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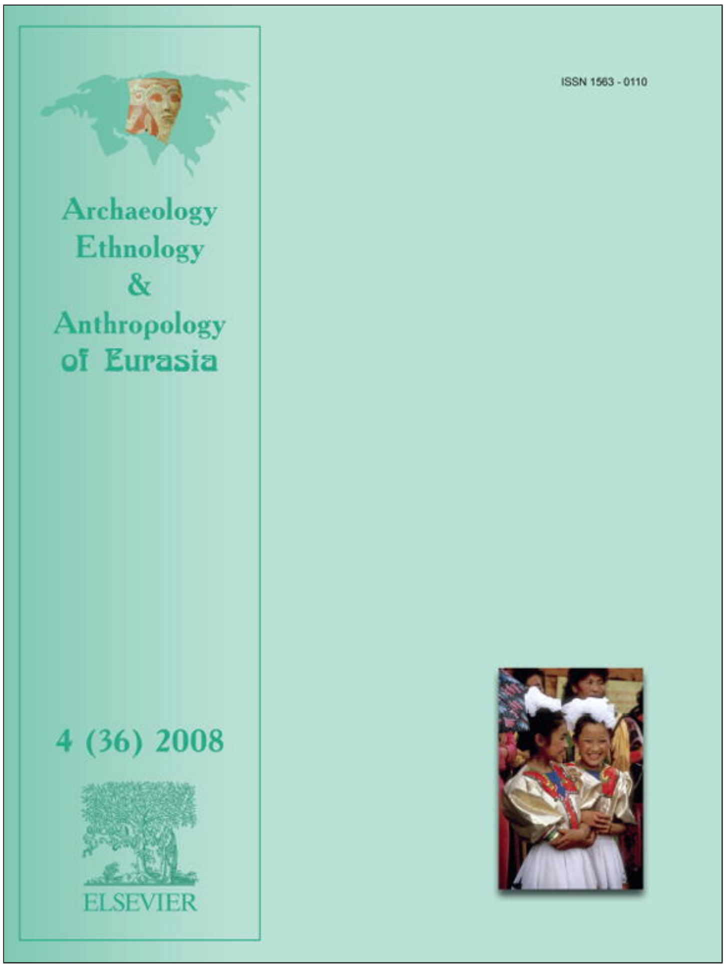

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PALEOENVIRONMENT. THE STONE AGE

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ENVIRONMENTAL CHANGES IN THE MONGOLIAN ALTAI DURING THE HOLOCENE*

Based on palynological and diatom analyses of the sediment core from Lake Hoton Nuur situated at 2083 m asl, environmental changes in the Mongolian Altai during the Holocene are described. The results suggest that the Late Pleistocene and Early Holocene (11.5–10.7 ka) climate of that area was cold and arid, and plant associations were of a steppe type. The Middle Holocene (9.3–6.5 ka) climate was warm and humid, resulting in the expansion of forests. After 6.5 ka, the climate became increasingly continental, and forests were largely replaced by tundra and steppe landscapes. Over the last 3000 years, the forests disappeared and the steppes expanded. The causes were likely not only climatic, but also anthropogenic.

Introduction

The Mongolian Altai, located in the central portion of Eurasia, serves as a watershed between rivers of the Arctic Ocean basin and the closed basin of Central Asia. It is characterized by an extreme continental climate, a special type of altitudinal zonality with a discontinuous forest belt, the development of tundra and cryophyte

*Paleoenvironmental interpretations presented in this article are not fully consistent with the later interpretations based on additional data and more robust quantitative analyses of the pollen and diatom records from Hoton Nuur and on the regional comparison with other paleoclimatic archives from northern Eurasia. We, however, would like to bring attention to the later publication: **N. Rudaya, P. Tarasov, N. Dorofeyuk, N. Solovieva, I. Kalugin, A. Andreev, A. Daryin, B. Diekmann, F. Riedel, N. Tserendash and M. Wagner.** 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. *Quaternary Science Reviews*, (in press), available online November 29, 2008.

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steppes in alpine regions as well as by a specific mosaic vegetation cover. The Mongolian Altai is a habitat of many rare and endemic animals and plants. The main economically exploitable natural resources such as forest, productive pastures, and sources of fresh water that have always attracted Central Asian nomads are concentrated in alpine regions. Although anthropogenic pressure on the Mongolian Altai is currently assessed as "moderate" (Ecosystems…, 2005), a tendency exists toward desertification and land degradation (Vegetation dynamics…, 1999; Ecosystems…, 2005).

Paleobiological and geochemical data derived from lake bottom sediments provide an integrated picture of environmental changes. Sediments drawn from the drainage basin accumulate in deepwater parts of lakes and incorporate remains of plants and animals inhabiting the basin and those of lacustrine organisms (Davydova, 1985; Battarbee, 1986; Battarbee et al., 2001).

The most extensive palynological study of bottom sediments of Mongolian lakes was conducted by the paleobotanic team of the joint Soviet-Mongolian expedition in the 1980s (Vipper et al., 1978, 1981; Dorofeyuk, Tarasov, 2000; Vegetation dynamics…, 1999; Tarasov, Dorofeyuk, Metel'tseva, 2000). E.M. Malayeva (1989) used pollen analysis for the examination of recent sediments from key sequences in Mongolia. Several studies published over the past decade address the reconstruction of climate and vegetation in Mongolia and are based on data derived from lake sediments of Uvs Nuur in the Great Lakes Basin (Grunert, Lehmkuhl, Walther, 2000) and of Telmen and Hovsgol in Central Mongolia (Peck et al., 2002; Fowell et al., 2003; Prokopenko et al., 2007).

The most detailed information concerning environmental and climatic changes in Central Asia in the Holocene comes from China (Winkler, Wang, 1993; Rhodes et al., 1996; Herzschuh et al., 2004, 2005, 2006; Wünnemann, Mischke, Chen, 2006; and others). Several publications are focused on the Late Pleistocene and Holocene environmental changes in Northern and Central Kazakhstan (Tarasov, Jolly, Kaplan, 1997; Kremenetski, Tarasov, Cherkinsky, 1997), and in the Russian Altai and Tuva (Blyakharchuk et al., 2004, 2007, 2008; Schlütz, Lehmkuhl, 2007). These works are supplemented by results of analysis of diatom (Westover et al., 2006) and chironomid remains (Ilyashuk B., Ilyashuk E., 2007) from the Altai and Tuva.

The present article addresses studies of Lake Hoton Nuur sediments. The lake is located on the eastern macroslope of the Mongolian Altai in Northwestern Mongolia (Fig. 1). Core sediments from an isolated bay were first subjected to pollen and diatom analyses in 1980 and a series of radiocarbon dates was obtained (Tarasov et al., 1996; Vegetation dynamics…, 1999). The analysis of the Hoton-1 profile was conducted with a low temporal resolution, and, although the general tendency of biotic and climatic changes in the region during the Holocene was established, the results do not allow for a detailed paleogeographic reconstruction (Tarasov, Dorofeyuk, Metel'tseva, 2000). In this article, we present the results of a high-resolution pollen and diatom analysis of deposits from the deep part of the lake (Hoton-2). Based on these results, we propose a reconstruction of environmental and climatic changes in the Mongolian Altai during the Holocene, and compare it with reconstructions for adjacent regions.

Natural setting

Lake Hoton Nuur (48°40′ N, 88°18′ E, 2083 m asl) is located in an intermontane tectonic depression in the

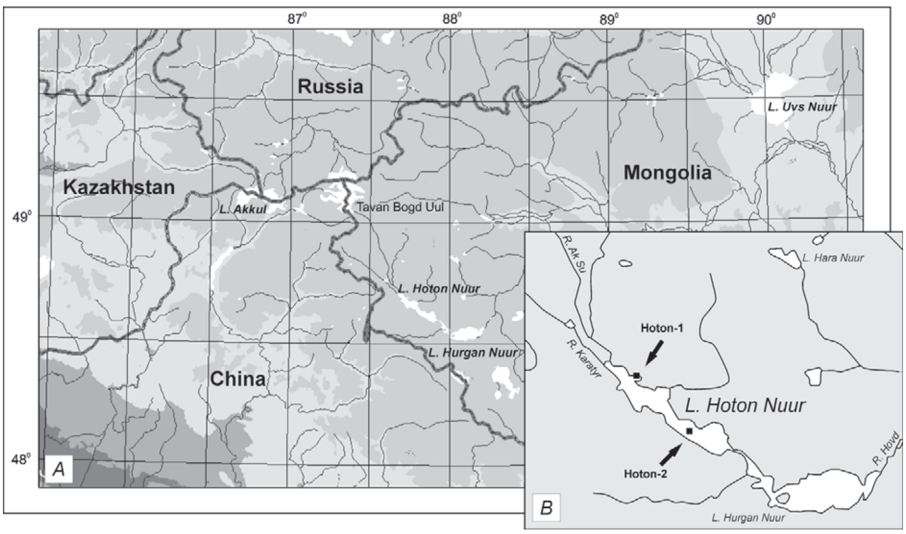

Fig. 1. Study area (*A*) and Hoton-1 and Hoton-2 drilling sites (*B*).

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northern portion of the Mongolian Altai (Fig. 1). Its surface area is 50.1 km^2; its length is approx. 21.5 km; the maximum width is 4.0 km; the average depth is 26.6 m; the maximum depth is approx. 58 m (Tarasov et al, 1994). This lake can be categorized as oligotrophic; the water is of the sodium bicarbonate group with mineralization of approx. 0.500 mg/l and pH = 7.5 (Sevastyanov et al., 1994).

The lake is primarily fed by the Karatyr and Ak Su rivers, as well as by some smaller streams flowing down the Altai slopes. The system of Hoton Nuur and Hurgan Nuur lakes, connected by a wide channel, is the source of the Hovd River which drains the whole Mongolian Altai. Lake Hoton Nuur was formed by glacial blockages, when the surface flow of the Karatyr and Ak Su was dammed by end moraines of the last Late Pleistocene glaciation (Khilko, Kurushin, 1982).

The Mongolian Altai is situated within the northern Gobi climatic province with an extremely continental climate that is characterized by low precipitation, persistent strong winds, and high-amplitude fluctuations of seasonal and diurnal temperatures. Winters are long and severe (mean January temperature is –24… –25 °C); short summers are cool (mean July temperature is approx. 12–15 °C) and moderately wet. The mean annual precipitation in the lake basin is approx. 250–300 mm (Natsionalny atlas..., 1990).

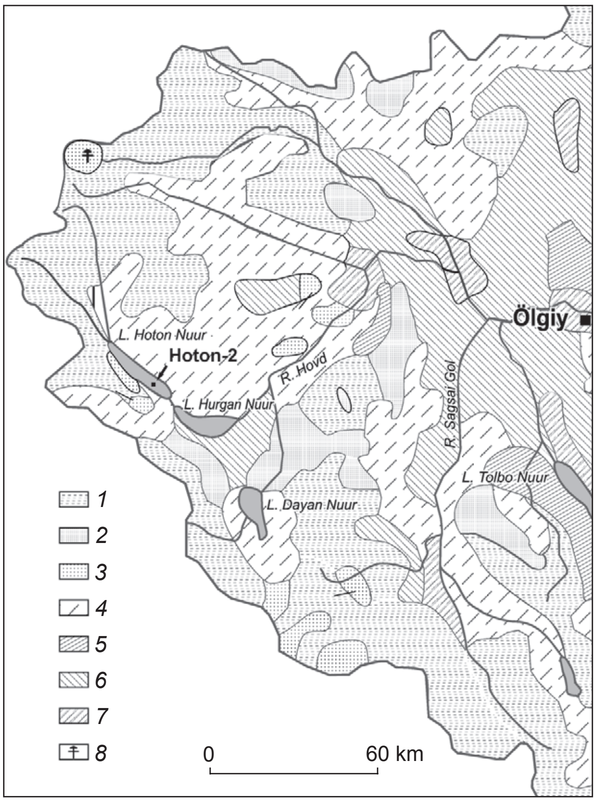

Fig. 2. Modern vegetation of the northern Mongolian Altai.

1 – lichen and moss-lichen tundra (*Cetraria*, *Cladonia*, *Alectoria*, *Aulacomnium*, *Polytrichum*); *2* – alpine kobresia and sedge vegetation (*Kobresia myosuroides*, *K. smirnovii*, *Carex stenocarpa*, *C. rupestris*); *3* – larch forests (*Larix sibirica*); *4* – cryophyte steppe (*Festuca lenesis*, *Oxytropis oligantha*, *Potentilla nivea*); *5* – forb and grass steppe (*Festuca lenesis*, *Poa attenuata*, *Koeleria macrantha*); *6* – dry forb and grass steppe (*Festuca lenensis*, *Agropyron cristatum*, *Potentilla sericea*); *7* – desert steppe (*Stipa glareosa*, *Anabasis brevifolia*); *8* – *Pinus sibirica*.

Lake Hoton Nuur is located in the alpine belt of the Mongolian Altai. The modern vegetation cover (Fig. 2) is mostly represented by dry mountain steppes with *Agropyron cristatum*, *Artemisia frigida*, *Arenaria meyeri*, *Potentilla sericea*, and *Astragalus brevifolia*. Cryophyte low bunchgrass and forb steppes (with *Festuca lenesis*, *Poa attenuata*, *Arenaria meyeri*, *Oxytropis oligantha*, *Androsace chamaejasme*) in combination with sedge (*Carex stenocarpa, C. rupestris*) and kobresian (*Kobresia myosuroides*, *K. smirnovii*) communities are spread on slopes in the northern part of the lake (Volkova, 1994).

The larch (*Larix sibirica*) is the most common tree in the lake environs. Larch forests with undergrowth composed of dwarf birch (*Betula rotundifolia*), grayleaf willow (*Salix glauca*), and a moss and grass cover of *Festuca altaica*, *Carex orbicularis*, *Hedysarum neglectum*, and *Aulacomnium turgidum* are spread in the upper reaches of the Ak Su River. Larch forests with Siberian spruce (*Picea obovata*) grow on mountain slopes in the southeastern part of the lake and along the river valleys. Siberian pine (*Pinus sibirica*), forming the timberline in the Russian Altai and the Sayans, occurs 50 km north of the lake, in the Ak Su valley (Grubov, 1982; Natsionalny atlas..., 1990). Lichen, moss, and yernik tundra (Volkova, 1994) appear at high altitudes (above 3000 m).

The Mongolian Altai is less densely populated than China, Kazakhstan, or the Russian Altai. The population of Bayan-Ölgiy aimag, where Hoton Nuur is situated, is just 18,000 (Natsionalny atlas..., 1990). The traditional lifestyle of the local population is nomadic, and animal breeding is the main occupation. Despite the low population density, anthropogenic pressure on the ecosystems in the river valleys and in the Hoton Nuur coastal area is currently assessed as moderate to high mainly due to overgrazing (Ecosystems..., 2005).

Data and methods

In 2004, in the southeastern part of Lake Hoton Nuur (48°37′18,1″ N, 88°20′45″ E), a bore was drilled at a depth of 35 m and a sediment core (Hoton-2) 257 cm long was obtained (Fig. 1, *B*). The core consists of two distinct sedimentary units: lower (257–205 cm) and upper (205–0 cm) separated by a cavity that was possibly formed in place of an ice lens. A sharp boundary between the units suggests a sedimentary hiatus. Generally, the sediments

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are rather homogeneous; they are represented by striate clay aleurite with organic admixtures (3–4 %) underlain by grayish-blue clay at a depth of approx. 205 cm. The granulometric analysis indicated that the average diameter of particles changes with respect to intervals as follows: 257–190 cm: 10–20 µm; 190–50 cm: 20–30 µm, 50–0 cm: 15–20 µm. Microscopic examination revealed particles of quartz, feldspar, light and brownish mica in the core sediments. The sediment composition changes in the interval between 185 and 150 cm: the content of Fe_2O_3, TiO_2, and MgO slightly increases; the content of SiO_2 decreases; magnetization decreases.

A low organic content in the core sediments caused a serious problem for radiocarbon dating. Ten samples containing an insignificant amount of organic remains were sent to the radiocarbon laboratory of Kiel University (Germany). Six of them proved to be insufficient for accelerator-mass spectrometer (AMS) dating. Two samples yielded dates older than 53 ka BP, i.e. beyond the limits of the radiocarbon method. A sample taken from a depth of 236.5–237 cm was dated to 32,450 ± 380 BP (Table 1), suggesting that the lower unit of grayish-blue clay was accumulated during the Late Pleistocene and before the last glacial maximum or, alternatively, that this date, too, is erroneous (too old). Thus, only the date of 9130 ± 40 BP obtained for the 174.5–175 cm level seems to be reliable. In order to provide better chronological control and to construct a depth/age model for the Hoton-2 core, radiocarbon dates generated in 1980 for the Hoton-1 core (Table 2) from a small bay in the northeast part of the lake at a depth of 4.8 m (Fig. 1, *B*) were used. Samples were taken near the shore, from the half-closed bay with stable sedimentation conditions and high organic matter content. As a result, a sequence of six radiocarbon dates within the range spanning the interval between 9070 and 2950 BP was obtained (Vegetation dynamics…, 1999; Tarasov, Dorofeyuk, Metel'tseva, 2000). The dates were calibrated (CalPal…) and used as a basis for the chronological model of the Hoton-1 core. The comparison of Hoton-1 and Hoton-2 pollen spectra revealed 13 matching events in the changes of proportions of 21 taxa. Based on the correlation of these events using calibrated dates for Hoton-1, the depth/age model for Hoton-2 was constructed (excluding the lower part of the sequence). The model represents a regression line with a second-degree polynomial fit (Fig. 3).

One hundred samples (1–2 grams of dry sediment each) were taken for pollen analysis using a standard procedure (Faegri, Iversen, 1989). Pollen grains and spores were counted under a light microscope with ×400 magnification. *Lycopodium* spore tablets were added to each sample in order to calculate the pollen and spore concentration. Taxonomic identification was performed using reference pollen collections and atlases (Kupriyanova, Alyeshina, 1972, 1978; Reille, 1992, 1995, 1998). In total, 54 pollen and spore taxa were identified, which is 2.5 times more than in the Hoton-1 core (Tarasov, Dorofeyuk, Metel'tseva, 2000). The palynological analysis revealed good preservation and a relatively high concentration of pollen and spores in the upper part of the

Table 1. **Dates generated on organic remains from the Hoton-2 core**

Depth, cm	Date BP		Laboratory code
	^{14}C	Calibrated	
49.5–50.0	55,000 + 5220/–3140	–	KIA32074
144.5–145.0	53,580 + 2870/–2110	–	KIA32075
174.5–175.0	9130 ± 40	10,304 ± 56	KIA32076
236.5–237.0	32,450 ± 380	36,987 ± 815	KIA29869

Table 2. **Dates generated on gyttja from the Hoton-1 core***

Depth, cm	Date BP		Laboratory code
	^{14}C	Calibrated	
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	10,195 ± 229	TA-1419

*After (Tarasov, Dorofeyuk, Metel'tseva, 2000).

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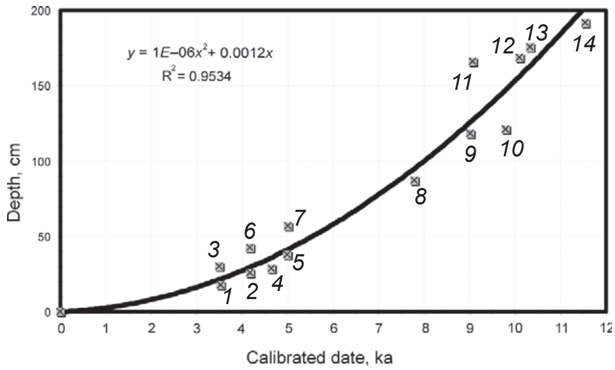

Fig. 3. Depth/age model for the Hoton-2 core sediments. Palynological events reflected by both pollen spectra (Hoton-1 and Hoton-2): *1* – maximum concentration of herbaceous pollen, especially of wormwood; *2* – decrease in concentration of herbaceous pollen (especially of wormwood) and a slight increase in concentration of arboreal pollen; *3* – maximum concentration of Chenopodium pollen; *4* – maximum concentration of herbaceous pollen (especially of wormwood) and decrease in concentration of arboreal pollen; *5* – maximum concentration of ephedra pollen and decrease in concentration of herbaceous pollen (especially of wormwood); *6* – maximum concentration of Siberian pine pollen; *7* – beginning of increase in concentration of wormwood and Chenopodium pollen and decrease in concentration of Siberian spruce pollen; *8* – maximum concentration of Siberian spruce pollen; *9* – maximum concentration of Siberian larch pollen; *10* – beginning of increase in concentration of herbaceous pollen; *11* – maximum concentration of arboreal pollen; *12* – increase in concentration of Siberian spruce pollen; *13* – AMS date of 10,304 ± 56 cal. BP for the Hoton-2 core; *14* – decrease in concentration of Siberian spruce pollen.

sequence (0–205 cm) – up to 500 grains per sample, while in the lower part of the core, the concentration is rather low (often less than 100 grains per sample) and insufficient for the statistical analysis (Faegri, Iversen, 1989). Therefore, percentages of all pollen taxa (relative to the pollen sum of all taxa) were calculated only for the upper part of the core, with the exception of spores, conifer stomata, and other non-pollen palynomorphs (NPP).

Samples prepared for the palynological analysis were also used for counting conifer stomata and other NPP. All the identified stomata from Hoton-2 belong to the genera *Picea* and *Larix* (identification according to (Trautmann, 1953; Sweeney, 2004)). NPP represented by fungi spores (*Glomus*), remains of green algae colonies (*Botryococcus braunii*, *Pediastrum* cf. *boryanum*), eggs of tardigrades (*Macrobiotus hibernicus*, *M. hufelandi*), and chironomid remains (*Cladotanytarsus*, *Mesocricotopus*) were identified using published descriptions, pictures, and photographs (Jankovska, 1991; Van Geel, 2001; Komarek, Jankovska, 2001).

Fifty-eight samples taken with a five-centimeter step were prepared for diatom analysis using the standard technique and disintegration method in hydrogen peroxide (Diatomovye vodorosli..., 1974; Battarbee, 1986). Then aliquots of evaporated suspensions were embedded in Naphrax. Diatoms were identified under a light microscope with phase-contrast oil immersion objectives with ×750 magnification and an ocular scale. At least 500–600 diatom valves per sample were counted on horizontal transects in the middle part of the cover glass. A concentration (total and that of separate species) in 1 gram of solid residue was qualitatively assessed using the technique and formula suggested by N.N. Davydova (1985). The concentration of each species was calculated relative to the total amount of diatoms. The following scale was established: below 1 % – rare; 1–5 % – common; 5–10 % – subdominant; and above 10 % – dominant.

In terms of attribution to biotopes, diatoms were subdivided into planktonic, benthic, and periphytic. With regard to water salinity, algae were classed into freshwater and mesohalobic. The former are represented by halophobous (living in water with a salt content less than 0.2 %), indifferent (0.2–0.3 %), and halophilic (0.4–0.5 %). Mesohalobic diatoms prefer water with a salt content exceeding 0.5 %. In relation to medium reaction, algae can be subdivided into acidophilic (water with pH < 7), circumneutral (pH ≈ 7), alkaliphilic ((pH ≥ 7), and alkalibiontic ((pH > 7). According to principal types of distribution areas, the following geographic groups were established: arctoalpine, boreal, and cosmopolitan.

Pollen and diatom diagrams were constructed using TILIA and TILIAGRAPH software (Grimm, 1991). Pollen and diatom zones were established using CONISS software (Grimm, 1987).

Results of pollen analysis

On the spore and pollen diagram, five pollen zones (PZ) are evident (Fig. 4).

PZ 5 (257–205 cm; up to 1800 grains/cm^3; the upper boundary of the zone is dated to ca 11,500 BP)*. Because of a low pollen concentration, taxa percentages were not calculated. Pollen of non-arboreal plants (Chenopodiaceae, *Artemisia*, Cyperaceae) and of desert/semidesert *Ephedra* is the most common. Isolated grains of *Picea obovata*, *Pinus sibirica*, and *Larix sibirica* are present.

PZ 4 (205–175 cm; up to 21,000 grains/cm^3; ~11,500–10,700 BP). Herbaceous taxa (including Chenopodiaceae and *Artemisia*) prevail and form up to 85 %. A characteristic feature of this zone is a significant percentage of *Ephedra* pollen (up to 15 %). Pollen of *Picea obovata* dominates the group of arboreal taxa. Pollen grains of *Pinus sibirica* and *Larix sibirica* are also encountered.

PZ 3 (175.0–97.5 cm; up to 25,000 grains/cm^3; ~10,700–7900 BP). This zone is characterized by a

*Here and below, all dates are given in calibrated form.

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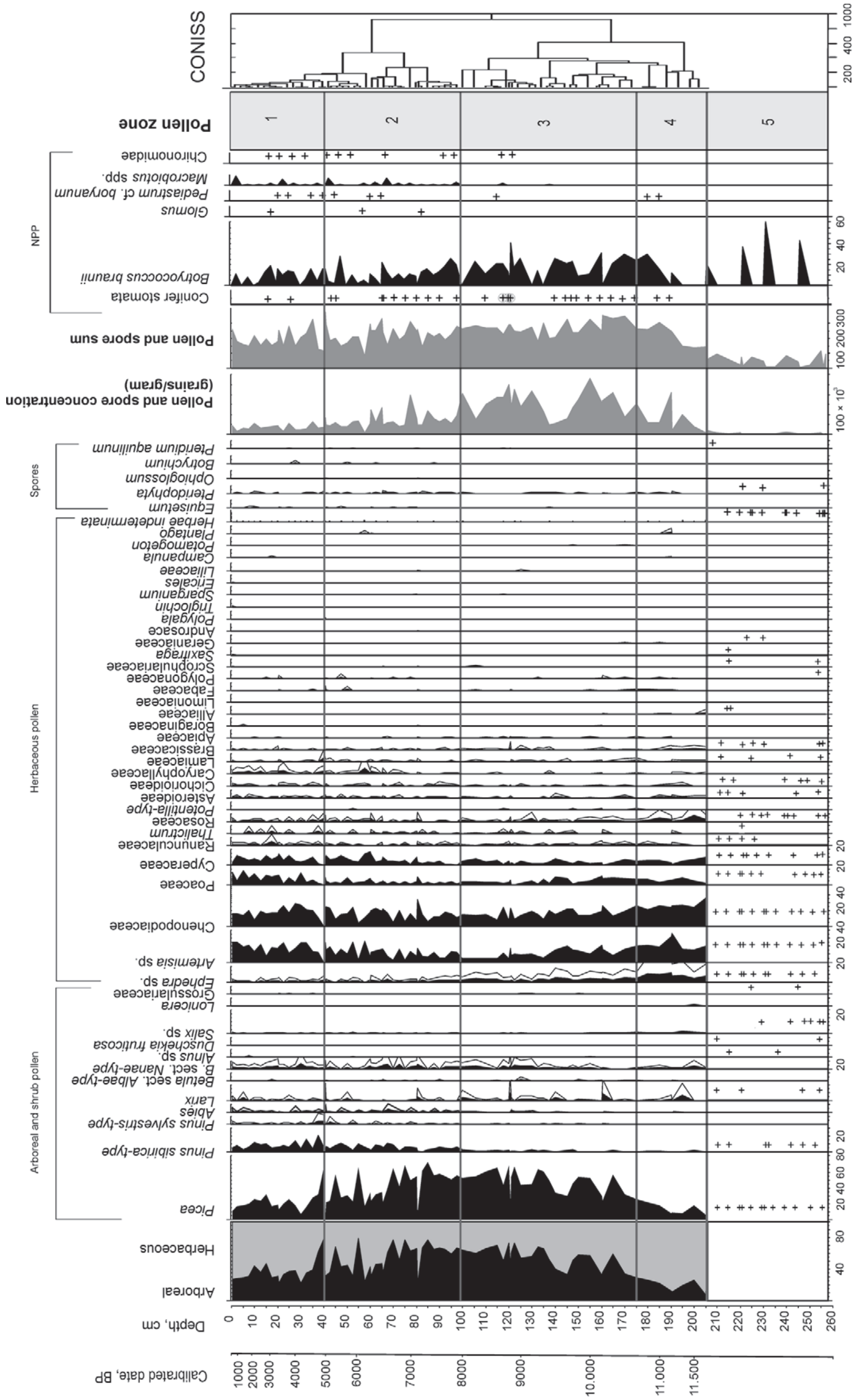

Fig. 4. Spore-pollen diagram for Hoton Nuur lake sediments (Hoton-2).
○ – presence of *Picea* stomata; + – presence of *Larix* stomata.

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dramatic increase of arboreal (up to 75 %) and decrease of herbaceous pollen. The share of *Picea obovata* reaches 70 %. Pollen grains of *Pinus sibirica*, *Larix sibirica*, and *Betula* sect. *Nanae* become more abundant. The percentage of Chenopodiaceae and *Artemisia* decreases.

PZ 2 (97.5–40.0 cm; up to 20,000 grains/cm^3; ~7900–4900 BP). A characteristic feature of this zone is a sharp change in the percentages of arboreal and herbaceous pollen, especially in the ratio of *Picea obovata* pollen (it varies from 10 to 75 %). The share of *Pinus sibirica* increases; the percentage of *Abies sibirica* reaches its maximum of 4 %. Among herbaceous taxa, the dominant ones are *Artemisia*, Chenopodiaceae, Poaceae, and Cyperaceae.

PZ 1 (40–0 cm; up to 6320 grains/cm^3; ~4900–0 BP). The general reduction of arboreal pollen (due to a decrease in the concentration of *Picea obovata* pollen to 10–40 %) is noteworthy. At the same time, the share of *Pinus sibirica* slightly increases. The percentage of non-arboreal pollen rises to 60–70 %. Pollen of *Artemisia*, Chenopodiaceae, Poaceae, and Cyperaceae still prevails.

Results of NPP analysis

One of the notable features of the Hoton-2 spectrum is the presence of larch and pine stomata in all pollen zones, with the exception of PZ 5 (Fig. 4). Despite their scarcity (maximum five stomata in a sample), they are rather often encountered in PZ 3 and 2; isolated stomata are present in PZ 4 and 1.

Other NPP are represented by remains of *Botryococcus braunii*, which appear in PZ 5 and are persistently present in PZ 3 and 1. *B. braunii* is a widely distributed alga that can be found in oligotrophic lakes and estuaries from the Arctic zone to low latitudes (Tyson, 1995; Smittenberg et al., 2005). PZ 1–4 contain remains of *Pediastrum* cf. *boryanum*. Eggs of tardigrades (*Macrobiotus hibernicus* and *M. hufelandi*) and jaws of *Cladotanytarsus* and *Mesocricotopus* (Chironomidae, Diptera) are present in sediments younger than 9000–9450 years (PZ 3). PZ 2 and 1 contain isolated chlamydospores of *Glomus*.

Results of diatom analysis

The diatom flora of Hoton Nuur is represented by 295 taxa belonging to 67 genera. The list of diatom taxa identified by Dorofeyuk and Tsetsegmaa (2002) has been supplemented by ninety new taxa first discovered in deepwater sediments. Thirteen taxa have been recorded in Mongolia for the first time: *Cyclotella operculata* var. *unipunctata*, *Amphora dusenii*, *Brachysira brebissonii*, *Caloneis tenuis*, *Cavinula jarnefeltii*, *C. lacustris*, *Cymbella behrei*, *Diploneis domblitensis*, *Eunotia polydentula*, *Gomphonema abbreviatum*, *Luticola* crf. *undulata*, *Navicula farta*, *Stauroneis sibirica*. Centric diatoms are represented by 21 taxa with *Cyclotella* (10) and *Aulacoseira* (5) being the most diverse. Pennate diatoms are mainly represented by the genera *Gomphonema* (15 taxa), *Cymbella* and *Navicula* (12 species each), and *Eunotia* (11 species).

In the dominant diatom complex (DC) of Hoton-2, centric planktonic species prevail: *Aulacoseira distans* f. *distans*, *A. italica* var. *italica* + var. *tenuissima*, *Cyclotella bodanica* var. *bodanica*, *C. ocellata*, *Ellerbeckia arenaria* var. *teres*, *Stephanodiscus minutulus*. At various stages of the lake evolution, it comprised Pennate diatom subdominants: *Achnanthidium minutissimum* var. *minutissimum*, *Campylodiscus noricus* var. *noricus*, *Cymbella delicatula*, *Martyana martyi*, *Navicula farta*, *Pseudostaurosira brevistriata*, *Staurosira construens* f. *construens*, *Staurosirella pinnata* var. *pinnata*.

The ecogeographic structure of the DC is shown in Fig. 5; the graph in Fig. 6 illustrates its evolution. Five diatom zones (DZ) have been established.

DZ 5 (257–205 cm; the upper boundary of the zone is dated to ca 11,500 BP). The DC is represented by planktonic *Cyclotella ocellata* typical of littoral plankton of oligotrophic, relatively shallow lakes; *C. bodanica*, a stenothermal species growing in the pelagic zone of deep lakes; and *Staurosirella pinnata*, a periphytic species widespread in plankton. Three phases were established in the evolution of this zone. Phase 5c (257–250 cm; 9.2–13.1 million valves/gram; 31–48 taxa) is dominated by *C. ocellata.* Phase 5b (250–235 cm; 3.1–7.5 million valves/gram; 32–40 taxa) is characterized by prevailing *C. bodanica*; *S. pinnata* is the second most frequent diatom; and *C. ocellata* occupies the third place. At a depth of 235 cm, *S. pinnata* dominates the DC. At phase 5a (235–250 cm; 4.5–22 million valves/gram; 58 taxa), *C. ocellata* becomes dominant again; *C. bodanica* and *S. pinnata* occupy alternately the second and third place.

DZ 4 (205–175 cm; 69 million valves/gram at a depth of 185 cm and 9 million valves/gram in the upper portion of the zone; 39–58 taxa; ~11,500–10,700 BP). All characteristics of DC are unstable. The dominant group of diatoms is the most variable. In most samples, *S. pinnata* and *C. bodanica* are the dominant species. *C. ocellata*, being the most frequent at the upper margin of the zone, becomes a co-dominant species and then falls out of DC. A characteristic feature of this zone is an intrusion of *Aulacoseira italica* into the DC. This planktonic species is widely distributed in continental mesotrophic and eutrophic waters. Starting from DZ 4, a slight, though noticeable increase in acidophilic species due to a higher content of *A. distans* can be observed (Fig. 4).

DZ 3 (175–70 cm; ~10,700–6600 BP). Two phases were established for this zone. At phase 3b (175.0–130.5 cm; 60–81 million valves/gram; ~10,700–9150 BP),

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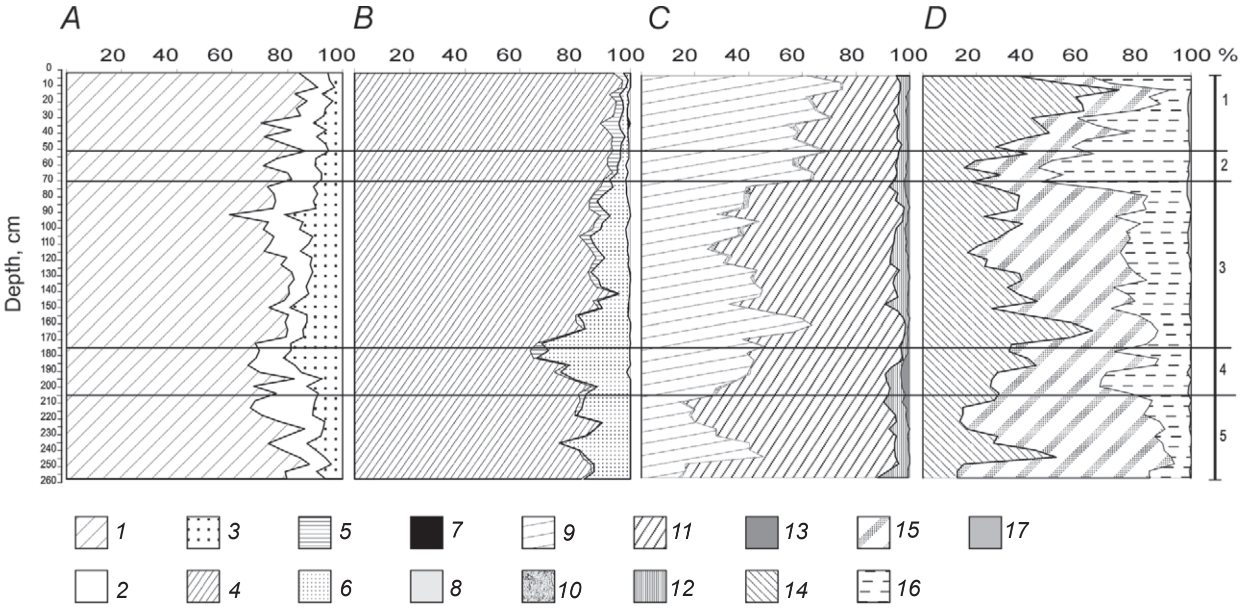

Fig. 5. Ecogeographic groups of diatoms for Hoton Nuur lake sediments (Hoton-2).
A – with regard to biotopes: *1* – planktonic, *2* – periphytic, benthic, *3* –benthic; *B* – with regard to water salinity: *4* – indifferent, *5* – halophobous, *6* – halophilic, *7* – mesohalobic, *8* – ecologically indistinct species; *C* – with regard to medium reaction: *9* – circumneutral, *10* – acidophilic, *11* – alkaliphilic, *12* – alkalibiontic, *13* – ecologically indistinct species; *D* – with regard to principal types of distribution areas: *14* – arctoalpine, *15* – boreal, *16* – cosmopolitan, *17* – others.

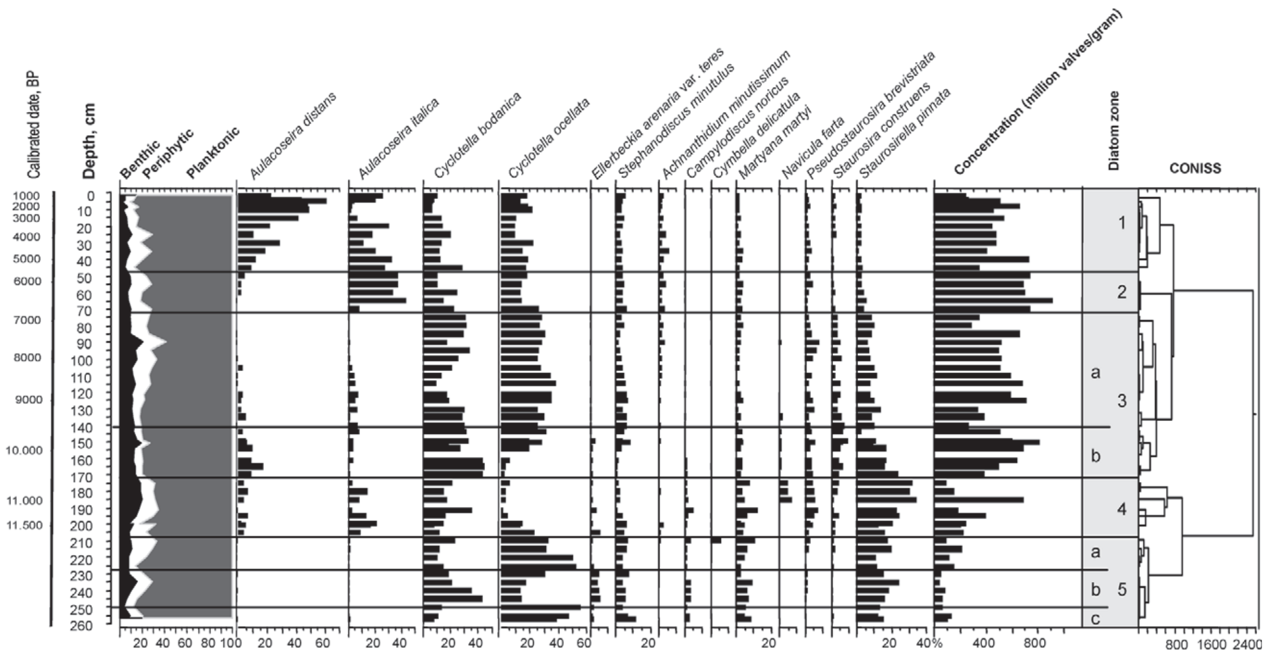

Fig. 6. Graph showing changes in the species composition of diatoms from Hoton Nuur (Hoton-2).

pelagic species *C. bodanica* dominates and *S. pinnata* co-dominates the DC. At phase 3a (130.5–70.0 cm; 28–70 million valves/gram; ~6600–9150 BP), *C. ocellata* dominates, shifting *C. bodanica* to the co-dominant position. Only in samples taken from a depth of 75–80 cm, does *C. bodanica* become the dominant species.

DZ 2 (70–50 cm; 69–91 million valves/gram; ~6600–5500 BP). This zone is characterized by dominating planktonic *Aulacoseira italica* var. *italica* and its ecological form *A. italica* var. *tenuissima* growing in mesotrophic and eutrophic lakes (Diatomovye vodorosli..., 1992). *C. ocellata* and *C. bodanica* are co-dominant in this zone.

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DZ 1 (50–0 cm; 23–73 million valves/gram; ~5500–0 BP). The planktonic species *Aulacoseira distans* prevails in DC. Other dominant species are *A. italica*, *C. ocellata* and *C. bodanica*. This zone is characterized by an increased percentage of acidophilic algae valves (up to 62 % at a depth of 5 cm) suggesting significant acidification of lake water (Fig. 4).

Interpretation of results

Climate of the Mongolian Altai during the Holocene. The lower part of the Hoton-2 core can be attributed to the final Pleistocene (ca 11,500 BP). The end of the Pleistocene and the beginning of the Holocene in the Mongolian Altai was characterized by a continental cold and dry climate. Continental features increased (the climate became dryer, though not warmer) between ~11,500 and ~10,700 BP. The decrease in continentality accompanied by development of forests began after ~10,700 and continued through the Middle Holocene. The most humid climatic conditions coincided with the period between 9300 and 6500 BP. Around 8000 BP, a slight cooling of the climate occurred. Aridity and continentality started to increase gradually after ~6500 BP. This tendency still persists.

Holocene history of Lake Hoton Nuur. The results of diatom and NPP analyses can be used to reconstruct the history of Lake Hoton Nuur. In the Early Holocene (~11,500 BP), the lake level was the highest and the water was the coldest for the entire reconstructed period. During the period between 11,500 and 10,700 BP, the cold oligotrophic phase passed into a shallow and mesotrophic one. The diatom complex of the Early to Middle Holocene transition is typical of deep-water oligotrophic and cold mountain lakes (with the exception of a short period between ~10,000 and ~9800 BP, when the lake level was low). The high lake level and oligotrophic conditions persisted up to ~6600; then the level gradually went down and presumably reached its minimum within the interval of 6600–5500 BP. The appearance and then the permanent presence of jaws of deep-water chironomids in Hoton-2 sediments suggests that, despite the progressive lowering of the level, the lake remained rather deep.

The Late Holocene diatom complex corresponds to a cold phase in the lake evolution. At the same time, a significant increase in water acidity (possibly associated with the lixiviation of base cations in soils of catchment basins) was recorded. This process could have been caused by climate changes, irregularities in the drainage regime due to forest fire and wind erosion, massive anthropogenic impact, and the transformation of soil and vegetative cover in the drainage area (Battarbee et al., 2001). The significant reduction of territories occupied by coniferous forests and expansion of steppe in the drainage basin in the Late Holocene resulted in the lixiviation of base cations in humus horizons and their ingression into the lake.

Holocene history of vegetation in the Mongolian Altai. In the final Pleistocene/initial Holocene, cryophyte and cryoxerophyte communities dominated by sedge and kobresia spread in the high mountain zone of the Mongolian Altai, while dry forb-grass steppes developed in its mid-elevation regions. In the Early Holocene (~11,500–10,700 BP), the vegetation cover composition did not undergo a significant change, though the increased share of ephedra pollen in palynological spectra might suggest the wider spread of desert-steppe communities during this time period.

From ca 10,700 BP, in the high mountain areas of the Mongolian Altai, tundra communities began to replace cryophyte steppes and sedge cryoxerophyte communities. At the same time, the forest vegetation (primarily forests composed of Siberian pines and Siberian larches) spread in the environs of Hoton Nuur, which is evidenced by the presence of conifer stomata in lake bottom sediments. They are indicative of coniferous trees (irrespectively of the concentration of conifer pollen in spectra) (Sweeney, 2004) growing within a radius of 29 m from the place where the samples were taken (Parshall, 1999). This fact is quite relevant for reconstructing the distribution area of larches around the lake, since, although the Siberian larch is the most common arboreal species in the Mongolian Altai (Volkova, 1994; Vegetation dynamics…, 1999), its pollen in the ancient spectra is usually sparse and poorly preserved (Pisaric et al., 2001), negatively affecting the validity of environmental reconstructions.

The maximum development of dark coniferous taiga occurred between 9300 and 6500 BP. Around 8000 BP, yernik tundra spread more widely at high altitudes. Diminution of forest areas paralleled by expansion of desert-steppe and steppe communities proceeded between ca 6500 and 5000 BP. This process continued after ~5000 BP. Tundra, steppe, and desert-steppe elements became important factors in the formation of the vegetation cover.

The period from 3000 BP down to the present time is characterized by progressing deforestation and the expansion of meadow steppe, cryoxerophyte communities dominated by sedge and kobresia, alpine tundra with dwarf birch and willow, as well as desert-steppe associations with wormwood and goosefoot. Coniferous forests were preserved possibly only on the western macroslope of the Mongolian Altai and in river valleys.

Palynological and NPP data derived from Hoton-2 sediments provide no evidence of significant human impact on the regional environments. Eggs of tardigrades (*Macrobiotus*), constantly present in spectra after ~8000, suggest unpolluted ecotopes (Jankovska, 1991).

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Chlamydospores of *Glomus* indicative of soil erosion in the lake basin, including that resulting from human activities (Van Geel et al., 2003), are extremely rare in the Hoton-2 core. Only diatom analysis shows a sharp increase in the percentage of acidophilic algae *Aulacoseira distans* within the interval of 2900–1200 BP. *Aulacoseira* species require a high silica content in the water. However, they are noncompetitive, so their wide distribution normally coincides with periods characterized by a low concentration of other diatoms (Wolfe et al., 2000). Such conditions might reflect climatic cooling or an increased anthropogenic impact (Battarbee et al., 2001).

Between 3000–2000 BP, tribes inhabiting the Mongolian Altai shifted to nomadic pastoralism (Novgorodova, 1989; Jacobson, 2001). The 1st millennium BC was characterized by population growth (Novgorodova, 1989). Thus, increased anthropogenic pressure could be one of the factors that caused the environmental changes in the Hoton Nuur basin.

Discussion

Evidence of an arid and cold climate that favored the development of cryophyte steppe in the Mongolian Altai in the Early Holocene has been also recorded in contiguous regions. In the final Pleistocene, dry and desertified steppes spread in intermontane basins of Northwestern Mongolia (Lake Achit Nuur). Even in basins and high altitude regions of the Khangai and the Khentei (Central Mongolia), forest and tundra communities were replaced by dry steppe (Vegetation dynamics…, 1999).

North of the Mongolian Altai, a cold and dry climate in the Early Holocene was reconstructed for the Russian Altai and Tuva (Blyakharchuk et al., 2004, 2007, 2008; Westover et al., 2006; Ilyashuk B., Ilyashuk E., 2007). In the southeastern portion of the Mongolian Altai and in Tuva, alpine meadow area coverage decreased, while wormwood steppe with ephedra in combination with yernik tundra expanded. The central part of the Russian Altai (which at present is covered by forest) was totally occupied by woodless tundra-steppe adjoining high altitude areas. In Northern Kazakhstan, the final Pleistocene/initial Holocene was characterized by the spread of wormwood and goosefoot communities with patches of birch forests (Tarasov, Jolly, Kaplan, 1997).

A period of maximum humidity and expansion of forests (9300–6500 BP) has been also recorded in regional environmental schemes of Central Mongolia. In the Middle Holocene, even the northwestern areas of modern desert steppes were covered by forest, mostly consisting of Siberian larch and Siberian pine (Vegetation dynamics…, 1999; Dorofeyuk, Tarasov, 2000).

In the Russian Altai, the forest belt formed between 9000 and ~6000 BP. Steppe communities were preserved only in intermontane basins and on south-facing slopes (Blyakharchuk et al., 2004). The area covered with dark coniferous taiga reached its maximum size ca 9500–7500 BP. Around 7500–6500 BP, Siberian spruce and Siberian fir disappeared; forests dominated by Siberian pine and Siberian larch prevailed in the vegetation cover. In Tuva, the development of coniferous forests with Siberian pine, Scots pine (*Pinus sylvestris*), Siberian larch, Siberian fir, and Siberian spruce in the Early and Middle Holocene has been also documented (Blyakharchuk et al., 2008). In Northern Kazakhstan, the climate also tended to become warmer and wetter: steppe communities grew in combination with birch forests (8600–8000 BP); Scots pine appeared in the Irtysh River basin in ca 7300 BP (Kremenetski, Tarasov, Cherkinsky, 1997; Tarasov, Jolly, Kaplan, 1997).

The shift from a dry continental climate to more humid conditions that occurred during the Middle Holocene has been also recorded in Northwestern China (Rhodes et al., 1996; Wünnemann et al., 2006). In the Dzungarian Gobi (Lake Manas in Xinjiang), the climate was the warmest and most humid over the period of 8300–6800 BP, when desert vegetation was replaced by wormwood steppe (Rhodes et al., 1996). In Inner Mongolia, the Early Holocene was characterized by increasing humidity and spreading arboreal vegetation between 9200 and 6500 BP (Jiang et al., 2006). Climate cooling occurred after 8000 BP in that region. The present authors recorded a synchronous event in the Mongolian Altai. On the Tibetan Plateau, the most arid area of Central Asia, increasing humidity and the reduction of continentality between 10,800–4400 BP resulted in the development of temperate steppe and sub-alpine shrubs (Herzschuh et al., 2006).

Around 6000–4900, the climate in the Mongolian Altai became more and more continental. Forest areas decreased due to the expansion of dry steppe. Similar events occurred in the Russian Altai and Tuva after 6500 BP. The climate became colder and more continental. Siberian pine forests covered the Russian Altai; cryophyte meadow and wormwood steppes developed in intermontane basins (Blyakharchuk et al., 2004, 2007, 2008; Ilyashuk B., Ilyashuk E., 2007).

In northwestern China (Dzungarian Gobi), the climate became more arid between 6800–5100 BP (Rhodes et al., 1996; Wünnemann et al., 2006). In Inner Mongolia, an increase in continentality accompanied by diminution in the deciduous forest areas and the development of coniferous forests occurred between 6500 and 5100 BP (Jiang et al., 2006).

Over the past 3000 years, the tendency toward increasing continentality and declining forest areas persisted in the Mongolian Altai. Remains of coniferous

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wood from a small basin in the Gobi Altai (Bayan Sayr, 45°34′20″ N; 96°54′36″ E) dated to 5000–3000 BP (Dinesman, Kiseleva, Knyazev, 1989) suggest that in the Late Holocene, patches of coniferous forest existed in appropriate ecozones located south of their modern habitat. The most recent dates obtained for fir and spruce are 3829 ± 159 BP and 4229 ± 330 BP, respectively. Remains of larch wood found in the Gobi Altai (Uert Am, 45°37′48″ N; 96°49′48″ E) are dated to 2171 ± 119 BP. The fact that no larch grows in this region today can be explained by increased economic activity.

Cooling and decreased humidity in the southwestern portion of the Russian Altai and in Tuva was recorded over the past 4000 years. Cold winters were conducive to permafrost formation and the spread of alpine tundra and cryophyte steppe. Over the past 3000 years, diminution of forest areas in Tuva can be attributed to increased grazing (Blyakharchuk et al., 2004, 2007, 2008). In Inner Mongolia, the Late Holocene (after 2600 BP) was also characterized by climate aridization and the development of steppe communities (Jiang et al., 2006).

In sum, the reconstruction of Holocene environments in the Mongolian Altai based on palynological and diatom analyses of the Lake Hoton Huur sediments agrees with regional schemes of climatic and vegetation changes in Northwestern and Central Mongolia, Northern Kazakhstan, and the highlands of Southern Siberia, North and Northwestern China. The intensification of pastoralism and deforestation, caused by both human activities and climate, could be an important factor influencing environmental changes in the Mongolian Altai during the Late Holocene.

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