconstructions of the timing and duration of dietary changes in infants and older subadults. Distinctions between the Early versus Late Neolithic *Cis*-Baikal groups suggest that differences in infant feeding practices could have contributed to different population sizes. Assessment of the myriad of socio-cultural, environmental, and demographic factors that contributed to infant morbidity and mortality in archaeological populations is a difficult task. However, our intra-long bone methodology permits us to determine whether an infant died during a period of breastfeeding or once weaning was well underway, that is during the time when morbidity and mortality are known to increase. High mortality among predominantly breastfed infants may suggest a considerable stressor was affecting the group.

## MATERIALS

### Sites

The subadults come from three mortuary sites (see Fig. 1). Subadults from the sites of Shamanka II (SHA  $n = 21$ ) and Lokomotiv (LOK and LOR  $n = 12$ ) are radiocarbon dated to the Early Neolithic (8,800–7,000/6,800 calBP), and those from the site of Ust'-Ida I (UID  $n = 16$ ) are radiocarbon dated to the Late Neolithic<sup>6</sup> (6,000/5,800–5200 calBP). In each cemetery, the majority of individuals were interred over the span of several hundred years at most (Weber et al., 2006). Ancient DNA (aDNA) analyses have shown that the Early Neolithic peoples are genetically distinct from Late Neolithic-Bronze Age groups (Mooder et al., 2006), which is also apparent in different funerary practices (Okladnikov, 1950, 1955; Weber, 1995; Weber and Bettinger, 2010). Several researchers have found differences between Early Neolithic and Late Neolithic-Bronze Age *Cis*-Baikal people as related to mobility, activity, demographic structure, population distribution and density, and health (Link, 1999; Weber et al., 2002; Lieverse et al., 2007a,b, 2009; Stock, 2010; Waters-Rist et al., 2010), which demonstrates that these groups had different adaptive strategies. Regional variation in the exploita-

tion of lake resources is the primary cause of dietary differences (Katzenberg and Weber, 1999; Weber et al., 2002; Katzenberg et al., 2009, 2010). Climate also varied, being more warm and humid in the Early Neolithic and more cool and dry in the Late Neolithic-Bronze Age (White and Bush, 2010). Weber et al. (2002, 2007, 2008; Weber and Bettinger, 2010) suggest that Early Neolithic groups established centers of relatively high population concentration in areas where food resources were plentiful as evidenced by the extended use of a few very large cemeteries. Marked differences in grave accoutrements suggest some degree of social inequity, and complex social and power relations (Bazaliiskii, 2003; Bazaliiskii and Savelyev, 2003). Late Neolithic cemeteries are smaller (Okladnikov, 1950, 1955) and at Ust'-Ida I grave accoutrements are relatively similar, which may imply a more evenly distributed regional population with less social inequity (Weber et al., 2002).

### Long bone samples

A total of 143 bone samples from 49 subadults under the age of 10 years are analyzed, 23 from infants aged from birth to 3 years, and 26 from children/juveniles aged 4–10 years. Forty-nine samples are from the diaphysis, 47 are from the proximal metaphysis, and 47 are from the distal metaphysis (two proximal and two distal metaphyses were missing or too damaged to permit sampling). Differential growth of the metaphyses is most pronounced in the humerus (Anderson et al., 1963; Pritchett, 1991; Table 1). To try to collect tissue deposited at different ages, the humerus was sampled in all cases where it was sufficiently complete and well-preserved ( $n = 41$ ). Other long-bones were sampled as follows: femur ( $n = 4$ ), ulna ( $n = 3$ ), and tibia ( $n = 1$ ).

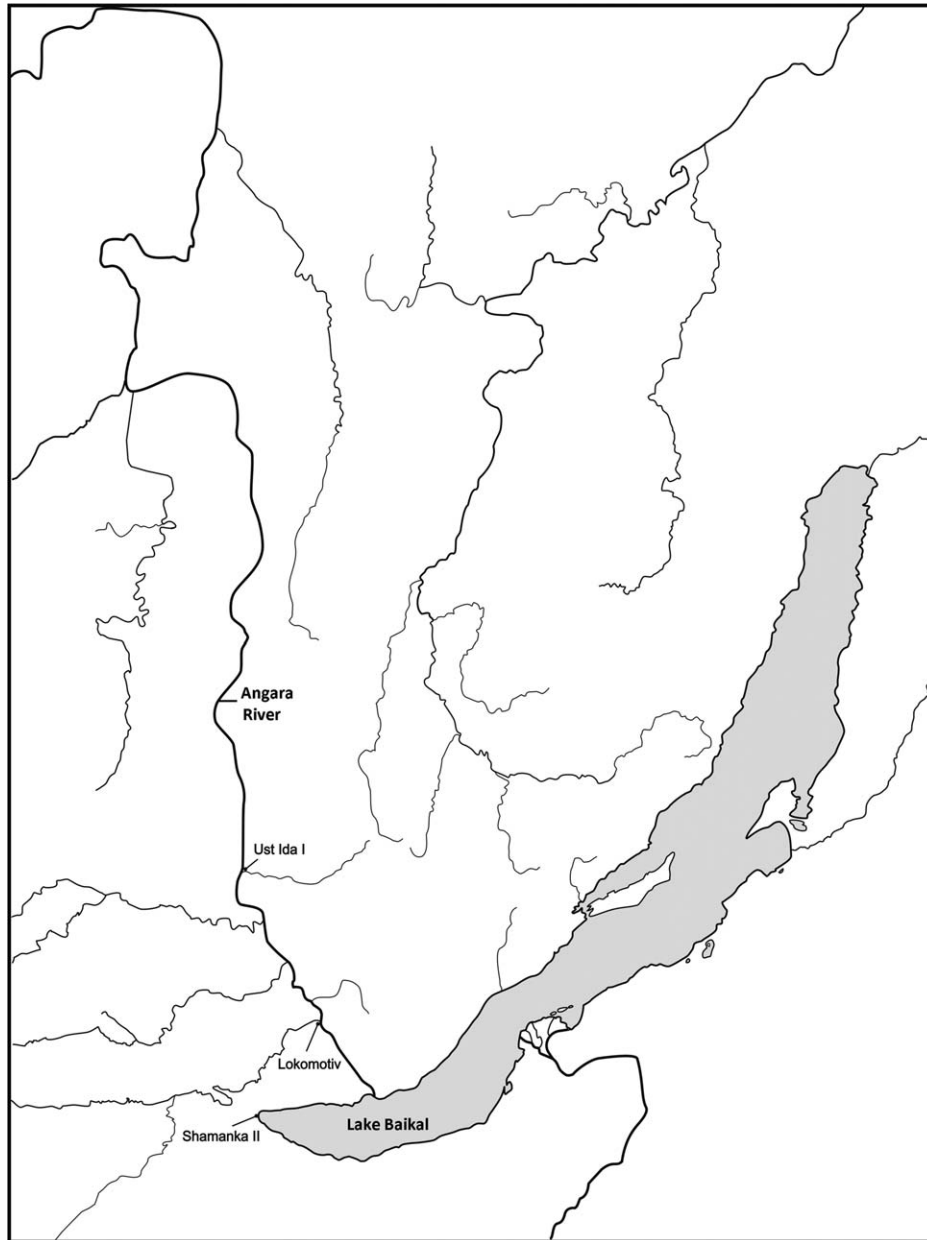
## METHODS

### Sample preparation and analysis

Small bone “chunks” (0.04–0.50 g; mean = 0.23 g) were removed using a hand-held Dremel tool fitted with a 0.6 mm disc bit. Diaphyseal samples were collected from the area of the primary nutrient foramen to collect the oldest tissue. Diaphyseal samples were collected from the periosteal through to the endosteal surface. Metaphyseal samples extended less than 1 mm to a maximum of 2 mm from the end of the bone in an effort to collect the most recently deposited tissue. Adhering sediment was removed and the sample was cleaned ultrasonically in double-distilled  $\text{H}_2\text{O}$ . Collagen was extracted following the method of Sealy (1986). Samples were soaked in very dilute HCl (0.5%), which was changed every 24–48 h. Dilute HCl was used to minimize protein loss (average number of HCl solution changes was 17, ranging from a minimum of 5 to a maximum of 35). Collagen pseudomorphs retained their shape after HCl treatment, suggesting that they could withstand the slight loss of protein that can occur with NaOH treatment, to remove humic contaminants. A 0.125% solution of NaOH was applied for 20 h.

Analyses of  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  were done on a Continuous Flow-Elemental-Analysis-Isotope Ratio Mass Spectrometer. Precision is  $\pm 0.2\text{‰}$  for  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ . Bone collagen is susceptible to diagenetic alteration which can distort biogenic isotope signals. The integrity of samples is assessed by collagen yield, atomic C/N ratio, and per-

<sup>6</sup>Ust'-Ida I adult female isotope data from Bronze Age burials are not included because there are no Bronze Age infants or children.



**Fig. 1.** Map of the Cis-Baikal area showing the mortuary sites of Shamanka II, Lokomotiv, and Ust'-Ida I.

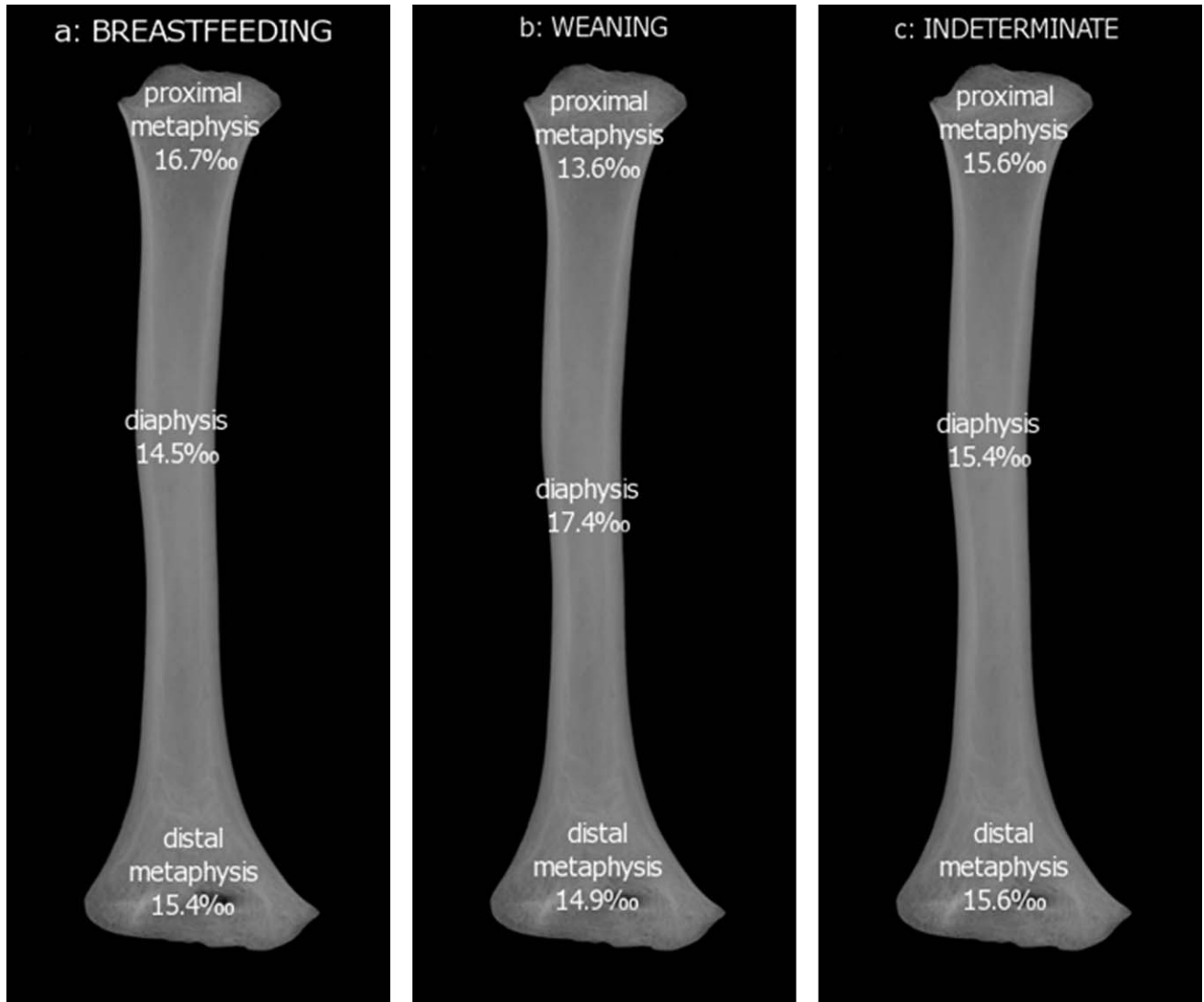
*TABLE 1. Relative amount of longitudinal growth in the proximal versus distal metaphyses of long bones*

Long bone	Proximal metaphysis	Distal metaphysis	Reference
Humerus	80%	20%	Pritchett (1991)
Radius	20–25%	75–80%	Pritchett (1991)
Ulna	15–25%	75–85%	Pritchett (1991)
Femur	30%	70%	Anderson et al. (1963)
Tibia	57%	43%	Anderson et al. (1963)

centage N and C by weight in collagen (DeNiro, 1985; Ambrose, 1990; van Klinken, 1999). Percentage N and C by weight were assessed with a Carlo Erba NA 1500 elemental gas analyzer giving the C/N ratio. Precision of percentage N and C are  $\pm 5.0\%$ . All samples had accepta-

ble atomic C/N ratios, between 2.9 and 3.6, and acceptable collagen yields that varied from 3.2 to 26.0%.<sup>7</sup> While all samples had percentage N and C values well above the recommended lower margin, two were slightly above the recommended upper margin for C (SHA 27-4b %C 52.5 and SHA 69-3c %C 52.3), even taking into consideration measurement imprecision. However, we have chosen not to exclude these samples from subsequent analyses because; (1) collagen of embryonic and early post-natal long bones contains twice as much of the carbon-rich amino acid hydroxylysine than mature lamellar

<sup>7</sup>Subadult bones have proportionally more collagen than adult bones (Baker et al., 1946) which is why the single collagen yield slightly above 25% is considered acceptable (SHA 31-1b, collagen yield 25.95%).



**Fig. 2.** Illustration of infant feeding intra-long bone  $\delta^{15}\text{N}$  scenarios: (a) breastfeeding, (b) weaning/weaned, (c) indeterminate [scenario (a) from SHA 38.1 3.0 years; scenario (b) from LOR 10-1 3.5 years; scenario (c) from SHA 82-1 1.75 years].

bone, which could account for the slightly high percentage C value (Miller et al., 1967; also see Gorski, 1998 who found a higher percentage of the carbon-rich amino acids aspartic- and glutamic-acid in the non-collagenous proteins of rapidly deposited woven bone), and; (2) these samples had acceptable yields and C/N values.

#### Subadult aging

Tooth eruption was the major criterion for determining age at death. Whenever possible tooth crown formation was also evaluated (Schour and Massler, 1941; Buikstra and Ubelaker, 1994); however, it was not possible to take radiographs in Irkutsk, Siberia, where the collections are curated. Crown and root formation were assessed macroscopically on loose teeth or on teeth that were fully visible within crypts. Diaphyseal length was used to estimate age for four subadults older than 5 years for whom teeth or jaws were not recovered (LOK 14-4, LOK 14-2, LOR 13-2, SHA 25-4). The longitudinal growth reference

standard of Merchant and Ubelaker (1977), developed on an Amerindian sample, was used.

#### $\delta^{15}\text{N}$ variation scenarios

The standard deviations of the  $\delta^{15}\text{N}$  values of adult females are used to assess the amount of isotopic variability within each site. In Shamanka II, the standard deviation of adult female  $\delta^{15}\text{N}$  is 0.7‰ ( $n = 20$ , range of 3.3‰ from 13.1 to 16.4‰); at Lokomotiv it is 0.8‰ ( $n = 19$ , range of 3.5‰ from 11.7 to 15.2‰); and at Ust'-Ida I it is 0.9‰ ( $n = 6$ , range of 1.9‰ from 11.1 to 13.0‰) (Katzenberg and Weber, 1999; Weber et al. 2002; Katzenberg et al., 2010). It is important to account for non-dietary sources of isotopic variation to avoid over-interpretation of data. Instrument imprecision is 0.2‰ and duplicate and triplicate samples varied by <0.3‰ for  $\delta^{13}\text{C}$  and 0.2‰ for  $\delta^{15}\text{N}$ . Other studies have similarly found stochastic isotope variation to be around 0.3‰ (Chisholm, 1989; Katzenberg and Lovell, 1999; also see

TABLE 2. Intra-long bone  $\delta^{15}\text{N}$  for subadults birth to 3 years of age ( $n = 23$ ) with suggested feeding status

Site and individual number <sup>a</sup>	Age range (years)	Age mean (years)	Long bone	$\delta^{15}\text{N}$ (‰)			Maximum difference from diaphysis	Pattern <sup>c</sup>	Suggested feeding status
				Proximal metaphysis <sup>b</sup>	Diaphysis	Distal metaphysis			
SHA 27-4	0.25–0.75	0.5	Humerus	<b>16.2</b>	16.3	16.4	±0.1	c	<b>Breastfeeding</b>
SHA 81-1	0.25–0.75	0.5	Humerus	<b>15.9</b>	14.0	16.3	+2.3	a	<b>Breastfeeding</b>
SHA 40-1	0.5–1.5	1.0	Ulna	17.4	15.8	n/a	+1.6	a	<b>Breastfeeding</b>
SHA 69-3	0.75–1.75	1.25	Humerus	<b>17.5</b>	18.1	18.2	−0.6	c	<b>Breastfeeding</b>
SHA 80-1	0.75–1.75	1.25	Humerus	<b>17.3</b>	16.5	17.4	+0.9	a	<b>Breastfeeding</b>
SHA 66-2	1.25–2.25	1.75	Humerus	<b>16.6</b>	16.6	17.6	+1.0	a	<b>Breastfeeding</b>
SHA 82-1	1.25–2.25	1.75	Humerus	<b>15.6</b>	15.4	15.6	+0.2	c	<b>Indeterminate</b>
SHA 48-2	2.0–3.0	2.5	Ulna	14.9	14.7	<b>12.7</b>	−2.0	b	<b>Weaning</b>
SHA 27-3	2.0–3.0	2.5	Humerus	<b>14.7</b>	15.6	14.3	−1.3	b	<b>Weaning</b>
SHA 28-1	2.0–4.0	3.0	Humerus	<b>16.1</b>	15.6	16.2	+0.6	c	<b>Breastfeeding</b>
SHA 38-1	2.0–4.0	3.0	Humerus	<b>16.7</b>	14.5	15.4	+2.2	a	<b>Breastfeeding</b>
SHA 72-1	2.0–4.0	3.0	Humerus	<b>16.6</b>	15.5	16.1	+1.1	a	<b>Breastfeeding</b>
SHA 56-1	3.0–5.0	4.0	Humerus	<b>15.9</b>	15.4	15.7	+0.5	c	<b>Weaned</b>
<b>Average</b>				16.3	15.7	16.0	+0.5		
<b>S.D.</b>				0.91	1.09	1.55	1.37		
LOK 3-1	1.0–1.5	1.25	Humerus	<b>18.0</b>	17.5	n/a	+0.5	c	<b>Breastfeeding</b>
LOR 7-3	2.0–3.0	2.5	Femur	14.5	15.4	<b>14.4</b>	−1.0	b	<b>Weaning</b>
LOR 10-1	3.0–4.0	3.5	Humerus	<b>13.6</b>	17.4	14.9	−3.8	b	<b>Weaned</b>
<b>Average</b>				15.5	16.4	15.0	−1.0		
<b>S.D.</b>				1.92	1.18	0.66	2.03		
UID 26-2	0.75–1.25	1.0	Humerus	<b>14.9</b>	15.6	15.1	−0.7	b	<b>Weaning</b>
UID 4-1	2.0–3.0	2.5	Humerus	<b>14.2</b>	15.1	14.0	−1.1	b	<b>Weaning</b>
UID 17-1	2.0–4.0	3.0	Femur	13.1	14.3	<b>13.3</b>	−1.2	b	<b>Weaning</b>
UID 55-1	2.0–4.0	3.0	Humerus	<b>13.2</b>	14.2	14.3	−1.0	b	<b>Weaning</b>
UID 25-1	3.0–4.0	3.5	Humerus	<b>11.0</b>	14.2	12.4	−3.2	b	<b>Weaned</b>
UID 26-3	3.0–4.0	3.5	Humerus	<b>11.5</b>	13.3	12.3	−1.8	b	<b>Weaned</b>
UID 36-1	3.0–4.0	3.5	Humerus	<b>12.7</b>	12.8	12.4	−0.4	c	<b>Weaned</b>
<b>Average</b>				12.9	14.2	13.4	−1.3		
<b>S.D.</b>				1.38	0.96	1.10	0.93		

<sup>a</sup> SHA = Shamanka II; LOK = Lokomotiv; LOR = Lokomotiv-Raisovet; UID = Ust'-Ida I.

<sup>b</sup> Metaphysis of majority growth in bold.

<sup>c</sup> As indicated in Figure 2 (for explanation see Methods section).

Adult female  $\delta^{15}\text{N}$  standard deviation is 0.7‰ at Shamanka II, 0.8‰ at Lokomotiv and Lokomotiv-Raisovet, and 0.9‰ at Ust'-Ida I. Values that are below this are highlighted in grey.

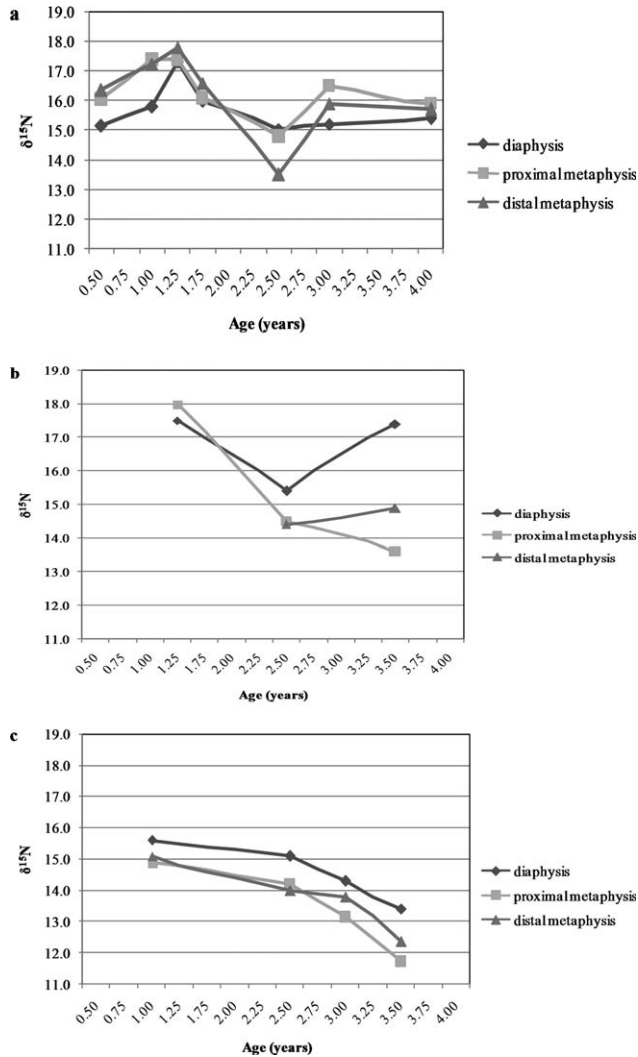
DeNiro and Schoeninger, 1983 and Schoeninger, 1989 for isotopic variation among different bones from the same individual). Since these values are considerably lower than adult standard deviations, we suggest that isotopic differences greater than the adult female standard deviation are a useful benchmark or “cut-off” by which biologically meaningful isotopic variation within a single bone can be identified with confidence. Thus, maximum difference  $\delta^{15}\text{N}$  values below this are not used to suggest feeding status, and maximum difference  $\delta^{15}\text{N}$  values equal to or above this are used to suggest feeding status. An evaluation of this method via logistic regression is presented at the beginning of the  $\delta^{15}\text{N}$  results section.

Three scenarios are illustrated in Figure 2 to show the patterning of stable nitrogen isotopes that we suggest indicate either (a) breastfeeding, (b) weaning, or (c) an indeterminate pattern. In Figure 2a,  $\delta^{15}\text{N}$  values are meaningfully higher at the metaphyses as compared with the diaphysis, which suggests the infant died during, or soon after, the period of breastfeeding. In Figure 2b,  $\delta^{15}\text{N}$  values are meaningfully lower at the metaphyses as compared with the diaphysis, suggesting the infant died after the weaning process had begun. When metaphyseal  $\delta^{15}\text{N}$  values reach the level of the adult females it is suggested that the infant has been completely weaned. Finally, in Figure 2c, it is not possible to suggest infant feeding status based on the patterning of  $\delta^{15}\text{N}$  values because of a

lack of meaningful isotopic variation. This may be due to i) an insufficient amount of time for a dietary change to be recorded in bone collagen at the metaphyses, ii) no dietary change occurred, for example no breastfeeding, or iii) the entire bone is tracking the same dietary behavior, for example the entire bone is reflecting breastfeeding. It must also be kept in mind that  $\delta^{15}\text{N}$  values can become elevated by physiological disruptions that result in negative nitrogen balance, such as malnutrition (White and Armelagos, 1997; Katzenberg and Lovell, 1999; Fuller et al., 2005; Mekota et al., 2006).

### Statistical analyses

Non-parametric statistics are used to compare isotope values among groups because of small sample sizes and the non-normal distribution of data in the Lokomotiv and Lokomotiv-Shamanka II combined sample as indicated by a Shapiro-Wilk test of normality (for Lokomotiv-Shamanka II combined  $\delta^{15}\text{N}$ : proximal metaphysis  $W = 0.942$ ,  $P = 0.003$ ; diaphysis  $W = 0.926$ ,  $P < 0.000$ ; distal metaphysis  $W = 0.943$ ,  $P = 0.004$ ). The Wilcoxon-Mann-Whitney test is used for the comparison of two samples [i.e., Early Neolithic vs. Late Neolithic] and the Kruskal-Wallis test (the non-parametric equivalent of a one-way analysis of variance (ANOVA)) is used for the comparison of three or more samples (i.e., among cemeteries). There are no statistically



**Fig. 3.** Comparison of the diaphyseal, proximal metaphyseal, and distal metaphyseal  $\delta^{15}\text{N}$  curves from (a) Shamanka II, (b) Lokomotiv, and (c) Ust'-Ida I infants, Cis-Baikal, Siberia.

significant differences in infant  $\delta^{15}\text{N}$  or  $\delta^{13}\text{C}$  values between the two Early Neolithic cemeteries (proximal metaphysis  $\delta^{15}\text{N}$   $\chi^2 = 0.767$ ,  $P = 0.381$ ; diaphysis  $\delta^{15}\text{N}$   $\chi^2 = 0.0122$ ,  $P = 0.893$ ; proximal metaphysis  $\delta^{13}\text{C}$   $\chi^2 = 2.007$ ,  $P = 0.157$ ; diaphysis  $\delta^{13}\text{C}$   $\chi^2 = 21.319$ ,  $P = 0.251$ ; distal metaphysis sample size too small for statistical analysis). There are, however, a few significant differences in children-juvenile  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values between Early Neolithic cemeteries (proximal metaphysis  $\delta^{15}\text{N}$   $\chi^2 = 6.381$ ,  $P = 0.012$ ; distal metaphysis  $\delta^{15}\text{N}$   $\chi^2 = 4.509$ ,  $P = 0.034$ ; diaphysis  $\delta^{13}\text{C}$   $\chi^2 = 7.331$ ,  $P = 0.007$ ; children-juvenile samples not reported are not statistically different). Because different cemeteries represent different analytical units, and stable isotope values are dissimilar in a few cases, Shamanka II and Lokomotiv are presented separately in Tables 2, 5, 6, 8 and in Figure 3. However, in the results and discussion, Shamanka II and Lokomotiv infants are considered as a combined Early Neolithic sample because they are not statistically different and the primary goal of this article is to compare biocultural groups. Analysis of covariance (ANCOVA) is performed to test group differences between maximum  $\delta^{15}\text{N}$  metaphyseal-diaphyseal values

while controlling for an age effect. Simple linear and polynomial regression is used to evaluate the relationship between age and the  $\delta^{15}\text{N}$  curve in infants.

Logistic regression analysis is used to evaluate the relationship between purported breastfeeding-weaning status and  $\delta^{15}\text{N}$  values. The dependent response variable is set as binary, where subadults are classified as "breastfeeding" or "not breastfeeding" (as listed in Table 2), and the independent variable is  $\delta^{15}\text{N}$ , which is analyzed separately and combined for the different sampling locations (proximal metaphysis, diaphysis, distal metaphysis). Logistic regression analysis is then used to evaluate the effectiveness of using adult female standard deviation values as indicative of biologically meaningful  $\delta^{15}\text{N}$  variation.

## RESULTS

### Adult female standard deviation method

The mean and median of the maximum difference between the diaphysis and proximal or distal metaphyseal  $\delta^{15}\text{N}$  is  $1.00 \pm 0.80$  and  $0.80$ , respectively.<sup>8</sup> Using the cut-off value of adult female  $\delta^{15}\text{N}$  standard deviation at each site (0.7‰ at Shamanka II, 0.8‰ at Lokomotiv, and 0.9‰ at Ust'-Ida I), and maximum difference  $\delta^{15}\text{N}$ , the relationship between purported breastfeeding-weaning status and  $\delta^{15}\text{N}$  values is highly significant, with a likelihood ratio of  $P < 0.000$  (Table 3). When all three sampling locations are combined ( $n = 44$ ), 88.6% of cases ( $n = 39$ ) were classified accurately according to the model parameters (three non-breastfeeding and two breastfeeding cases were not correctly classified). In our logistic regression model, we can manipulate the dependent variable response (breastfeeding vs. non-breastfeeding) to evaluate the effectiveness of the cut-off value. Basically, if we increase or decrease the cut-off value do we obtain improved infant feeding prediction, or a better-fit? The number of classifications that meet the expectations of our model does not increase by altering the cut-off value by plus or minus 0.1, 0.2, or 0.3‰. Therefore, using adult female  $\delta^{15}\text{N}$  standard deviation as the cut-off value for sufficient intra-individual  $\delta^{15}\text{N}$  variation is a method that should draw our attention to meaningful isotopic variation.

### Stable nitrogen isotopes ( $\delta^{15}\text{N}$ )

**Infants.** Table 2 presents the intra-long bone  $\delta^{15}\text{N}$  values of infants (birth to 3 years of age;  $n = 23$ ). The column "suggested feeding status" is based upon; a) the dietary pattern as indicated by the scenarios outlined in the methods section and Figure 2 (scenario a, b or c), and b) the level of infant  $\delta^{15}\text{N}$  compared with the adult female  $\delta^{15}\text{N}$  mean. Using exclusively the scenario data, it is possible to suggest a dietary pattern of breastfeeding or weaning/weaned in 16/23 (69.6%) of infants from the Early Neolithic cemeteries, while the dietary pattern of seven infants is indeterminate because intra-long bone  $\delta^{15}\text{N}$  values are not sufficiently variable. When infant  $\delta^{15}\text{N}$  relative to adult female  $\delta^{15}\text{N}$  mean is also considered, it is possible to suggest feeding status for six of the seven indeterminate infants. Neither the intra-long bone nor infant to adult comparative  $\delta^{15}\text{N}$  values are dissimilar enough in SHA 82-1 to suggest feeding

<sup>8</sup>It is necessary to note median because data are slightly positively skewed (skewness = 1.662).

TABLE 3. Logistic regression analysis of breastfeeding or non-breastfeeding feeding status via  $\delta^{15}N$  values for Neolithic Cis-Baikal subadults using SPSS (version 15)

	N	$\beta$	SE $\beta$	Wald's $\chi^2$	df	p	$e^\beta$ (odds ratio)
Proximal Metaphysis	46	1.572	0.484	10.554	1	0.001	4.815
Constant		-25.028	7.607	10.824	1	0.001	0.000
Diaphysis	93	1.470	0.412	12.745	1	0.000	4.350
Constant		-24.026	6.335	14.382	1	0.000	0.000
Distal Metaphysis	46	1.741	0.562	9.592	1	0.002	5.703
Constant		-27.413	8.650	10.044	1	0.002	0.000
Test of all 3 sampling locations combined (n = 44)				$\chi^2$	df	p	
Overall model evaluation							
Likelihood ratio test				23.885	3	0.000	
Goodness of fit test							
Hosmer and Lemeshow				5.953	8	0.652	

TABLE 4. Mean  $\delta^{15}N$  (‰) by age-category

Age category	Shamanka II				Lokomotiv				Ust'-Ida I			
	pm	dia	dm	mean	pm	dia	dm	mean	pm	dia	dm	mean
0-3 years	16.3 (13)	15.7 (13)	16.0 (12)	16.0 $\pm 1.1$	15.4 (3)	16.8 (3)	14.7 (2)	15.7 $\pm 1.7$	12.9 (7)	14.2 (7)	13.4 (7)	13.5 $\pm 1.2$
4-10 years	15.3 (8)	15.0 (8)	14.9 (8)	15.1 $\pm 0.9$	14.2 (8)	14.5 (9)	13.9 (9)	14.2 $\pm 0.4$	12.0 (8)	12.7 (9)	12.3 (9)	12.3 $\pm 0.7$
Adult females	14.8 $\pm$ 0.7 (20)				14.1 $\pm$ 0.8 (19)				12.1 $\pm$ 0.8 (6)			

pm = proximal metaphysis, dia = diaphysis, dm = distal metaphysis. Numbers in parentheses are sample sizes.

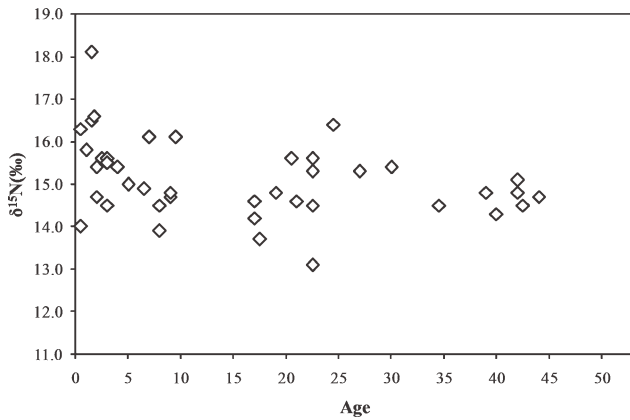


Fig. 4.  $\delta^{15}N$  values by age for Early Neolithic subadults (n = 21) and adult females (n = 20) from the mortuary site of Shamanka II, Siberia.

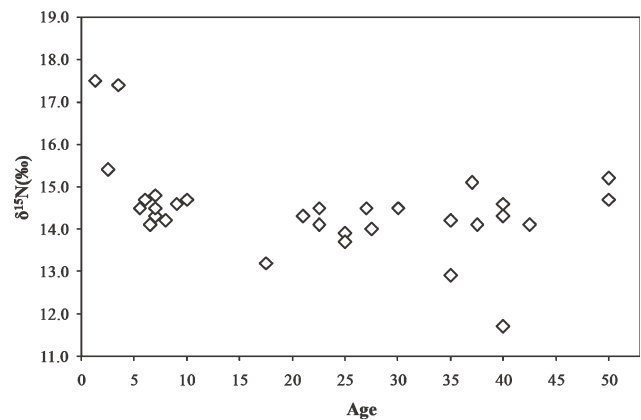


Fig. 5.  $\delta^{15}N$  values by age for Early Neolithic subadults (n = 12) and adult females (n = 19) from the mortuary site of Lokomotiv, Siberia.

status: it is possible there was no dietary shift, or that the entire bone is reflecting a dietary pattern of breastfeeding or weaning. In total, we are able to suggest feeding status for 22/23 (95.7%) of the Early Neolithic infants: 10 (62.5%) were breastfeeding, which encompasses the ages of 0.5-3.0 years, and five were weaning or weaned, encompassing the ages of 2.0-4.0 years. Elevated  $\delta^{15}N$  values in the metaphyses are still present in several of the 2.0-4.0-year-olds. This patterning suggests that significant decreases in breast milk consumption did not occur until 2.0-3.0 years of age and that complete weaning occurred around 3.5-4.0 years of age. Variation in the feeding patterns of the 2.0-4.0-year-olds (five infants have a pattern of weaning/weaned and three have a pattern of breastfeeding) may indicate a high level of group heterogeneity in infant feeding practices.

For the Late Neolithic site (Ust'-Ida I) all seven infants (100%), spanning the ages of 1.0-3.5 years, were weaning or weaned, although there was only one indi-

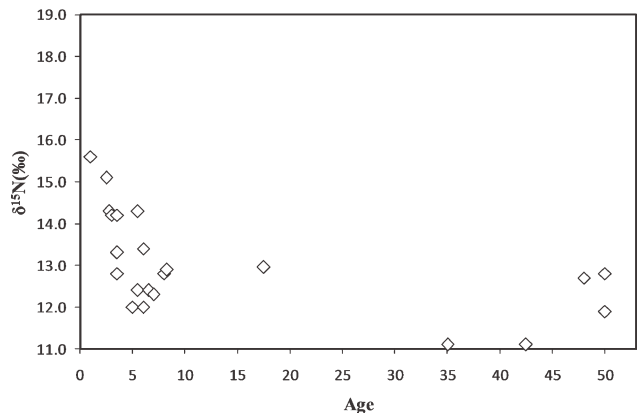


Fig. 6.  $\delta^{15}N$  values by age for Late Neolithic subadults (n = 16) and adult females (n = 6) from the mortuary site of Ust'-Ida I, Siberia.



TABLE 5. Intra-long bone  $\delta^{15}\text{N}$  for subadults four to ten years of age ( $n = 26$ )

Site and individual number <sup>a</sup>	Age range (years)	Age mean (years)	Long bone	$\delta^{15}\text{N}$ (‰)			Maximum difference from diaphysis <sup>c</sup>
				Proximal metaphysis <sup>b</sup>	Diaphysis	Distal Metaphysis	
SHA 31-1	4.0–6.0	5.0	Humerus	<b>15.1</b>	15.0	14.7	–0.3
SHA 55-2	5.25–7.75	6.5	Humerus	<b>16.4</b>	14.9	15.0	+1.5
SHA 26-3	6.0–8.0	7.0	Humerus	<b>15.9</b>	16.1	15.5	–0.6
SHA 26-6	7.0–9.0	8.0	Humerus	<b>14.6</b>	13.9	13.5	+0.7
SHA 67-1	7.0–9.0	8.0	Humerus	<b>13.4</b>	14.5	14.0	–1.1
SHA 25-4	6.0–12.0	9.0	Tibia	<b>15.6</b>	14.7	15.9	+1.2
SHA 64-2	8.0–10.0	9.0	Ulna	14.6	14.8	<b>14.4</b>	–0.4
SHA 56-2	8.25–10.75	9.5	Humerus	<b>16.6</b>	16.1	16.3	+0.5
<b>Average</b>				15.3	15.0	14.9	+0.2
<b>S.D.</b>				1.07	0.76	0.96	0.92
LOK 14-4	4.0–7.0	5.5	Humerus	<b>13.7</b>	14.5	14.3	–0.8
LOK 41-2	5.0–7.0	6.0	Humerus	<b>13.7</b>	14.7	13.7	–1.0
LOR 9-1	6.0–7.0	6.5	Humerus	<b>14.1</b>	14.1	13.8	–0.3
LOK 18-1-3	6.0–8.0	7.0	Humerus	<b>14.2</b>	14.5	14.2	–0.3
LOK 24-3	6.0–8.0	7.0	Humerus	<b>14.4</b>	14.8	14.0	–0.8
LOR 13-1	6.0–8.0	7.0	Femur	14.3	14.3	<b>14.2</b>	–0.1
LOK 14-2	6.0–10.0	8.0	Humerus	<b>13.8</b>	14.2	14.0	–0.4
LOK 24-4	8.0–10.0	9.0	Humerus	<i>n/a</i>	15.3	14.6	–0.7
LOR 13-2	8.0–12.0	10.0	Femur	14.4	14.7	<b>13.1</b>	–1.6
<b>Average</b>				14.1	14.6	14.0	–0.7
<b>S.D.</b>				0.30	0.36	0.43	0.46
UID 53-2	4.0–6.0	5.0	Humerus	<b>11.0</b>	12.0	11.7	–1.0
UID 15-1	5.0–6.0	5.5	Humerus	<b>12.0</b>	12.4	13.1	+0.7
UID 44-2	5.0–6.0	5.5	Humerus	<b>11.4</b>	14.3	12.3	–2.9
UID 21-2	5.0–7.0	6.0	Humerus	<i>n/a</i>	13.3	13.4	+0.1
UID 26-5	5.0–7.0	6.0	Humerus	<b>11.5</b>	12.0	12.3	–0.5
UID 9-1	6.0–7.0	6.5	Humerus	<b>11.9</b>	12.4	11.9	–0.5
UID 8-1	6.0–8.0	7.0	Humerus	<b>12.4</b>	12.3	11.9	–0.4
UID 5-1	7.0–9.0	8.0	Humerus	<b>12.6</b>	12.9	12.5	–0.4
UID 25-2	7.0–9.0	8.0	Humerus	<b>11.5</b>	12.8	12.3	–1.3
<b>Average</b>				11.8	12.7	12.4	–0.7
<b>S.D.</b>				0.54	0.73	0.56	1.01

<sup>a</sup> SHA = Shamanka II; LOK = Lokomotiv; LOR=Lokomotiv-Raisovet; UID = Ust'-Ida I.

<sup>b</sup> Metaphysis of majority growth in bold.

<sup>c</sup> Adult female  $\delta^{15}\text{N}$  standard deviation is 0.7‰ at Shamanka II, 0.8‰ at Lokomotiv and Lokomotiv-Raisovet, and 0.9‰ at Ust'-Ida I.

vidual under the age of 2.0 years. This suggests that decreases in breast milk consumption occurred by the age of 1.0 and that complete weaning occurred by 3.0 years of age. Overall, the  $\delta^{15}\text{N}$  data suggest that the age of weaning initiation and completion occurred earlier in the Late Neolithic compared with the Early Neolithic.

As we are interested in how infant feeding changes with age,  $\delta^{15}\text{N}$  differences are analyzed statistically using the maximum metaphyseal-diaphyseal difference values, rather than absolute  $\delta^{15}\text{N}$  values which are known to be significantly different between time-periods, and regions, due to dietary variation (Katzenberg and Weber, 1999; Weber et al., 2002; Katzenberg et al., 2010). Without controlling for age, a Wilcoxon-Mann-Whitney test produces significant results for the maximum metaphyseal-diaphyseal  $\delta^{15}\text{N}$  difference values between the Early Neolithic and Late Neolithic infants ( $Z = -2.273$ ,  $P = 0.023$ ). However, significance below the 0.05 level is not maintained when age is incorporated as a covariate in an ANCOVA test ( $F = 2.731$ ,  $P = 0.114$ ).

The differential longitudinal growth of the proximal versus distal metaphyses of long bones permitted us to sample the “metaphysis of majority growth” and the “metaphysis of minority growth.” In many of the infants for whom both metaphyses are present (14/21, 66.7%), the  $\delta^{15}\text{N}$  value of the “metaphysis of majority growth” is not significantly different from that of the “metaphysis

of minority growth” (Wilcoxon-Mann-Whitney: Early Neolithic breastfeeding infants  $n = 8$ ,  $Z = 0.0526$ ,  $P = 0.958$ ; Early Neolithic weaning infants  $n = 5$ ,  $Z = 0.838$ ,  $P = 0.402$ ; Late Neolithic weaning infants  $n = 7$ ,  $Z = 0.512$ ,  $P = 0.609$ ). In the children-juveniles, there is also no consistent pattern of  $\delta^{15}\text{N}$  values being higher or lower in the “metaphysis of majority growth” (SHA no difference  $n = 4$ , higher  $n = 3$ , lower  $n = 1$ ; LOK/LOR no difference  $n = 5$ , higher  $n = 0$ , lower  $n = 4$ ; UID no difference  $n = 5$ , higher  $n = 0$ , lower  $n = 3$ ).

Figure 3a–c displays a comparison of mean diaphyseal, proximal metaphyseal, and distal metaphyseal  $\delta^{15}\text{N}$  curves of the infants from Shamanka II, Lokomotiv and Ust'-Ida I. For Ust'-Ida I each of the sampling locations displays a closely-matched gradual descending slope, with the largest decrease in  $\delta^{15}\text{N}$  occurring at 2.5–3.0 years of age. The  $\delta^{15}\text{N}$  values from the diaphyseal samples of the Ust'-Ida I infants consistently decrease with age as evidenced by a high coefficient of determination of simple linear regression ( $R^2 = 0.834$ ). Shamanka II and Lokomotiv  $\delta^{15}\text{N}$  curves also decrease at age 2.5 years; however, this is followed by an increase in values (in all sampling locations except Lokomotiv proximal metaphysis). In Shamanka II,  $\delta^{15}\text{N}$  values from the different sampling locations meet up at age 4.0 years. Hence, there are two “peaks and dips” in the Shamanka II curve, the middle of which we see in the Lokomotiv curve. A combined Shamanka II-Lokomotiv diaphyseal

$\delta^{15}\text{N}$  curve does not vary predictably with age using a simple linear regression model ( $R^2 = 0.002$ ) because of the high variability among infants. However, a polynomial regression model that predicts two paired curves (therefore 5 + 1 constraints) provides a much higher coefficient of determination ( $R^2 = 0.704$ ).

Table 4 displays the mean  $\delta^{15}\text{N}$  values of groups by age category (0–3 years, 4–10 years, and adult female). Figures 4–6 show individual  $\delta^{15}\text{N}$  values for infants, children-juveniles, and adult females from Shamanka II, Lokomotiv, and Ust'-Ida I, respectively (diaphyseal  $\delta^{15}\text{N}$  values are shown for the infants and children-juveniles; adult female  $\delta^{15}\text{N}$  data are from Katzenberg and Weber, 1999; Weber et al., 2002; Katzenberg et al., 2010). In both the Early and Late Neolithic groups, infant diaphyseal  $\delta^{15}\text{N}$  values are significantly different from non-infants (with children-juveniles and adult females grouped Wilcoxon-Mann-Whitney: Early Neolithic  $Z = 4.256$ ,  $P < 0.000$ , Late Neolithic  $Z = 3.039$ ,  $P = 0.002$ ; with children-juveniles and adult females considered separately Kruskal-Wallis: Early Neolithic  $\chi^2 = 19.482$ ,  $df = 2$ ,  $P < 0.000$ , Late Neolithic  $\chi^2 = 10.347$ ,  $df = 2$ ,  $P = 0.006$ ).

**Children and juveniles.** There is no significant difference between children-juvenile and adult female  $\delta^{15}\text{N}$  values at any of the three mortuary sites (Wilcoxon Mann-Whitney: Shamanka II  $Z = 0.612$ ,  $P = 0.540$ ; Lokomotiv  $Z = 1.706$ ,  $P = 0.088$ ; Ust'-Ida I  $Z = -1.064$ ,  $P = 0.287$ ). Table 5 contains the  $\delta^{15}\text{N}$  values for the children-juveniles. In four of the young children, there is a further lowering of  $\delta^{15}\text{N}$  values at the metaphyses (compared with higher values at the diaphysis), which suggests that bone collagen enriched in the heavier isotope is being retained in the diaphysis until the age of 5.0–6.0 years (LOK 14-4, 5.0 years; LOK 41-2, 6.0 years; UID 53-2, 5.0 years; UID 44-2, 5.5 years). The elevated mean diaphyseal  $\delta^{15}\text{N}$  value of the 4.0–10.0-year-olds at Lokomotiv and Ust'-Ida I demonstrates that, as expected, the diaphysis is the slowest part of the bone to reflect dietary changes. However, this phenomenon is not seen in Shamanka II. In subadults older than 6 years,  $\delta^{15}\text{N}$  values are not consistently or significantly different among sampling locations: at Ust'-Ida I one juvenile has meaningful dissimilarity in metaphyseal to diaphyseal  $\delta^{15}\text{N}$  values (UID 25-2-1), and at the Early Neolithic sites three subadults have higher metaphyseal to diaphyseal  $\delta^{15}\text{N}$  values (SHA 55-2, SHA 26-6, SHA 25-4), four have lower metaphyseal to diaphyseal  $\delta^{15}\text{N}$  values (LOK 41-2, LOK 24-3, SHA 67-1, LOR 13-2), and eight have no meaningful dissimilarity (LOR 9-1, SHA 26-3, LOK 18-1-3, LOR 13-1, LOK 14-2, SHA 64-2, LOK 24-4, SHA 56-2).

### Stable carbon isotopes ( $\delta^{13}\text{C}$ )

**Infants.** Table 6 shows the  $\delta^{13}\text{C}$  values of the diaphysis and metaphyses of the infants with feeding status listed (based on  $\delta^{15}\text{N}$  as indicated in Table 2). In the majority of infants from both time-periods, the level of intra-long bone variation in  $\delta^{13}\text{C}$  values is less than the standard deviation of adult female  $\delta^{13}\text{C}$  values (0.8‰ at all three sites). Seven Early and three Late Neolithic infants display  $\delta^{13}\text{C}$  variation equal to or greater than adult female  $\delta^{13}\text{C}$  standard deviation, however there is no clear trend of more or less enriched values. There is no significant variation between the mean  $\delta^{13}\text{C}$  values of the infants, children-juveniles, and adult females from the Early or Late Neolithic (Kruskal-Wallis: Early Neolithic  $\chi^2 = 5.564$ ,  $df = 2$ ,  $P = 0.062$ ; Late Neolithic  $\chi^2 = 0.661$ ,  $df = 2$ ,

$P = 0.719$ ), although there is a trend toward more negative values in the infants from Shamanka II, and infants and children-juveniles from Ust'-Ida I (Table 7).

**Children and juveniles.** Table 8 shows the intra-long bone  $\delta^{13}\text{C}$  values for subadults aged 4–10 years ( $n = 26$ ). The majority of individuals ( $n = 19$ ) have variation between the metaphyses and diaphysis that is less than the adult female  $\delta^{13}\text{C}$  standard deviation. For those individuals with intra-long bone variation equal to or above this level, there is no trend in metaphyseal to diaphyseal values being higher or lower, although the three individuals with more positive  $\delta^{13}\text{C}$  metaphyseal values have relatively large differences (SHA 55-2 + 3.5‰, SHA 25-4 + 1.8‰, UID 15-1 + 2.1‰) that may indicate a dietary shift before death.

## DISCUSSION

Infant feeding reconstructions of three *Cis*-Baikal mortuary sites allow us to evaluate the hypothesis first put forward by Link (1996, 1999) concerning the reasons for the (reconstructed) demographic differences between Early Neolithic versus Late Neolithic-Bronze Age groups. Link (1996, 1999) suggested that different demographic patterns may have been caused by differences in weaning age and inter-birth intervals. Breastfeeding lengthens the amount of time between successive births in non-industrial, non-contracepting populations reducing the total number of births to each woman because the period of postpartum amenorrhea and the interval from menses to subsequent ovulation is lengthened (Rosa, 1975; Konner and Worthman, 1980). In several non-contracepting populations with late weaning, birth spacing is greater than 3 years (see review in Rosa (1975)). This intra-long bone  $\delta^{15}\text{N}$  analysis reveals significant differences in the initiation and completion, and hence duration, of the weaning process between Early versus Late Neolithic groups from the *Cis*-Baikal. The Early Neolithic sites of Shamanka II and Lokomotiv show evidence for weaning, via significantly lower  $\delta^{15}\text{N}$  values at the metaphyses, in three infants aged 2.0–2.5 years (SHA 48-2, SHA 27-3, LOR 7-3), while three infants aged 3.0 years (SHA 28-1, SHA 38-1, SHA 72-1) have higher  $\delta^{15}\text{N}$  values at the metaphyses suggesting breast milk consumption was still considerable. Evidence for complete weaning is not seen until the age of 3.5 (in the metaphyses) to 4.0 years (in the diaphysis) (LOR 10-1, SHA 56-1). The duration of the weaning process as indicated by  $\delta^{15}\text{N}$  values is around 1.0–1.5 years.

In contrast, in the Late Neolithic infants from Ust'-Ida I, a pattern of weaning is observed in the 1-year-old infant (UID 26-2), and in all of the 2.5 and 3.0-year-olds (UID 4-1, UID 17-1, UID 55-1). A pattern of complete weaning is observed in all the infants older than 3.0 years (UID 25-1, UID 26-3, UID 36-1). Certainly the interpretation of infant feeding practices at Ust'-Ida I is constrained by the paucity of infants under the age of 2.0 years ( $n = 1$ ),<sup>9</sup> however the data can be cautiously

<sup>9</sup>There are few infants aged from birth to 6 months ( $n = 0$  at Ust'-Ida I;  $n = 1$  at Lokomotiv;  $n = 1$  at Shamanka II) which is not congruent with the high mortality of very young infants in non-industrial populations (Goodman and Armelagos, 1989; Kelly, 1995) and likely represents the mortuary treatment of very young infants in another way (Link, 1996, 1999; Weber et al., 2002). From 6 months to 2 years of age the number of interred infants increases ( $n = 1$  at Ust'-Ida I;  $n = 2$  at Lokomotiv;  $n = 8$  at Shamanka II) although it is still relatively low.

TABLE 6. Intra-Long Bone  $\delta^{13}C$  for subadults birth to 3 years of age ( $n = 23$ )

Site and individual number <sup>a</sup>	Age range (years)	Age mean (years)	Long bone	$\delta^{13}C$ (‰)			Maximum difference from diaphysis <sup>c</sup>	Suggested feeding status from $\delta^{15}N$
				Proximal metaphysis <sup>b</sup>	Diaphysis	Distal metaphysis		
SHA 27-4	0.25–0.75	0.5	Humerus	<b>-17.9</b>	-16.6	-18.0	-1.4	<b>Breastfeeding</b>
SHA 81-1	0.25–0.75	0.5	Humerus	<b>-17.0</b>	-17.1	-17.0	+0.1	<b>Breastfeeding</b>
SHA 40-1	0.5–1.5	1.0	Ulna	-16.0	-16.6	<b>n/a</b>	+0.6	<b>Breastfeeding</b>
SHA 69-3	0.75–1.75	1.25	Humerus	<b>-12.5</b>	-14.8	-14.2	+2.3	<b>Breastfeeding</b>
SHA 80-1	0.75–1.75	1.25	Humerus	<b>-15.7</b>	-16.4	-16.1	+0.7	<b>Breastfeeding</b>
SHA 66-2	1.25–2.25	1.75	Humerus	<b>-17.5</b>	-17.6	-17.5	+0.1	<b>Breastfeeding</b>
SHA 82-1	1.25–2.25	1.75	Humerus	<b>-18.9</b>	-17.8	-18.8	-1.1	<b>Indeterminate</b>
SHA 48-2	2.0–3.0	2.5	Ulna	-17.8	-17.2	<b>-17.5</b>	-0.6	<b>Weaning</b>
SHA 27-3	2.0–3.0	2.5	Humerus	<b>-15.5</b>	-16.4	-16.2	+0.9	<b>Weaning</b>
SHA 28-1	2.0–4.0	3.0	Humerus	<b>-15.6</b>	-15.9	-15.2	+0.7	<b>Breastfeeding</b>
SHA 38-1	2.0–4.0	3.0	Humerus	<b>-15.5</b>	-17.4	-16.6	+1.9	<b>Breastfeeding</b>
SHA 72-1	2.0–4.0	3.0	Humerus	<b>-16.6</b>	-17.2	-16.8	+0.6	<b>Breastfeeding</b>
SHA 56-1	3.0–5.0	4.0	Humerus	<b>-16.8</b>	-15.1	-16.3	-1.7	<b>Weaned</b>
<b>Average</b>				-16.4	-16.6	-16.7	-0.2	
<b>S.D.</b>				1.59	0.92	1.23	1.19	
LOK 3-1	1.0–1.5	1.25	Humerus	<b>-16.2</b>	-16.6	n/a	+0.4	<b>Breastfeeding</b>
LOR 7-3	2.0–3.0	2.5	Femur	-15.5	-15.3	<b>-15.8</b>	-0.5	<b>Weaning</b>
LOR 10-1	3.0–4.0	3.5	Humerus	<b>-15.4</b>	-16.3	-15.6	+0.9	<b>Weaned</b>
<b>Average</b>				-15.7	-16.1	-15.7	+0.3	
<b>S.D.</b>				0.44	0.68	0.14	0.71	
UID 26-2	0.75–1.25	1.0	Humerus	<b>-18.6</b>	-19.5	-18.5	+1.0	<b>Weaning</b>
UID 4-1	2.0–3.0	2.5	Humerus	<b>-17.4</b>	-17.3	-17.5	-0.2	<b>Weaning</b>
UID 17-1	2.0–4.0	3.0	Femur	-17.3	-17.3	<b>-17.3</b>	0.0	<b>Weaning</b>
UID 55-1	2.0–4.0	3.0	Humerus	<b>-17.6</b>	-17.5	-17.5	-0.1	<b>Weaning</b>
UID 25-1	3.0–4.0	3.5	Humerus	<b>-18.3</b>	-17.4	-17.9	-0.9	<b>Weaned</b>
UID 26-3	3.0–4.0	3.5	Humerus	<b>-18.9</b>	-17.3	-18.1	-1.6	<b>Weaned</b>
UID 36-1	3.0–4.0	3.5	Humerus	<b>-18.5</b>	-18.5	-18.4	+0.1	<b>Weaned</b>
<b>Average</b>				-18.1	-17.8	-17.9	-0.3	
<b>S.D.</b>				0.64	0.85	0.47	0.82	

<sup>a</sup> SHA = Shamanka II; LOK = Lokomotiv; LOR=Lokomotiv-Raisovet; UID = Ust'-Ida I.

<sup>b</sup> Metaphysis of majority growth in bold.

<sup>c</sup> Adult female  $\delta^{13}C$  standard deviation is 0.8‰ at Shamanka II, Lokomotiv and Lokomotiv-Raisovet, and Ust'-Ida I.

TABLE 7.  $\delta^{13}C$  (‰) by age-category

Age category	Shamanka II				Lokomotiv				Ust'-Ida I			
	pm	dia	dm	mean	pm	dia	dm	mean	pm	dia	dm	mean
0–3 years	-16.4 (13)	-16.6 (13)	-16.7 (12)	-16.6 $\pm 1.25$	-15.7 (3)	-16.1 (3)	-15.8 (2)	-15.9 $\pm 0.5$	-18.1 (7)	-17.8 (7)	-17.9 (7)	-17.9 $\pm 0.6$
4–10 years	-16.0 (8)	-16.4 (8)	-16.2 (8)	-16.2 $\pm 1.2$	-15.7 (8)	-15.5 (9)	-15.8 (9)	-15.7 $\pm 0.4$	-18.0 (8)	-17.9 (9)	-17.9 (9)	-18.0 $\pm 0.6$
Adult Females	-16.2 $\pm$ 0.8 ( $n = 20$ )				-15.9 $\pm$ 0.8 ( $n = 19$ )				-17.5 $\pm$ 0.8 ( $n = 6$ )			

pm = proximal metaphysis, dia = diaphysis, dm = distal metaphysis. Numbers in parentheses are sample sizes.

interpreted to suggest that a significant reduction in breast milk consumption occurred from the age of 1.0 year on. A larger number of older infants (2.5–3.5 years of age,  $n = 6$ ) allow us to suggest with confidence that weaning was complete by the age of 3.0 years. An earlier weaning age, however slight, may have led to reduced intra-birth intervals and more children (although this does not mean more children survived to adulthood). The duration of the weaning process as indicated by  $\delta^{15}N$  values was around 2.0 years, which suggests that weaning may have been a less gradual process in the Early Neolithic and more gradual process in the Late Neolithic. A prolonged, gradual weaning process has been correlated with higher survivorship and decreased illness in many studies of modern populations (Hayward, 1983; Habicht et al., 1986; Launer, 1990; López-Alarcón et al., 1997) and thus may have contributed to a lower infant mortality rate in the Late Neolithic people. Overall, our intra-long bone  $\delta^{15}N$  data support Link's (1999)

hypothesis that the different demographic profiles of the Early Neolithic versus Late Neolithic-Bronze Age Cis-Baikal groups are, at least in part, due to differences in the weaning process.

Our data suggesting that breastfeeding continued into and beyond the third year, are in keeping with many ethnographic accounts of hunter-gatherer groups (eHRAF, 2010). There is a paucity of ethnographic data on breastfeeding practices among southern Siberian groups; however, for more northern populations, such as the Koryaks, Yakuts, and Dolgani, reports mention that breastfeeding occurred until 3 and up to 5 years of age (Krashennikov, 1764; Jochelson 1908; Popov, 1946). An eighteenth century ethnographic account of the Koryak states that "They gave their children the breast till they are 3-year old and upwards" (Krashennikov, 1764: 233).

There is an assumption that non-agricultural groups did not have access to appropriate weaning foods, such as cereals that could be formed into paps and gruels,

TABLE 8. Intra-long bone  $\delta^{13}\text{C}$  for subadults four to ten years of age ( $n = 26$ )

Site and individual number <sup>a</sup>	Age range (years)	Age mean (years)	Long bone	$\delta^{13}\text{C}$ (‰)			Maximum difference from diaphysis <sup>c</sup>
				Proximal metaphysis <sup>b</sup>	Diaphysis	Distal Metaphysis	
SHA 31-1	4.0–6.0	5.0	Humerus	–15.8	–16.2	–15.9	+0.4
SHA 55-2	5.25–7.75	6.5	Humerus	–12.9	–16.4	–15.4	+3.5
SHA 26-3	6.0–8.0	7.0	Humerus	–16.8	–16.4	–15.9	+0.5
SHA 26-6	7.0–9.0	8.0	Humerus	–15.6	–15.7	–16.2	–0.5
SHA 67-1	7.0–9.0	8.0	Humerus	–18.8	–17.3	–17.8	–1.5
SHA 25-4	6.0–12.0	9.0	Tibia	–15.1	–16.4	–14.6	+1.8
SHA 64-2	8.0–10.0	9.0	Ulna	–17.1	–16.8	–17.5	–0.7
SHA 56-2	8.25–10.75	9.5	Humerus	–15.7	–15.8	–16.0	–0.2
<b>Average</b>				–16.0	–16.4	–16.2	+0.4
<b>S.D.</b>				1.71	0.51	1.05	1.58
LOK 14-4	4.0–7.0	5.5	Humerus	–16.2	–16.5	–15.9	+0.6
LOK 41-2	5.0–7.0	6.0	Humerus	–16.1	–15.4	–16.4	–1.0
LOR 9-1	6.0–7.0	6.5	Humerus	–15.5	–15.8	–16.1	±0.3
LOK 18-1-3	6.0–8.0	7.0	Humerus	–15.5	–15.3	–15.6	–0.3
LOK 24-3	6.0–8.0	7.0	Humerus	–14.8	–15.4	–15.5	+0.6
LOR 13-1	6.0–8.0	7.0	Femur	–15.4	–15.3	–15.5	–0.2
LOK 14-2	6.0–10.0	8.0	Humerus	–16.0	–15.5	–15.8	–0.5
LOK 24-4	8.0–10.0	9.0	Humerus	<i>n/a</i>	–15.0	–15.2	–0.2
LOR 13-2	8.0–12.0	10.0	Femur	–15.7	–15.7	–16.3	–0.6
<b>Average</b>				–15.7	–15.5	–15.8	–0.2
<b>S.D.</b>				0.49	0.45	0.38	0.58
UID 53-2	4.0–6.0	5.0	Humerus	–18.1	–18.3	–18.0	+0.3
UID 15-1	5.0–6.0	5.5	Humerus	–17.1	–18.8	–16.7	+2.1
UID 44-2	5.0–6.0	5.5	Humerus	–18.3	–17.1	–17.9	–1.2
UID 21-2	5.0–7.0	6.0	Humerus	<i>n/a</i>	–17.5	–17.2	+0.3
UID 26-5	5.0–7.0	6.0	Humerus	–18.6	–18.7	–18.6	+0.1
UID 9-1	6.0–7.0	6.5	Humerus	–18.5	–17.7	–18.3	–0.8
UID 8-1	6.0–8.0	7.0	Humerus	–17.9	–18.0	–18.7	–0.7
UID 5-1	7.0–9.0	8.0	Humerus	–17.9	–17.2	–17.6	–0.7
UID 25-2	7.0–9.0	8.0	Humerus	–17.9	–17.7	–18.4	–0.7
<b>Average</b>				–18.0	–17.9	–17.9	–0.1
<b>S.D.</b>				0.47	0.61	0.67	1.00

<sup>a</sup> SHA = Shamanka II; LOK = Lokomotiv; LOR=Lokomotiv-Raisovet; UID = Ust'-Ida I.

<sup>b</sup> Metaphysis of majority growth in bold.

<sup>c</sup> Adult female  $\delta^{13}\text{C}$  standard deviation is 0.8‰ at Shamanka II, Lokomotiv and Lokomotiv-Raisovet, and Ust'-Ida I.

which is viewed as one of the causes of later weaning. However, in a cross-cultural meta-analysis Sellen and Smay (2000) found no significant difference in the timing of introduction of supplementary foods between groups practicing different subsistence strategies. In fact, in many cases, hunter-gatherers introduced supplementary foods at an earlier age than agriculturalists, although the duration of breastfeeding was usually longer. *Cis-Baikal*  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  data agree with this characterization. After approximately 6 months of age breast milk alone cannot meet an infant's nutritional requirements for growth (McDade and Worthman, 1998; Oddy, 2002) and supplementary foods should be introduced. Among northern Siberian hunter-gatherers complementary foods were introduced early in infancy, and included small pieces of fat and pre-masticated or cooked fish and meat. Among the Koryak, Jochelson (1908: 757) noted that "At a very early age the child is given pieces of fat of reindeer or seal to suck." Among the Ainu of Hokkaido, complex hunter-fisher-gatherers with a diet based heavily on fish, the practice of pre-mastication of food was common: "Partly because women nurse children for a prolonged period of time the Ainu do not make special dishes for babies. The mother simply chews regular food, especially good fish like salmon, before she gives it to her child" (Ohnuki-Tierney, 1974: 57). Pre-mastication of food items has benefits for the child (Pelto et al., 2009).

Obviously, food items are broken down into smaller, softer pieces that do not require substantial chewing. In addition, maternal saliva begins the chemical process of enzymatic digestion of complex carbohydrates, an ability that develops slowly in infants (Zheng et al., 1996). Saliva also contains secretory IgA, and IgM and IgG, which promote immunological health (Norhagen et al., 1989), as well as several cytokines, anti-inflammatory factors, and growth factors that may help with the maturation and maintenance of the mucosal lining of the infant's gastrointestinal tract (see Table 1 in Pelto, 2009).

The technological innovation of ceramic cooking pots is also hypothesized to have facilitated the increased and improved preparation of weaning foods (Buikstra et al., 1986). In the *Cis-Baikal* habitation sites, ceramics are very rare in Early Neolithic layers and much more common and diverse in Late Neolithic deposits (Khlobystin, 1969; Savelyev, 1989; McKenzie, 2010). Thus, the more frequent use of pots to cook and soften foods could be a factor contributing to earlier weaning age in the Late Neolithic group.

Different types of weaning foods will result in distinctive isotope ratios. If fat were a common weaning food, this would result in more negative  $\delta^{13}\text{C}$  values as lipids are depleted in  $^{13}\text{C}$  relative to proteins and carbohydrates (Tieszen et al., 1983; Post et al., 2007). In the *Cis-Baikal*

salmonoid fatty fish such as lenok (*Brachymystax lenok*) and the graylings (*Thymallus sp.*) would have been good sources of fat (comparatively lean, non-fatty fishes include northern pike, cod and perch). Groups who lived near the lake hunted freshwater seals (*Phoca sibirica*) (Katzenberg and Weber, 1999; Weber et al., 2002; Katzenberg et al., 2009), which would have been an excellent source of fat. Riverine fishes or terrestrial mammals may have been sources of fat for groups living farther from the lake. As seen in Table 7, infants from Shamanka II and Ust'-Ida I have lower  $\delta^{13}\text{C}$  values than adult females. In other samples, breastfeeding infants have been shown to display a slight +1‰ trophic level effect (Fuller et al., 2006), which we do not see. Several factors are likely contributing to the lack of a correlation between breastfeeding and  $\delta^{13}\text{C}$  in Cis-Baikal infants, including an adult diet based on freshwater fish with variable  $\delta^{13}\text{C}$  values (with more  $\delta^{13}\text{C}$  variation in fish from Lake Baikal than the Angara River). However, if early weaning foods were indeed isotopically depleted in  $^{13}\text{C}$ , then  $\delta^{13}\text{C}$  values are reflecting the introduction of solid foods to the diet and would mask a slight nursing carbon isotope effect.

An additional aspect of infant feeding may be evident in the intra-long bone  $\delta^{15}\text{N}$  data as displayed in Figure 3. Subadult  $\delta^{15}\text{N}$  curves usually display a single peak and decline pattern, as seen in the Ust'-Ida I sample (Fig. 3c). The existence of a second peak in mean  $\delta^{15}\text{N}$  values of the Early Neolithic infants (2.0 to 3.5-year-old sample) is not common and requires consideration. This second  $\delta^{15}\text{N}$  peak is unlikely to be due to the consumption of high trophic level foods as they would not cause  $\delta^{15}\text{N}$  values to be elevated as much as is seen in the infants. Interestingly, if the second  $\delta^{15}\text{N}$  peak represents the recommencement of higher levels of breast milk consumption it could be hypothesized to have occurred because of a period of food scarcity. Indeed "emergency breastfeeding" has been documented as a relatively common and effective way of improving survival chances of infants and children during famines and wars (Arifeen et al., 2001; Jakobsen et al., 2003). Although this would have had to occur for at least several weeks to be recorded in metaphyseal bone collagen and it is improbable that "emergencies" happened often enough to account for this overall pattern. Thus, it is also important to consider that the pattern of two  $\delta^{15}\text{N}$  curves is based on the phenomenon of selective mortality (Wood et al., 1992): the younger sample contains the frailest individuals who may have died with lower  $\delta^{15}\text{N}$  values. Those individuals over the age of 2.0 years represent the group that survived this period and they show a pattern of regular breast milk consumption until the age of 3.5 years. Finally, the variation in weaning age may be a "real" phenomenon reflecting cultural heterogeneity. Certainly, flexibility in infant feeding practices would make adaptive sense over the life span of the group. Early Neolithic groups have substantial heterogeneity in intra- and inter-regional stable isotopes ratios (Weber et al., 2002; Katzenberg et al., 2010) so it is not unreasonable to propose that infant feeding practices may also have varied. At Ust'-Ida I there is little variation in individual  $\delta^{15}\text{N}$  curves despite the fact that Late and Early Neolithic peoples occupied the area for a similar amount of time.

Undoubtedly our results are impacted by the unavoidable imprecision of our dental formation and eruption age estimation methods, which are on the order of plus or minus 3 months for the young infants (birth to 1.5

years) and plus or minus 6 months for the older infants (1.5–4.0 years), a problem which could be compounded by our relatively small sample sizes. For example, if the age of a single infant is under- or over-estimated by only half a year this could considerably alter our interpretation of the timing of weaning initiation or completion, particularly at Ust'-Ida I. Yet, given the antiquity of these skeletal remains and the fact that hunter-gatherer cemeteries are relatively rare it is important to attempt to answer questions about infant feeding and its potential effect on demographic characteristics such as population growth. Furthermore, the use of an intra-individual sampling approach improved the accuracy of feeding status determination. Indeed, the specificity of age-related changes in weaning would not have been detectable without the use of an intra-individual sampling methodology, with the comparison of diaphyseal to metaphyseal samples being the most informative.

The comparison of the "metaphysis of majority growth" with the "metaphysis of minority growth" was less informative. While a few infants displayed a pattern of  $\delta^{15}\text{N}$  values that would be expected based on different tissue deposition periods, the overall results were not significant. This may be due the use of bulk collagen samples from the metaphyses that were not precise enough to exclusively collect the most recently deposited tissue. Furthermore, in some cases an insufficient amount of time may have elapsed to permit a dietary change to be recorded at a significant level in metaphyseal bone collagen. This problem could be further exacerbated because the speed of protein accretion in the metaphyseal area may lag with inadequate protein intake which may have occurred in sick, ailing infants. Finally, there is variation in the level and rate of collagen formation at each individual metaphysis such that  $\delta^{15}\text{N}$  values from collagen samples that represent several months of growth may not necessarily replicate the approximated overall difference in metaphyseal growth calculated for the entire period. This situation is not helped by our imprecise knowledge of the rates of bone modeling or remodeling during different ages or growth periods.

It is also important to consider that  $\delta^{15}\text{N}$  values can become elevated by high protein catabolism rates, as a result of protein-energy malnutrition and/or disease, which could mimic elevated  $\delta^{15}\text{N}$  values due to breastfeeding (White and Armelagos, 1997; Katzenberg and Lovell, 1999; Fuller et al., 2005; Mekota et al., 2006). A diet exceedingly high in protein can also cause enriched  $^{15}\text{N}$ , as a result of high deamination (the breakdown of amino acids in the liver) rates (Focken, 2001). It is not possible to tease apart these different causes of  $^{15}\text{N}$  enrichment. In fact, taking into consideration all the variables that can affect  $\delta^{15}\text{N}$  values, it is not surprising that some infants do not show a clear breastfeeding or weaning pattern. The second  $\delta^{15}\text{N}$  peak in the Early Neolithic infants, as well as elevated metaphyseal values in three of the children-juveniles (SHA 55-2, SHA 26-6, SHA 25-4), may be in part due to malnutrition (either markedly low or high protein consumption) or disease. However, four children-juveniles have low  $\delta^{15}\text{N}$  values at the metaphyses (LOK 41-2, SHA 67-1, LOR 13-2, UID 25-2), suggesting that  $^{15}\text{N}$  enrichment due to causes other than breastfeeding was not a widespread phenomenon and should not cause a major distortion in our  $\delta^{15}\text{N}$  interpretations.

Our intra-long bone methodology permits an examination of whether infants died while breast milk was still a major protein source and consider the results based on the different morbidity and mortality expectations of “predominant breastfeeding” versus “predominant weaning.” The weaning period is associated with increased physiological stress and mortality due to the loss of important nutrients from breast milk, the immaturity of the infant’s gastrointestinal system, loss of passive immunity, and increased contact with environmental pathogens (Maher, 1992; Pelletier, 2000). It is, therefore, not unusual to find that all of the Late Neolithic infants died once weaning had commenced. On the other hand, because breastfeeding buffers infants from illness and malnutrition (Hayward, 1983; Habicht et al., 1986; Launer et al., 1990; López-Alarcón et al., 1997), the fact that a large percentage of infants (9/13, 69.2%) from the Early Neolithic cemetery of Shamanka II died while still breastfeeding is noteworthy. It may suggest that a considerable stressor was affecting the population to the point at which the capacity of breastfeeding to buffer infants from malnutrition and/or disease was impaired. We can only speculate about the types of stress encountered by Early Neolithic peoples, but enamel defect data have shown an annual periodicity in stress episodes (Waters-Rist et al., 2006) that fits well with ethnographic reports of seasonal late winter to early spring famines in northern populations (Eidlitz Kuoljok, 1969; Stefansson, 1946, “rabbit malaise”; Turner and Davis, 1993). Perhaps regular annual periods of food scarcity were an important factor leading to later weaning age among Early Neolithic peoples, and this stressor was not experienced with the same regularity or intensity in Late Neolithic peoples. We must be cautious in this comparison, however, because the age when breastfeeding no longer substantially moderates morbidity and mortality is variable within and between populations since it is associated with many factors including bacterial and viral pathogens (McDade and Worthman, 1998), and the quality and quantity of weaning foods (Sellen and Smay, 2000). Prolonged breastfeeding with inadequate complementary foods would be at least as physiologically stressful as early weaning (Dettwyler, 1991; Kennedy, 2005). Katzenberg et al. (1996) further point out that we should not assume that weaning *a priori* causes physiological stress because a weaning diet composed of abundant, nutrient-rich foods and uncontaminated water, and a gradual decrease in breast milk, should result in low morbidity and mortality.

After infancy stable isotope values indicate that children-juveniles were consuming the same types of food as adults (adult males have  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values that are statistically indistinguishable from adult females; Katzenberg and Weber, 1999; Katzenberg et al., 2009, 2010; Weber et al., 2002). *Cis*-Baikal isotope data agree with a notion of childhood as distinct from the period of infancy and “toddlerhood.” Bird-David (2005) notes that in many hunter-gatherer groups childhood begins at the age of 3–4 years with important parameters including weaning, walking, being carried around less often, and the child’s engagement with other persons independently of their parents in a responsive and culturally appropriate manner. Once “toddlerhood” has passed children eat what everyone else eats (see Hewett and Lamb, 2005, for examples). In these *Cis*-Baikal groups, we do not observe evi-

dence of different diets past early childhood suggesting that there was not a culturally based system of differential access to and/or allocation of foods by age.

## CONCLUSION

Studies of modern populations serve to demonstrate the complexity and variability of causes of morbidity and mortality during infancy and childhood as related to diet (Lee, 1979; Habicht et al., 1986; Popkin et al., 1986; Stuart-Macadam and Dettwyler, 1995; Pelletier, 2000). Using an intra-individual isotopic method that documents dietary change within the life span of subadults, we produced a clearer picture of the links between diet, morbidity and mortality, and demographic structure in Neolithic hunter-fisher-gatherers from the *Cis*-Baikal. In this way, a limitation inherent in cross-sectional analyses of skeletal samples, namely the “hidden heterogeneity in risk” (Wood et al., 1992), can be partly addressed (Wright and Yoder, 2003). Overall, our analysis supports the hypothesis of different weaning patterns in Early Neolithic versus Late Neolithic *Cis*-Baikal groups, and is in agreement with a substantial body of research demonstrating that these two foraging populations had quite distinct biocultural adaptations.

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