Last glacial–interglacial vegetation and environmental dynamics in southern Siberia: Chronology, forcing and feedbacks

Elena V. Bezrukova, Pavel E. Tarasov, Nadia Solovieva, Sergey K. Krivonogov, Frank Riedel

1. Introduction

Worldwide terrestrial and marine sedimentary archives demonstrate that the last 50-kyr interval in the Earth’s history experienced a number of long- and short-term climatic oscillations (Guiot et al., 1989; Vincens et al., 2005; Heusser et al., 2006; Bout-Roumazeilles et al., 2007; Svensson et al., 2008). High-resolution and accurately dated pollen and sedimentary records of the late-glacial/early Holocene interval exist for several regions of Europe (Litt and Stebich, 1999; Allen and Huntley, 2000; Brauer et al., 2008) and East Asia (Stebich et al., 2009), providing important insight into the environmental dynamics in the North Pacific and North Atlantic regions. However, a recent global-scale synthesis of the Holocene climatic data (Wanner et al., 2008) demonstrates a lack of palaeorecords of comparable dating quality and resolution from the vast areas of Eurasia, including Siberia and Central Asia. The dating problem becomes even more obvious, when the pre-Holocene interval of the late Quaternary is considered. The maximal spread of the Younger Dryas (YD) based on the Greenland NGRIP ice core records. The maximal spread of the taiga communities in the region is associated with a warmer and wetter climate than the present prior to ~7 ky BP. This was followed by a wide spread of Scots pine, indicating the onset of modern environments.

Radiocarbon-dated pollen and diatom records from Lake Kotokel in southern Siberia help to reconstruct the environmental history of the area since ~47 ky BP. Pollen spectra composition and reconstructed biome scores suggest predominance of a tundra–steppe vegetation and variable woody cover (5–20%) between ~47 and 30 ky BP, indicating generally a harsh and unstable climate during this interval, conventionally regarded as the interstadium, within the last glacial. The short-term climate amelioration episodes in the glacial part of the records are marked by the peaks in taiga and corresponding minima in steppe biome scores and appear synchronously with the hemispheric temperature and precipitation changes recorded in the Greenland ice cores and Chinese stalagmites. Transition to full glacial environments occurred between 32 and 30 ky BP. The interval at ~30–24 ky BP was probably the driest and coldest of the whole record, as indicated by highest scores for steppe biome, woody coverage <5%, absence of diatoms and reduced size of the lake. A slight amelioration of the regional climate at ~24–22 ky BP was followed by a shorter than the previous and less pronounced deterioration phase. The late-glacial (~17–11.65 ky BP) is marked by a gradual increase in tree/shrub pollen percentages and re-appearance of diatoms. After 14.7 ky BP the climate became warmer and wetter than ever during ~47–14.7 ky BP, resulting in the deepening of the lake and increase in the woody coverage to 20–30%, 14.5–14 ky and 13.3–12.8 ky BP. These two intervals correspond to the Meiendorf and Allerød interstadials, which until now were interpreted as part of the undifferentiated Bølling/Allerød interstadiatal complex in the Lake Baikal region. The increase in tundra biome scores and pronounced change in the diatom composition allow for the unambiguous identification of the Younger Dryas (YD) in the Lake Baikal region at ~12.7–11.65 ky BP, in agreement with the formal definition and dating of the YD based on the Greenland NGRIP ice core records. The maximal spread of the taiga communities in the region is associated with a warmer and wetter climate than the present prior to ~7 ky BP. This was followed by a wide spread of Scots pine, indicating the onset of modern environments.

Keywords: Eurasia, Pollen and diatom records, Quantitative vegetation reconstruction, Late Pleistocene interstadials, Last glacial maximum, Younger Dryas, Holocene climatic optimum.
2001), and palaeoecology, e.g. discussing local presence/absence of boreal trees and shrubs during the last glacial (Grichuk, 1984).

Numerous publications on the Lake Baikal region (e.g. Kuzmin et al., 1993; Williams et al., 1997; Prokopenko et al., 2002; Shichi et al., 2009 and references therein) presented coarse-resolution (millennial- or multi-century-scale) qualitative reconstructions of the Quaternary environments. Although the long cores from Lake Baikal span millions of years (Williams et al., 1997; Khursevich et al., 2005), research was mainly focused on the Holocene and earlier interglacials (Demske et al., 2005; Tarasov et al., 2005, 2007a; Prokopenko et al., 2007, 2010). However, little is known about glacial intervals due to the problems associated with very low pollen concentrations, poor organic content, low sedimentation rates and poor dating (Horiuchi et al., 2000; Oda et al., 2000). Until recently, even the YD cooling was not unequivocally identified and dated in the Baikal records. This led to various hypotheses suggesting that Lake Baikal could either mask or delay the effect of global change (Bezrukova et al., 2005; Demske et al., 2005; Shichi et al., 2009).

This study presents new pollen and diatom records from Lake Kotokel (Fig. 1c) and aims to reconstruct regional vegetation and environmental history since ~47 kyr BP (1 kyr = 1000 cal yr); to compare it with the oxygen isotope records from the North Atlantic and North Pacific regions; and to discuss the underlying mechanisms of the environmental change in the region. Both time resolution and dating control are substantially improved in comparison to the earlier studies (e.g. Vipper and Smirnov, 1979; Bezrukova et al., 2008; Shichi et al., 2009).

2. Site setting and environments

Lake Kotokel (458 m a.s.l.) has an area of ~67 km², a maximum length of ~15 km and a maximum width of ~6 km (Galaziy, 1993). In the west a low-elevated mountain ridge (729 m a.s.l.) separates the lake from Lake Baikal (Fig. 1), and the Ulan-Burgasy Ridge (up to 2033 m a.s.l.) bounds it in the east. The average water depth is 5–6 m, and the maximum depth is about 15 m (Shichi et al., 2009; Tarasov et al., 2009 and references therein).

The regional climate is continental with long winters and a well-pronounced summer precipitation maximum (Alpat'ev et al., 1976). The mean January temperature is −20 °C near the lake, but decreases to below −26 °C with increasing elevation. The mean July temperature is 14–16 °C. The annual precipitation reaches 300–400 mm in the coastal area and above 500 mm in the mountains (Galaziy, 1993). In July and August westerly winds dominating through the year become weak, and southeastern cyclones bringing warm and wet Pacific air to the region cause heavy rainfalls at the eastern branch of the Polar front (Bezrukova et al., 2008). The Atlantic air masses entering the region with the westerly flow may bring precipitation all year round, but mainly during autumn and spring. Dry, cold and sunny winter weather is associated with the high pressure cell centred over eastern Siberia (Alpat'ev et al., 1976).

Modern vegetation east of Lake Baikal is a mosaic of boreal coniferous and deciduous forests (Galaziy, 1993) and swampy communities, widely distributed in the Selenga River delta and

Fig. 1. Simplified maps, which show: (a) northern Eurasia and the Lake Baikal region, (b) the Lake Kotokel study area, (c) location of the 47-kyr long KTK2 core (this study) and the 15-kyr long KTK1 core (Tarasov et al., 2009). The location of Lake Shalatlungwan (SHL) is indicated by a black triangle.
south of Lake Kotokel (Takahara et al., 2000; Shichi et al., 2009). Forests are mainly composed of *Pinus sylvestris* (Scots pine), *Larix sibirica* (Siberian larch) and *Betula* (birch) trees, with some admixture of *Populus tremula* (aspen) and *Alnus fruticosa* (shrubby alder). Boreal evergreen conifers, including *Pinus sibirica* (Siberian pine), *Abies sibirica* (Siberian fir) and *Picea obovata* (Siberian spruce) grow on the Ulan-Burgasy slopes. Above 1800 m this mountain taiga vegetation is replaced by open birch and larch forests and shrubby sub-alpine associations represented by *Pinus pumila* (shrubby pine), *Alnus fruticosa* and *Betula middendorffii* (shrubby birch). Alpine tundra occupies large areas north and northeast of Lake Baikal, while the steppe is characteristic of Olkhon Island (Fig. 1) and semiarid depressions along the Selenga River, where precipitation drops to ~160 mm/yr, (Galaziy, 1993).

3. Data and methods

3.1. Core lithology and age determination

The KTK2 sediment core (52°47′N, 108°07′E; Fig. 1c) was retrieved from a depth of ~3.5 m in the southern part of Lake Kotokel in August 2005. The Livingston-type piston corer of 7.5 cm diameter was applied to the upper and softer biogenic sediment (Fig. 2a) and the 4.6 cm diameter corer was used to penetrate lower more compact layers (Shichi et al., 2009). The upper part of the core (Fig. 2a) consists of the soft brownish black gyttja (0–660 cm) underlined by the grey or blackish slightly laminated silty clay (660–740 cm), laminated grey silty clay (740–1010 cm) and dark-grey or grey silty clay unit (1010–1253 cm).

Eleven bulk sediment samples from the KTK2 core were submitted to Poznan Radiocarbon Laboratory. The distribution of obtained radiocarbon ages versus composite core length (Fig. 2b, Table 1) demonstrates no reversals and a clear trend of increasing age with depth. The sediment is non-calcareous, thus ensuring that a reservoir effect, which usually complicates accurate dating of the Baikal cores (Colman et al., 1996; Demske et al., 2005), is not an issue in Lake Kotokel. The KTK2 core lithology and radiocarbon dates suggest an uninterrupted accumulation of sediment between ~47 kyr BP and the present.

The KTK2 14C AMS dates were converted to calendar dates (Table 1), which were then used to construct an age-depth model based upon linear interpolation between the neighbouring dates (Fig. 2c). In addition, the KTK2 age model was compared with the annually laminated sedimentary and high-resolution pollen records...
from Lake Sihailegwan (SHL: Fig. 1a) and dated by both varve-counting and 40 calibrated AMS dates (Stebich et al., 2009). The earlier studies suggested that the late-glacial–early Holocene shifts in vegetation and climate in the Lake Baikal region were broadly synchronous to the major oscillations in the oxygen isotope records from China (Tarasov et al., 2007a, 2009), reflecting changes in the Northern Hemisphere (NH) temperature and East Asian monsoon intensity (Yuan et al., 2004). For the first time a direct comparison of the high-resolution pollen records from both regions became possible.

The characteristic changes in the SHL pollen/climate stratigraphy (Stebich et al., 2009) were compared to the similar events in the KTK2 pollen record (Table 2). Both datasets show a good correspondence (Fig. 2c), suggesting the reliability of the KTK2 age model during the climatically unstable late-glacial interval. In particular, the onset of the Holocene interglacial conditions is well pronounced in both records and can be independently dated in the KTK2 core to ~11.65 kyr BP (pollen-based correlation with the LSH) and to ~11.68 kyr BP (AMS dates from KTK2).

3.2. Pollen extraction and microscopic analysis

The KTK2 core material was stored in plastic liners at the Institute of Geochemistry (Irkutsk) and sampled there for pollen analysis. A total of 212 samples comprising 1 cm³ of the wet sediment were taken with a 6-cm step, yielding an average temporal resolution of 220 years. A standard procedure was used to extract pollen, including HCl and KOH treatment, heavy-liquid separation and acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). Pollen and spores, mounted in glycerin, were counted under the light microscope with ×400–1000 magnification. Identification of the pollen and spores was performed using regional pollen atlases and the reference pollen collection (Tarasov et al., 2007a and references therein).

All samples were rich in pollen, permitting counting up to 1800 pollen grains per slide. The KTK2 pollen diagram (Figs. 3a and 4) was constructed using the Tilia/Tilia-Graph/TGView software (Grimm, 2004). Relative percentages for all terrestrial pollen taxa at each level were calculated from a terrestrial pollen sum taken as 100%. Percentages for aquatic and cryptogam taxa were calculated in relation to the total sum of counted pollen and spores. The diagram was subdivided into local pollen zones (PZ), using visual inspection supported by the results of biome score calculation described in the section below. This method takes into account the ecology of pollen-producing plants (Prentice et al., 1996) and does not entirely rely upon a statistical similarity between pollen assemblages composed of numerous taxa representing ecologically different plant functional types. Pollen zones were also defined using CONISS, which performs a stratigraphically constrained cluster analysis useful for zonation (for technical details see Grimm, 1987). In the CONISS analysis only terrestrial pollen taxa with values of 2% or greater and abrupt and short-term peaks were used as the basis for the pollen zones (PZ2, using visual inspection supported by the results of biome score calculation described in the section below. This method takes into account the ecology of pollen-producing plants (Prentice et al., 1996) and does not entirely rely upon a statistical similarity between pollen assemblages composed of numerous taxa representing ecologically different plant functional types. Pollen zones were also defined using CONISS, which performs a stratigraphically constrained cluster analysis useful for zonation (for technical details see Grimm, 1987). In the CONISS analysis only terrestrial pollen taxa with values of 2% or greater and appearing in more than one sample were considered (Gervais et al., 2002). Results obtained with different methods are shown in Fig. 3.

3.3. Quantitative vegetation reconstruction

The biome reconstruction method (Prentice et al., 1996) permits the objective assignment of pollen taxa to major vegetation types/
biomes on the basis of the bioclimatic tolerance, ecology and biogeography of pollen-producing plants. The method was successfully tested using extensive regional surface pollen datasets and applied to the last glacial–interglacial fossil pollen records from northern Eurasia (Edwards et al., 2000; Tarasov et al., 2000; Mokhova et al., 2009), from Lake Baikal (Tarasov et al., 2005, 2007a), and to the poorly-dated KTK1 record from Lake Kotokel spanning the past 15 kyr (Tarasov et al., 2009). In the present study all identified terrestrial pollen taxa from the KTK2 record were assigned to regional biomes using the biome-taxon matrix presented in Table 3.

A complementary approach (Williams et al., 2004), which combines satellite-based vegetation cover dataset (DeFries et al., 1999) and modern surface pollen dataset from northern Eurasia (Tarasov et al., 2007b) with the best modern analogue (BMA) approach (Guiot et al., 1989), was applied to the KTK2 pollen record in order to reconstruct changes in the woody cover. The test of the method demonstrated that pollen-based modern woody cover reconstructions and original satellite measurements match well in northern Asia, providing satisfactory estimates of percent variance explained and root mean square error (RMSE) for both the total woody cover ($r^2 = 0.77$, RMSE = 11.69) and the broadleaved ($r^2 = 0.66$, RMSE = 3.31), needle-leaved ($r^2 = 0.79$, RMSE = 10.23) woody cover fractions at modern pollen sites (see Tarasov et al., 2007b for the method evaluation and design). The robustness of the reconstruction for the past 15 kyr was ensured by comparison with the results obtained earlier for the KTK1 pollen record (Tarasov et al., 2009).

### 3.4. Diatom analysis and pH reconstruction

A total of 125 samples, sampled at 10-cm intervals, were prepared for diatom analysis using the standard hydrogen peroxide technique (Battarbee et al., 2001). Aliquots of evaporated suspensions were embedded in Naphrax. Counting of at least 300–600 diatom valves per sample along ten horizontal transects using the light microscope with phase-contrast oil immersion objectives at ×400–1000 magnification was possible for most of the samples. However, diatom valves were rare or not found at all in 28 samples from the glacial part of the record. Diatom concentrations ($\times 10^6$ valves per gram of air-dried sediment) and percentage diatom abundances (based on the total sum of all diatoms counted in each sample) were calculated. Diatom nomenclature followed Krammer and Lange-Bertalot (1986–1991) and AL:PE guidelines (Cameron et al., 1999). The AL:PE diatom–pH calibration dataset consists of surface-sediment diatom assemblages from 118 lakes and contains 530 taxa. The AL:PE training set is from high-altitude or high-latitude lakes in the Alps, Norway, Svalbard, Kola Peninsula, UK, Slovenia, Slovakia, Poland, Portugal and Spain.

The modern pH of Lake Kotokel water (about 7.0) fits within the AL:PE pH range (4.5–8.0) and the fossil diatom assemblages of Lake
Kotokel are generally well represented in the AL:PE dataset. Therefore, the AL:PE diatom–pH model was used for pH inferences (see Cameron et al., 1999 for the details of the AL:PE pH diatom model performance). The reconstruction was performed using the computer programme C2 ver. 1.5 (Juggins, 2007) using jack-knifed cross-validation. The second component in the Weighted Averaging Partial Least Squares (WAPLS) regression showed the best predictive performance (Table 4) and was used for pH reconstruction. The modern measured lake pH varies between 6.8 and 7.3 (Kuzmin, 1988) and the pH predicted by the AL:PE model is 7.8, implying that the model gives slightly overestimated values. The fossil diatom assemblages between 543 and 501 cm are dominated by *Ellerbeckia arenaria* and *E. arenaria* var. *teres*, which are both absent from the modern dataset. Therefore, the pH inferences between 543 and 501 cm solely rely on other fossil diatom taxa and samples between 543 and 501 cm provide poor analogues for pH reconstruction.

Detrended canonical correspondence analysis (DCCA) was used to estimate the overall species turnover measured in standard deviation (SD) units and to generate sample scores for axis 1, which provide an estimate of compositional change along a temporal gradient (ter Braak, 1986). The samples’ age was used as a sole environmental variable in DCCA. In DCCA, species data were square-root transformed, no rare species down-weighting was applied, and nonlinear rescaling and detrending by segments were used. DCCA was carried out using CANOCO 4.5 (ter Braak and Šmilauer, 2002). ZONE software (Juggins, 1991) was used to split the diatom diagram into stratigraphic zones.

**Fig. 4.** Simplified pollen percentage diagram of the KTK2 core (analyst E. Bezrukova). See Fig. 2a for the description of lithological units.

**Table 3**
Terrestrial pollen taxa identified in the KTK2 record (this study) and used in the biome and woody cover reconstructions (after Tarasov et al., 2000, 2009).

<table>
<thead>
<tr>
<th>Biome</th>
<th>Taxa included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra</td>
<td>Alnus fruticosa, Betula sect., Nanoe/Frictociceae, Cyperaceae, Ericales, Poaceae, Polemonium, Polygonum, Rumex, Salix, Saxifragaceae, Valeriana</td>
</tr>
<tr>
<td>Cold deciduous forest</td>
<td>Alnus, Betula sect., Alnus, Ericales, Larix, Pinus sylvestris (subgen. Diploxylon-type), P. sylvestris (subgen. Haploxylon-type), Salix</td>
</tr>
<tr>
<td>Taiga</td>
<td>Abies sibirica, Alnus, Betula sect., Alnus, Ericales, Larix, Picea obovata, Pinus sylvestris, P. sibirica (subgen. Haploxylon-type), Ribes, Salix</td>
</tr>
<tr>
<td>Cool conifer forest</td>
<td>Abies sibirica, Abies, Betula sect., Alnus, Ericales, Corylus, Larix, Picea obovata, Pinus sylvestris, P. sibirica (subgen. Haploxylon-type), Ribes, Salix, Ulmus</td>
</tr>
<tr>
<td>Steppe</td>
<td>Apiaceae, Artemisia, Asteraceae (incl. subfam. Asteroideae and Cichorioideae), Brassicaceae, Caryophyllaceae, Chenopodiaceae, Fabaceae, Lamiaeae, Liliaceae, Plantago, Poaceae, Polygonum, Ranunculaceae, Rosaceae, Rubiaceae, Rumex, Scrophulariaceae, Thalictrum, Urtica, Valeriana</td>
</tr>
<tr>
<td>Desert</td>
<td>Artemisia, Boraginaceae, Chenopodiaceae, Ephedra, Polygonum</td>
</tr>
</tbody>
</table>

**Table 4**
Apparent and predictive (jack-knifed) statistics for the AL:PE pH–diatom model applied to the fossil diatom data from Lake Kotokel.

<table>
<thead>
<tr>
<th>Performance statistics</th>
<th>pH WAPLS, 2nd component</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r^2$</td>
<td>0.928</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.203</td>
</tr>
<tr>
<td>Average bias</td>
<td>$-2.299e^{-0.005}$</td>
</tr>
<tr>
<td>Maximum bias</td>
<td>0.384</td>
</tr>
<tr>
<td>$r^2$ (jack-knifed)</td>
<td>0.789</td>
</tr>
<tr>
<td>RMSEP</td>
<td>0.349</td>
</tr>
<tr>
<td>Jack-knifed average bias</td>
<td>0.011</td>
</tr>
<tr>
<td>Jack-knifed maximum bias</td>
<td>0.734</td>
</tr>
</tbody>
</table>
was then established using the programme BSTICK (Bennett, 1996). Changes in DCCA sample scores on axis 1 were also used as an additional method of stratigraphic zone boundary identification. In the diatom percentage diagram (Fig. 6), the taxa were ordered according to their weighted average score, highlighting the diatom floristic changes. *Aulacoseira granulata* agg. includes *A. granulata* var. *angustissima*, and *Staurosira construens* agg. includes ecologically close subspecies, which have identical stratigraphic distribution in the KTK2 core (i.e. *S. construens* var. *construens*, *S. construens* var. *venter* and *S. construens* var. *binodis*). *Staurosirella pinnata* agg. includes *S. pinnata* var. *pinnata* and *S. pinnata* var. *lancetella* for the same reasons.

4. Results and interpretations

4.1. Pollen record and vegetation reconstruction

The pollen diagram (Fig. 4) is subdivided into eight local pollen zones (PZ) on the basis of changing pollen composition and variations in the dominant biome scores. A brief characteristic of the pollen/biome zones provided here aims to facilitate further discussion.

PZ KTK2-8 (1253–1000 cm; ~47–30 kyr BP) demonstrates high percentages of herbaceous and shrubby taxa, mainly *Artemisia* (30–50%) and *Betula* sect. *Nanae/Fruticosae* (up to 40%). Arboreal pollen percentages reach up to 20–30% in the lower (*Picea*) and upper (*Larix*, and *Pinus*) parts of this zone, but remain at 10%-level in the middle part. The biome reconstruction shows that steppe and tundra have the highest scores (Fig. 5b), and scores of the taiga biome are ~5–10, in line with the moderately low woody cover (~10%) around the lake (Fig. 5d). The vegetation was probably a mosaic of scattered trees and/or isolated forest stands, shrubby and herbaceous tundra communities occupying wetter habitats and dominant cold steppe communities.

PZ KTK2-7 (1000–850 cm; ~30–23 kyr BP) reveals the highest percentages of *Artemisia* (40–50%) and *Poaceae* (25–40%) and extremely low percentages of boreal tree and shrub pollen. The biome reconstruction demonstrates the highest scores for steppe (>20) and lowest taiga scores (Fig. 5), suggesting that cold steppe vegetation absolutely predominated in the region. However, the presence of arboreal pollen, even in very low percentages, and quantitative woody cover reconstruction do not support the total disappearance of cold/drought-tolerant boreal trees/shrubs from the vegetation.

PZ KTK2-6 (850–655 cm; ~23–14.5 kyr BP) reveals the highest percentages of *Artemisia* (up to 80%) in the lower part of this zone and a progressive increase in the tree/shrub pollen percentages (>40%) towards the uppermost part of this zone. The steppe remains the dominant biome, but the tundra communities once again start to play
a more important role. Both biome and woody cover reconstruction results point to a greater-than-present openness of the landscape around Lake Kotokel.

PZ KTK2-5 (655–540 cm; −14.5–12.65 kyr BP) demonstrates a sharp increase in arboreal taxa percentages, mainly Picea (20–50%), birch and alder shrubs (up to 40%). For the first time, taiga becomes the dominant biome, closely followed by tundra. Two peaks in woody cover percentages are reconstructed, −14 kyr (up to 25%) and −13 kyr BP (up to 35%), separated by an interval with lower woody coverage. The vegetation likely resembled the present-day boreal woodland/forest-tundra with a significant contribution of spruce, fir and larch trees and shrubs of alder, birch and willow.

PZ KTK2-4 (540–506 cm; −12.65–11.65 kyr BP) reveals a sharp decrease in arboreal taxa percentages and an increase in herbaceous taxa (up to 35%). Abies pollen is not recorded in this zone and pollen of shrubby birch almost replaces shrubby alder (Fig. 4). The quantitative reconstruction shows that the tundra becomes the dominant biome and suggests a decrease in the woody cover to −15%.

PZ KTK2-3 (506–422 cm; −11.65–10.6 kyr BP) reveals the dominance of arboreal taxa (mainly Betula – a well-known woody pioneer) and the return of Abies to the pollen assemblages. The biome reconstruction demonstrates equally high scores for the tundra and taiga biomes, suggesting a quick recovery of arboreal communities and boreal woodland vegetation around the lake, in line with the reconstructed increase in the total woody cover up to 40%.

PZ KTK2-2 (422–310 cm; −10.6–6.8 kyr BP) demonstrates a minimal contribution of herbaceous taxa to the pollen assemblages. The taiga scores are noticeably higher than the scores of non-forest biomes, suggesting well-established boreal forest in the region. The total woody cover increased to above 50% and exceeded present-day values.

PZ KTK2-1 (310–0 cm; −6.8–0 kyr BP) shows that Pinus is replacing Betula as the dominant taxon. This likely reflects change in the forest composition and the regional spread of Scots pine after 7 kyr BP. In this zone taiga scores are noticeably higher than the scores of non-forest biomes, but the woody cover decreases to its present-day level of −45%.

4.2. Diatom record and lacustrine environments

The fossil diatom assemblages of the KTK2 core from Lake Kotokel comprise 143 diatom taxa in total. The percentage diagram (Fig. 6) was divided into seven diatom zones (DZ). The reconstructed pH shows little change throughout the core, fluctuating around 8. No or very few (1–30 valves) diatoms occurred at 1149.5, 1087.5, 1025–880, 865.5, 823.5 and 810–718 cm (Fig. 6), eliminating these samples from further analyses.

DZ KTK2-7 (1240–1069 cm; −46–34.6 kyr BP) is dominated by small benthic Staurosirella pinnata agg., Staurosira construens agg., Pseudostaurosira brevistriata and Ophephora martyi. The latter is particularly abundant in the lower and upper parts of this zone. A few planktonic species, Cyclotella bodanica and Cyclotella ocellata and meroplanktonic, heavily silicified Aulacoseira ambigua, reach their highest abundance in the middle of the zone and disappear in the upper part of the zone. Total diatom concentration (TDC) reaches its highest values (>100×10^6 valves g^-1) in the lower-middle part of the zone and then quickly decreases. DCCA axis 1 sample scores slightly increase throughout the zone (Fig. 6), tracking the overall modest floristic changes in the diatom assemblages. The dominance of pioneer benthic diatom taxa (e.g. Staurosirella pinnata agg. and Ophephora martyi) is typical of early stages of lake development. These taxa are commonly found in many post-glacial lakes and in late-glacial lacustrine sediments (Haworth, 1976; Smol, 1983; Solovieva and Jones, 2002; Finkelstein and Gajewski, 2008) and at present in many arctic and subarctic lakes with a short open-water season (Smol, 1988; Lotter and Bigler, 2000; Smol and Douglas, 2007).

Regionally, small Fragilariaefl-dominated diatom assemblages occurred throughout the Holocene in a small lake from the Altai Mountains, central Siberia (Westover et al., 2006) and in the early Holocene in a large deep-water lake from the Mongolian Altai (Rudaya et al., 2009). Diatom assemblages suggest a turbulent and turbid environment implying strong winds and a high level of erosion. These taxa are indicators of disturbed environmental conditions, as they survive today in harsh arctic environments with low light penetration where other more sensitive taxa would not succeed (Smol, 1988). The lake level was high enough to sustain well-established planktonic species at 10–20% abundance. The increase in two small planktonic Cyclotella species in the middle of the zone at the expense of heavily silicified Aulacoseira ambigua and small benthic Pseudoaustrosira brevistriata and Ophephora martyi might imply a slight amelioration of climate. The 20th century climate warming was found to be the most plausible mechanisms underlying the replacements of, for example, the larger and heavier Aulacoseira taxa and/or small benthic Fragilaria taxa by smaller planktonic Cyclotella taxa in many arctic, subarctic and temperate lakes (Ruhland et al., 2008, Winder et al., 2009).

DZ KTK2-6 (1069–1025 cm; −34.6–31.5 kyr BP). In this zone Ophephora martyi, Staurosira pinnata agg. and Staurosira construens continue to decline. Cyclotella ocellata, C. bodanica and Aulacoseira ambigua, which made a brief appearance in the middle of the previous zone, are replaced by planktonic Aulacoseira subarctica (max 20%) and A. islandica (max 36%). Both A. subarctica and A. islandica are heavier and more silicified taxa compared to small and light Cyclotella and they require high water turbulence to maintain their position in the water column and usually prevail during spring/autumn water turnover periods (e.g. Ruhland et al., 2008; Solovieva et al., 2008). This implies that the lake environment might have changed either by shortening the summer period of stratified water, when Cyclotella has the competitive advantage, or by increasing the spring/autumn period of water turbulence. Both changes suggest climate cooling and the extension of the ice-cover season. TDC remains low, fluctuating between 0.16 and 22.73×10^6 valves g^-1. DCCA sample scores increase, reaching the highest values (2.3) for the whole core. Diatoms do not occur between 31.5 and 24.2 kyr BP suggesting particularly harsh lake conditions.

DZ KTK2-5 (880–810 cm; −24.2–21.9 kyr BP) shows the disappearance of meroplanktonic and heavily silicified diatoms (Aulacoseira subarctica and A. islandica), a considerable decrease in the abundance of Ophephora martyi and the almost complete dominance of the Staurosirella pinnata agg. complex, which may survive harsh environmental conditions where other diatom taxa would not succeed (e.g. Smol, 1988). TDC remains low. DCCA samples scores decrease in DZ3 to 0.71 on average. These dramatic changes in the diatom assemblages might have resulted from some catchment disturbance or/and a particularly cold/dry climate between 31.5 and 24.2 kyr BP, when almost no diatoms were found. As in earlier intervals diatoms were also extremely rare or totally absent between 810 and 718 cm (−21.9–16.9 kyr BP), indicating conditions unfavourable for diatom development.

DZ KTK2-4 (718–550 cm, −16.9–12.7 kyr BP) follows another disturbance episode coinciding with the LGM, during which almost no diatoms occurred in the lake. This zone reveals the first occurrence of planktonic Aulacoseira granulata, a heavy silicified diatom, which is typical for plankton of large eutrophic and mesotrophic lakes and reservoirs (e.g. Fluin et al., 2010; Ohtaka et al., 2010). Cyclotella ocellata (max 35%) and Aulacoseira ambigua (max 34%) are two other co-dominant planktonic species in this zone, which made a brief occurrence in the middle of DZ KTK2-7. The re-occurrence of small Cyclotella taxa might again indicate climate amelioration and a longer open-water season (e.g. Ruhland et al., 2008). A progressive increase in the abundance of planktonic Cyclotella diatoms is accompanied by a pronounced decrease in benthic species (Fig. 6). Amphora perpusilla,
the periphytic diatom, occurs exclusively in this zone, first reaching 11% and then decreasing to 3%. Similar to DZ KTK2-7, C. ocellata abruptly disappears in the upper part of the zone replaced by A. ambigua, implying possible deterioration of climate and shortening of the open-water season. TDC peaks in the middle of the zone, reaching $156.3 \times 10^6$ valves g$^{-1}$. It decreases to $19.1 \times 10^6$ valves g$^{-1}$ towards the end of the zone implying an abrupt decline in diatom productivity. This decrease is concomitant with the decrease in Cyclotella ocellata and also might suggest deteriorating environmental conditions, in particular, colder climate. DCCA sample scores range between 0.5 and 0.7 throughout the zone. The occurrence and subsequent dominance of planktonic eutrophic/mesotrophic Aulacoseira granulata, together with relatively high abundances of Cyclotella ocellata in the middle of the zone and two peaks of A. ambigua, suggest that the nutrient status of the lake changed. It is likely that following deglaciation catchment erosion increased, which led to decreased water transparency and light penetration and, therefore, a sharp decrease in benthic species and the dominance of the above Aulacoseira taxa.

DZ KTK2-2 (495–130 cm; ~11.6–4 kyr BP) shows continuing dominance of Aulacoseira granulata (45–98%). Staurosira construens is another dominant taxon at some levels with abundances between 2 and 40%. Both Ellerbeckia arenaria var. arenaria and Ellerbeckia arenaria var. teres abruptly decrease down to very low numbers, similarly to Pseudostaurosira breviatriata, Ophephora martyi and Staurosirella pinnata agg. TDC fluctuates frequently between $13.3 \times 10^6$ and $136.5 \times 10^6$ valves g$^{-1}$. DCCA sample scores remain almost unchanged at about 0.45 on average. The diatom assemblages of this zone suggest mesotrophic/eutrophic environments, indicated by dominance of Aulacoseira granulata, a relatively heavy diatom with thick siliceous frustules, which is common in the large lakes, water reservoirs, and rivers with a relatively high nutrient content (e.g. Kilham and Kilham, 1975; Margalef, 1983; Kuzmin, 1988; Gómez et al., 1995; Fluin et al., 2010; Ohtaka et al., 2010). Similarly to other Aulacoseira taxa from Lake Kotokel, it usually peaks during spring/autumn water turnover periods, requiring high water turbulence to maintain its position in the water column (Gómez et al., 1995). The reasons behind the abrupt disappearance of Ellerbeckia are unclear.
Most likely it implies that the catchment erosion decreased, and nutrient supply to the lake increased and these favored development of competing diatom taxa, namely *Aulacoseira granulata*.

DZ KTK2-1 (130–0 cm; –4–0 kyr BP) differs from the previous zone by a slight decrease in *Aulacoseira granulata*, *Staurosira construens* agg. and *Pseudostaurosira brevistriata*, the reappearance in notable abundances of *Ellerbeckia arenaria var. teres* (up to 11%), and the total disappearance of *Staurosirella pinnata* agg. TDC remains at a similar level to DZ6, and DCCA sample scores slightly increase compared to the previous zone. The further reduction in benthic and periphytic diatom taxa and the thriving planktonic community imply a possible increase in water depth or decrease in water transparency/light penetration, which affected the benthic taxa by reducing their habitat availability. Higher values of *Staurosira construens* agg. compared with other Fragilariaceae might imply warmer climate conditions (e.g. Finkelstein and Gajewski, 2008).

5. Discussion and conclusions

The KTK2 pollen and diatom records span a ~47-kyr interval, which includes the middle glacial interstadial conventionally attributed to the marine isotope stage 3 (MIS3), the last glacial maximum (LGM) followed by the late-glacial climate amelioration (MIS2) and the Holocene interglacial (MIS1). In this section changes in the pollen and diatom assemblages are discussed in terms of the late Quaternary climate dynamics in the Lake Baikal region of southern Siberia.

5.1. The MIS3 interstadial (~47–30 kyr BP)

The MIS3 interstadial was identified in the palaeorecords from NH and conventionally dated to ~35–25 ka 14C kyr BP (~40–30 kyr BP) (Frenzel et al., 1992). The KTK2 pollen record and quantitative vegetation reconstruction suggest the predominance of tundra-steppe communities with *Artemisia*, Poaceae and Cyperaceae and a moderately low, but variable woody cover (5 to 20%) during ~47–30 kyr BP, reflecting generally harsh and unstable climatic conditions. Boreal tree and shrub taxa could grow continuously in the locally moist habitats, expanding rapidly during the intervals of interstadial-like climate amelioration (e.g. ~45–42 and ~35–31 kyr BP), and shrinking in their distribution areas with the onset of the cold/dry stadial-like climate (e.g. prior to ~45 and ~42–35 kyr BP). A relatively short peak in *Cyclotella ocellata*, *C. bodanica*, and *Aulacoseira ambigua* and the corresponding peak in TDC between 45 and 42 kyr BP corroborates a response of the lake system to climate amelioration. Interestingly, another warm event at ~35–31 kyr BP is not as clearly reflected by the lake diatom assemblages. A distinct *Picea* pollen maximum in the KTK2 record at ~45–43 kyr BP allows a more precise allocation of the similar event found in the low-resolution and poorly-dated pollen record from Lake Baikal (Shichi et al., 2007). It is broadly synchronous with the larch woodland development in the Indigirka Lowland, northeastern Siberia, ~45 kyr BP (Anderson and Lozhkin, 2001), the formation of the black soil in western Siberia (Frenchen et al., 2005), and the increased diversity and abundance of testate amoebae in the MIS3 interstadial sediments on the Laptev Sea coast (Müller et al., 2009).

The KTK2 diatom record suggests relatively deep oligo-mesotrophic environments in Lake Kotokel prior to ~31.5 kyr BP, in line with the pollen-based interpretation. A pronounced decrease in the diatom concentration recorded after ~42 kyr and after ~32 kyr BP likely indicates two major steps in climatic deterioration during the MIS3.

5.2. The full glacial (~30–17 kyr BP)

The full glacial occurs in the KTK2 pollen record at ~30–17 kyr BP and is marked by an increase in herbaceous taxa percentages, the highest scores for steppe and the lowest scores for taiga biome, suggesting an increased aridity/continentality of the regional climate and the predominance of open herbaceous communities in the landscape. The noticeable decrease in diatom concentrations followed by the virtual disappearance of diatoms from the KTK2 sediment (laminated grey silty clay) at ~31.5–17 kyr BP might be another indicator of the dry and cold climate with strongly pronounced seasonality. A similar dramatic reduction in diatom abundance occurred in Lake Baikal during periods of climate deterioration during the MIS3 interstadial (Swann et al., 2005; Mackay, 2007). The peak in cryptogam spore percentages (mainly *Equisetum*) recorded at ~31–30 kyr BP suggests that the coastal horsetail-covered zone became closer to the KTK2 coring site than before. The highest percentages of *Ranunculaceae* pollen at ~30–23 kyr BP further support a shift of meadow/wetland communities closer to the coring point, suggesting that Lake Kotokel was much smaller in size than today during this probably the driest interval of the whole record.

The reappearance of diatoms in small quantities might be a sign of a slight amelioration of the regional climate at ~24–22 kyr BP, which might have influenced the aquatic ecosystem of a small lake, but was not strong enough to cause visible changes in the KTK2 core lithology and pollen assemblages/terrestrial vegetation. Both herb/grass-dominated pollen assemblages, the absence of aquatic macrophytes and the sporadic presence of diatoms in the KTK2 records at ~22–17 kyr BP point to a second phase of climate deterioration, conventionally associated with the LGM.

5.3. The late-glacial (~17–11.65 kyr BP)

A gradual increase in tree/shrub pollen percentages after ~18 kyr BP and changes in the diatom and lithology records after ~17 kyr BP indicate the late-glacial climate amelioration in the region. Particularly noticeable changes suggested by the KTK2 proxies and proxy-based environmental reconstructions occurred at ~14.7–12.7 kyr BP. At that time the regional climate became warmer and wetter than during the MIS3 interval, although it did not yet reach the Holocene levels. These changes resulted in the spread of forest vegetation (increase in the woody cover percentages up to 20–30%), and a possible increase in lake level/water depth due to the melting of the mountain glaciers, thawing of the permafrost active layer and increase in atmospheric precipitation (Bezrukova et al., 2005). The increase in small planktonic *Cyclotella ocellata* also suggests climate amelioration (Winder et al., 2009). Recorded increases in arboreal pollen percentages and associated peaks in taiga scores and woody cover percentages indicate that trees could have quickly spread out of their glacial refugia at least twice during the late-glacial interval, corroborating with the results obtained from the poorly-dated KTK1 core (Tarasov et al., 2009). This study allows a more accurate dating of the woodland intervals to ~14.5–14 kyr and 13.3–12.8 kyr BP. Chronological comparison of vegetation/environmental changes around Lake Kotokel with the European records (Sirocko, 2009 and references therein) puts the later phase within the Allerød interstadial (13.58/13.35–12.7/12.68 kyr BP), in line with other palaeobotanical records from northern Asia (e.g. Andreev and Tarasov, 2007), the Lake Baikal region (e.g. Demske et al., 2005; Bezrukova et al., 2008; Shichi et al., 2009) and northeastern China (Steich et al., 2009). The earlier phase of forest development seems to be an analogue of the Meindorf interstadial (14.7–14.05/13.8 kyr BP, Sirocko, 2009), which until now was not distinguished in the lower-resolution pollen records from the Lake Baikal region and is likely interpreted as a part of the undifferentiated Bølling/Allerød interstadial complex (e.g. Bezrukova et al., 2005; Demske et al., 2005; Shichi et al., 2009). There is no clear evidence for the short-lived Bølling event (13.67–13.58/13.54 kyr BP, Sirocko, 2009) in the KTK2 records, probably because resolution is not high enough.

The pollen and diatom records from Lake Kotokel (e.g. decrease in woody cover, increase in tundra biome scores and marked changes in
the diatom assemblages) clearly identify the YD stadial in the Lake Baikal region. The KTK2 age model allocates it within ~12.7–11.7 kyr BP. The YD climate reconstructions suggest lower than present temperatures (by 2–4 °C in July and by 8 °C in January) and lower precipitation (by 100 mm/yr) around Lake Baikal (Tarasov et al., 2007a, 2009). Very low diatom concentrations and disappearance of small ‘warm’-water planktonic Cyclotella ocellata from the KTK2 sediment might imply climate deterioration and shortening of the open-water season. Predominance of Ellerbeckia arenaria var. arenaria implies increased amounts of glaciogenic sediments, higher erosion and a turbid water regime during the YD (Hickman and Reasoner, 1994). Frustules of finer and thinner diatoms, for instance, small Fragilariaceae, might not have been well-preserved in the highly minerogenic sediments, whereas robust and thick Aulacoseira granulata and Ellerbeckia arenaria might have a better chance to be preserved in the lake sediments and therefore might be over-represented in the fossil record. Overall, it is obvious from the KTK2 records that the YD event clearly affected the regional environments. However, the YD climate remained warmer and wetter than at any time between ~47 and 17 kyr BP.

5.4. The Holocene (11.65 kyr BP – present)

The Holocene vegetation and climate dynamics in the region under study was recently reconstructed from the KTK1 pollen record (Tarasov et al., 2009). The chronological sequence of environmental change reconstructed from the KTK2 records shows great similarity with the previous study. The shift to Holocene environments appears in the KTK2 diatom and pollen records at ~11.7–11.65 kyr BP, suggesting an almost synchronous response of terrestrial and aquatic ecosystems to the global climate change. The KTK2 date agrees with the formal definition and dating of the Global Stratotype Section for the base of the Holocene (~11.650 cal yr BP), derived from the Greenland NGRIP ice core and selected regional records (Walker et al., 2009), suggesting a synchronous onset of the Holocene interglacial across Eurasia. Results of pollen analysis and pollen-based biome and woody cover reconstructions from the KTK2 core correlate well with the KTK1 results (Tarasov et al., 2009), demonstrating that a boreal woodland spread around Lake Kotokel at ~11.65–10.5 kyr BP in response to a noticeable increase in precipitation and in winter and summer temperatures. The maximal spread of the boreal forest (taiga) communities is associated with higher-than-present July (17–18 °C) and January (~19 °C) temperatures and precipitation (500–550 mm/yr), reconstructed at ~10.5–7 kyr BP (Tarasov et al., 2009). The pollen-based reconstruction of a slight decrease in woody cover around Lake Kotokel (~7–6.5 kyr BP) likely indicates a gradual decrease in precipitation and temperatures towards their present-day values. A noticeable increase in Pinus sylvestris pollen recorded after ~7 kyr BP reflects the spread of Scots pine in the Lake Baikal region (Demskie et al., 2005; Bezrukova et al., 2008; Shichii et al., 2009), in line with the onset of drier and colder (similar to present) climate. The changes in diatom assemblages support these pollen-based reconstructions. The absolute dominance of meroplanktonic Aulacoseira granulata (maximum ~11.6–10 kyr BP), disappearance of Ellerbeckia arenaria var. arenaria by ~11.6 kyr BP and reappearance of benthic taxa suggest establishment of deep- and transparent-water environments already in the early Holocene. Although this system remained rather stable throughout the Holocene, minor changes in the diatom assemblages likely indicate gradual natural enrichment of the lake after ~7 kyr BP.

5.5. Factors controlling the late Quaternary environmental dynamics in the Lake Baikal region

The Lake Kotokel records contribute to the continuous debate concerning the degree of climate amelioration and the chronological framework of the MIS3 interstadial in Siberia (e.g. Anderson and Lozhkin, 2001; Kienast et al., 2005; Muller et al., 2009). Frenzel et al. (1992) reconstructed a colder (by 6–8 °C in winter and by 4–5 °C in summer) and drier (by 100–200 mm/yr) than present interstadial climate in Siberia at ~40–30 kyr BP. Other authors (e.g. Shahgedanova, 2002 and references therein) suggested that it could have been regionally (e.g. in western Siberia) warmer than the present. The palaeobotanical (Hubberten et al., 2004; Kienast et al., 2005) and isotopic studies (Tütken, 2003; Popp et al., 2006) in the arctic parts of eastern Siberia led to the reconstruction of an extreme-continental climate, characterised by low precipitation, mean annual and winter temperatures, but relatively high summer temperatures and/or a longer snow-free period compared to today. The discontinuous pollen data from northeastern Siberia were used to infer a regional climate similar to the present (~43.2–37.5 kyr BP, but colder/drier-than-present environments prior to and after this interval (Anderson and Lozhkin, 2001). The KTK2 records presented here point to a drier/colder-than-present late Pleistocene climate in the southern part of eastern Siberia even during the interstadial episodes of climatic amelioration that are visible, for example, in the taiga (maxima) and steppe (minima) biome scores (Fig. 7d). The reconstructed pattern of changes in the regional environments demonstrates that the late Pleistocene climate dynamics in southern Siberia were more complex than previously thought, and resemble the temperature variations (e.g. Greenland interstadials and Heinrich events) expressed in the δ18O record from Greenland ice (Fig. 7a) and the East Asian Monsoon intensity signal in the δ18O record from Chinese stalagmites (Fig. 7e). Minor inconsistencies could be explained by the lower accuracy of the KTK2 age model and the lower resolution of the KTK2 record in comparison to the above δ18O records. Wang et al. (2001) demonstrated that the isotope records from Hulu Cave near Nanjing and from Greenland ice cores bear a remarkable resemblance, suggesting that the intensity of the summer Pacific monsoon, which brings moisture to the eastern part of Asia, changed in accordance with North Atlantic temperatures between 75 and 11 kyr BP. Evidence for climatic teleconnections between Europe and Lake Baikal during MIS3 was discussed by Swann et al. (2005) and Mackay (2007). The Lake Kotokel records presented here link changes in the North Atlantic and North Pacific climate, which are responsible for the sub-latitude transport of heat and moisture to the central parts of Eurasia.

Further comparison of the KTK2 records with orbitally-induced insolation variations (Fig. 7b) and with the global sea level reconstruction (Fig. 7c) suggests that the phase with the maximal spread of cold steppe communities and minimal representation of woody taxa in the regional vegetation (Fig. 7d) occurred during the interval, when the NH summer insolation and global sea level reached their minima, with the global ice volume consequently reaching its maximum. The records summarized in Fig. 7 and the KTK2 diatom record imply that the LGM in the Lake Baikal region and probably on the global scale should be placed at ~25–24 kyr BP and not ~21 kyr BP, as conventionally used in the palaeoenvironmental studies (e.g. Tarasov et al., 2000; Yokoyama et al., 2000; Clark et al., 2006) and in modelling experiments (e.g. Kageyama et al., 2001). Our conclusion based upon the Lake Kotokel data is in line with the growing body of evidence from elsewhere that suggests an earlier onset of the LGM (e.g. Allen and Huntley, 2000; Peltier and Fairbanks, 2006; Genty, 2008, Veres et al., 2008; Sirocko, 2009).

The relatively high temporal resolution and reliable AMS-based age model of the KTK2 pollen record enable its comparison with the reference palaeoclimatic archives representing North Atlantic (e.g. Litt and Stebich, 1999; Brauer et al., 2008; Svensson et al., 2008; Sirocko, 2009) and North Pacific regions (Yuan et al., 2004; Stebich et al., 2009). This comparison suggests that the reconstructed shifts in late Pleistocene–Holocene vegetation and environments in the Lake Baikal region could have been controlled by the major factors controlling NH climate (Fig. 7). The correspondence between the KTK2 record and very high-resolution isotope and pollen records from far distant North
Atlantic and North Pacific regions implies that southern Siberia, despite its location in the interior of the Eurasian landmass, responded swiftly to global change. This conclusion is a key point in the ongoing debate on the synchronic/non-synchronic environmental dynamics of terrestrial environments within the Lake Baikal region during the last 15 kyr, based upon less accurately dated pollen records (see Demske et al., 2005; Shichi et al., 2009 for discussion and references).

Moreover, in the current absence of better-resolved and dated sequences, the KTK2 core from Lake Kotokel may serve as a regional stratotype section (Bezrukova et al., 2008), which allows one to revisit the chronologies of the earlier published pollen/environmental records from the Lake Baikal region and possibly reconsider some of the earlier interpretations.

Acknowledgements

This paper is a contribution to the German Research Foundation (DFG) project TA-540/1. The study was also partly supported by the Russian Foundation for Basic Research (RFBR) project 09-05-00123. We would like to acknowledge Prof. H. Takahara and all team members for participating in the coring campaign at Lake Kotokel in 2005, Prof. T. Goslar (Poznan, Poland) for the AMS dating of the KTK2 samples, and Dr. E. Schalk for polishing the English. We are grateful to Prof. J.P. Smol, Dr. K. Kremenetski and Prof. A.P. Kershaw for their thorough review, which helped to improve the manuscript. The authors like to acknowledge fruitful discussions of the results presented in the current study during the RFBR- and DFG-sponsored (TA-540/4) International Workshop "Bridging Eurasia" (Freie Universität Berlin, April 28–May 2 2010). The paper is dedicated to Natalia V. Ignatova, who passed away in August 2008.

References
