Elsevier Editorial System(tm) for Quaternary International
Manuscript Draft

Manuscript Number: QUATINT-D-12-00191R1

Title: Multiproxy evidence for abrupt climate change impacts on terrestrial and freshwater ecosystems in the Ol'khon region of Lake Baikal, central Asia

Article Type: Baikal-Hokkaido

Keywords: climate reconstruction; pollen; ostracod; geochemistry; shallow lake, central Asia

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Manuscript Region of Origin: RUSSIAN FEDERATION

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Multiproxy evidence for abrupt climate change impacts on terrestrial and freshwater ecosystems in the Ol'khon region of Lake Baikal, central Asia.

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Abstract

A palaeolimnological study of Lake Khall was undertaken to reconstruct impacts from five thousand years of climate change and human activity in the Ol'khon region of Lake Baikal. Taiga biome dominated regional landscapes, although significant compositional turnover occurred due to the expansion of eurythermic and drought resistant Scots pine. Climate during the mid-Holocene was wetter than the present, and Lake Khall was fresh, with abundant molluscs. By 4.4 cal ka BP, sedimentary geochemistry indicated a gradual change in lake water chemistry with an increase in lake salinity up to the present day, most likely controlled by groundwater influences. Vegetation turnover rate was highest between 2.75 – 2.48 cal ka BP, with the onset of drier, more continental climate, which resulted in an influx of aeolian particles to the lake. This abrupt shift was coincident with ice rafted debris event (IRD-2) in North Atlantic sediments and an attenuation of the East Asian summer monsoon. A second arid period occurred shortly afterwards (2.12 – 1.87 cal ka BP) which resulted in the decline in ostracod numbers, especially *Candona* sp. A rather more quiescent, warmer period followed, between 1.9 – 0.7 cal ka BP, with very little change in vegetation composition, and low amounts of detrital transfer from catchment to the lake. Peak reconstructed temperatures (and low amounts of annual precipitation) were concurrent with the Medieval Climate Anomaly. Between 0.77 – 0.45 cal ka BP, climate in the Ol'khon region became colder and wetter, although Lake Khall did not become more fresh. Cold, wet conditions are seen at other sites around Lake Baikal, and therefore represent a regional response to the period concurrent with the Little Ice Age and IRD-0. After AD 1845 the region warms, and *Pediastrum* appears in the lake in high abundances for the first time. We ascribe this increase to nutrient enrichment in the lake, linked to the rapid increase in regional pastoral farming.

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1. **Introduction**

Since 2001 a major interdisciplinary programme (Baikal Archaeology Project) has sought to characterise Holocene cultural dynamics among hunter-gatherer and pastoralist populations in central Asia (Weber et al., 2010). Results from this on-going research have redefined our understanding of hunter-gatherer adaptive strategies during the Neolithic–Bronze Age, including aspects of culture, subsistence and diet, mobility patterns, genetic structure, and social and political relations. Most of these new archaeological data have been derived from numerous well-preserved formal cemetery contexts, which has allowed detailed analyses of human skeletal remains. Focus has especially centred on a distinct biocultural discontinuity during the late Neolithic – early Bronze Age (Weber et al., 2002), and more recently the expansion of pastoralist populations (Nomokonova et al., 2010).

One of the oldest records of human occupation in this region (ca. 9 ka BP) was recorded at the Sagan-Zaba cove, in the Ol'khon region (known as *Priol'khon'e* in the Russian geographical literature) of Lake Baikal (Nomokonova et al., in review). The white marble cliffs adjacent to the cove are world renown for their petroglyphs, dating as far back as 4 ka BP. Since the late Holocene, pastoralists dominated the Ol'khon region, herding a range of animals including cattle, sheep, goats and horses (Nomokonova et al., 2010). Subsistence patterns at Sagan-Zaba were more diverse than neighbouring regions, possibly because of the relatively harsh environment, such that, unusual for pastoralists, these populations also hunted *nerpa*, Lake Baikal's freshwater seal.

Despite the long history of prehistoric populations around Lake Baikal, there is very little evidence to suggest that they had a significant impact on regional landscapes (Tarasov et al. 2007). However, the pollen source area of Lake Baikal is vast and indicative of very broad regional-scale variability (Sugita 1994), such as biomes (Seppä and Bennett, 2003; Tarasov et al., 2007). One would not necessarily expect therefore Lake Baikal sediments to record impacts from regional prehistoric populations. Smaller lakes have smaller source areas (Jacobson and Bradshaw, 1981), and therefore potentially offer a better possibility for disentangling natural (e.g. climatic) from anthropogenic impacts. Around Lake Baikal, smaller lakes are increasingly being investigated (e.g. Tarasov et al., 2009; Ptitsyn et al., 2010; Mackay et al., 2012), although very few studies have looked at palaeoenvironmental changes in the semi-arid region to the west of the lake (Sklyarov et al., 2010).

The principal aim of this study is to provide a detailed palaeolimnological record of environmental change in the climatically sensitive Ol'khon region of Lake Baikal, where there is a long, dynamic history of human occupation.

2. Geology and regional climate

The study area lies to the south of Ol'khon Island on the west coast of Lake Baikal and is represented by Paleozoic Ol'khon metamorphic terrane (Sklyarova et al., 2002). The flat-topped Ol'khon Island and Ol'khon region form part of the Middle Baikal inter-basinal link. Small grabens and horsts shape the link's surface and form linear en-echelon systems. The grabens are confined to two types of recent faults in the process: northeast linear faults inherited from the Early Paleozoic structures and north-northeast pull-apart structures related to late left-lateral strike-slip dislocations of the Baikal rift formation. Numerous fresh and salt-water lakes are associated with these faults (Sklyarova et al., 2002), with their long-term existence being dependent on faults draining deep, groundwater horizons (Sklyarov et al., 2010). The study site, Lake Khall, is located on marble and surrounded by two intrusions – Birkhinsky in the north (gabbro, gabbro-norites, olivine gabbro) and Tsagan-Zabinsky in the south (andesites, andesite-basalts and basalts). It is a shallow, isometric, freshwater bicarbonate lake located in a structural low of one these northeast linear faults. Lake Khall is probably fed from subaqueous groundwater, and so its chemical composition reflects the chemistry of the feeder groundwater (Sklyarova et al., 2002). The region is arid to semi-arid because it sits in the rain shadow of the neighbouring Primorsky Mountain Range (Fig. 1). Annual precipitation is low between 200 – 350 mm/yr (Atlas Baikala, 1993). Vegetation is therefore a mixture between light coniferous taiga forest with fragmented steppe landscape, including the Tazheran steppes (Sklyarov et al., 2010).

3. Methods

Fieldwork took place on 26th July 2006. pH and conductivity were measured *in situ* using a Fisher Scientific accumet AP85 pH/conductivity meter. The pH of the surface water was 9.0 pH units, and conductivity was 790 μS/cm. Due to time constraints, it was not possible to conduct a detailed bathymetry of the lake, although a Plastimo Echotest II handheld depth sounder was used to estimate the deepest region at 3.10 m, from where coring was undertaken. A 71 mm diameter Livingstone core was initially extracted (44 cm length), which maintained the surface sediment – water interface, followed by a second overlapping Livingstone drive of 91 cm. Core location co-ordinates were 106°25'50.70"E, 52°41'14.54"N.

3.1 Chronology

Extracted lake sediments were highly humified and from many levels it was not possible to obtain sizeable plant macrofossils for radiocarbon analyses. Radiocarbon dating of humified sediments was instead performed on total organic carbon (TOC) from 5 bulk sediment samples. *Potamogeton* seeds were isolated from a further four levels. All nine samples were radiocarbon dated using accelerator mass spectrometry (AMS) at the Poznan Radiocarbon Laboratory, Poland (Goslar *et al*., 2004) (Table 1). The amount of radiocarbon reservoir effect (i.e. shift towards older ages) was estimated on the basis of ^{14}C dating contemporary leaf sample of *Potamogeton* from the littoral region of Lake Khall. The result of 105.58±0.33 pMC suggests a reservoir age of 100-200 years (Table 1). We have therefore added the reservoir correction of 150±50 years to the age model for Lake Khall sediment core.

Calibration of radiocarbon dates was undertaken using the Intcal09 calibration curve (Reimer et al., 2009). The calibration was performed by "Bacon" software simultaneously to building the calendar age scale for the whole core. In order to produce the age-depth model this programme simulates the accumulation of deposit through small random increments, and also takes into account the limitations on accumulation rate and its variability (Blaauw and Christen, 2011). Although some of the obtained ^{14}C dates can clearly be regarded as outliers, all results of radiocarbon dating were included in the modeling performed for Lake Khall. Additionally, the sampling year AD 2006 was assigned to the depth 0 and AD 1963 at 6.25 cm, identified on the basis of ^{137}Cs peak. The age-depth model was calculated with 20 sections. The *a priori* information for accumulation rate was set as a gamma distribution with mean 30 yrs/cm and shape 2, and a beta distribution with strength 4 and mean 0.7 was fixed for the accumulation variability, following the recommendation by Blaauw and Christen (2011). The age-depth model resulting from 2640000 iterations is presented in Figure 2.

The uppermost 36 cm of sediment were also dated using ^{210}Pb, a naturally-produced radionuclide that has been extensively used in the dating of recent sediments (Appleby, 2001) and ^{137}Cs, an artificially produced radionuclide, introduced to the study area by atmospheric fallout from nuclear weapons testing. Core sub-samples were counted on a Canberra well-type ultra-low background HPGe gamma ray spectrometer to determine the activities of ^{210}Pb, ^{137}Cs and other gamma emitters. Spectra were accumulated using a 16K channel integrated multichannel analyzer and analysed using the Genie 2000 system. Energy and efficiency calibrations were carried out using bentonite clay spiked with a mixed gamma-emitting radionuclide standard, QCYK8163, and checked against an IAEA marine sediment certified reference material (IAEA 135). The $^{210}Pb_{excess}$ activity was estimated by subtraction of the average value of ^{210}Pb activity in deeper core samples (14 Bq/kg), where total ^{210}Pb activities had fallen to virtually constant values and so approximate the "background" or supported ^{210}Pb activity. Sediment accretion rates were determined using the Constant Flux, Constant Sedimentation (CF-CS) model of ^{210}Pb dating, where the sedimentation rate is given by the slope of the least squares fit for the natural log of the $^{210}Pb_{excess}$ activity versus depth (Krishnaswami et al., 1971; Robbins, 1978).

3.2 Pollen analysis

Twenty-nine 1 cm^3 sediments were processed for pollen analysis using standard laboratory methods, including HCl and KOH treatments, heavy-liquid separation and subsequent acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). Pollen and spores were mounted in glycerin and counted using light microscopy at ×400–×1000 magnification. Identification of fossil pollen and spores was assisted with the use of regional pollen atlases (Kuprianova and Alyoshina, 1972; Bobrov et al., 1983; Moore et al., 1991) and the reference collection held at the Institute of the Earth Crust, Irkutsk. Between 176 and 518 terrestrial pollen grains were counted at each level (304 on average). Relative abundances of individual taxa were based on the sum of all terrestrial pollen grains. *Haploxylon*-type pine pollen (*Pinus sibirica*, *Pinus pumila*) were separated from *Diploxylon*-type pine pollen (*Pinus sylvestris*) based on the position of the sacci in polar view. *Pediastrum* coenobia colonies contain sporopollenin which allowed us to count them alongside pollen (e.g. Nielsen and Sørensen, 1992). *Pediastrum* relative abundances were calculated in relation to the total sum of terrestrial pollen. We used the pollen-based biome reconstruction method and equation presented in Prentice et al. (1996) and a regionally approved biome-taxon matrix (Tarasov et al., 2009; Bezrukova et al., 2010), which assigns all selected pollen taxa to appropriate biomes. All terrestrial pollen taxa from Lake Khall sediments were assigned to regional plant functional types (PFTs) and biomes– see Tarasov et al. (2009) for full details. Quantitative climate reconstructions were performed using best modern analogue (BMA) approach (Overpeck et al., 1985; Guiot, 1990) previously applied to the Holocene pollen records from Lake Baikal (Tarasov et al., 2007) and Lake Kotokel (Tarasov et al., 2009). A reference modern dataset based on the global climate averages (New et al., 2002) and extensive modern surface pollen data from northern Eurasia, with a good representation of the Lake Baikal region (see Tarasov et al., 2005 for details). Reconstructions undertaken were annual precipitation (Pann), mean July temperatures (Tw, also referred to here as mean temperature of the warmest month), and mean January temperature (Tc, also referred to here as mean temperature of the coldest month).

3.3 Ostracods

Forty samples were processed for ostracod determinations. Wet sediment samples were dispersed in tap water overnight and then gently sieved through a 250 µm mesh. The coarse residues were dried at 105˚C. All of the ostracod shells were picked from these residues under a low-power binocular microscope using a fine (4/0) moistened paintbrush, sorted into taxonomic groups and stored in micropalaeontological slides. Results are expressed in numbers of valves per unit weight of sediment.

3.4 Mineral Magnetics

At least 1.5 g of freeze-dried sediment from forty-one samples was packed into plastic magnetics sample pots. Low-frequency and high-frequency magnetic susceptibility was measured for each sample using a Bartington MS2 Magnetic Susceptibility meter.

3.5 Particle size

Particle-size analysis was undertaken on the <2 mm fraction of sediment from 40 samples. In practice, most of the sediment from the core was less than 2 mm diameter, so the grain-size analyses are essentially bulk-sample determinations. Each sample was dispersed in water, sieved through a 2 mm mesh and then disaggregated ultrasonically prior to analysis using a Malvern Mastersizer laser particle-sizer. The results were processed using

GRADISTAT (Blott and Pye, 2001). For plotting purposes, we used the grain-size statistics produced from the Folk and Ward (1957) method.

3.6 X-ray fluorescence (XRF) spectrometry analysis

Up to 2 g of freeze dried sediment was finely ground and compressed into 25 mm deep polythene sample pots for XRF analysis of fortyone samples. Samples were subjected to gamma photons from a silicon (lithium) semi-conductor detector for 240 s each, using a Spectro Xlab 2000 energy dispersive XRF spectrometer. Calibration was conducted with two known sediment standards of Buffalo River Sediment.

3.7 Statistical Analyses

Detrended correspondence analysis (DCA) was initially undertaken to establish the magnitude of vegetation turnover. Relative abundance data were log (x+1) transformed in order to stabilize species variance and rare species were down-weighted. The axis 1 gradient length (standard deviation units) was 1.049, indicating that linear ordination techniques were more appropriate for analyses. Principal components analysis (PCA) with symmetric scaling of the ordination scores to optimise scaling for both samples and species was undertaken (Gabriel, 2002). Species data were log (x+1) transformed and both species and samples were centred to give a log-linear contrast PCA, appropriate for closed relative abundance data (Lotter and Birks, 1993). XRF data were analysed using PCA with samples centred and standardised. Significance of PC axes were tested with a broken stick model (Jollifer, 1986) using BSTICK v1.0 (Line and Birks, 1996). Compositional change in the palynological data (β-diversity) was estimated using detrended canonical correspondence analysis (DCCA) with the data constrained using dates obtained from the age-depth model (Birks, 2007). All ordination analyses were undertaken using Canoco v. 4.5 (ter Braak and Šmilauer, 2002). Monte Carlo permutation tests for temporally ordered data were used to determine significance levels (n = 499). Stratigraphical profiles were constructed using C2 Data Analysis Version 1.5.1 (Juggins, 2007). Stratigraphical zones for each proxy were delimited by optimal partitioning (Birks and Gordon, 1985) using the unpublished programme ZONE (version 1.2) (Juggins, 1991).

4. Results

4.1 Core description and chronology

The core consisted mainly of homogenous, silty clay sediment between 0 – 76 cm (colour 5Y-4/1-2), with the bottom sediments (76 – 91 cm; colour 10YR-3/1) packed full of broken bivalve shells. The age-depth model for Lake Khall shows that the core spans the past ca. 5.2 cal ka BP (i.e calibrated years before AD 1950, taken as present, are consistently used) (Fig. 2). Although the sedimentation rate underwent temporal variability, some distinct sections can be distinguished, for which the sedimentation rate was relatively constant. For the uppermost section from 0 to 8 cm (ca. 10 cal BP) the average sedimentation rate derived from the Bacon model was 1.48±0.25 mm/year, which is in accordance with the number obtained on the basis of ^{210}Pb measurements (1.11±0.44 mm/year). The mean accumulation rate for the section between 8 cm (10 cal BP) and 74 cm (ca. 2.6 cal ka BP) was 0.36±0.02 mm/year. The oldest part of the sediment was characterized by lower sedimentation rate, 0.16±0.043 mm/year.

4.2 Pollen stratigraphy

Taiga was the dominant biome throughout the sequence (Fig. 3) suggesting the record reflects the regional ‘forest’ signal rather than only the local ‘steppe’ one. Compositional turnover in the palynological data was high (β-diversity=1.281), although greatest change occurred between 5.15 – 2.48 cal ka BP, with a very rapid change between 2.75 – 2.48 cal ka BP (Fig 6). Between 1.76 – 0.84 cal ka BP there was very little change in vegetation composition, but variability increased markedly from ca. AD 1800 to the present. Only PCA axis 1 was significant and accounted for 71.1% of variation in the species data. Three zones were delimited within the pollen stratigraphy (Fig. 3).

- Khall-3 (91 – 73.5 cm; 5.15 - 2.61 cal ka BP) was characterised by highest abundances of *Betula* sect. *Albae* (25-50%) and *Artemisia* (10-19%). *Pinus sibirica* percentage values, initially very high at the very base of the profile (25%), declined abruptly to 3 % and then increased to 10-13% again. *Pinus sylvestris* was initially present in only very low abundances (3-4%) at the base of the profile and quickly increased, reaching up to 36-41% in upper part of this zone. *Picea obovata* and *Alnus fruticosa* reached their highest values (up to 5%) in this zone.
- Khall-2 (73.5 – 13.25 cm; 2.61 – 0.15 cal ka BP [ca. AD 1800]) was dominated by *P. sylvestris* pollen, with values fluctuating between 60-84%. *P. sibirica* was also well represented (10-25%), and contribution from *Artemisia* varied between 0.5-9%. *Alnus fruticosa* pollen was absent or present in low abundances. *Picea* percentages were also generally low and did not exceed 3%.
- Khall-1 (13.25 - 0 cm; ca. AD 1800 – AD 2006) had a pollen composition similar to Khall-2, with slightly lower and fluctuating percentage values of *P. sylvestris* and slightly higher abundances of *B.* sect. *Albae* and Cyperaceae pollen. Within this zone *Pediastrum* algae spores appeared for the first time in the record, and rapidly increased to very high abundances.

4.3 Ostracods

We only present preliminary results here: detailed taxonomic and palaeoecological accounts of the ostracod assemblages will follow in a future publication. The ostracod assemblages were fairly low diversity (<10 species in total) and dominated by a member of the genus *Limnocythere*, which has yet to be identified to specific level (Fig. 4). Other taxa present include *Candona* spp., *Pseudocanodona* spp., *Cyclocypris* sp., *Cypris* sp., *Ilyocypris* sp. and *Potamocypris* sp. as well as several others that remain unidentified. In most of the core levels examined, adult and juvenile shells were found. Concentrations varied from about 300 to less than 2 valves per gram of sediment. Concentrations were greatest in the basal 10 cm of the core, declining above this. Candonids were absent above 2.10 cal ka BP. A varying proportion of the valves displayed a black coating. Energy dispersive spectroscopy (EDS) analysis under a scanning electron microscope suggested that the coating was non-metallic but laser Raman determinations were inconclusive.

4.4 Mineral Magnetics

Low field magnetic susceptibility measurements ranged between 0.1 - 4.7 10^{-5} SI (Fig. 5). Values increased by small amount from the base of the core up to ca. 2.8 cal ka BP (2 – 2.6 10^{-5} SI). There was a substantial increase in values between ca. 2.6 – 2.1 cal ka BP from 2.6 – 4.3 10^{-5} SI. Values showed almost no change between 1.4 – 1.0 cal ka BP, after which they declined to the top of the profile, with very rapid decline after AD 1800.

4.5 Particle Size

Mean particle size (Mz; μm) ranged between 12.7 – 48.3 μm) (mean = 20.6; median 17.6). Five peaks greater than mean Mz occurred at 5.12, 2.52, 1.88, 0.79 cal ka BP and AD 1925 (Fig 5). Sorting of the grain size distributions ranged between 3.2 and 7.1 μm (mean = 3.9; median 3.7). Five sorting peaks greater than the mean occurred at identical times as peaks in Mz. Almost all skewness values were negative (mean = -0.1; median = -0.1), except for 5 positive values that occurred at the same times as high values for mean grain size and sorting.

Kurtosis (mean = 1.0; median = 1.0) exhibited a different pattern from other grain size parameters. Values were above average between 5.12 – 3.03 cal ka BP, and declined to lowest value at 2.52 cal ka BP, when values of other particle size proxies increased. But peaks in kurtosis did co-occur at 1.88, 0.79 cal ka BP and 1925 AD.

4.6 XRF spectrometry analysis

Selected elements are presented in Figure 7. Ti, Al and K increased from 5.08 cal - 1.80 cal ka BP. Between 1.80 – 0.80 cal ka BP values showed little variation, and then they declined up to ca. AD 1950. The rate of decline increased at the top of zone Khall-2, from 0.12 ka BP, concomitant with rapid increase in sedimentation rate and decline in magnetic susceptibility values. Only PCA axis 1 was significant, accounting for 73.8% of variance in geochemical data. This axis was driven by a strong gradient between high Ca and Sr concentrations at the bottom of the core, and high concentrations of most other elements between ca. 1.90 – 0.50 cal ka BP (notably Fe, Y, Zn, Rb, K, Ti, Cu and and Al) (Fig. 6). Although axis 2 was insignificant, elevated concentrations of S and Cl were especially abundant in the uppermost sediments.

5. Discussion

Taiga biome dominated the vegetation reconstruction from the Ol'khon region since at least 5.2 ka BP. However, compositional turnover was very significant; β-diversity values were considerably higher than for longer Holocene sequences in other boreal regions such as southern Norway (Birks, 2007) and the eastern Sayan Mountains (Mackay et al., 2012). This suggests that the semi-arid, Ol'khon region was more sensitive to climate variability and environmental change than other boreal regions with higher precipitation. Such sensitivity was responsible for major directional shifts during the past 5.2 cal ka in Lake Khall and the surrounding region. DCCA and zonation analyses delimited most rapid periods of vegetation change at 2.74 – 2.48 cal ka and after AD 1800. Pollen assemblage composition showed a progressive decrease in birch pollen and shift to a predominance of Scots pine pollen between 5.15–2.48 cal ka, which drove overall compositional turnover. Scots pine produces vast amounts of pollen, and once established, it dominates pollen assemblages. The numerical scores of the taiga biome (Fig. 3) demonstrated minor fluctuations, but did not show decreasing or increasing trend through the whole record. Therefore, the increase in arboreal pollen percentages between 2.75 – 2.48 cal ka BP likely does not imply greater regional afforestation, nor any decrease in steppe communities, but are indicative of change in forest composition, with the spread of eurythermic and drought resistant Scots pine rather than noticeable spread in regional woody cover. These findings are in line with the woody cover reconstruction derived from Lake Kotokel pollen records on the opposite shore of Lake Baikal (Fig. 1) (Tarasov et al., 2009; Bezrukova et al., 2010).

5.1 Mid-Holocene environmental change

Up to 4.5 cal ka BP, forest-steppe communities dominated local vegetation in Ol'khon region, especially tree birches (*Betula* sect. *Albae*), *Artemisia* and Chenopodiaceae taxa. Reconstructed temperature of the coldest month and annual precipitation were highest during this period. Owing to the lack of formal identification of the ostracod species, interpretations of the assemblages remain circumspect at this stage, although we can say that assemblages were deposited *in situ*, because in most of the core levels examined, both adult and juvenile shells were found. However, candonids generally only tolerate low salinity waters (Holmes et al., 2010) and the Lake Khall assemblage suggests that the lake was fresher in the past. The geochemical record also provides evidence for a fresher lake in the past; low Sr/Ca ratios indicate low lake-water salinity (Marshall, 1969). Detrital transport from the catchment into the lake are represented by e.g. Ti, Al and K, and these elements were lowest when precipitation was highest. Ca on the other hand may come from both authigenic production within the lake and from detrital flux (e.g. Wünnemann et al., 2010). In order to distinguish between these two processes we use the Ca/Al ratio, which at the base of the core was very high (60), indicative of high authigenic production. High production occurs at the same time as highest concentrations of ostracods, and shell remains of a, as yet unidentified, bivalve. We have as yet to characterise mineralogy of the sediments (e.g. using XRD) but low K/Rb and high Ti/K ratios suggest dominance of clays and micas, although feldspars became more important after 3.59 cal ka BP. Elsewhere in the Lake Baikal region, other records of pollen-inferred annual precipitation were also high (e.g. Tarasov et al., 2007; Tarasov et al., 2009), as was isotopic evidence for elevated precipitation-dominated discharge into Lake Baikal (Mackay et al., 2011; Fig 8). Further afield, isotopic records from Dongge Cave in southern China (Fig 8) were indicative of strong East Asian Summer Monsoon (EASM) linked to relative high summer insolation (Wang et al., 2005).

Between ca. 4.4 – 2.8 cal ka BP, the pollen record is poorly resolved. However, there was a significant expansion of Scots pine (*P. sylvestris*) and, to a lesser extent, Siberian pine (*P. sibirica*) (a major component of dark, coniferous taiga), concomitant with a decline in deciduous forest. The expansion of Scot's pine occurred substantially later than at neighbouring regions e.g. Lake Hovsgöl (10.0 cal ka BP; Prokopenko et al., 2007), Altai Mountains, (9.5 cal ka BP, Blyakharchuk et al., 2004), Eastern Sayan Mountains (9.1 cal ka BP, Mackay et al., 2012), southern Lake Baikal (7 cal ka BP, Demske et al., 2005) and Lake Kotokel (ca. 6.9 - 6.4 cal ka BP (Bezrukova et al., 2008; Shichi et al., 2009). The expansion of Scots pine in Ol'khon is in close agreement with the expansion of Scots pine to the north of Lake Baikal (5.2 cal ka BP, Bezrukova et al., 2006), highlighting that distinct regional differences exist in the spread of conifer forest to coastal regions of Lake Baikal. The period of conifer expansion in Ol'khon region occurred during a period of increasing aridity, as inferred from several of the proxies studied. For example, Sr/Ca ratios indicate a progressive increase in salinity of Lake Khall, likely linked to reductions in pollen-inferred precipitation anomalies, while pollen-inferred temperatures remained above values experienced in recent decades (Fig. 8). Detrital input (inferred from Al, Ti and K) also increased at this time. Given the similarity between PCA of the vegetation and geochemistry, it is likely that both were influenced by the same drivers. Elsewhere, $\delta^{18}O_{diatom}$ showed a marked decline during this period, indicative of a decline in the proportion of rain-fed discharge into Lake Baikal (Mackay et al., 2011; Fig. 8). The shift to a more arid climate was also reflected further afield in the weakening of the EASM (Wang et al., 2005; Fig. 8).

5.2 Abrupt environmental change

Compositional turnover in vegetation communities was greatest between 2.75 – 2.48 cal ka BP, which continued to change up to 1.87 cal ka BP, linked to the maximum expansion of dark coniferous taiga. Particle size characteristics in Lake Khall show that they were generally very poorly sorted, i.e. they had not undergone efficient sorting before their burial into the bottom sediments, which is common for shallow lakes (Mischke et al., 2010). One of the largest peaks in mean particle size occurred at 2.52 cal ka BP, which was likely caused by strong aeolian influx because these large particles were also extremely unsorted (Fig. 5). Pollen-inferred annual precipitation anomalies dropped rapidly, and values remained low, below that of the present day, for much of the remainder of the Holocene (Fig. 8). There was also a marked decline in mean temperature of coldest month, while mean temperatures of the warmest month increased. The climate in the Ol'khon region therefore became more continental. The start of these climatic and vegetation changes are coincident with a peak in ice rafted debris material in North Atlantic sediments (IRD-2; Bond et al. 1997), which also resulted in low $\delta^{18}O$ isotopic values in Lake Baikal and in Dongge cave, indicative of a decline in proportion of rain-fed discharge into Lake Baikal (Mackay et al., 2011) and an attenuated EASM (Wang et al., 2005) respectively.

Between 2.12 – 1.87 cal ka BP there was a significant decline in mean annual precipitation and mean temperature of the coldest month but an increase in mean temperature of the warmest month (Fig 8). Drier, more continental climate resulted in peak abundance of Scots pine, which drove compositional turnover in the Ol'khon region. An increase in Sr/Ca ratio suggested that chemical composition of the groundwater that feeds Lake Khall may have became more saline, and this event may have caused the final decline in substantial numbers of the ostracod *Candona* sp. Therefore it seems likely that the region underwent a period of extreme drought, which led to a decline in ostracoda in general. The rapid increase in sedimentation rate was concurrent with small peaks in particle size, perhaps indicative of increased aeolian transport onto the lake.

5.3 Late Holocene variability

Between ca. 1.9 – 0.7 cal ka BP, taxa indicative of cold coniferous forest declined and steppe communities virtually disappeared from the record altogether, coincident with marked increases in warmest month temperature anomalies. This period in general was characterised by little vegetation compositional change, and stable input of catchment derived particles (Figs. 3, 5, 7). Increased reconstructed summer and winter temperatures were likely linked to increased northern hemisphere temperatures, as inferred from the GRIP borehole (Dahl-Jensen et al., 1998) (Fig. 8). Elsewhere in the Lake Baikal region, steppe communities were also less common (Tarasov et al., 2007), while high biogenic silica concentrations within Lake Baikal sediments were indicative of high aquatic productivity (Prokopenko et al., 2007). Peak reconstructed summer temperatures occurred between 1.33 – 0.77 cal ka BP, coincident with the period known as both the Medieval Warm Period (MWP) and Medieval Climate Anomaly (MCA). This period is distinct because although temperatures in many regions were warm (Mann et al., 2009) precipitation anomalies were also apparent in many regions in the world (Stine, 1994), leading to severe drought in e.g. northern Europe (Helama et al., 2009) and North America (Seager and Burgman, 2011). In the Ol'khon region, precipitation anomalies were higher than the previous period of drought, but still lower than the present. One of the few stratified deposits in the Lake Baikal region was excavated at Sagan-Zaba and dated between 2.0 – 0.9 cal ka BP. These deposits were likely associated with pastoralists, and although we are not able to say if the evidence of pastoralism was linked to a particularly quiescent period of environmental change, warmer summer and milder winter temperatures may have been conducive to a pastoral way of life.

For a short period between ca. 0.77 – 0.45 cal ka BP, local climate in the Ol'khon region became wetter and substantially colder, leading to an increase in *P. sibirica*, *Picea obovata* and sedge pollen. *P. obovata* (Siberian spruce) is characteristic of soils with elevated moisture content, and likely represents real increases in tree abundance close to the lake (Bezrukova et al., 2005). However, there did not appear to be a substantial influence on Lake Khall itself – Sr/Ca ratios continued to increase, while ostracods only showed small increases in concentration. It is noteworthy that candonids did not recolonise the lake in any substantial numbers, and that black coatings on the ostracod valves almost disappeared. On the basis of the EDS and laser Raman determinations detailed in section 4.3, it was assumed that the coatings were organic and indicative of reducing conditions in the upper layers of the sediment following death of the ostracods. Blackened valves dominated the lower part of the core, and were less common above 0.68 cal ka BP, suggesting a significant change in the ventilation of the lake after this time. Further work still needs to be done to determine the nature of the black coatings. Wetter climate has also been reconstructed from peat bog sequences from the northern shore of Lake Baikal (Bezrukova et al., 2006), and further afield in the Eastern Sayan mountains (Mackay et al. 2012). This period is coincident with IRD0 in North Atlantic sediments and attenuation of the EASM (Wang et al., 2005; Fig 8), and is concurrent with the Little Ice Age. Young moraines, associated with re-advancing glaciers at this time, can be found in the Sayan Moutnains (Ivanovsky and Panychev, 1978 in Shahgedanova et al., 2002), indicative of cooler, regional environments (Krenke and Chernavskaya, 2002). Chironomid-inferred temperatures from lake ESM-1 in the Eastern Sayan Mountains also showed a distinct cooling (Mackay et al., 2012).

Since ca. AD 1845, the increase in deciduous forest was linked to increased pollen-inferred precipitation and pollen-inferred temperature anomalies of the coldest and warmest months. The most striking change in the palynological record however, is the rapid increase in *Pediastrum* algae. *Pediastrum* belongs to the Chlorophyceae green algae, and is often characteristic of more nutrient rich waters. Palaeoenvironmental interpretations from *Pediastrum* records in lake sediments are not straightforward. Several studies tie the presence of *Pediastrum* to high lake levels in the semi-arid regions of e.g. Inner Mongolia (Jiang et al., 2006) and NE Tibetan Plateau (Zhao et al., 2007). In southern Scandinavia, increased concentrations of *Pediastrum* coenobia occurred during periods of warmer climate and increased lacustrine productivity (Sarmaja-Korjonen et al., 2006; Panizzo et al., 2008). In Lake Khall, increasing *Pediastrum* was coincident with increases in temperature of the coldest month and annual precipitation. During this period there was a rapid increase in sediment accumulation rate, the fastest for the past 5 ka, concomitant with a rapid decline in low field initial magnetic susceptibility measurements. This suggests that there was a decline in magnetisable sediments, possibly related to increased organic content and presence of algal growth. The increase in *Pediastrum* sp. therefore is likely indicative of a more nutrient rich lake. Animal husbandry intensified in the Lake Baikal region at this time because of the influx of Russian populations (Tarasov et al., 2007). Local populations later undertook tree-felling (Sizykh, 2007), and although there is limited pollen evidence of anthropogenic activities, impacts on lacustrine ecosystems could be expected.

6. Conclusions

A multiproxy study of a small, shallow lake in the Ol'khon region of Lake Baikal was undertaken to determine climatic and human impacts on the landscape over the mid- to late-Holocene. We could only relate the significant turnover in vegetation composition to climate variability, and we found no evidence for anthropogenic activity despite the region having a long history of pastoralism. Geochemical evidence suggested that Lake Khall was once more fresh than it is today, and that over the study period, groundwater feeding the lake became more saline. The change in chemical composition had a negative impact on aquatic fauna by 2 cal ka BP. Pollen based reconstructions from Lake Kotokel, a satellite to Lake Baikal (Tarasov et al., 2009) and regional climate modelling (White and Bush, 2010) exhibited similar trends to reconstructions from Lake Khall. For example, general trends demonstrated a decline in atmospheric precipitation and increase in continentality. The decrease in precipitation was accompanied by the changes in its seasonality, i.e. late Holocene strengthening of Westerlies in the region caused relative increase in winter (snow) accumulation. This feature together with drier summer conditions favoured the spread of drought resistant Scots pine. Reconstructed cool, moist conditions during the Little Ice Age are consistent with other palaeolimnological records, highlighting the regional nature of the response. Proxy records from Lake Khall also show a period of relative stability concurrent with the Medieval Climate Anomaly and a period of abrupt change between 2.75 – 2.48 cal ka BP, concurrent with influence from IRD-2 event in the north Atlantic. Finally, although human impact could not be determined from the terrestrial pollen record, preserved *Pediastrum* colonies may be indicative of a major recent phase of human impact as numbers of pastoralists migrated into the region in the last 100 years.

Acknowledgements

We gratefully acknowledge funding through the Baikal Archaeology Project, supported by the Major Collaborative Research Initiative (MCRI) programme of the Social Sciences and Humanities Research Council of Canada. Thanks are given to Cath D'Alton for help in preparing figures and to Holly Watson for undertaking magnetic susceptibility measurements and particle size analysis.

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Figure Legends

Fig. 1. Map of Lake Baikal and its immediate catchment, showing the location of key sites: Lake Khall, Ol'khon region, Lake Kotokel and Primorsky Mountain Range.

Fig. 2. Age-depth model based on ^{137}Cs and calibrated radiocarbon AMS dates, constructed using 'Bacon' (Blaauw and Christen, 2011). Grey-shaded area represents 95% confidence intervals of modelled ages (black line).

Fig. 3. Pollen, spore and *Pediastrum* coenobia colony relative abundances plotted on the calibrated age scale. Taiga biome scores are also shown – see section 3.2 for details. Significant PCA axis 1 sample scores (+ eigenvalue; EV) and significant compositional turnover (beta diversity; SD units) value for vegetation data is also given ($p = 0.05$; $n=499$). Pollen zones have been delimited using optimal partitioning.

Fig. 4. Total ostracod concentrations (valves/g) are plotted on the calibrated age scale, along with the two most abundant genera *Lymnocythere* sp. and *Candona* sp. The concentration of blackened valves is also given.

Fig. 5. Low-frequency magnetic susceptibility measurements and particle size statistics produced from Folk and Ward (1957) method (mean particle size, sorting, skewness and kurtosis). Sedimentary mean values are shown with a vertical line for each of mean particle size, sorting, skewness and kurtosis.

Fig. 6. PCA biplot of geochemical data. Axis 1 is plotted against axis 2. Axis 1 accounts for significant 73.8% variation in element data. Axis 2 accounts for only 10.0% variation in the data which broken stick shows is not significant.

Fig. 7. Geochemical stratigraphy of Lake Khall. Selected major elements are shown, expressed either as percentages (Al, Ti, K, Si, P, S, Mn, Fe) or concentrations (ug/g: Rb, Pb, Ca, Sr). Significant PCA axis 1 sample scores (+ eigenvalue; EV) are also shown.

Fig. 8. Composite stratigraphical plot showing: (i) pollen DCCA axis 1 sample scores; (ii) mean grain size; (iii) pollen-inferred reconstruction anomalies (total annual precipitation – Pann; mean temperature of the coldest month – Tc; mean temperature of the warmest month – Tw); (iv) geochemical ratio of selected elements Sr/Ca (x1000), Ca/Al, P/Al, Ti/K, K/Rb; (v) concentrations of *Candona* sp.; (vi) oxygen isotope data from Lake Baikal biogenic silica (Mackay et al., 2011); (vii) oxygen isotope data from Dongge Cave, southern China (Wang et al., 2005); (viii) palaeo-temperatures inferred from the GRIP borehole (°C) (Dahl-Jensen et al., 1998); (ix) July insolation at 60 °N (W/m^2) (Berger and Loutre, 1991)

Figure 1

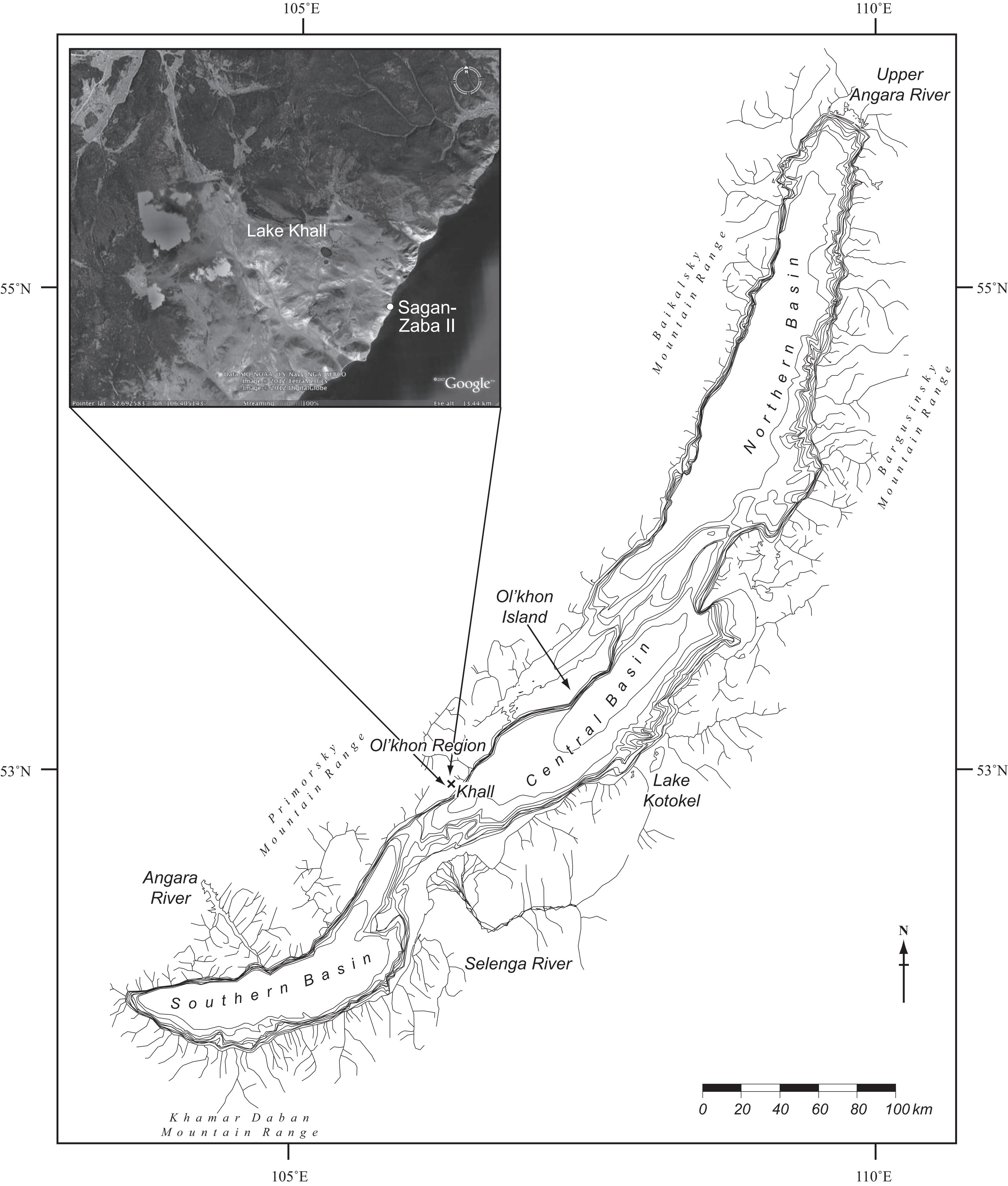

105°E
110°E
55°N
53°N
Lake Khall
Sagan-
Zaba II
Google
Upper
Angara River
Baikalsky
Mountain Range
Northern Basin
Bargusinsky
Mountain Range
Ol'khon
Island
Central Basin
Ol'khon Region
Khall
Primorsky
Mountain Range
Lake
Kotokel
Angara
River
Selenga River
Southern Basin
N
0 20 40 60 80 100 km
Khamar Daban
Mountain Range

Figure 2

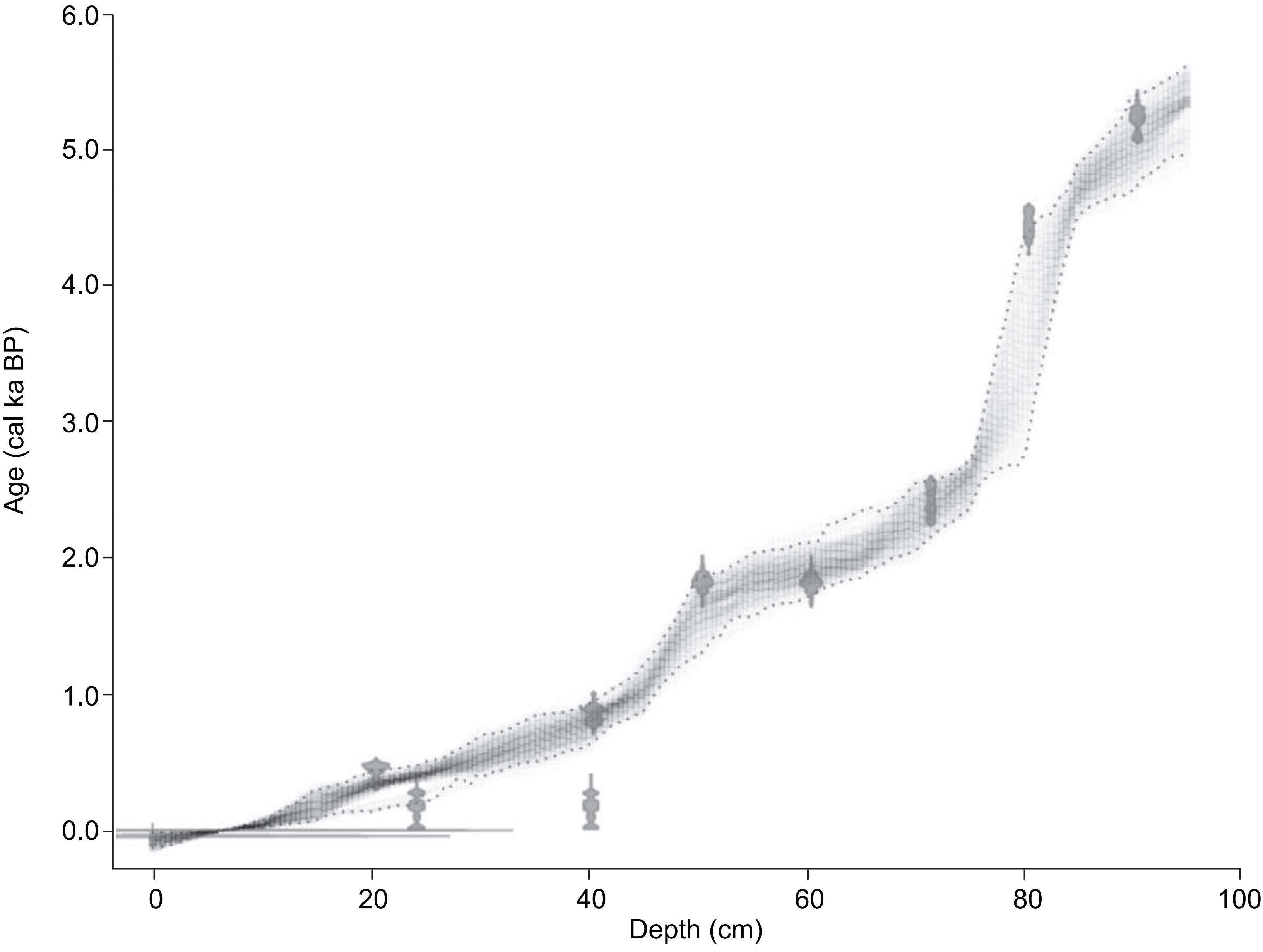
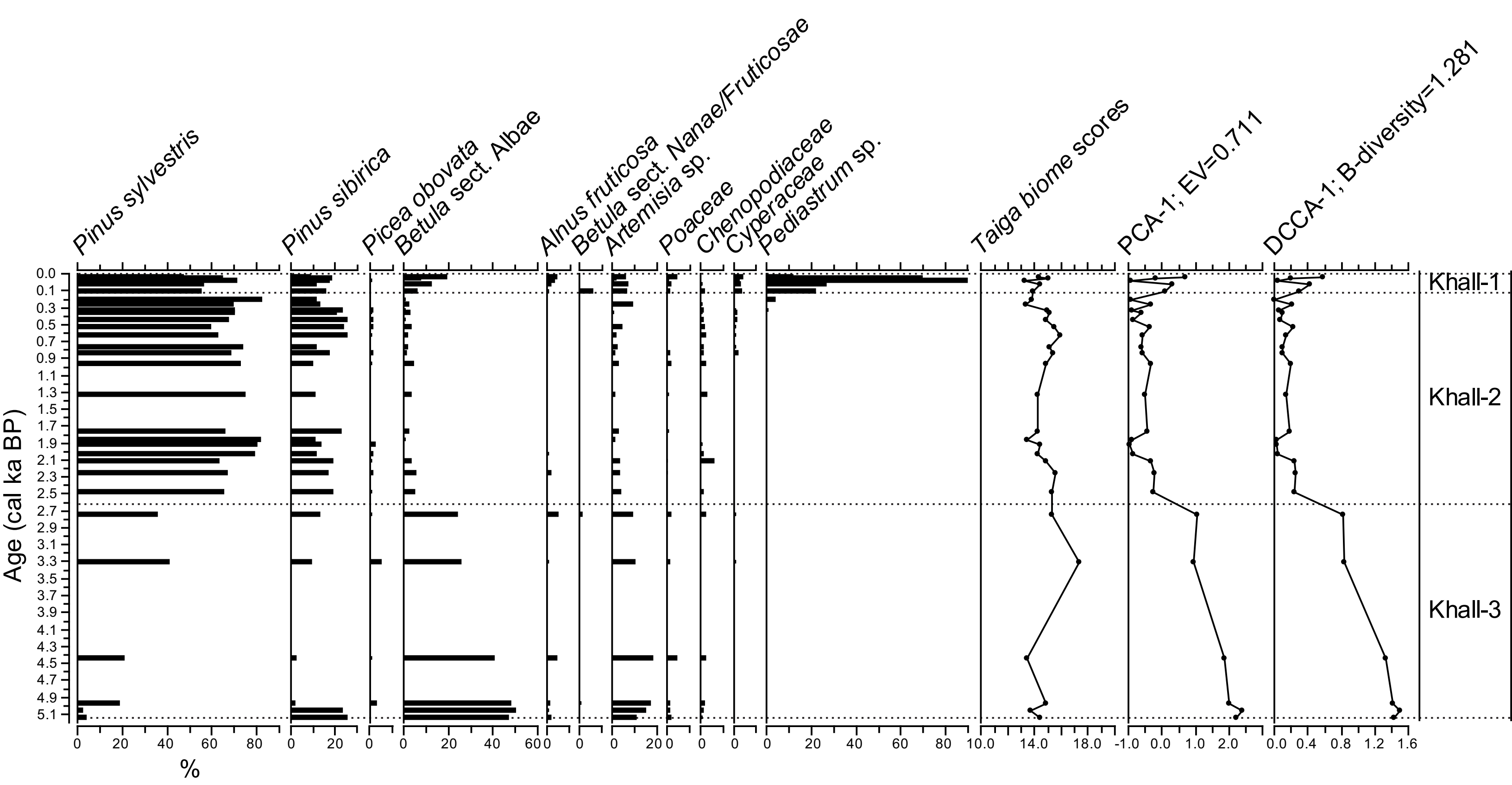


Figure 3



Pinus sylvestris
Pinus sibirica
Picea obovata
Betula sect. Albae
Alnus fruticosa
Betula sect. Nanae/Fruticosae
Artemisia sp.
Poaceae
Chenopodiaceae
Cyperaceae
Pediastrum sp.
Taiga biome scores
PCA-1; EV=0.711
DCCA-1; B-diversity=1.281
Age (cal ka BP)
%
Khall-1
Khall-2
Khall-3

Figure 4

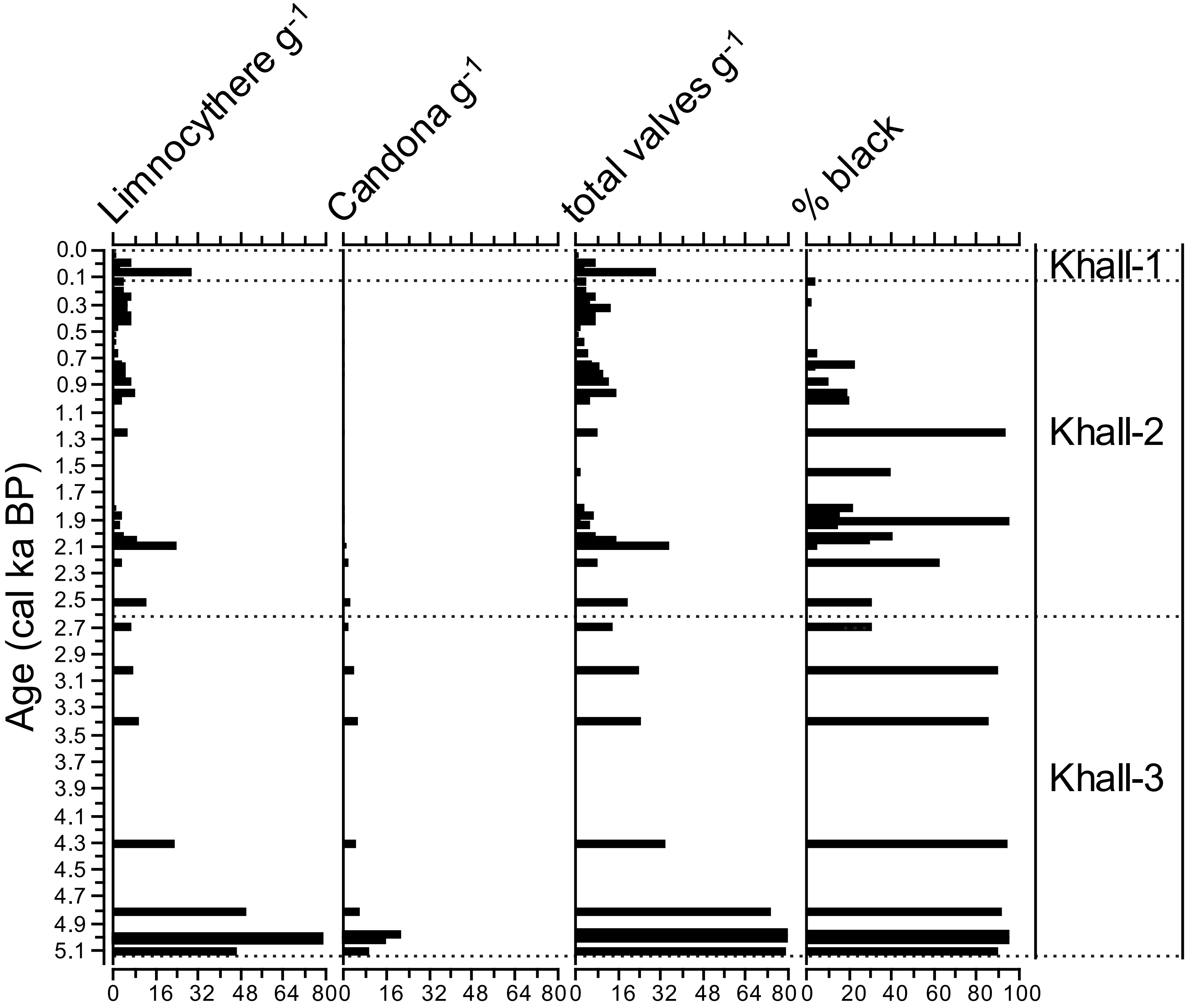
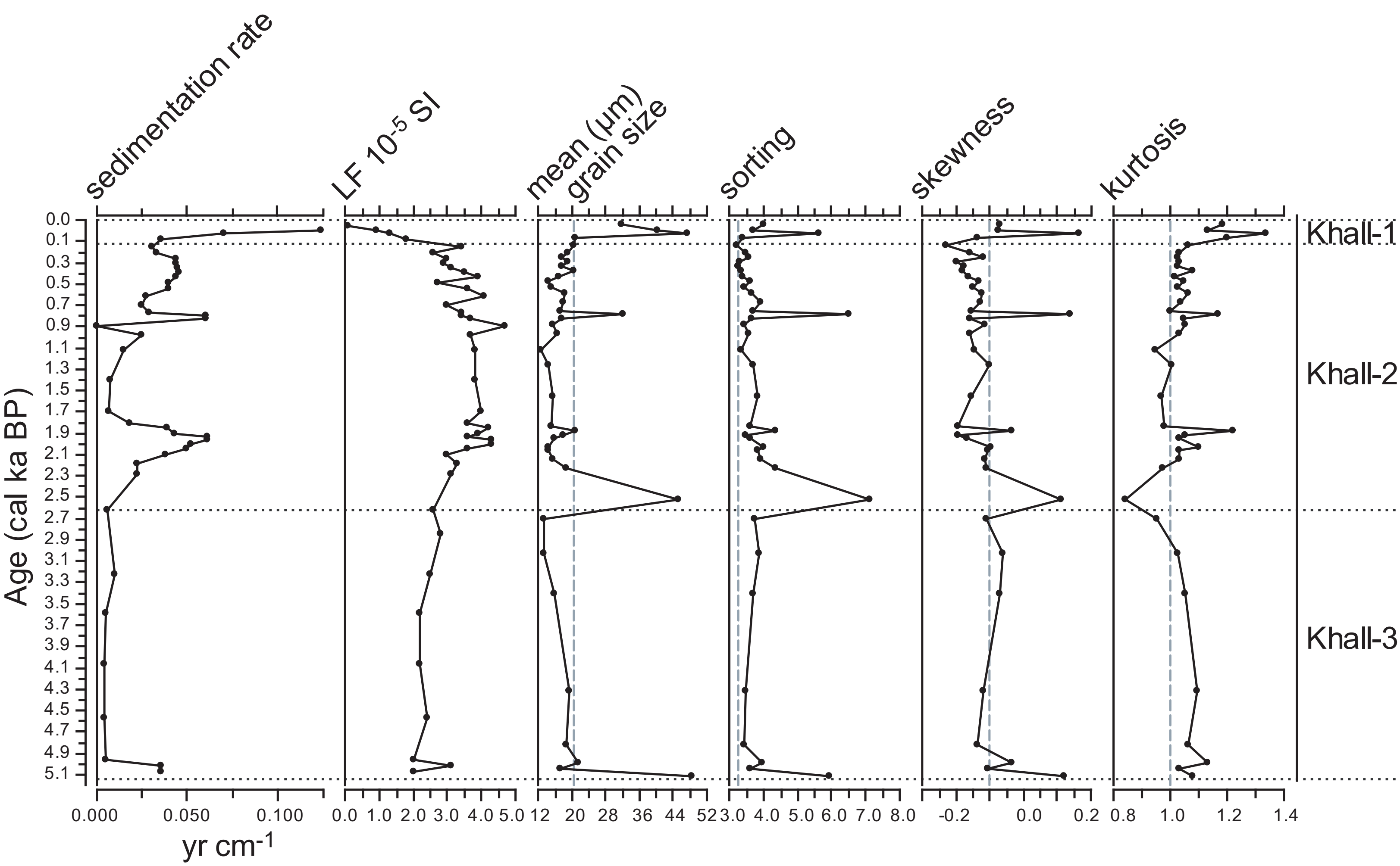
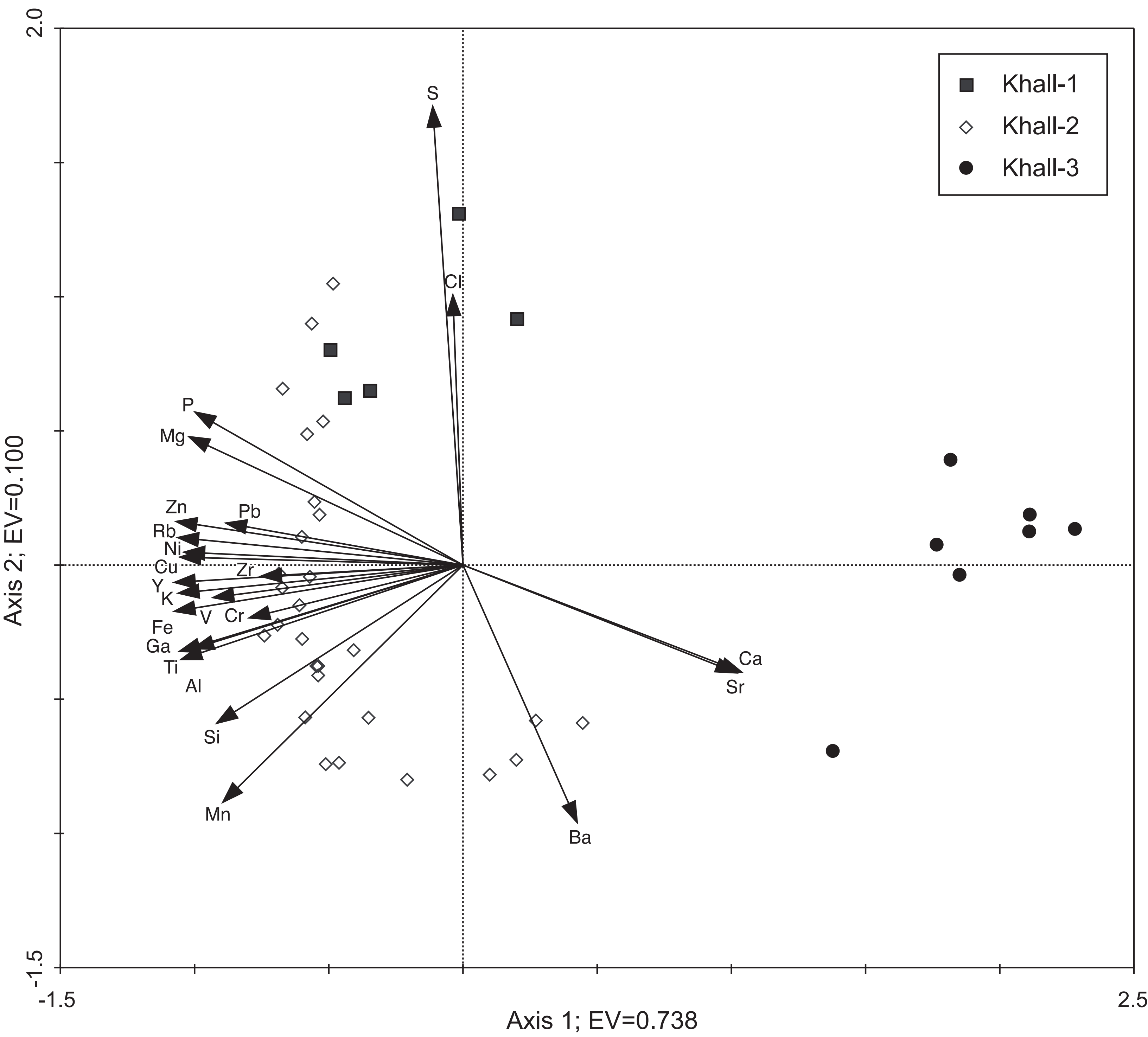

Limnocythere g-1
Candona g-1
total valves g-1
% black
Age (cal ka BP)
0.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
5.1
0 16 32 48 64 80
0 16 32 48 64 80
0 16 32 48 64 80
0 20 40 60 80 100
Khall-1
Khall-2
Khall-3

Figure 5



sedimentation rate
LF 10^-5 SI
mean (µm) grain size
sorting
skewness
kurtosis
Age (cal ka BP)
yr cm^-1
Khall-1
Khall-2
Khall-3

Figure 6



Khall-1
Khall-2
Khall-3
S
Cl
P
Mg
Zn
Pb
Rb
Ni
Cu
Zr
Y
K
V
Cr
Fe
Ga
Ti
Al
Si
Mn
Ba
Ca
Sr
2.0
-1.5
-1.5
2.5
Axis 2; EV=0.100
Axis 1; EV=0.738

Figure 7

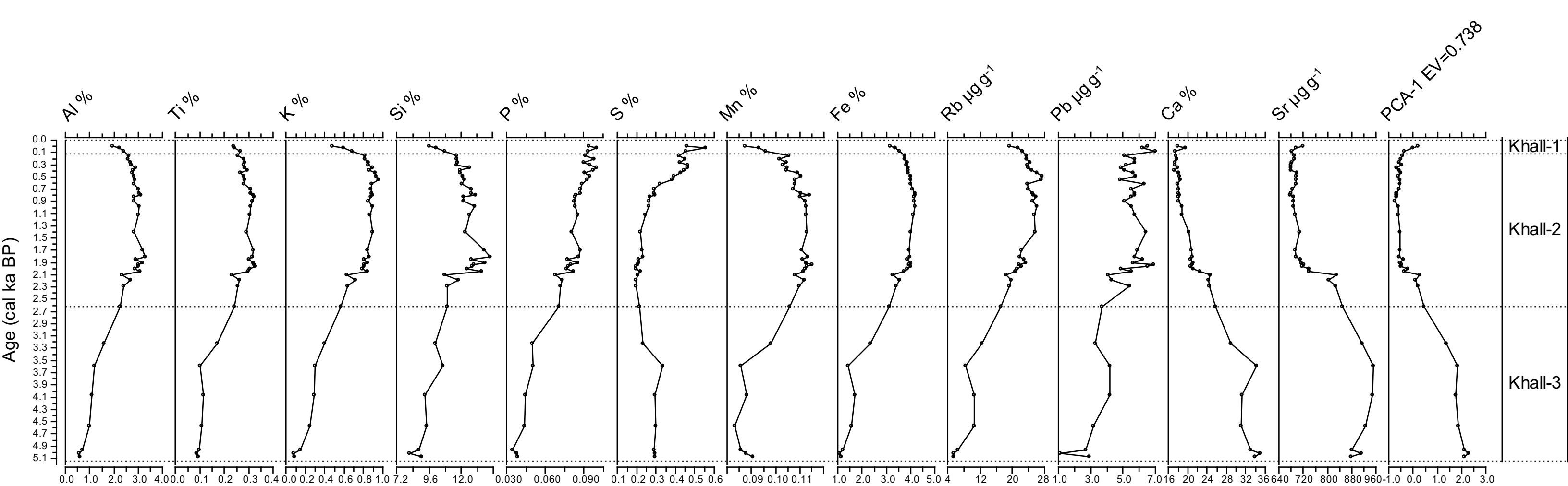
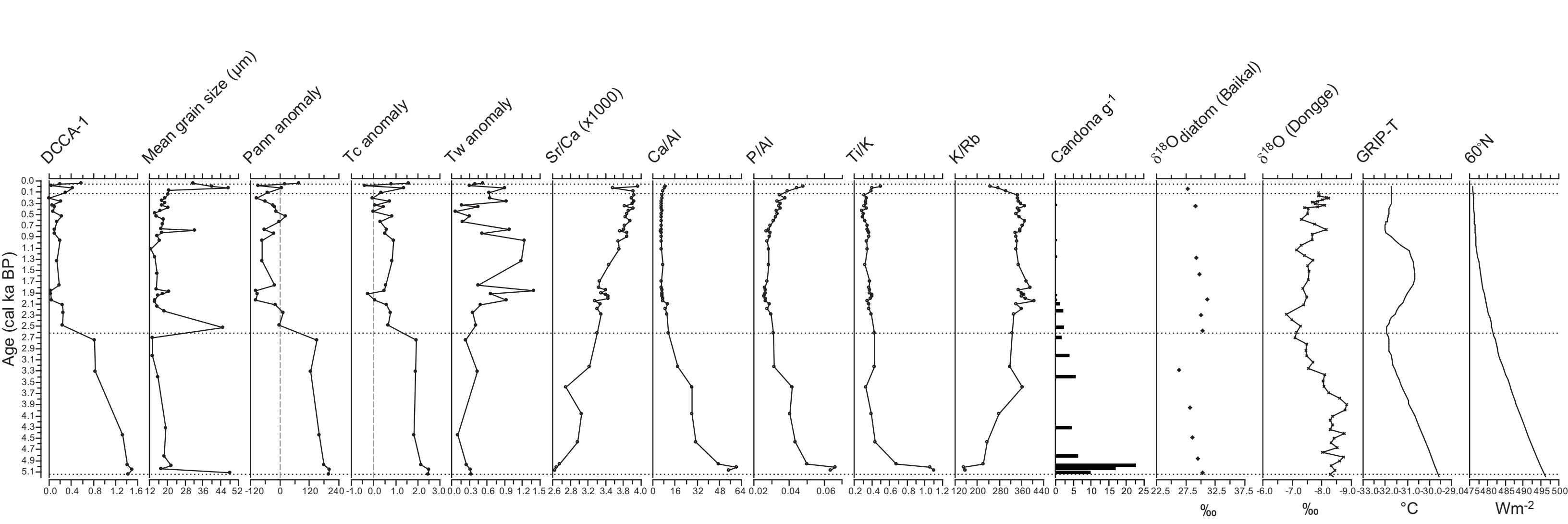

Al %
Ti %
K %
Si %
P %
S %
Mn %
Fe %
Rb µg g-1
Pb µg g-1
Ca %
Sr µg g-1
PCA-1 EV=0.738
Age (cal ka BP)
Khall-1
Khall-2
Khall-3

Figure 8


DCCA-1
Mean grain size (μm)
Pann anomaly
Tc anomaly
Tw anomaly
Sr/Ca (x1000)
Ca/Al
P/Al
Ti/K
K/Rb
Candona g-1
δ18O diatom (Baikal)
δ18O (Dongge)
GRIP-T
60°N
Age (cal ka BP)
‰
‰
°C
Wm-2

Table

Table 1: Results of AMS radiocarbon dating for Lake Khall sediment core. Depth range and mid-depth are the original depths of samples from core. Calibration of independent ^{14}C dates from the core was performed using IntCal09 radiocarbon calibration curve (Reimer et al., 2009) and OxCal software ver. 4.1.7 (Bronk Ramsey, 2009), assuming the reservoir correction of 150±50 years.

Sample code	**Sample material**	**Depth range, cm**	**Mid-depth, cm**	**^{14}C age BP**	**Calibrated age range calBP (68.2%)**		**Calibrated age range calBP (95.4%)**	
Poz-25686	Contemporary macrophytes	n/a	n/a	105.58±0.33 pMC	n/a	n/a	n/a	n/a
Poz-30449	TOC	20-21	20.5	555±30	626	532	640	519
Poz-25740	*Potamogeton* seed	24-24.5	24.25	345±30	465	319	485	313
Poz-25682	*Potamogeton* seed	40-40.5	40.25	330±30	455	316	474	308
Poz-30448	TOC	40-41	40.5	1140±30	1072	980	1169	968
Poz-33695	TOC	50-51	50.5	2110±35	2131	2009	2295	1992
Poz-30447	TOC	60-61	60.5	2105±30	2123	2010	2150	1995
Poz-33696	TOC	71-72	71.5	2605±35	2759	2724	2787	2545
Poz-25683	*Potamogeton* seed	80-81	80.5	4285±35	4865	4835	4964	4822
Poz-25684	*Potamogeton* seed	90-91B	90.5	4930±70	5730	5596	5892	5487