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Holocene environments and climate in the Mongolian Altai reconstructed from the Hoton-Nur pollen and diatom records: a step towards better understanding climate dynamics in Central Asia

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A B S T R A C T

This study presents the results of the palynological and diatom analyses of the sediment core recovered in Hoton-Nur Lake (48°37′18″N, 88°20′45″E, 2083 m) in 2004. Quantitative reconstruction of the Holocene vegetation and climate dynamics in the semiarid Mongolian Altai suggests that boreal woodland replaced the primarily open landscape of northwestern Mongolia at about 10 kyr BP (1 kyr = 1000 cal yr) in response to a noticeable increase in precipitation from 200–250 mm/yr to 450–550 mm/yr. A decline of the forest vegetation and a return to a predominance of open vegetation types occurred after 5 kyr BP when precipitation sums decreased to 250–300 mm/yr. Prior to 11.5 kyr PB diatom concentrations are relatively low and the lake is dominated by planktonic *Cyclotella* and small Fragilariaceae, suggesting the existence of a relatively deep and oligotrophic/mesotrophic lake. The great abundance of *Staurosirella pinnata* from the beginning of the record until 10.7 kyr BP might imply intensified erosion processes in the catchment and this is fully consistent with the presence of scarce and dry vegetation and the generally arid climate during this period. From about 10.7 kyr BP, more planktonic diatom taxa appeared and increased in abundance, indicating that the lake became more productive as diatom concentration increased. This change correlates well with the development of boreal woodland in the catchment. Decrease in precipitation and changes in the vegetation towards steppe are reflected by the rapid increase in *Aulacoseira distans* from about 5 kyr BP. The Holocene pollen and diatom records do not indicate soil and vegetation cover disturbances by the anthropogenic activities, implying that the main transformations of the regional vegetation occurred as a result of the natural climate change. Our reconstruction is in agreement with the paleomonsoon records from China, demonstrating an abrupt strengthening of the summer monsoon at 12 kyr BP and an associated increase in precipitation and in lake levels between 11 and 8 kyr BP, followed by the stepwise attenuation of the monsoon circulation and climate aridization towards the modern level. The records from the neighboring areas of Kazakhstan and Russia, situated west and north of Hoton-Nur, demonstrate spatially and temporally different Holocene vegetation and climate histories, indicating that the Altai Mountains as a climate boundary are of pivotal importance for the Holocene environmental and, possibly, habitation history of Central Asia.

1. Introduction

Mongolia lies in the centre of Asia. It comprises an area of 1.566×10^6 km^2 and has an average population density of less than two people per square kilometer. Mongolia experienced a peak in

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the paleoenvironmental studies during the 1970s–80s when radiocarbon-dated sedimentary records from over twenty lakes and key sequences were published in Russian (see Gunin et al., 1999 for detailed summary). During the past ten years a few publications reporting new results of paleoenvironmental studies have appeared in English (Grunert et al., 2000; Peck et al., 2002; Fowell et al., 2003; Miehe et al., 2007; Prokopenko et al., 2007; Schlütz et al., 2008).

The current study is primarily focused on Hoton-Nur (also known as Khoton Nuur), a large fresh-water lake in the Mongolian Altai (Fig. 1). The lake was first cored in 1980 and the core sediments were radiocarbon dated and coarsely analyzed for pollen and diatoms (Tarasov et al., 1994). These records indicate an amelioration of the regional climate in the early-mid-Holocene and a shift towards drier environments during the late Holocene (Gunin et al., 1999; Tarasov et al., 2000). Such pattern resembles climatic change reconstructed in monsoonal China, but is notably different from that recorded in the regions controlled by the Atlantic air masses (Tarasov et al., 2007b).

The Altai Mountains with elevations above 4500 m and an extension of more than 1200 km is the most prominent sub-longitudinal mountain range in Central Asia. The northwest part of the range (also known as the Russian Altai or simply the Altai) merges with the Sayan Mountains in the east and with the Mongolian Altai in the south. From the northwestern corner of Mongolia the range extends southeast, where it gradually becomes lower and finally merges into the high plateau of the Gobi Desert. The location of the Altai Mountains in the centre of Asia at the

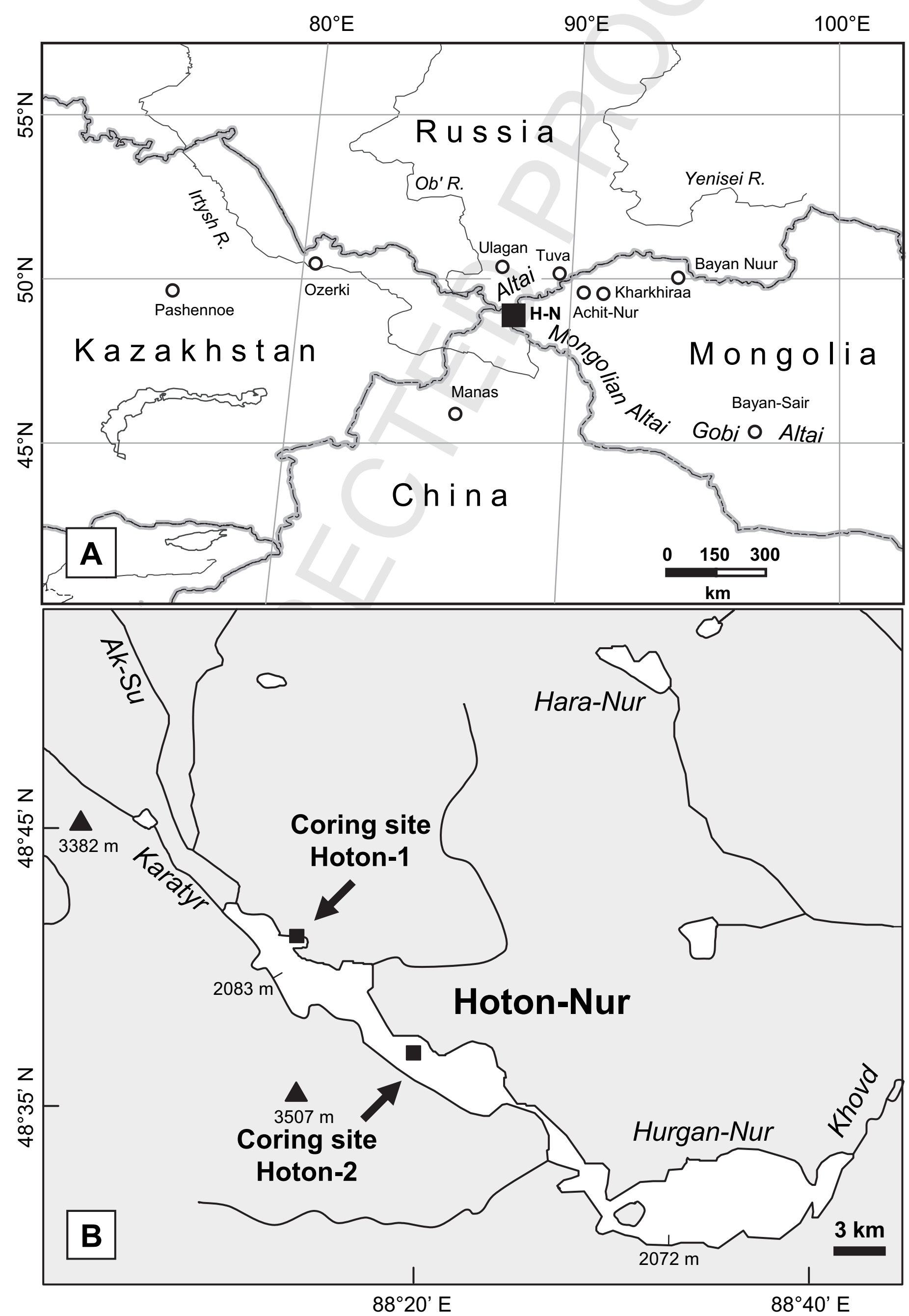

Fig. 1. Map of Central Asia (A) and the region around Hoton-Nur with locations of the analyzed pollen and diatom records (B).

limits of both Pacific and Atlantic influences implies that this mountain system is an important climatic boundary in Central Asia, and thus requires careful investigation.

In this paper we present (i) the results of the fine-resolution palynological and diatom analyses of the sediment core recovered from Hoton-Nur in 2004; (ii) quantitative reconstructions of the Holocene lacustrine environments, vegetation and climate; further, (iii) we interpret these new results in terms of the regional environmental dynamics in the Mongolian Altai, and (iv) discuss them together with the environmental records from the neighboring regions of Kazakhstan, Russia and China.

2. Regional setting

Hoton-Nur (48°40′N, 88°18′E, 2083 m) is situated in the intermountain depression in the sparsely populated northern part of the Mongolian Altai (Fig. 1). The lake has an area of 50 km^2 with a maximum water depth of 58 m (see Tarasov et al., 1994 for details and references). It has inflow from the rivers Karatyr, Ak-Su and several small streams and outflow southward to Hurgan-Nur and further to the Khovd River. Geomorphological and geological investigations suggest that the formation of the Hoton-Nur basin occurred during the late Pleistocene, when the valley was dammed by the end moraine deposits of the mountain glaciers. Earlier studies suggest that during the late Pleistocene mountain glaciers extended to lower elevations than they do at present, but, because of the dry climate, did not occupy large areas in the region. However, the history of the Pleistocene glaciation in the Mongolian Altai is still not satisfactorily understood (Gunin et al., 1999).

The climate around Hoton-Nur is characterized by long, cold, dry winters and short, cool, relatively wet summers (National Atlas, 1990). Mean temperatures vary between −20 and −25 °C in January and are about 12–15 °C in July. Mean annual precipitation (P_{ann}) is around 250 mm at the lake level, reaching 300 mm at elevations above 3000 m. The bioclimatic variables calculated by a weighted distance interpolation method applied to the global meteorological dataset representing the 1961–1990 observation Q2 interval (Leemans and Cramer, 1991) are −20 °C for mean January (coldest month) temperature (T_c), 14 °C for mean July (warmest month) temperature (T_j) and 0.45 for moisture index (α—ratio of actual over potential evapotranspiration sensu Prentice et al., 1992), corresponding to the present-day cool steppe biome (Tarasov et al., 2000).

Modern vegetation distribution in the Mongolian Altai reflects its cold and semi-arid climate modified by the altitude and slope orientation (Volkova, 1994). In the lower alpine belt (~3000 m) vegetation is dominated by shrubby birch (*Betula rotundifolia*) and northern willow (*Salix glauca*), grasses and sedges. Steppe communities generally occur in the elevation belt between 1800 and 2400 m, but may penetrate up to 3200 m a.s.l. In the eastern and northern parts of the Hoton-Nur basin cold-tolerant steppe vegetation is widespread and often intercalated with kobresian and sedge communities. Semi-desert vegetation grows in the dry isolated intermountain basins. A narrow and discontinuous forest belt dominated by larch (*Larix sibirica*) and spruce (*Picea obovata*) occurs in the western and north-western part of the Mongolian Altai at the altitudes of 1900–2000 m a.s.l. *L. sibirica* open stands were described north of Hoton-Nur and in the upper part of the Ak-Su River valley (National Atlas, 1990; Volkova, 1994) and closest *P. obovata* stand is located 50 km north of the lake. Pollen of a few other tree taxa was identified in the Hoton-Nur record, including Siberian pine (*Pinus sibirica*), Scots pine (*P. sylvestris*) and fir (*Abies sibirica*). The nearest to Hoton-Nur *P. sibirica* woods grow about 50 km north of the lake in the Tsagan-Gol and Ak-Su River valleys. *P. sylvestris* and *A. sibirica* distribution areas do not reach the Mongolian Altai (National Atlas, 1990; Gunin et al., 1999) and are restricted to the Russian and Kazakh parts of the Altai Mountains (Alpat'ev et al., 1976; Ogureeva, 1980).

The area of the Olgiy Aymag, where Hoton-Nur is located, is home to about eighty thousand people (National Atlas, 1990). The traditional life style of the local population is nomadic and animal breeding is the main occupation. Present-day anthropogenic pressure on the ecosystems may reach the moderate to high level in the river valleys and in the coastal area around Hoton-Nur mainly due to overgrazing (Ecosystems of Mongolia. Atlas, 2005). Q1

3. Data and methods

3.1. Coring and lithology

In August 2004, the 257 cm long sediment core (Hoton-2) was recovered from 32 m depth in the southeastern part of Hoton-Nur (48°37′18″N, 88°20′45″E, Fig. 1b). Coring was carried out by a gravity corer of 100 mm diameter with a blade catcher. The recovered core consists of compact inorganic gray-blue clay (below 205 cm) and striate gray clay and silt (above 205 cm) with a touch of organic matter (Fig. 3). A sharp boundary between the two units may point to a sedimentary hiatus. However, such suggestion requires further proof. The grain-size analysis of the core material performed with a 0.5 cm step shows very little variations in the median diameter of the sedimentary particles (Fig. 3). Quartz, feldspar, light and brownish mica are identified in the mineral composition of the core. The sediment composition shows a slight change towards an increase in the contents of Fe_2O_3, TiO_2 and MgO and a slight decrease in SiO_2 and magnetization between 185 and 150 cm. Gradual changes in the vegetation cover and/or in availability of the eroded moraine sediments in the lake catchment area can both be invoked to explain these minor lithological changes.

3.2. Radiocarbon dating and age–depth model

Small organic remains from the Hoton-2 core were hand-picked and for accelerator-mass spectrometer (AMS) dating. The analysis of six samples among them showed not enough material for the dating. Among the remaining four samples (Table 1), two demonstrated ages exceeding the limit of the ^{14}C method. The older ages are related to the scarcity of the organic material and reworked character of the found non-identifiable particles. The sample from 236.5–237 cm depth was dated to 32,450 ± 380 ^{14}C yr BP, suggesting that the lower clay unit accumulated during the late Pleistocene. Alternatively, this date could be also interpreted as being too old. The date 9130 ± 40 ^{14}C yr BP obtained for the

Table 1
AMS and conventional ^{14}C dates from the Hoton-2 (this study) and Hoton-1 (Tarasov et al., 2000) core sediments.

Core depth, cm	^{14}C ages (^{14}C yr BP)	Calibrated ^{14}C ages (cal yr BP)	Laboratory no.
Hoton-2 core			
49.5–50	55000+5220/−3140	Age is too old	KIA32074
144.5–145	53580+2870/−2110	Age is too old	KIA32075
174.5–175	9130 ± 40	10304 ± 56	KIA32076
236.5–237	32450 ± 380	Age is possibly too old	KIA29869
Hoton-1 core			
70–95	2950 ± 80	3122 ± 119	TA-1471
147–170	3900 ± 140	4331 ± 199	TA-1440
195–220	5360 ± 80	6141 ± 106	TA-1472
245–270	5975 ± 150	6841 ± 188	TA-1439
295–320	7910 ± 120	8780 ± 166	TA-1473
350–375	9070 ± 150	10195 ± 229	TA-1419

Calibration was performed using the latest version of the CalPal University of Cologne Radiocarbon Calibration Program Package (http://www.calpal.de).

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174.5–175 cm level seemed to be the only reliable one. However, it was held to be insufficient for reliable age control given the poor quality of the other dates.

In order to construct an adequate age–depth model for the Hoton-2 core and to verify the reliability of its single date we decided to include in the analysis ^{14}C dates obtained for the Hoton-1 core recovered in 1980 (Tarasov et al., 1994). The earlier core was taken from the central part of a relatively small bay located in the northeastern part of Hoton-Nur at a water depth of 4.8 m (Fig. 1b). The distance between the Hoton-1 and Hoton-2 coring sites is ~11 km. The near-shore location of the Hoton-1 site in the semi-closed bay, stable sedimentation environments without river inflows and high organic content of the Hoton-1 core sediment allowed to obtain a sequence of six ^{14}C dates (Table 1).

For the purpose of this study we performed the following steps: (i) calibrated radiocarbon dates from Hoton-1 core (Table 1); (ii) applied the established age–depth model to the Hoton-1 pollen record; (iii) compared Hoton-1 and Hoton-2 pollen records and transferred ages of all coinciding changes in the relative abundance of the 21 terrestrial pollen taxa commonly identified in both records from the Hoton-1 age model to the Hoton-2 record; and (iv) used the resulting set of calibrated ages inferred via pollen-based correlation of two records to construct the age–depth model for the Hoton-2 records presented in this study (Fig. 2). The age–depth model represents a regression line with the second-degree polynomial fit. To our satisfaction the early-Holocene date from the Hoton-2 core (Table 1) fitted well into the newly constructed age–depth model, thus strengthening the Hoton-2 chronology. However, we left unresolved the age determination for the lower part of the Hoton-2 core (205–257 cm). In this paper, calibrated ages before present (expressed as kyr BP, where 1 kyr = 1000 cal yr) are used throughout the text.

3.3. Pollen analysis

A total of 100 samples, each consisting of one or two grams of the dry sediment taken with an average interval of 2.5 cm from the Hoton-2 core, were treated for pollen analysis using standard procedure (Faegri and Iversen, 1989). *Lycopodium* spore tablets were added to each sample in order to calculate total pollen and spore concentration. Pollen residues mounted in glycerin were analyzed under the light microscope with a ×400–1000 magnification. The identification of the pollen and spores was performed using reference pollen collection and regional pollen atlases (Kuprianova and Alyoshina, 1972; Reille, 1992, 1998).

In total, 51 pollen and spore taxa representing vascular plants were identified in the Hoton-2 core (Appendix A), e.g. 2.5 times more than in the low-resolution Hoton-1 record. In this study pollen of *Pinus* was separated into two morphological types. In the study area and surrounding regions these two pollen types are produced by *P. sylvestris* and *P. sibirica* trees, respectively. *Betula* pollen was also divided into two morphological types—*B.* sect. *Nanae* (shrub birch) and *B.* sect. *Albae* (tree birch).

The microscopic analysis revealed moderately high pollen concentration and generally good preservation of pollen grains in the upper sedimentary unit (0–205 cm), allowing an easy counting of up to 500 terrestrial pollen grains per sample. However, pollen spectra from the lower unit demonstrated extremely low pollen concentration, which resulted in counting of less than 100 terrestrial pollen grains per sample. Such low pollen sums are not recommended for further statistical analysis (Faegri and Iversen, 1989). Conventionally, we showed only a presence or absence of a certain pollen taxon in the pollen diagram below 205 cm depth (Fig. 3). For the remaining spectra, percentages were calculated based on a total sum of all pollen taxa taken as 100%.

3.4. Non-pollen palynomorphs

Samples prepared for the pollen analysis were also used to count coniferous stomata and other recognizable non-pollen palynomorphs (NPP). Identification of stomata was carried out using published reference keys (Trautmann, 1953; Sweeney, 2004); fungi spores, remains of green algae colonies, eggs of Tardigrada and chironomid remains were identified using descriptions, pictures and photographs published by Jankovska (1991), van Geel, 2001, and Komarek and Jankovska (2001). The NPP counts are **Q4** provided in Appendix A and the simplified results are plotted together with the results of pollen analysis (Fig. 3).

3.5. Diatom analysis

A total of 58 samples, picked up with the 5-cm step, were prepared for diatom analysis using the standard technique and

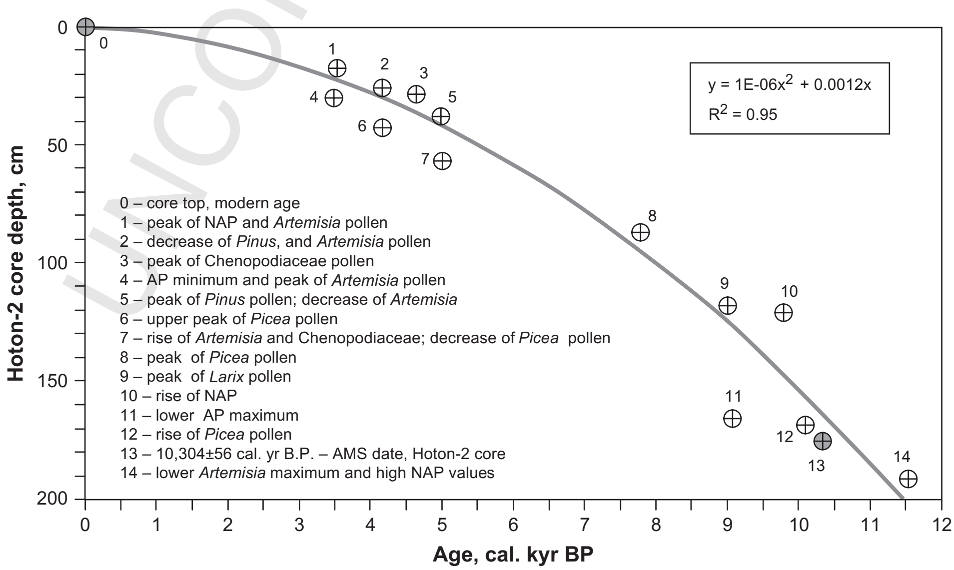

Fig. 2. Age–depth model applied to the pollen record of Hoton-Nur Lake (Hoton-2). Dots mark characteristic changes in the pollen assemblages which are parallel in the Hoton-1 (Tarasov et al., 2000) and Hoton-2 (this study) pollen records.

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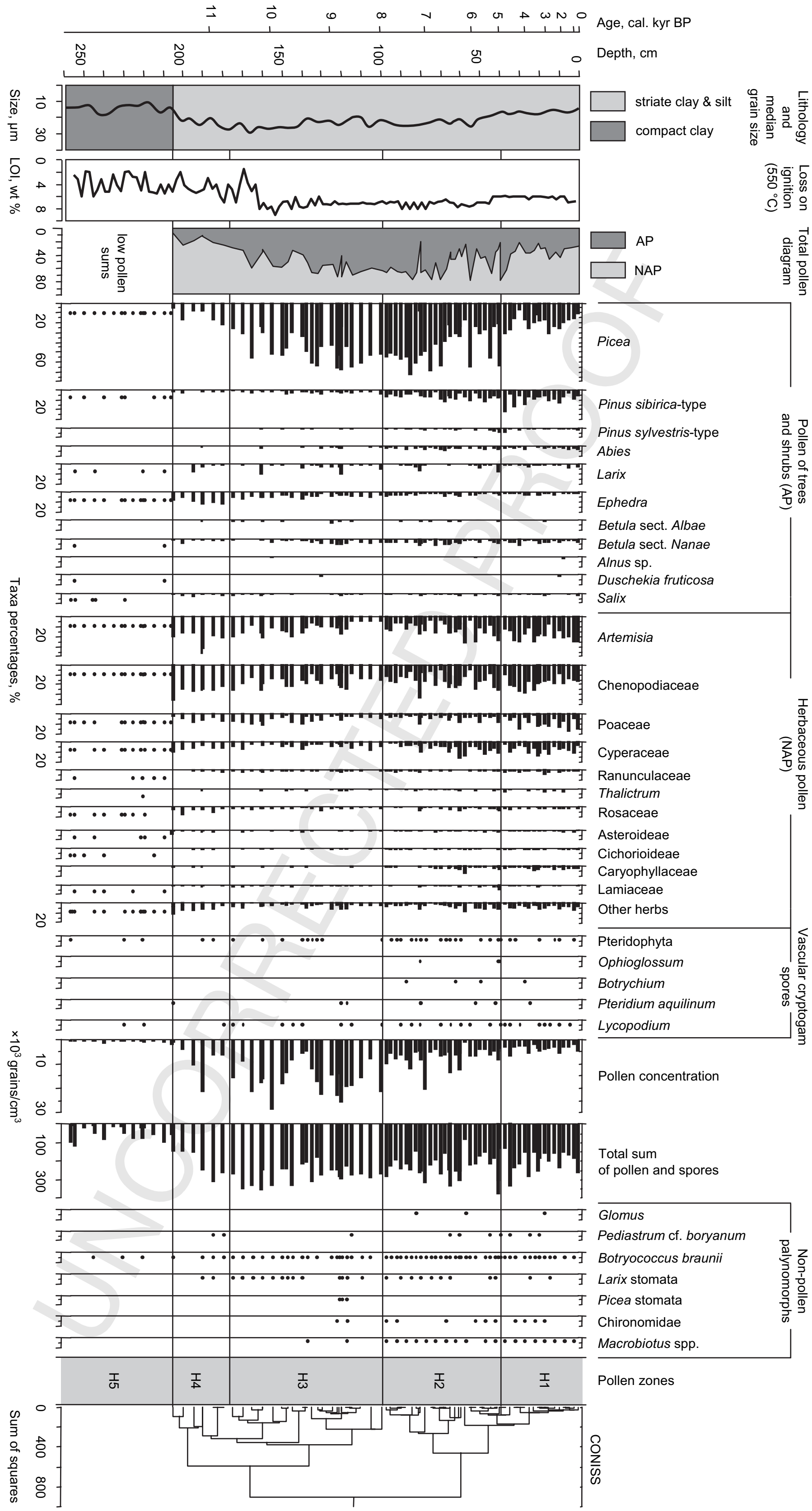

Fig. 3. Diagram presenting lithological characteristics and results of palynological analysis of the Hoton-2 core produced with the Tilia/TiliaGraph software (Grimm, 1991). The visual definition of the pollen zones is supported by CONISS (Grimm, 1987). Black dots indicate presence of a certain taxon in the given spectrum (see Appendix A for further details).

disintegration method in hydrogen peroxide (Battarbee, 1986). Aliquots of evaporated suspensions were embedded in Naphrax. At least 500–600 diatom valves per sample were counted on horizontal transects in the light microscope with phase-contrast oil immersion objectives at ×750 magnification. Diatom concentrations were calculated using an equation (Schrader, 1974) adapted for the continental diatoms (Davydova, 1985). Diatom nomenclature followed Krammer and Lange-Bertalot (1986–1991). The total sum of all diatoms counted in each sample (Appendix B) was taken as 100%, based upon which the relative abundances of individual taxa were calculated in order to construct the diatom diagram (Fig. 4).

To facilitate discussion of the diatom record, we accepted the following abundance classes for the individual taxa (Dorofeyuk and Tsetsegmaa, 2002): <1% = rare; 1–5% = common; 5–10% = subdominant; and >10% = dominant. The AL:PE diatom-pH model was used for pH inference (Cameron et al., 1999). The pH reconstruction (Fig. 4) was performed with the aid of the internet-based European Diatom Database (http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp) facility. Summary prediction statistics are given in Table 2. Inverse regression was chosen for the presentation of the final results as it generated a slightly lower root mean square error of prediction (RMSEP).

3.6. Quantitative methods of vegetation and climate reconstruction

The method applied in the biome reconstruction is a quantitative approach introduced by Prentice et al. (1996) which has proved to be a powerful tool for the objective vegetation reconstruction from the late Quaternary pollen data and for data-model comparison (Texier et al., 1997; Prentice et al., 2000). The method has been adapted for the reconstruction of the northern Eurasian, particularly Mongolian biomes (Tarasov et al., 1998, 2000; Gunin et al., 1999). In this paper we use the biome-taxon matrix and calculation equation proposed in the latter studies, in which all commonly identified pollen taxa are attributed to ten biomes growing in Mongolia and in northern Eurasia. When applied to 102 surface pollen spectra from Mongolia, this method assigns 83% of the samples to the correct biome (Gunin et al., 1999).

The pollen records from Mongolia have been frequently used for qualitative interpretation of the Holocene climate (Gunin et al., 1999; Grunert et al., 2000; Tarasov et al., 2000; Fowell et al., 2003; Prokopenko et al., 2007). In this study we applied the quantitative technique known as the "best modern analogue (BMA) method" (Q3 Overpeck et al., 1985; Guiot, 1990) to the Hoton-Nur pollen records in order to reconstruct atmospheric precipitation—a climatic variable, which controls regional vegetation distribution (Alpat'ev et al., 1976; Gunin et al., 1999). The BMA method was tested using an extensive surface pollen and meteorological datasets from northern Eurasia and Mongolia, and performance statistics demonstrated a capability to reproduce modern bioclimatic variables with a high degree of confidence (e.g. Solovieva et al., 2005). In the present study we used the BMA design and reference modern pollen/climate datasets from Tarasov et al. (2007a), who applied the method to the Eemian and Holocene pollen records from Lake Baikal. In the reference data set, the sum of 81 terrestrial pollen taxa from northern Eurasia, including all taxa identified in the Hoton-1 and Hoton-2 records, is taken as 100%. All calculations were performed with Polygon 1.5 software (Nakagawa et al., 2002; http://dendro.naruto-u.ac.jp/~nakagawa/).

4. Analytical results

4.1. Pollen

The Hoton-2 pollen diagram (Fig. 3) is subdivided into five pollen zones (PZ) on the basis of changing pollen taxa composition and abundance. Below we provide a brief characteristic of the Hoton-2 pollen zones from the bottom to the top of the core.

PZ H5 (257–205 cm, >11.5 kyr BP). The pollen concentrations (up to 1.8×10^3 grains/cm^3) and abundances are extremely low preventing from the pollen percentage calculation. Pollen of non-arboreal (NAP) taxa, including Chenopodiaceae, *Artemisia*, Cyperaceae and *Ephedra* are relatively abundant (Appendix A). Only single grains of *Picea*, *P. sibirica*-type and *Larix* representing arboreal pollen (AP) taxa are found.

PZ H4 (205–175 cm, 11.5–10.7 kyr BP) is characterized by the high pollen concentrations (up to 21×10^3 grains/cm^3) and the predominance of herbaceous taxa (up to 85%) including Chenopodiaceae (up to 35%) and *Artemisia* (up to 35%). The content of both Cyperaceae and Poaceae pollen may reach 10% and the relative abundance of *Ephedra* pollen may reach up to 15%. Among the AP taxa *Picea* predominates over *P. sibirica*-type and *Larix*.

PZ H3 (175–97.5 cm, 10.7–7.9 kyr BP). This zone reveals the highest pollen concentrations (up to 25×10^3 grains/cm^3) and a sharp increase in AP percentages (up to 75%). The *Picea* pollen content may reach 70% and percentages of *P. sibirica*-type, *Larix* and *B.* sect. *Nanae* pollen also become higher in this zone. Among the NAP taxa a relative increase in Poaceae percentages is noticeable.

PZ H2 (97.5–40 cm, 7.9–4.9 kyr BP). This zone is notable for the decrease in pollen concentrations (up to 20×10^3 grains/cm^3) accompanied by abrupt variations in the AP and NAP taxa percentages, e.g. the content of *Picea* varies between 10% and 75%. *Abies* reaches its maximum (4%) and *P. sibirica*-type amounts to 15%. Among herbaceous pollen taxa *Artemisia*, Chenopodiaceae, Poaceae, and Cyperaceae are most abundant.

PZ H1 (40–0 cm, 4.9–0 kyr BP) shows a general decrease in pollen concentrations (up to 6.3×10^3 grains/cm^3) and in AP percentages. *Picea* pollen abundance varies between 10% and 40%. However, *P. sibirica*-type percentages reach a maximum in this zone. The share of NAP increases to 60–70%, and *Artemisia*, Chenopodiaceae, Poaceae and Cyperaceae remain among the dominant taxa.

4.2. Non-pollen palynomorphs

Coniferous stomata are found in a total of 27 samples, representing all pollen zones, except for the lowermost PZ H5 (Fig. 3). Their abundance is generally low and does not exceed 5 stomata per sample (Appendix A). The *Larix* stomata are found in 27 samples, more frequently in PZ H3 and PZ H2 and only occasionally in PZ H4 and PZ H1, while stomata of *Picea* are found only in 3 samples from PZ H3.

Other NPP are also found in relatively low numbers (Appendix A). Remains of colonial green alga *Botryococcus braunii* show the highest frequencies and appear already in PZ H5 (Fig. 3), where no other NPP are found. *B. braunii* is a widely distributed alga inhabiting lakes and rivers from the arctic to tropical latitudes. It is mainly observed in the upper photic zone and is most characteristic of the oligotrophic lakes, although occurrence in the mesotrophic waters is possible (Tyson, 1995; Smittenberg et al., 2005). In PZ H4, except *B. braunii* few remains of colonial alga *Pediastrum* cf. *boryanum* are found in 2 samples. In PZ H3, except permanently present *B. braunii*, *P.* cf. *boryanum* is found in one sample and eggs of *Macrobiotus hibernicus* and *M. hufelandi* representing Tardigrada appear in the sediments younger than 9.5 kyr BP. Between 8 kyr BP and the core top their content is fairly stable, e.g. 2–7 eggs per sample. Jaws of chironomids (*Cladotanytarsus* and *Mesocricotopus*) are also found (1–7 per sample) in the PZ H3 in the sediment younger than 9 kyr BP. Single *Glomus* spores are found in two samples from PZ H2 and in one sample from PZ H1.

4.3. Diatoms and reconstructed pH

Dorofeyuk and Tsetsegmaa (2002) reported that the modern diatom flora of Hoton-Nur consists 57 taxa. The fossil diatom flora

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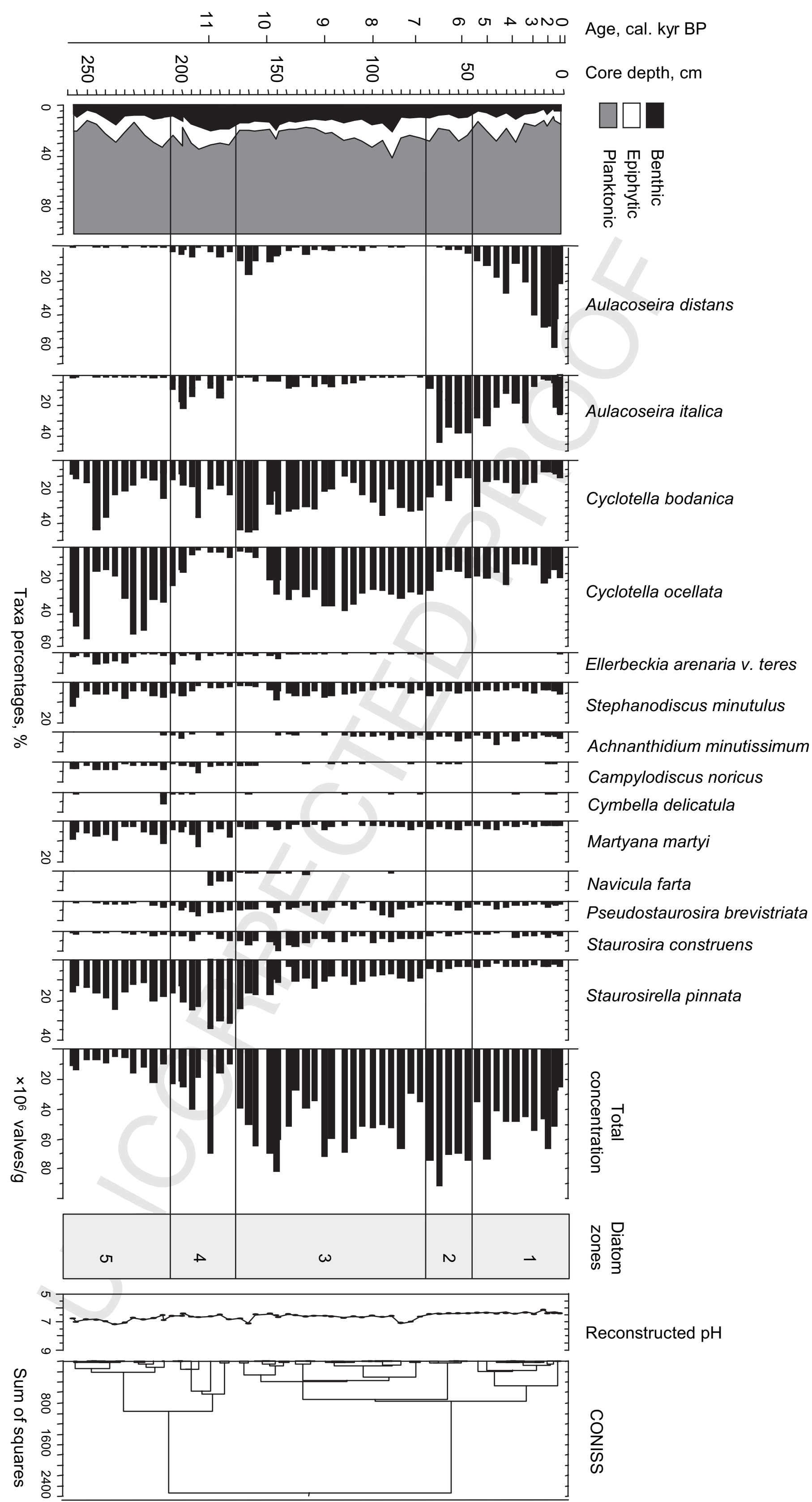

Fig. 4. Diatom stratigraphy and AL:PE-reconstructed pH from the Hoton-2 core. Construction of the diatom diagram was performed with Tilia/TiliaGraph software (Grimm, 1991), and local diatom zone boundaries were drawn on the basis of the visual inspection supported by CONISS (Grimm, 1987).

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Table 2
Apparent and prediction statistics of AL:PE pH model.

Apparent statistics		Prediction "jackknife" statistics	
RMSE	0.297	RMSEP	0.356
r^2	0.847	r^2	0.780
Average bias	0.0005	Average bias	0.001
Max. bias	0.495	Max. bias	0.624

from the Hoton-2 core is richer and consists of 294 taxa from 65 genera (Appendix B). Among them 90 taxa identified in this study are new for deep-water lake sediments and 13 taxa are found for the first time in Mongolia. These include *Cyclotella operculata* var. *unipunctata*, *Amphora dusenii*, *Brachysira brebissonii*, *Caloneis tenuis*, *Cavinula jaernefeltii*, *C. lacustris*, *Cymbella behrei*, *Diploneis domblittensis*, *Eunotia polydentula*, *Gomphonema abbreviatum*, *Luticola undulata*, *Navicula farta* and *Stauroneis anceps* var. *siberica*.

The diatom diagram (Fig. 4) has been subdivided into the following five diatom zones (DZ).

DZ 5 (257–205 cm; >11.5 kyr BP). Diatom concentrations vary between 3.1 and 20.7 × 10^6 valves/g. The dominant complex is represented by planktonic *Cyclotella ocellata* and *C. bodanica*, and *Staurosirella pinnata* which can be planktonic as well as benthic (Dorofeyuk and Tsetsegmaa, 2002). The lower part of this zone (257–227.5 cm) is notable for its relatively low concentrations (3.1–13.1 × 10^6 valves/g) and species diversity (31–48 taxa). The dominant species is *C. ocellata* (below 250.5 cm) and *C. bodanica* (above 250.5 cm). The uppermost part (227.5–205 cm) is characterized by an increase in diatom concentrations (4.5–22 × 10^6 valves/g) and number of species (58 taxa) and the predominance of *C. ocellata*, *C. bodanica* and *S. pinnata*.

DZ 4 (205–172.5 cm; 11.5–10.7 kyr BP) is characterized by the further increase in concentrations up to 69 × 10^6 valves/g at 185 cm. However, a drop in concentration down to 9 × 10^6 valves/g is recorded in the upper part of the zone. The dominant taxa are *C. ocellata*, which is abundant in the bottom part of the zone, *S. pinnata*, which reaches a maximum at 185 cm, and *C. bodanica*, prevailing in the interval between 209.5 and 191.5 cm. Another notable feature of this zone is the appearance of planktonic *Aulacoseira italica*, a widespread species in continental mesotrophic and eutrophic waters.

DZ 3 (172.5–72.5 cm; 10.7–6.6 kyr BP) experiences high diatom concentrations (60–81 × 10^6 valves/g) in the lower part (172.5–140.5 cm; 10.7–9.6 kyr BP). The dominant species is *C. bodanica* (26–43%) accompanied by *S. pinnata*. The upper part of this zone demonstrates greater variations in diatom concentrations (28–70 × 10^6 valves/g) and the predominance of *C. ocellata* and *C. bodanica*.

DZ 2 (72.5–47.5 cm; 6.6–5.6 kyr BP) experiences high diatom concentrations (69–91 × 10^6 valves/g) and is characterized by the predominance of planktonic *A. italica* var. *italica* and *A. italica* var. *tenuissima*. *C. ocellata* and *C. bodanica* are also abundant, but their role becomes less pronounced in this zone.

DZ 1 (47.5–0 cm; 5.6–0 kyr BP) is characterized by the decrease in diatom concentrations down to 23–73 × 10^6 valves/g. *Aulacoseira distans* reaches 61% at 5 cm depth and together with planktonic *A. italica*, *C. ocellata*, and *C. bodanica* predominates within this zone.

The reconstructed pH profile (Fig. 4) shows little change throughout the Hoton-2 core, fluctuating between minimum 6.10 (10 cm) and maximum 7.15 (235 cm). There is no sign of either natural or anthropogenic acidification as the lake is well buffered and remote from possible pollution sources. It is likely that the AL:PE model slightly underestimates the lake pH, since the measured pH is about 7.5. Generally, the reconstructed pH compares well with the reconstructed pH profile from the Hoton-1 core, with the Hoton-1 record being slightly more acidic.

5. Interpretation

5.1. Vegetation dynamics

Prior to 11.5 kyr BP very low pollen concentrations and the predominance of NAP taxa well adapted to both dry and cold environments (Fig. 3) suggest a treeless and probably discontinuous vegetation cover around the lake, similar to that of the modern dry steppes and semi-deserts. The early Holocene pollen spectra reveal an increase in pollen concentrations but the pollen composition remains similar to the late Pleistocene phase. Biome reconstruction (Fig. 5a,b) demonstrates that steppe biome scores have the highest values, suggesting the predominance of this vegetation type (Fig. 5c), and scores of taiga and tundra biomes are relatively low between 11.5 and 10.7 kyr BP. Relatively high percentages of *Ephedra* pollen may as well point to the open character of vegetation and the wide spread of dry steppe and semi-desert communities around the lake.

After 10.7 kyr BP vegetation cover became denser as suggested by the higher pollen concentrations. Both pollen spectra composition and biome reconstruction suggest the spread of trees around the lake from this period onward. One of the main indicators of the local presence of coniferous trees, including *Larix* and *Picea*, is the presence of their stomata in the lake sediment (Parshall, 1999; Sweeney, 2004). The finds of *Larix* stomata are especially important, considering that larch pollen is usually strongly underrepresented in the pollen diagrams (Gunin et al., 1999; Pisaric et al., 2001). Biome reconstruction demonstrates a decrease in steppe scores and an associated increase in taiga scores, suggesting the spread of boreal trees and open woodland vegetation around Hoton-Nur 10–8 kyr BP. The increase in *B.* sect. *Nanae* pollen percentages suggests that shrub birches became spread in the sedge-grass alpine belt or/and in the woodland understorey. However, reconstructed tundra scores do not change significantly in comparison with the earlier time interval.

After 7.9 kyr BP the decrease in pollen concentrations and strong variations in the AP and NAP taxa percentages suggest rather unstable environmental conditions and an increased importance of the non-arboreal vegetation in the region. Occurrence of *Picea* and *Larix* stomata and relatively high quantities of *Picea*, *Abies*, *P. sibirica*-type and *Larix* pollen suggest that trees were still well present in the regional vegetation until 5 kyr BP. Relatively high scores of taiga biome supports this interpretation.

From 4.9 kyr BP the greater role of semi-desert and steppe taxa in the pollen spectra indicate a strengthening of these vegetation communities in the area around Hoton-Nur and an associated retreat of the boreal woods to the refugia with slightly better moisture conditions. The reconstruction shows the increase in the steppe biome scores during the past 5 kyr consistent with the qualitative interpretation of the pollen record. Relatively high percentages of coniferous taxa, particularly of *P. sibirica*-type and *Picea*, in the late Holocene pollen spectra likely indicate their transport from the taiga forests growing in the northern and northwestern parts of the Altai Mountains, rather than the presence of local woods. This interpretation is supported by relatively low pollen concentrations and the disappearance of conifer stomata from the analyzed sediments.

5.2. Lacustrine environments

The lower part of the Hoton-Nur core consists of gray-blue clay usually associated with the deep and cold-water oligotrophic lake (Tarasov et al., 1994). Prior to 11.5 kyr PB diatom concentrations are relatively low and the lake is dominated by planktonic *Cyclotella* and small Fragilariaceae, suggesting a deep and oligotrophic/mesotrophic lake. Small Fragilariaceae species (e.g. *S. pinnata*) are

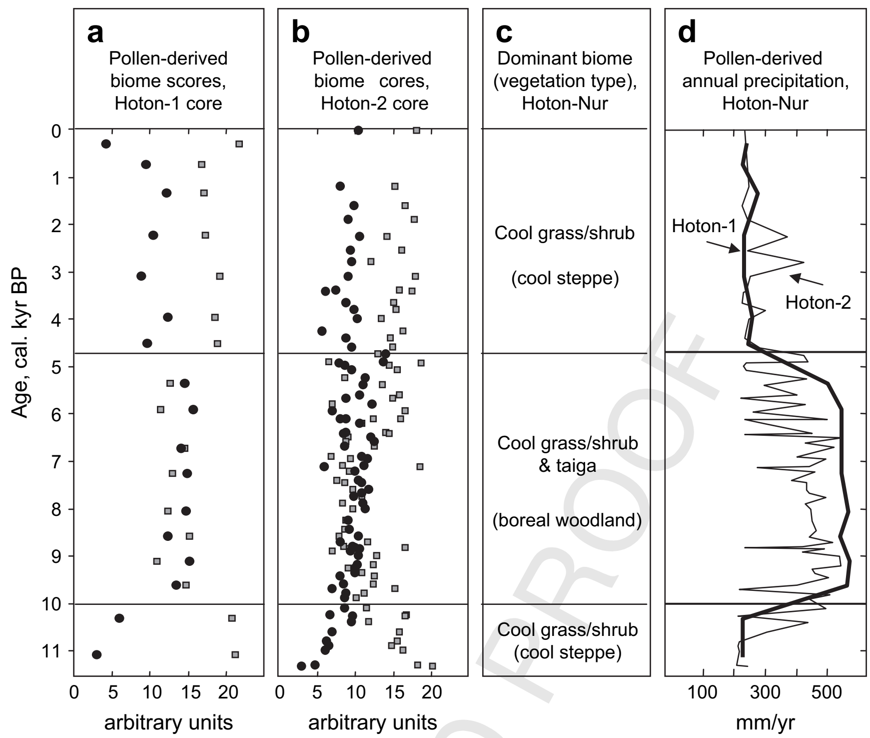

Fig. 5. Numerical scores of the dominant biomes (circles = taiga, and squares = steppe) reconstructed from the Hoton-1 (a) and Hoton-2 (b) pollen records used for the reconstruction of changes in vegetation (c) and annual precipitation (d).

commonly found in disturbed glacial and/or arctic environments (Haworth, 1976; Anderson, 2000). The high abundance of *S. pinnata* from the beginning of the record until 10.7 kyr BP might imply intensified erosion processes in the catchment and this corresponds well with the presence of scarce and dry vegetation and the generally arid climate during this period. The boundaries of the first two pollen and diatom zones coincide, suggesting the lake ecosystem responded quickly to the changes in the catchment.

From about 10.7 kyr BP, more planktonic diatom taxa appeared and increased in abundance, indicating that the lake diatom flora became more established and diverse. The abundance of small mesotrophic *Cyclotella* taxa also increased. The lake became more productive as diatom concentration increased. This change correlates well with the development of boreal woodland in the catchment (Fig 6). The decrease in precipitation and changes in the catchment vegetation towards drier steppe are reflected by the rapid increase in *A. distans* from about 5 kyr BP. The ecology of *A. distans* is not entirely clear; it is likely that *A. distans* is either a planktonic or meroplanktonic species, i.e. it spends at least part of its life-cycle in the water column (Turkia and Lepisto, 1999). The increase in *A. distans* coincides with the development of a steppe landscape that is more open and drier than before. Relatively heavy, silicified *A. distans* thrive in lakes with wind-induced turbulence (Ruhland et al., 2003), which is greater in open country than in woodland.

Floristically, the Hoton-Nur *Aulacoseira*/*Cyclotella*/Fragilareaceae dominated diatom assemblages are close to deep oligo/mesotrophic lakes located in remote arctic, subarctic and alpine areas of Canada (Rühland et al., 2003; Smol et al., 2005), Scandinavia (Sorvari et al., 2002), and Spain (Catalan et al., 2002). It is likely that the late-Holocene increase in *A. distans* in the lake can be linked to changes in the ice-cover regime as well as the increase in wind-induced turbulence due to the vegetation changes in the catchment. The increase in *C. ocellata* in early- to mid-Holocene might also be partially linked to the change in the lake ice-cover regime (e.g. shortening of the ice-cover season) due to the increased humidity. Similar changes in the arctic Scandinavian and Canadian lakes during the 20th century have been attributed to the shortening of the ice cover due to global climate warming (Sorvari et al., 2002; Smol et al., 2005).

Pollen data suggest the late Holocene change in the vegetation cover towards a more open landscape, causing an intensification of the wind and water erosion and a higher risk of wild or anthropogenic fires. Neither diatom nor non-pollen macrofossil analysis of the Hoton-Nur sediment cores provide evidence of significant human impact on the regional environments. Eggs of *Macrobiotus*, recorded from 8 kyr BP onward, usually indicate unpolluted ecotopes (Jankovska, 1991). *Glomus* spores, often reported as an indicator of human-influenced soil erosion in the catchment of the lake (van Geel et al., 2003), are found in the Hoton-2 sediment at Q5 extremely low levels of abundance.

5.3. Climate dynamics

Pollen and diatom data from Hoton-Nur demonstrate changes in the vegetation and algal communities, which can be interpreted in terms of the past climate dynamics. Both climate-based vegetation modeling (Prentice et al., 1992) and biogeographical studies on the modern vegetation (Gunin et al., 1999) suggest that T_c, α and P_{ann} are the most relevant climatic parameters for defining boundaries between the principal vegetation types in Mongolia. For example, $T_c = -35\,°C$ separates cold deciduous forest dominated by *Betula* and *Larix* from taiga where boreal deciduous and evergreen coniferous (e.g. *Picea*, *Abies*, *P. sibirica*) taxa can grow together (Prentice et al., 1992). Similarly, $\alpha = 0.65$ separates cool steppe from forest biomes. The use of α is limited to the modeling studies, while P_{ann} is more frequently used in the paleoclimate research based on biological and sedimentary proxies and can be easily compared with meteorological observations and climatic maps. The modern climatic variables at Hoton-Nur (e.g. 0.45 for α, 250 mm/yr for P_{ann}

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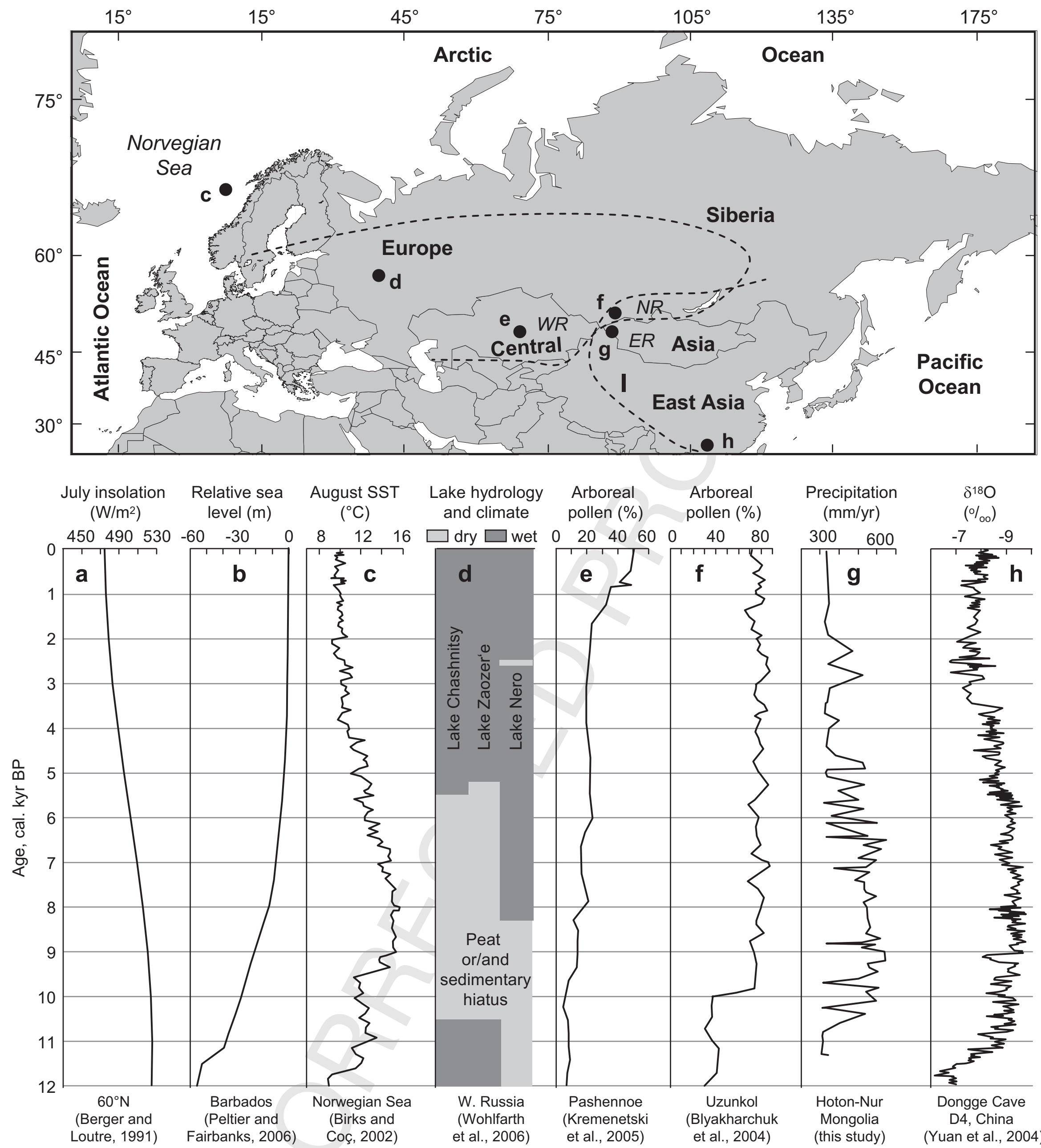

Fig. 6. Summary chart showing the distribution of the Holocene paleoclimate records from Eurasia discussed in the text (upper panel) and a comparison of selected global forcings and several paleoclimate proxies from Eurasia plotted along the time axis (lower panel). Individual graphs show (a) July insolation at 60°, (b) relative sea level changes (e.g. global ice volume equivalent) from the Barbados corals, (c) diatom-based August sea-surface temperature reconstruction from the Norwegian Sea, (d) lacustrine environment and its climatic implication for three lakes from the Yaroslavl' Region in central European Russia, (e) AP percentages from Pashennoe Lake in eastern-central Kazakhstan representative of the Western Region (WR) of Central Asia which experienced the late-Holocene westerly-associated moisture increase, (f) AP percentages from Uzunkol Lake in the Russian Altai representative of the Northern Region (NR) of Central Asia which experienced both the early-Holocene monsoon-associated moisture increase and the late-Holocene westerly-associated moisture increase, (g) pollen-based precipitation reconstruction from Hoton-Nur representative of the Eastern Region of Central Asia which experienced the early-Holocene monsoon-associated moisture increase but late-Holocene moisture decrease, and (h) oxygen isotope record (e.g. indicator of the Pacific summer monsoon intensity) from the stalagmite D4, Dongge Cave, China.

and −20 °C for T_c) suggest that the modern steppe vegetation around the lake and small isolated woody stands are more sensitive to the moisture parameters, while only a large drop in T_c can destabilize the system. The results of the pollen-based precipitation reconstruction are shown in Fig. 5d. Both Hoton-1 and Hoton-2 records suggest that the regional climate was relatively dry (P_{ann} ~ 200–300 mm/yr and α ~ 0.3–0.5) prior to 10 kyr BP. The climate became substantially wetter (P_{ann} ~ 300–550 mm/yr and α ~ 0.5–0.8) during the following interval between 10 and 5 kyr BP. The onset of a relatively dry climate comparable to the present occurred soon after 5 kyr BP. This climate reconstruction (Fig. 5d) is consistent with the vegetation reconstruction (Fig. 5a–c).

Comparison of the results inferred from the deep-water Hoton-2 record with the reconstruction based on the Hoton-1 record obtained from the coastal bay reveals greater pollen/climate variability in the Hoton-2 record (Fig. 5d). For example, during the late-Holocene the climate reconstruction from Hoton-1 demonstrates precipitation values similar to today, while the Hoton-2 record suggests a 50–100 mm increase in precipitation between 3 and 2 kyr BP. Another example is several short-term variations in the pollen percentages and in the pollen-based reconstructions of biome scores and precipitation values from the Hoton-2 record, particularly during the mid-Holocene humid interval. Observed discrepancies between the Hoton-1 and Hoton-2 records can be explained by (i) larger sample size and lower temporal resolution of the pollen analysis of the Hoton-1 core and/or (ii) a different sampling site location and the various sources of pollen entering it. In a large overflowing lake, pollen spectra from its central deep-water part (Hoton-2) tend to represent a larger region, receiving greater input from regional, rather than local or extra-local vegetation to the pollen assemblages (Jacobson and Bradshaw, 1981). In the Hoton-Nur basin more arid vegetation communities are concentrated at the lower elevations south and east of the lake (Volkova, 1994). Thus, the contribution of the dry taxa to the Hoton-2 pollen assemblages is greater in comparison with the Hoton-1, and this is consistent with the reconstruction of generally lower taiga biome scores and precipitation values of the Hoton-2 record (Fig. 5). In several cases during the early and late Holocene the higher taiga scores/precipitation values are derived from the Hoton-2 pollen assemblages with very low pollen concentration (Fig. 3). In latter cases, the reconstruction might be an artefact caused by an increasing role of the long-distant AP transport during the arid intervals characterized by the low local pollen production in the Hoton-2 record (Tarasov et al., 2007b). Overall, the Hoton-1 core collected from a small and relatively closed bay without direct river inflow shows a more stable signal.

6. Discussion: holocene climatic and environmental changes in Central Asia

6.1. Holocene vegetation and climate records from the Altai Mountains and neighboring areas

Occupying a central position in the mid-latitude Asian interiors, the Altai Mountains resemble a gigantic "T", which splits the area into three characteristic geographical regions: eastern, western and northern. In this section the Holocene vegetation records from these three regions are summarized to facilitate further discussions of the spatial pattern of the Holocene climate and its background mechanisms.

6.1.1. Eastern Region (ER): the Mongolian Altai

The Hoton-1 and Hoton-2 records demonstrate generally parallel changes in the reconstructed environments (Fig. 5), suggesting that the area was characterized by a relatively dry climate and cool steppe vegetation prior to 10 kyr BP. Generally wetter than present conditions occurred between 10 and 5 kyr BP causing a spread of boreal trees. The re-establishment of steppe as a dominant vegetation type was associated with a significant decrease in atmospheric precipitation after 5 kyr BP. Other vegetation records from the ER are in line with this reconstruction. For example, the pollen data from Achit-Nur (49°30′N, 90°36′E, 1435 m, Fig. 1) demonstrate a quick increase in AP from less than 5% prior to 10.5 kyr BP to 35–50% between 10 and 5 kyr BP (Gunin et al., 1999), suggesting a wetter than present mid-Holocene climate and open woodland vegetation. The "Kharkhiraa south side" pollen record (49°26′N, 91°15′E, 2570 m, Fig. 1) provides further proof of humid conditions between 10.6 and 5.3 kyr BP and dry vegetation and climate during the earlier and later periods (Schlütz, 2000). The palynological study of the Bayan Nuur (50°00′N, 93°58′E, 932 m, Fig. 1) core also suggests a phase of higher humidity during the middle Holocene, as indicated by the highest AP percentages between 10 and 6.9 kyr BP (Krengel, 2000; Grunert et al., 2000). Radiocarbon dating of numerous *Picea*, *Abies* and *Larix* wood fragments identified in peat deposits from Bayan-Sair (47.75°N, 96.91°E, 2600 m, Fig. 1) proves the disappearance of spruce and fir from the local vegetation between 5 and 3.8 kyr BP, while larch was present until 3 kyr BP (Gunin et al., 1999). The mid-Holocene presence of taiga woods in the southern Mongolian Altai would require P_{ann} to be ~100–150 mm/yr higher than present (Tarasov et al., 2000).

6.1.2. Western Region (WR): the Kazakh Upland

Pollen records from Ozerki Swamp (50°24′N, 80°28′E, 210 m, Fig. 1) in the Irtysh River valley and from Pashennoe Lake (49°22′N, 75°24′E, 871 m, Fig. 1) in the Karkaraly Mountains (Kremenetski et al., 1997; Tarasov et al., 1997) reveal the high percentages of steppe- and desert-associated herbaceous taxa throughout the late glacial, early and middle Holocene. The Ozerki pollen record suggests a local presence of the riparian birch forests in the Irtysh River valley around 8.5 kyr BP. However, the encroachment of the pine forests into the Kazakhstan steppe became a distinctive feature of the second half of the Holocene. Pollen records from lakes Mokhovoe (53°46′N, 64°15′E) and Karasye (53°02′N, 70°13′E) situated in northern Kazakhstan (Kremenetski et al., 1997; Tarasov et al., 1997) suggest that the pine-dominated island forests were established in the northern part of the WR about 6 kyr ago and then spread southwards. Around remotely located Lake Pashennoe (Fig. 1) the forest apparently reached its maximum spread only during the last millennium (Tarasov et al., 2007b).

6.1.3. Northern Region (NR): the Russian Altai

The pollen records from the Ulagan Plateau (50°27′–50°30′N, 87°06′–87°40′E, 1985–2150 m, Fig. 1) suggest that the trees appeared in the area from 12 kyr BP (Blyakharchuk et al., 2004). However, the full expansion of the evergreen boreal coniferous forests occurred rapidly only after 10 kyr BP. The role of *Picea* and *Abies* in these forests decreased by about 7.5 kyr BP and the vegetation cover has changed very little since that time until today. The pollen records from lower elevation Dzhangyskol (50°11′N, 87°44′E, ~1800 m) also suggest spread of woods after 11 kyr BP (Blyakharchuk et al., 2008). However, maximal expansion of boreal forests in the area coincides with the highest lake levels in Dzhangyskol during the late Holocene. By contrast to the western area, the pollen records from Tuva (50°15′–50°16′N, 89°27′-89°37′E, 2204–2413 m, Fig. 1) located in the relatively dry eastern part of the NR indicate the taiga development in response to increased humidity between 11 and 6 kyr BP, and a shift to a drier climate similar to present after 6 kyr BP (Blyakharchuk et al., 2007).

6.2. Mechanisms driving the Holocene vegetation and climate dynamics in Central Asia

The records summarized in Section 6.1 demonstrate spatially variable Holocene vegetation and climate histories in the large area of Central Asia separated by the main watersheds of the Altai Mountains into three well-defined geographical regions. The recorded regional differences imply different driving mechanisms of the post-glacial environmental dynamics and encourage a search for those mechanisms.

Great distances separate the Altai Mountains from all the oceans and thus from the main sources of precipitation in the Eurasian mid-latitudes. The present-day precipitation and plant-available moisture in the WR is mainly controlled by cyclonic advections from the Atlantic Ocean (Alpat'ev et al., 1976; Martyn, 1992). However, the ER bordered from the west by the Altai Mountains stays in the rain shadow. In eastern Asia, the modern precipitation pattern is controlled by the summer monsoon transporting moisture from the Pacific Ocean (Domrös and Peng, 1988). The modern limit of the summer monsoon is commonly placed along the eastern border of Mongolia and as far as the eastern parts of the Tibetan Plateau (Winkler and Wang, 1993; Wei and Gasse, 1999).

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However, meteorological observations suggest that in the Mongolian Altai incursions of Pacific air masses amplified by the mountain relief are responsible for the precipitation during the warm season (Tarasov et al., 2000). In the NR, precipitation is controlled by western and northwestern cyclones bringing warm and moist air during the summer season (Alpat'ev et al., 1976). In winter, very cold, sunny and predominantly dry weather caused by the Siberian anticyclone prevails in all the discussed regions of Central Asia (Martyn, 1992).

Vegetation and climate reconstructions for the ER have been interpreted as evidence of the early–middle Holocene strengthening of the summer monsoon (Harrison et al., 1996; Tarasov et al., 2000). The study on oxygen isotopes in lacustrine sediments from western and northwestern China (Wei and Gasse, 1999) suggested, for its part, that the Pacific monsoon did influence northwestern China between 11 and 4.5/3.5 kyr BP and provided constantly high precipitation in northeastern and central Tibet 11–8 kyr BP (Wei and Gasse, 1999). Prior to 11 kyr BP desert-like environments are reconstructed around Lake Manas (45°45′N, 86°00′E, Fig. 1) followed by a 3 kyr episode when the lake became fresh and deep and steppe vegetation grew around it (Rhodes et al., 1996). The $\delta^{18}O$ record from Manas correlates very well with the environmental reconstructions for the Mongolian Altai presented in this study, suggesting the same mechanism for the early- to mid-Holocene increase in precipitation.

The early- to mid-Holocene monsoon-associated increase in summer rainfall in the upper Irtysh River, which originated from northwestern China, may well account for the local development of the riparian birch forests in the Irtysh River valley around 8.5 kyr BP, as seen in the Ozerki pollen diagram (Kremenetski et al., 1997; Tarasov et al., 1997), but not in the other records from Kazakhstan situated beyond the range of Irtysh influence. By contrast to the ER (Fig. 6g), the first half of the Holocene was drier than at present in the WR, where a shift towards wetter conditions did not occur until 7 kyr BP. The late Holocene spread of pine and birch forests in northern and central Kazakhstan (Fig. 6e), indicating an increase in precipitation or a decrease in evaporation losses, has been noted (Kremenetski et al., 1997; Tarasov et al., 1997). Recently it was suggested (Tarasov et al., 2007b) that both the movement of Atlantic air masses driven by a northward shift in westerly flow, and the efficiency of advective water recycling during moisture transport to the Asian interiors, may be responsible for the late Holocene improvement of the regional water balance. The late Quaternary lake-status (Harrison et al., 1996) and isotope (Bar-Matthews and Ayalon, 2004) records demonstrate that the Mediterranean region, which at present receives precipitation associated with the winter westerlies, became drier than before after 6 kyr BP, while the region of northern Europe experienced a shift towards wetter conditions after 5 kyr BP and most of the analyzed lakes there reached the highest levels during the last millennia (Harrison et al., 1996; Barber et al., 2004; Snowball et al., 2004). Wohlfarth et al. (2006) also demonstrated that the lakes in the central Russian Plain, recently controlled by the westerly through most of the year, experienced very low levels between 13 and 5.5 kyr BP, before turning to more humid conditions after that (Fig. 6d).

The present-day atmospheric circulation and precipitation regime of the WR (including Kazakhstan) resemble those of northern and eastern Europe (Martyn, 1992). Taking into account a similarity in the reconstructed Holocene changes in the regional precipitation/water budgets we assume that they have the same background mechanism. The transition from warm and dry early and middle Holocene to cool and wet late-Holocene in western Eurasian mid-latitudes was explained by declining summer insolation (Fig. 6a), the cooling of Arctic waters (Fig. 6c) and reduced summer temperatures/evaporation (Snowball et al., 2004). A parallel increase in winter insolation and sea level rise (Fig. 6b) indicating a decrease in the global ice volume (Peltier and Fairbanks, 2006) could also play an important role, as it might be responsible for the weakening of the winter monsoon in Siberia, which then allowed farther eastward penetration of the relatively warm and wet Atlantic air masses. This process was complicated by a number of regional factors, which could be responsible for a highly meridional circulation pattern over Europe during the first half of the Holocene in comparison to a zonal circulation pattern observed today (Harrison et al., 1996).

The pollen records from the NR (Fig. 6f) show the humidity/precipitation pattern, which makes it similar to the ER before 6 kyr BP and to the WR after that. Ilyashuk and Ilyashuk (2007), using chironomid and lithology records and results of the diatom analysis (Westover et al., 2006), suggested that the Pacific monsoon brought precipitation to the Russian Altai in the early Holocene, whereas cyclones associated with the Atlantic westerlies were likely responsible for the moisture transport during the second half of the Holocene. The reconstructed mid-Holocene phase of relatively dry climatic conditions falls in an interval when a major transformation of the atmospheric circulation occurred in Eurasia. During this period the attenuation of the Pacific monsoon circulation and the retreat of the summer monsoon front documented in the records from western Mongolia and north-western China caused a reduction of precipitation in the Russian Altai, whereas the Atlantic influence in the NR, as proved independently by the evidence from Kazakhstan and Russia. A comparison between the pollen/vegetation/climate records from the western (e.g. Ulagan, Dzhangyskol) and eastern part (Tuva) of the NR demonstrates that both areas had two precipitation maxima. However, the early Holocene (summer monsoon-associated) maximum was more pronounced in the eastern part, and the late Holocene (westerly-associated) maximum could be better seen in the western part of the NR, in line with the records from Kazakhstan and Mongolia.

6.3. Holocene vegetation dynamics in the Mongolian Altai: climate change or human activities?

The interpretation of changes in AP content in terms of climate is not unambiguous, since the forest degradation and associated changes in the pollen assemblages can be also explained by human activities. Thus, pollen-based climatic inferences benefit from additional evidence from independent proxies. Changes in the moisture balance reconstructed from 11 Mongolian lakes (Tarasov et al., 1996; Walter et al., 2003) closely resemble the pollen-based climate reconstruction (Fig. 6g), and support the assumption that the vegetation dynamics reconstructed from the Hoton-Nur record are primarily driven by the changes in precipitation.

Archaeological records, e.g. a great number of petroglyphic images and ritual structures in the river valleys of Tsagaan Salaa and Baga Oigor (49°25′N, 88°15′E, ~2350–2650 m) situated 75 km north of Hoton-Nur, suggest more or less continuous habitation of the Mongolian Altai since 12 kyr BP (Jacobson, 2001). Small communities subsisting on hunting of forest- and steppe-associated animals, fishing and gathering were present in the region prior to 4 kyr BP. The number of images of forest animals (e.g. bear, true dear and elk) decreases after 4 kyr BP and images of wild boar, an inhabitant of the riparian forests and shrubs, and wild yak, preferring open steppe landscapes, become more important in line with our environmental reconstruction (Fig. 5). The emergence of mounted pastoralism after 3 kyr BP concluded the transition from a hunting-gathering economy to a nomadic or semi-nomadic pastoral economy in the Mongolian Altai (Jacobson, 2001). Wood of coniferous trees (mainly *Larix*) was commonly used to construct tomb chambers during 2.9–2 kyr BP (Parzinger, 2006; Heussner and Sljusarenko, 2007), e.g. only after the main transformation

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from woodland to steppe was completed as the result of the climate change towards aridity. It is possible that the disappearance of *Larix* from the Gobi Altai after 3 kyr BP (Gunin et al., 1999; Miehe et al., 2007) was initially triggered by climate change and then aggravated by human activities under conditions unsuitable for tree re-growth. However, the absence of diagnostic anthropogenic indicators in the Hoton-Nur pollen and diatom records indicates that human disturbance of soils and vegetation cover was less significant than might have been expected. Our conclusion is consistent with the recent results from the Khentey Mountains (49°04′48″N, 107°17′15″E, 900–1600 m, Schlütz et al., 2008), where the absence of charcoal and other anthropogenic indicators in the palynological records until modern times imply that the steppe islands are of natural origin and not a replacement of the former taiga due to burning or grazing.

7. Conclusions

1. A quantitative reconstruction of Holocene vegetation and climate dynamics was inferred from the Hoton-Nur records from the semiarid Mongolian Altai. Our reconstruction suggests a rapid forestation in the primarily open landscape of northwestern Mongolia after 10 kyr BP in response to a noticeable increase in precipitation from 200–250 mm/yr to 450–550 mm/yr. A return to a predominance of open vegetation types occurred after 5 kyr BP when precipitation decreased to modern values of 250–300 mm/yr.
2. This reconstruction is in agreement with the $\delta^{18}O$ records from China, demonstrating an abrupt strengthening of the monsoon in the early Holocene and an associated increase in precipitation and in lake levels in northwestern China between 11 and 8 kyr BP, followed by the stepwise attenuation of the monsoon circulation and climate aridization towards the modern level between 8 and 4.5/3.5 kyr BP.
3. Occupying a central position in the mid-latitude Asian interiors, the Altai Mountains resemble a gigantic "T", which splits the area into three characteristic geographical regions: eastern (ER), western (WR) and northern (NR). Comparisons of records from the Mongolian Altai (ER), the Kazakh Upland (WR) and the Russian Altai (NR) reveal spatially and temporally different Holocene vegetation and climate histories.
4. During the first half of the Holocene the WR was drier than present whereas the ER was moister than present. A shift towards wetter conditions occurred in the WR only during the second half of the Holocene, when the mid-latitudinal belt, stretching from the Baltic Sea to northern Kazakhstan and southern Siberia, came under the control of the Atlantic air masses. At the same time conditions in the ER became dry. Productivity of the steppes shifted from east to west at about 3 kyr BP, so migration movements of animal-keeping human communities proved by archaeological and historical records are the logical consequence.
5. The pollen/vegetation/climate records from the NR, however, display two precipitation maxima during past 12 kyr BP. While the early Holocene (summer monsoon-associated) maximum was more pronounced in the eastern part of the region, the late Holocene (westerly-associated) maximum could be better seen in the western part, in line with the records from the ER and WR, respectively.
6. Despite the more or less permanent presence of humans in the Mongolian Altai since the early Holocene, the absence of diagnostic anthropogenic indicators in the Hoton-Nur pollen and diatom records indicates that human disturbance of soils and vegetation cover was less significant than might have been expected. The emergence of mounted pastoralism after 3 kyr BP and well-documented use of wood to construct tomb chambers in the NR (2.9–2 kyr BP) occurred only after the main transformation from woodland to steppe in the ER was completed as the result of the climate change towards aridity.

Uncited references

Berger and Loutre, 1991; Birks and Koç, 2002; Schlütz and Lehmkuhl, 2007; Tarasov and Harrison, 1998; Yuan et al., 2004. Q6

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Appendix B. Supplementary data

Supplementary information for this manuscript can be found in the online version, at doi:10.1016/j.quascirev.2008.10.013.

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