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CHRONOLOGY OF HOLOCENE CLIMATE AND VEGETATION CHANGES AND THEIR CONNECTION TO CULTURAL DYNAMICS IN SOUTHERN SIBERIA

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ABSTRACT. Two sediment sequences from Big Kyzylkul Lake and the Shushenskoe paleolake in the Minusinsk depression, Southern Siberia, were studied by pollen, microfossil, and geochemical analyses, as well as radiocarbon dating. The records indicate the persistence of an arid period between ~11.7–7.6 cal kyr BP, increased effective moisture since ~7.6 cal kyr BP, 2 humid impulses at ~5.1 and 2.8 cal kyr BP separated by a dry interval, and the return to generally drier conditions after ~1.5 cal kyr BP. This is contrary to the findings noted for the Eurasian temperate zone, but agrees with proxy data reported for arid and semi-arid zones of Central Asia. Reconstructed changes in climate and environment are in good agreement with archaeological data. Almost no evidence of the Mesolithic-Neolithic cultures has been reported for the depression, which is consistent with a dry early and mid-Holocene. Effective moisture started to rise from ~7.6 cal kyr BP, followed by the beginning of human occupation at ~6 cal kyr BP. Two maxima of humidity are recorded in the late Holocene, corresponding to the arrival of trees in the depression. No gap was to be found from the Early Bronze to the Iron ages cultures at this time, with the exception of a dry interval at ~3.6–3.3 cal kyr BP, when the Minusinsk depression was sparsely occupied. The data obtained suggest a close relationship between climate change and cultural dynamics in the steppe zone of Southern Siberia.

INTRODUCTION

Archaeological studies in Southern Siberia have continued over the last 2 centuries. The regional cultural history has been well investigated (Vadetskaya 1986; Bokovenko et al. 1992) and supported by a large radiocarbon database (Alekseev et al. 2001; GÖrsdorf et al. 2001, 2004; Zaitseva and van Geel 2004; Zaitseva et al. 2005). Nevertheless, some cultural events appear to have no archaeological explanation. Thus, in contrast to European Russia, evidence for the Mesolithic and Neolithic cultures (~11–6 cal kyr BP) is practically absent in the intermountain depressions of Southern Siberia, including south of the Krasnoyarsk Province and in Khakassia (Zaitseva and van Geel 2004). Human occupation started at the end of the Neolithic period and became more intense in the Late Bronze Age (~3.3–2.9 cal kyr BP). An increase in the density of human population is reported for the area at the transition from the Bronze to Iron ages (~2.8 cal kyr BP), when the most impressive Scythian cultures emerged (van Geel et al. 2004). We suggest that Holocene climate change could be one of the factors affecting regional cultural development.

Not much is known about the Holocene climate and environments of Southern Siberia. This large area comprises intermountain depressions within the Altai and Sayan mountain systems. A chain of isolated depressions belonging to the ancient steppe belt in the center of Asia extends from the Siberian temperate forests in the north to the desert and semi-desert depressions of northwestern Mongolia. Prevailing dry conditions result in poor organic deposition and low sediment/soil accumulation rates in the region that prevent high-resolution records being obtained or the creation of a reliable chronology. This is the reason for the general scarcity and poor age control of previous paleoenvironmental studies (Savina 1986; Yamskikh 1995). Moreover, most of the records obtained for

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the steppe zone are rather short. The known long records covering the entire Holocene are from the less dry mountain areas (Chernova et al. 1991; Blyakharchuk et al. 2004). Given the sites' locations, these data do not clearly reflect environmental changes in the lowlands. In order to make this evident, we studied sediment cores from lakes located within the intermountain depressions, by pollen, microfossil, and geochemical analyses, and ^{14}C dating. The first results have been obtained for the Uyuk depression in northern Tuva and the Minusinsk depression (Dirksen and van Geel 2004; van Geel et al. 2004; Zaitseva et al. 2004, 2005). We use new records from 2 sites in the Minusinsk depression to discuss first the environmental response to Holocene climate change and then the possible relationship between past climate and cultural development in the region.

STUDY AREA

The Minusinsk intermountain depression is located to the north of the Sayan Mountains and includes the Khakassia Republic and the southern part of Krasnoyarsk Province (Figure 1). This is one of the largest depressions in Southern Siberia.

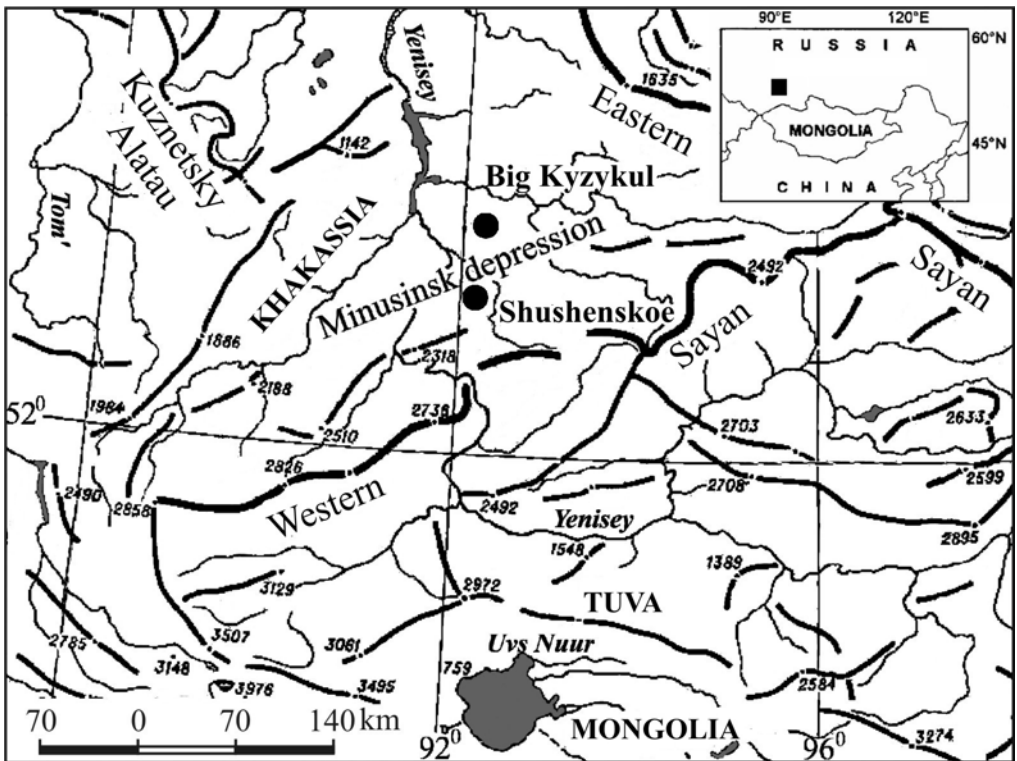


Figure 1 Regional orographic scheme. Bold circles indicate the location of studied sites. Bold lines are ridges with main peaks and their absolute heights. Large rivers and lakes (shaded areas) are indicated in italics. The inset map shows the location of study area (indicated by the bold square) within the larger region.

The climate is controlled mainly by Siberian and Asian air masses and partly by the Westerlies. The penetration of northwestern moisture-laden air masses strongly depends on orography. The changes in elevation in the studied sites result in a large gradient in precipitation from the western and central parts of the depression, with annual rainfall of 200–250 mm to the east, while annual rainfall on

windward slopes of the Sayan Mountain ridges reaches 1200–1500 mm (Gavlina 1954). The maximum precipitation is in summer, and the mean annual temperature is about 0 °C. The climate is continental with large seasonal temperature variations of >50 °C and temperature inversions in winter.

The lowlands are disturbed presently by agriculture and settlement. Preserved present-day steppe communities suggest that the high-productivity bunchgrass and grass steppe originally dominated on the floor of the depression (Kuminova et al. 1976). Forest-steppe occurs at the outer edge of the depression, from the mountain base upslope to 700–1000 m elevation, where it is replaced by mixed mountain forest with *Pinus sylvestris*, *Betula pendula*, and *Larix sibirica*. From 1300–1800 m, the vegetation is replaced by mountain dark-coniferous taiga with *Pinus sibirica*, *Abies sibirica*, and *Picea obovata*. Upper altitudinal belts of vegetation are subalpine shrubs and meadows, alpine meadows, and mountain tundra (Kuminova et al. 1976; Sedelnikov 1988).

The 2 sites under investigation are located ~50 km apart at the eastern part of the depression within an area of sand dunes covered occasionally by pine forest. There are several lakes, mainly brackish and currently shrinking. A few freshwater lakes are preserved where surrounding patches of pine forest remain undisturbed. The Big Kyzykul Lake (53°43'N, 92°07'E; 320 m asl; about 3 × 4 km in size) is one of these lakes. The Shushenskoe Lake (53°19'N, 92°03'E; 300 m asl) was a small, isolated basin in a former river meander, which later became a peat bog. We use records from both of these sites to improve the reliability of regional climate and vegetation change reconstruction in this poorly studied area.

METHODS

A sediment core from Big Kyzykul Lake (BKZ) was obtained from a site near the lakeshore at a water depth of 20 cm. A Russian corer was used for soft gyttja and a Dakhnovsky corer for basal sandy deposits. The total length of the extracted core was 285 cm, taking the water surface as zero. Silty sediment at 270–260 cm and non-decomposed plant remains at the upper part of the core (90–20 cm) were water-saturated and therefore lost during core extraction. Given this, in this study we used the core from 285 to 90 cm with a sediment hiatus between 270 and 260 cm. A 100-cm sequence of peat-lacustrine sediments was sampled at the Shushenskoe site (SHU) with a plastic tube directly from the wall of an excavated pit. Bulk samples of peat and gyttja for conventional ¹⁴C dating were obtained from the pit in the field as well as pollen samples of underlying alluvial deposits at 100–130 cm depth. The main sediment cores BKZ and SHU were transported to the Institute for the History of Material Culture (St. Petersburg), where they were subsampled for pollen, geochemical analyses, and accelerator mass spectrometry (AMS) dating.

Sample preparation for pollen and microfossil analyses was carried out in the University of Amsterdam following a standard method (Faegri and Iversen 1998). A specific amount of *Lycopodium* spores was added per sample of known volume to calculate pollen concentrations. An average of 558 and 467 pollen grains per sample was counted for the BKZ and SHU sets, respectively. Nomenclature of pollen and spore taxa follows common plant nomenclature (Cherepanov 1995). Non-pollen palynomorphs (remains of invertebrates, algae, fungi) and charcoal pieces were counted and identified (Kats et al. 1977; van Geel et al. 1983, 1989; van Geel 2001) from the same slides as for pollen. The calculation of pollen and microfossil percentages was based on a pollen sum including trees, shrubs, and upland herbs. Discovery of sedge rootlets and charred grass epidermis fragments indicate that the deposition of Cyperaceae and Poaceae pollen may have had a local origin. On the other hand, pollen of Poaceae may originate from shore wetlands (e.g. *Phragmites*) as well as from surrounding steppe vegetation where grass species are abundant. Considering this, Poaceae pollen

was included in the basic pollen sum. The results obtained are given as percentage pollen, and microfossil diagrams of selected taxa (Figures 2 [page 1107] and 4 [page 1108]) were constructed with the Tilia/Tilia-Graph and TGView programs (Grimm 1991, 1994). The diagrams were subdivided by eye into zones based on visual similarity of pollen and microfossil assemblages, and pollen concentrations. The subzones reflect mainly the minor changes in assemblages of local pollen (in the sense of Janssen [1973]) and microfossils derived from the sources at or close to the sampling site, and are probably related to development of local environments. The ages of the zone boundaries were estimated using both interpolation and extrapolation.

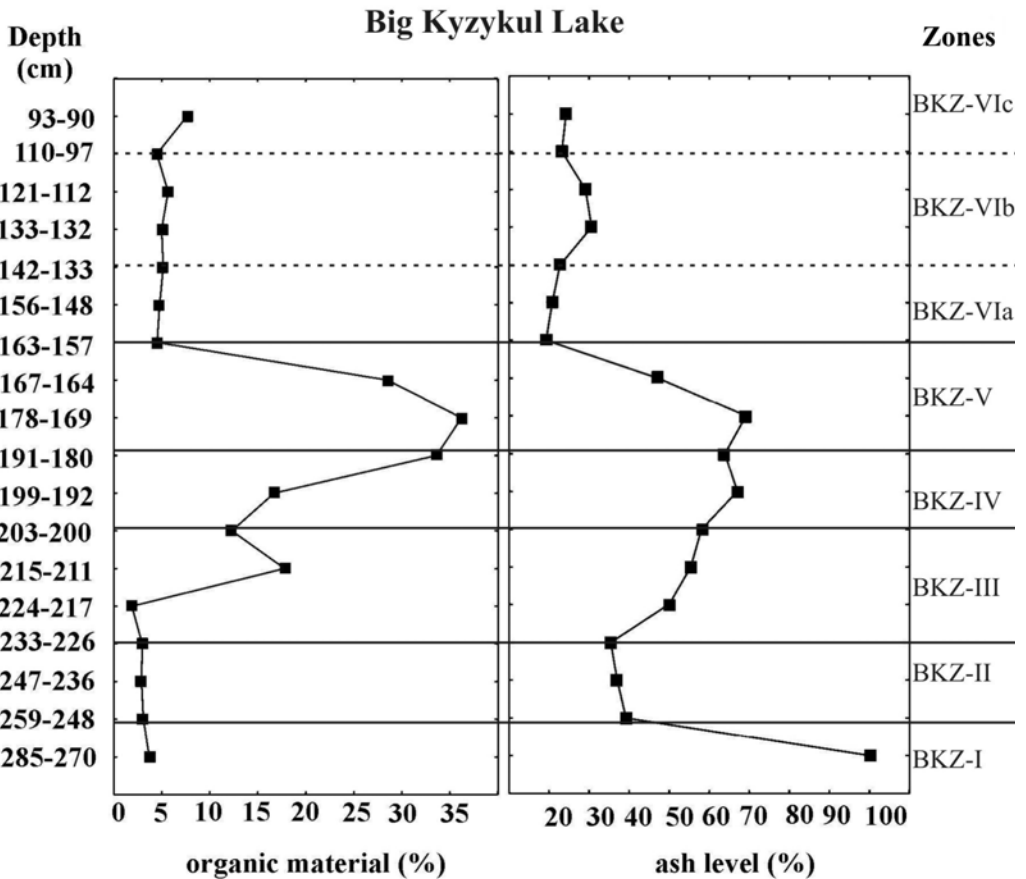


Figure 3 Variations of organic content (LOI) and ash level in the Big Kyzkykul Lake sediment sequence. Zones shown in the right-hand column are the same as those in Figure 2.

The weight percent organic matter in the BKZ and SHU core sediments was determined by means of loss on ignition (LOI) after heating at 550 °C for 2.5 hr (Heiri et al. 2001). The ash level was established by the standard method (Klimova 1975) to determine a total terrigenous component of the deposit. The mineral composition of the terrigenous component for the SHU sediment sequence was carried out by infrared (IR) spectroscopy analysis; the energy of IR absorption spectra in the region of 400–1600 cm^{-1} was determined and compared with those of calibration spectra of pure substances (Farmer 1974; Stolpovskaya et al. 2006). The main changes in sedimentation and organic accumulation for both records are presented in Figures 3 and 5.

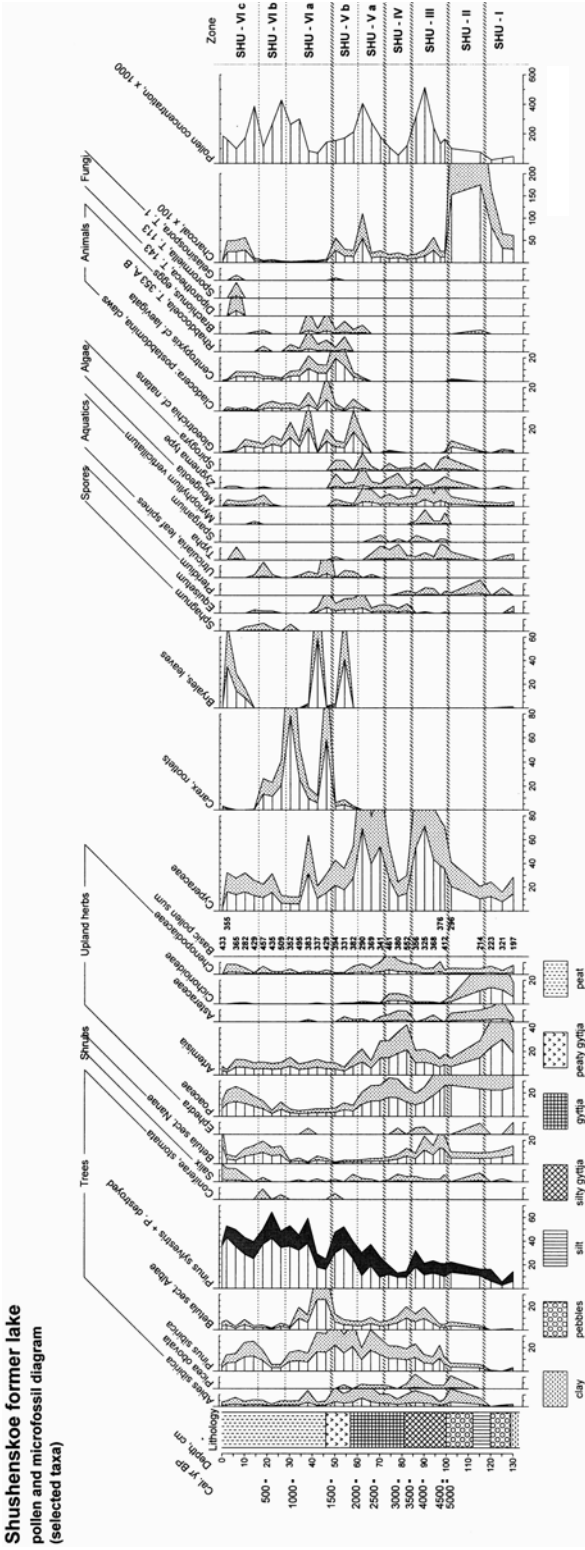


Figure 4 Pollen and microfossil diagram for the Shushenskoe former lake. The timescale follows the depth-age model in Figure 6. Analysis by V Dirksen.

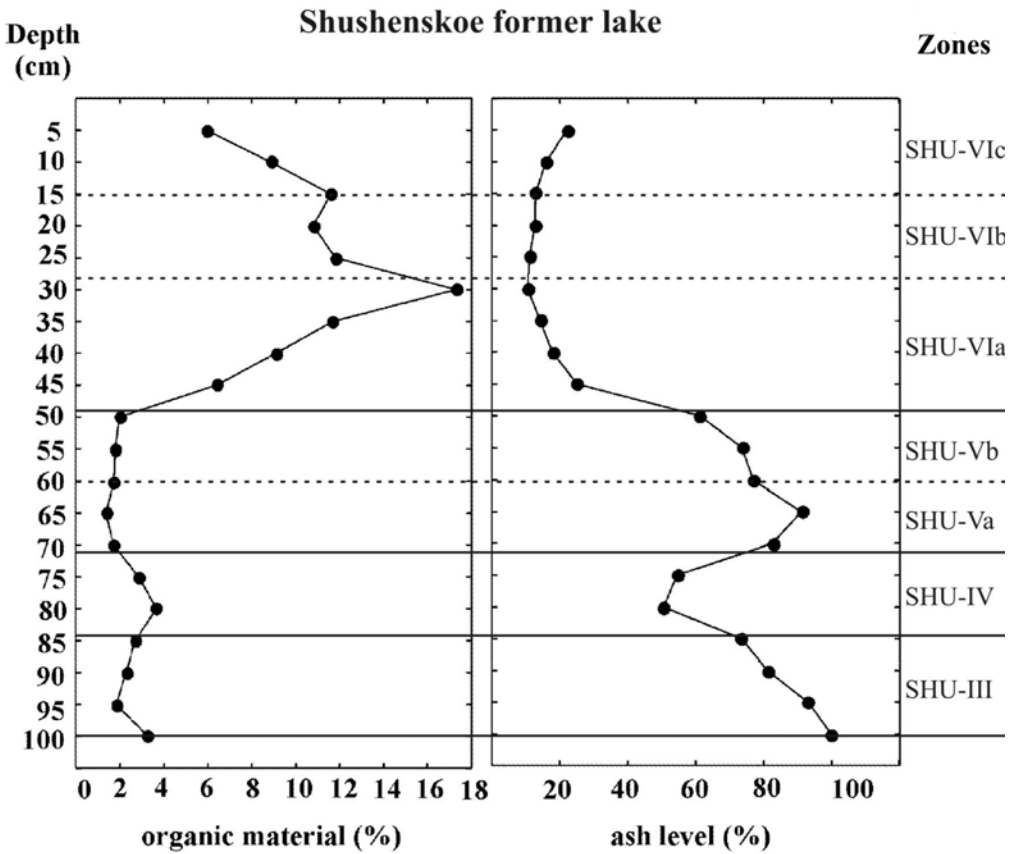


Figure 5 Variations of organic content (LOI) and ash level in the Shushenskoe sediment sequence. Zones shown in the right-hand column are the same as in Figure 4. LOI and ash level were not determined below 100 cm.

The age of the sediment sequences was determined by ^{14}C analysis in the Institute for the History of Material Culture (bulk samples) and in the Groningen University and SUERC accelerator mass spectrometry facilities. The sampling of the SHU open cross-section allowed bulk samples suitable for conventional ^{14}C dating to be obtained. AMS dating established the chronology of the BKZ core with samples of small volume and low organic matter content such as the basal sediments. For both sites, the material dated is humic acid extracted from gyttja and peat. The ^{14}C dating results were calibrated to calendar ages BP using OxCal v 3.10 (Bronk Ramsey 1995, 2001) and the IntCal04 calibration curve (Reimer et al. 2004) and are listed in Table 1. The age-depth models are shown in Figure 6. All ages from the literature are cited in their original date format. To integrate the uncalibrated ^{14}C dates from some papers of interest into the discussion, the results obtained are given in calendar yr BP and ^{14}C yr (yr BP). In order to correlate cultural and paleoclimatic events, the traditional dating of the cultural periods in calendar yr BC is supplemented by the corresponding ages in calendar yr BP.

RESULTS

Because of different temporal resolution and age ranges, we describe the BKZ and SHU records separately and focus mainly on changes that may have a regional climatic significance.

Table 1 ^{14}C dates for investigated sites.

Depth (cm)	Lab code	^{14}C age (yr BP)	Calendar yr BP (2σ)
Shushenskoe former lake			
15–20	Le-6657	410 \pm 50	530–310
20–25	Le-6658	675 \pm 45	690–550
30–35	Le-6660	1160 \pm 20	1180–980
35–40	Le-6661	1270 \pm 20	1275–1170
40–45	Le-6662	1540 \pm 25	1520–1360
45–50	Le-6663	1610 \pm 20	1550–1410
50–55	Le-6664 b	1710 \pm 35	1710–1540
55–60	Le-6665	1980 \pm 30	2000–1870
60–65	Le-6666 b	2260 \pm 35	2350–2150
65–70	Le-6667 c	2540 \pm 50	2760–2450
70–75	Le-6668 b	2740 \pm 35	2930–2760
75–80	Le-6669 b	2850 \pm 35	3080–2860
85–90	Le-6671 b	3660 \pm 80	4250–3700
95–99	Le-6673 b	3790 \pm 35	4300–4000
99–101	Le-6674 b	4389 \pm 80	5290–4830
Big Kyzikul Lake			
93–93.5	SUERC-5646	545 \pm 35	650–510
110–110.5	SUERC-5647	2180 \pm 40	2330–2060
142.5–143	SUERC-5648	2970 \pm 40	3320–3000
163–163.5	GrA-28590	4115 \pm 35	4830–4520
168–168.5	GrA-27904	4285 \pm 40	4970–4710
178.5–179	GrA-27905	4465 \pm 40	5300–4960
198.5–199	GrA-27894	6530 \pm 45	7560–7320
240–240.5	SUERC-5649	8700 \pm 40	9790–9540
284–285	GrA-27896	10,120 \pm 50	12,000–11400

Big Kyzikul (BKZ) Lake Record

This is the first well-dated record covering the entire Holocene age range that has been obtained for the Minusinsk depression. We identified 6 zones in the BKZ diagram (Figure 2). The changes in organic matter content and ash level are represented in Figure 3.

BKZ-I (285–260 cm; 11,725–10,640 calendar yr BP)

This zone is in basal sand deposits poor in organic matter. Pollen concentrations are very low, pointing to bare soils in the surroundings with sparse vegetation cover. The predominance of *Artemisia* with abundant Poaceae and the permanent presence of xerophytic *Ephedra* and Chenopodiaceae suggest a stony, semi-desert or dry steppe around the lake. The frequency of Asteraceae, Cichorioideae, and Caryophyllaceae may also indicate the persistence of poorly developed soils because many present-day pioneer species belonging to these families (Kuminova et al. 1976). The long-distance transport of tree pollen is very low, suggesting a sparse forest or even no trees in the surrounding mountains. This evidence points to an arid and possibly still cold climate.

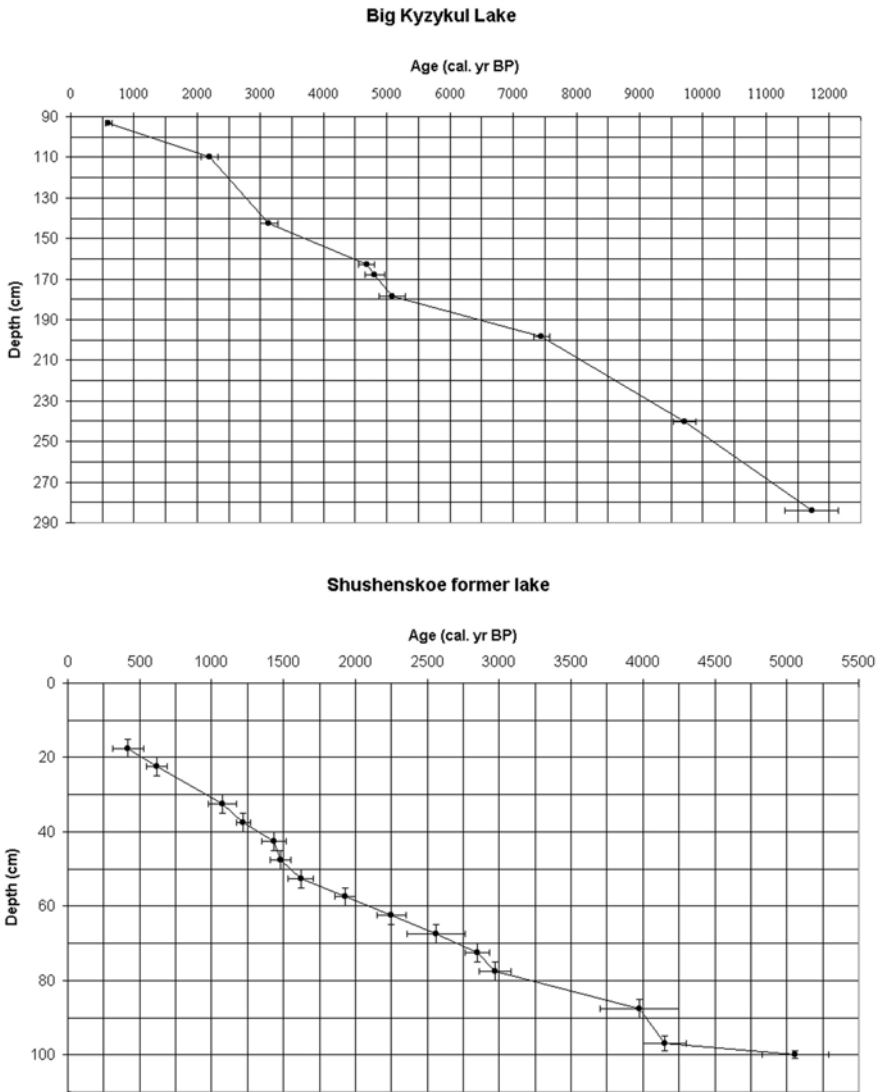


Figure 6 Depth-age models for the 2 investigated sites. For the Shushenskoe site, the curve was not continued below 100 cm, suggesting sedimentary hiatus; vertical bars in the curve indicate the thickness of bulk samples (cal. yr BP = calendar years BP).

BKZ-II (260–226 cm; 10,640–8960 calendar yr BP)

The beginning of the zone corresponds to the overlying of sand and silt sediment by gyttja, suggesting lower erosion and higher local biological production. Indeed, a sharp blooming of green algae species recorded synchronously with the lake sediment change denotes higher nutrient availability; however, the rates of organic accumulation remain low. The presence of *Cyperaceae*, *Typha*, and some *Poaceae* were established along the margins of the lake. This clear local change indicates a warming trend that is supported by a gradual increase of *Abies*, *Picea*, and *Pinus sibirica*, suggesting dark-coniferous taiga development in the mountains. On the other hand, high values of *Artemisia* pollen with the presence of *Chenopodiaceae* and *Ephedra* are signs that steppe vegetation covered

the surrounding region; some Poaceae pollen may also come from the nearby steppe. Furthermore, *Betula* sect. *Albae* (tree birch) and *Pinus sylvestris* pollen show the lowest values and therefore suggest that mixed mountain forests below the mountain taiga belt and forest-steppe, within the depression where these trees predominate, were almost absent. The present-day distributions of both mixed forest and forest-steppe are controlled mainly by moisture availability that may indicate dry conditions at lower elevations in the past. *Betula* sect. *Nanae* (shrub birch species) pollen may have had a long-distance origin, while the mountain forest was reduced; its increase possibly reflects a subalpine shrub development. The local and regional changes recorded in the zone suggest warmer and dry conditions in the lowlands and warmer and drier conditions in the mountains.

BKZ-III (226–202 cm; 8960–7650 calendar yr BP)

In this zone, a maximum of mesophytic *Abies* and a higher amount of other tree pollen indicate both increased humidity and temperature. The higher content of organic matter in gyttja, and a maximum of cyanobacteria (*Gloeotrichia*) may also reflect a trophic change in the lake as a local response to greater warming. However, abundant *Artemisia* with the presence of xerophytic *Ephedra* and Chenopodiaceae and increasing *Selaginella sanguinolenta*—which is a common plant in the dry, stony steppe (Kuminova et al. 1985)—are evidence that dry conditions still persisted in the lowlands.

BKZ-IV (202–179 cm; 7650–5090 calendar yr BP)

This zone is almost entirely contained within a gyttja layer that is rich in shells. The organic content of the sediment increases sharply. Pollen concentrations also increase, suggesting denser vegetation cover in the surroundings. The main change recorded in the zone is a general decrease of xerophytic *Artemisia*, *Ephedra*, and Chenopodiaceae and an increase in pine and tree birch pollen frequencies, indicating a transition from treeless to locally forested lowlands. The forest spreading downslope suggests an increasing moisture level. A maximum of *Picea* also supports the climate becoming less dry. A gradual decline of *Abies* pollen transported from the mountain taiga is a sign that the temperature has decreased. All evidence points to the end of long-term aridity and a change to wetter conditions in the highlands and lowlands.

BKZ-V (179–162 cm; 5090–4600 calendar yr BP)

This zone is in the gyttja with the highest organic matter content and the greatest amount of shells and *Cladocera* remains, which indicate enhanced local biological production. The well-expressed maximum of *Pinus sylvestris* pollen content suggests a local pine forest near the lake and therefore increasing humidity. A drop in *Artemisia* pollen percentages supports the climate becoming wetter. The temperature change recorded in the zone is less clear. Colder conditions could be supported by the complete disappearance of cyanobacteria and Spongillidae and by a sharp drop in pollen concentration at the beginning of the zone. On the other hand, these local changes may have had ecological causes.

BKZ-VI (162–92 cm; 4600–500 calendar yr BP)

This zone is found in the gyttja overlain by peat at the top of the core. A sharp transition from shells to a coarse plant remains layer that underlies the gyttja may suggest a hiatus in sedimentation at the boundary between zones V and VI. A sudden onset of Cyperaceae at the beginning of the zone correlates well with the sediment change. The abundance of sedge and increasing findings of other local aquatics upward through the zone reflects wetland development that may indicate shallower water at the study site, and further, a general lake-level drop during the latest period. The appearance of fungal spore Type 200 also indicates shallow water conditions and temporary desiccation (van

Geel 1989). A feature of the zone also pointing to drier conditions is the gradually declining values for *Abies*, *Picea*, and partly *Pinus sibirica* that suggest a degradation of dark-coniferous taiga in the mountains. Unfortunately, a swamping of the pollen assemblages by both local pollen of *Pinus sylvestris* and Cyperaceae make the regional signals of climate change unclear. Based on local signals, 3 subzones were recognized:

In subzone BKZ-VI a (162–134 cm; 4600–2880 calendar yr BP), a shift towards a continental climate is suggested by the slightly increasing role of tree birch in the local forest instead of pine (Kuminova et al. 1976; Sedelnikov 1988). An appearance of local ferns with frequent rhizopods and abundant *Typha* indicates that the nearby wetlands started to spread.

Subzone BKZ-VI b (134–103 cm; 2880–1550 calendar yr BP) shows development of wetlands. Finds of hyphopodia of *Gaeumannomyces* sp. and sedge rootlets are signs that the Cyperaceae species grew near the study site (van Geel et al. 1983; van Geel 2001).

Subzone BKZ-VI c (103–92 cm; 1550–500 calendar yr BP) is in the peat that overlies the lake sediments. The peat layer correlates well with a greater amount of sedges and moss remains, and increasing sedges and *Triglochin* pollen values suggest that the lake continued to infill and contract.

Shushenskoe (SHU) Record

The sharp change in sediment lithology observed at 100 cm may imply a sedimentary hiatus and prevents the age extrapolation downwards. The upper part of the record has high temporal resolution providing detailed information about the late Holocene environment. Six zones were identified on the SHU diagram (Figure 4). Geochemical data (Figure 5) show that the sediments from 100 to 50 cm have a low organic matter content. The mineralogical composition of the terrigenous complex includes quartz, feldspar, and clay minerals. In the depth range of 55–50 cm, carbonate minerals appeared in the sediments. From 45 to 10 cm depth, the content of carbonate minerals and organic material increased.

SHU-I (130–117 cm)

The undated zone is in the basal clay and coarse pebbles. The pollen concentration is very low, indicating a predominance of bare soils near the site. An abundance of Cichorioideae and Asteraceae is a sign that pioneer vegetation covers the surrounding dunes (Kuminova et al. 1976). High values of Poaceae pollen compared with those of *Artemisia* and Chenopodiaceae and a local Cyperaceae presence may reflect vegetation succession under a dry but not very arid climate.

SHU-II (117–100 cm)

The zone lies in the silt and pebble layer. Even with such low pollen concentrations in both lower zones, their pollen assemblages are different. Increasing *Abies* and *Picea* pollen transported from the mountains is observed, with a dominance of Poaceae, while *Artemisia* shows a distinct decrease, therefore suggesting a relatively warmer and wetter climate.

SHU-III (100–84 cm; 5060–3630 calendar yr BP)

The lower zone boundary is a transition from pebbles to organic lake sediments, and the zone lies entirely in the basal gyttja. The sediment change is consistent with increasing algae micro-remains and the appearance of open water plants such as *Myriophyllum verticillatum* and *Sparganium*. A sharp rise in Cyperaceae pollen values coinciding with greatly increasing pollen concentration reflects denser vegetation cover near the site. All these features indicate higher local biological productivity compared to earlier zones. The important regional signals are increasing *Picea* and gener-

ally higher tree pollen percentages, pointing to a wet climate. The drop in Poaceae and *Artemisia* pollen content supports this. On the other hand, abundant tree birch and low values of *Abies* pollen suggest rather continental and possibly colder conditions in the mountains.

SHU-IV (84–72 cm; 3630–2830 calendar yr BP)

This zone is found in the gyttja and there is no evidence of a coarse sediment layer or higher terrigenous input (Figure 5) that may explain the lower pollen deposition. However, pollen concentration decreases dramatically. We suggest, therefore, that signals expressed in the record reflect both local and regional responses to climate change. Increasing Poaceae, *Artemisia*, Chenopodiaceae, Asteraceae, and Cichorioideae indicate re-advanced steppe and even open soils (or barren dunes) with sparse vegetation in the surroundings. The sharp drop in Cyperaceae pollen values suggests a reduction of wetlands near the lake, while increasing *Equisetum* may indicate shallower water with a drier climate. In addition, a decline of moisture-demanding *Picea* is suggested for the mountain forest. All the evidence points to a general decrease in moisture availability and a dry climate.

SHU-V (72–49 cm; 2830–1530 calendar yr BP)

This zone shows the forest advance inferred to occur was both a local and regional phenomenon. The gradually increasing *Pinus sylvestris* pollen curve clearly reflects forest spreading in the lowlands, indicating wetter conditions, and decreasing Poaceae, *Artemisia*, and Chenopodiaceae support this. *Abies* and *Pinus sibirica* pollen percentages reach their maxima, suggesting an extension of dark-coniferous taiga in the mountains that is a sign of the establishment of a warmer and wetter climate. However, *Picea* pollen has permanently low values that may indicate generally lower moisture availability compared with that in zone SHU-III. The subzones recognized reflect local change in progress:

Subzone SHU-V a (72–60 cm; 2830–2100 calendar yr BP) shows a second maximum of Cyperaceae pollen coinciding with higher pollen concentration.

Subzone SHU-V b (60–49 cm; 2100–1530 calendar yr BP) is in the transitional layer from lake sediments to peat. This is consistent with findings of sedge rootlets, moss leaves, and diverse animal microscopic remains in the deposits, and increasing *Equisetum*. An appearance and sharp blooming of cyanobacteria in the lake may reflect shallower and generally warmer conditions. This is supported by the first appearance of carbonate minerals in the sediment. A large increase in *Pinus sylvestris* and the first finds of conifer stomata are signs that the local pine forest began to establish in the surrounding dunes.

SHU-VI (49–0 cm; 1530 calendar yr BP to the present)

The upper zone is entirely in the peat, recording mainly peat bog development at the former lake depression. The pine pollen is over-represented due to the locally forested landscape; therefore, a regional response to climate change is less pronounced. A gradual decline of *Abies* and a complete absence of *Picea* in the mountain forests is noted, but it remains unclear whether the reason is generally drier climate or the local pollen being over-represented. Based on local changes, we identify 3 subzones:

Subzone SHU-VI a (49–28 cm; 1530–870 calendar yr BP) shows drier and more continental conditions with the sharply increasing role of tree birch instead of pine in the local forest. A greater amount of plant and animal microscopic remains and absence of algae correlate well with sediment change and the increased content of carbonate minerals, indicating that the lake has shrunk.

In subzone SHU-VI b (28–16 cm; 870–380 calendar yr BP), a re-advance of pine forest near the site is suggested by both increasing *Pinus sylvestris* and findings of conifer tree stomata. Increasing shrubs with the

appearance of some algae and *Sphagnum*, which is a generally uncommon plant for the regional peat bogs (Kuminova et al. 1976, 1985), may indicate wetter and cooler conditions.

For local changes in subzone SHU-VI c (16–0 cm; 380 calendar yr BP to the present), a human cause is more likely than a climatic one. The presence of coprophilous fungi (e.g. *Sporormiella*; van Geel 2001) and greater values for charcoal dust may signal increased human influence on the environment at the study site.

DISCUSSION

Climate and Environmental Changes During the Holocene

The 2 new records from the Minusinsk depression, supported by an excellent chronology, provide data for a reconstruction of climatic and environmental conditions in Southern Siberia during the last 11.7 cal kyr. Both records originate from similar present-day environments. This makes correlation easier, considering that the main changes inferred from regional signals most likely have the same climatic significance. It is necessary to note that temperature changes were more difficult to detect reliably in both records compared with those of humidity. The reason is the greater sensitivity of generally dry environments to changes in moisture availability (Sedelnikov 1988). On the other hand, temperature controls the effective moisture balance (precipitation minus evaporation), which responds to vegetation cover density and total biological productivity in arid and semi-arid zones (Chen et al. 2003); therefore, any relative evaluation of temperature is important.

The persistence of aridity from about 11.7 to 7.6 cal kyr BP (~10.1–6.7 kyr BP) is well represented in the BKZ record, and the undated zone SHU-I most likely belongs to this period. Initially cold (zone BKZ-I), the climatic conditions became warmer after ~10.6 cal kyr BP (~9.4 kyr BP), supporting algal blooms and organic gyttja sedimentation in the lake (zone BKZ-II). Pollen of mesophytic *Abies*, transported from the mountain periphery of the depression, increases and reaches its highest values in zone BKZ-III between ~9–8.5 cal kyr BP (~8–7.5 kyr BP); this marks a period of thermal maximum. This is in agreement with pollen data from the Altai Mountains, west of the study area, suggesting the dominance of dark-coniferous taiga with *Abies* between 9.5–7.5 cal kyr BP, at the present-day timberline (Blyakharchuk et al. 2004), as well as with pollen data from Lake Baikal to the east of the Minusinsk depression, which recorded the maximum development of dark-coniferous taiga in the nearby mountains between 11–7.5 cal kyr BP (Demske et al. 2005). Increased temperature was probably the main factor explaining the large difference between the environments of the highlands and lowlands in the region. The coexistence of moderate climatic conditions at the mountains, supported forest development, and aridity at the depression where dry steppe persisted were likely to have been caused by enhanced evaporation over precipitation at the lower elevations, while effective moisture increased upwards due to the altitudinal climatic gradient.

The switch to higher moisture availability since ~7.6 cal kyr BP is suggested in zone BKZ-IV, and undated zone SHU-II records the same change. Expansion of mixed forests with pine and birch in the lowlands would require wetter conditions than those prevailing earlier. *Pinus sibirica* and *Picea*, which are less sensitive to decreased temperature, replaced *Abies* in mountain taiga; therefore, increased effective moisture was more likely caused by a gradually lowering temperature and evaporation than higher precipitation.

This near-synchronous change occurred in both records at ~5.1 cal kyr BP (~4.4 kyr BP). The beginning of organic sedimentation recorded in zone SHU-III and the greatest biological productivity in the lake and local forest near the Big Kyzkykul site (zone BKZ-V) are signs that humidity increased. This correlates well with such unusual events for semi-arid zones as the peat bog formation reported

for the Minusinsk depression; the oldest peats found within the present-day steppe were dated at 4.5–4.3 kyr BP (Yamskikh 1995). Indirect data obtained from the records suggest cooler conditions that are consistent with the 4–3 kyr BP cold pulse widely represented in the Asian mountains and attributed to the Neoglacial (Lehmkuhl and Haselein 2000). Such a cold event may have provided greatly increased effective moisture as evaporation dropped. On the other hand, lower temperatures may have also resulted in a larger seasonal contrast and thus an enhanced degree of continentality of the climate.

The dry event between ~3.6–2.8 cal kyr BP (~3.4–2.7 kyr BP) is clearly observed in zone SHU-IV but is not evident in the BKZ record, where the over-representation of the local pollen input swamps the pollen assemblages. A poorly dated pollen record from the nearest site (Savina 1986) may support the establishment of drier conditions since ~3.5 kyr BP. However, reliable age limits for the period, considering a possible hiatus in sedimentation, remain uncertain, as does the trend in temperatures.

The appearance of a local pine forest at the Shushenskoe site (around 2.5 kyr later than that at Big Kyzkul) and the re-advance of dark-coniferous taiga with *Abies* in the surrounding mountains (zone SHU-V) indicate a second humid pulse occurred at ~2.8–1.5 cal kyr BP (2.7–1.6 kyr BP) under warmer and less continental conditions. The relationship between temperature and precipitation was probably optimal for the semi-arid zone and provided higher biological productivity and diversity both in the highlands and lowlands. This is in good agreement with regional data obtained earlier (Savina 1986; Dirksen and van Geel 2004).

During the latest period, the climate was generally drier and warmer. The shift to drier conditions and a greater degree of continentality is suggested at ~1.5 cal kyr BP, when birch trees become more important in the forest-steppe and gyttja overlain by peaty deposits suggests lake shrinkage and degradation.

In summary, the BKZ and SHU records suggest the persistence of aridity during the early to middle Holocene between ~11.7–7.6 cal kyr BP (~10–6.7 kyr BP); increased effective moisture since ~7.6 cal kyr BP (~6.7 kyr BP); 2 humid pulses at ~5 and 2.8 cal kyr BP (~4.4 and 2.7 kyr BP, respectively) separated by a dry interval during the late Holocene; and the return to generally drier conditions after ~1.5 cal kyr BP (~1.6 kyr BP). Comparing our results with available proxy data from neighboring regions of Central Asia, we found a good correlation with records derived from arid and semi-arid areas in China and Mongolia located at or beyond the modern limit of the Asian summer monsoon. Thus, dry events occurred at 8–4.3 kyr BP in the Hobq Desert, Inner Mongolia (Chen et al. 2003) and during 7.5–4.5 kyr BP in the Mu Us Desert (Xiaoqiang et al. 2003), both in China; between ~8.2–7.3 and 4.1–2.6 kyr BP at Bayan Nuur Lake in northwestern Mongolia (Grunert et al. 2000); at 8.3–4.1 kyr BP in northern Mongolia (Feng 2001); and at ~7.1–4.4 cal kyr BP at Telmen Lake in north central Mongolia (Peck et al. 2002). According to available data, mid-Holocene aridity was generally associated with higher temperatures. Furthermore, as reported in these studies, the wettest events occurred in the early Holocene, and in the late Holocene between ~4.5 and 1.3 kyr BP, while the evidence of increased effective moisture was found around 6.4 kyr BP in Inner Mongolia (Chen et al. 2003) and ~6.7 kyr BP in northwestern Mongolia (Grunert et al. 2000). The period of humidity maximum is consistent with the Neoglacial time (~4–3 kyr BP) that was wetter and cooler than today in Central Asia and supported lake-level rises around 3–2 kyr BP (Lehmkuhl and Haselein 2000). Our results are in agreement with this, but are contrary to a large body of paleoclimatic information obtained from the less arid sites in China (An et al. 2000, 2006), Western Siberia (Khotinsky 1987, 1989), and from the even closer Baikal region (Demske et al. 2005) and adjacent

mountain areas such as the Russian Altai (Blyakharchuk et al. 2004) and the Mongolian Altai (Tarasov et al. 2000). Those data reported the rather synchronous occurrence of thermal and humidity Holocene maxima between ~11–5 cal kyr BP (~9.5–4 kyr BP) and decreased temperature and precipitation during the late Holocene. This discrepancy may be due to the different response in dry environments in the center of Asia compared with that of the Eurasian temperate zone. Despite the different climatic systems influencing the arid and semi-arid regions of Central Asia during the Holocene, the mechanisms produced the mid-Holocene dryness, when the rates of evaporation exceeded the rates of precipitation and may have been similar in these different regions. In contrast, during the cooler late Holocene, the effective moisture increased as evaporation dropped, creating a large environmental change in initially dry areas.

Environmental Change and Cultural Dynamics

According to archaeological data, the Paleolithic Afontovo culture is well represented in the Minusinsk depression (Vadetskaya 1986). However, the Mesolithic and Neolithic cultures (9th–4th millennium BC; ~11–6 cal kyr BP) represented over Eurasia are almost absent in the intermountain depressions of Southern Siberia (Vasiliev 2001). Some Mesolithic-Neolithic sites are found in the present-day forested mountains but not in the steppe lowlands. This gap in cultures correlates well with reconstructed early to mid-Holocene aridity from ~11.7 to 7.6 cal kyr BP (Figure 7). Greater differences in the conditions of the lowlands and highlands suggested for this period may be an explanation for the differences in human occupation patterns. Forested areas in the mountains would support the population, while the lowlands with scarce vegetation and generally unfavorable environmental conditions remained almost uninhabited.

The first notable archaeological culture that appeared in this region is the Afanasievo (4th to 3rd millennium BC; ~6–5 cal kyr BP) belonging to the Eneolithic (Charcolithic) or the Early Bronze Age. This is a European culture that used metals (copper) and was the most easterly among the stockbreeding groups of Eurasia (Vadetskaya 1986). It should be noted that the Afanasievo culture did not have local roots and this population came into the Minusinsk depression from elsewhere, while the similar cultures of Europe and Kazakhstan originated from the local Neolithic population. The appearance of the Afanasievo culture agrees well with increased effective moisture after ~7.6 cal kyr BP, coinciding with forest expansion to the lower, initially tree-less elevations. The lowlands, now covered with denser vegetation, became more attractive living areas and human occupation of the depression began.

The subsequent culture is the Okunevo (Middle Bronze Age). The beginning of this culture is dated to the end of the 3rd millennium BC or ~5 cal kyr BP (Görsdorf et al. 2001, 2004). This population was not genetically connected with the Afanasievo because there are significant differences in the burial tradition and anthropogenic characteristics. Most probably, the Okunevo population originated from the Neolithic communities in the Siberian forest zone to the north of the Minusinsk depression. The beginning of this culture corresponds to the wet period starting at ~5 cal kyr BP, when forests invaded the depression and the biological productivity of lowland ecosystems increased greatly. However, the colder climate and increased continentality suggested for this time may have resulted in severe living conditions and thus set the Okunevo apart from other cultures.

The Middle Bronze Age continues with the Andronovo culture (18th to 14th century BC; ~3.7–3.3 cal kyr BP; Görsdorf et al. 2004), found only in the northern part of the Minusinsk depression; this was the southernmost region where this culture occurred. Compared to neighboring Kazakhstan and Western Siberia, the Andronovo sites are relatively poorly represented in the depression. There is no archaeological explanation as to why the Andronovo population did not spread to the southern part

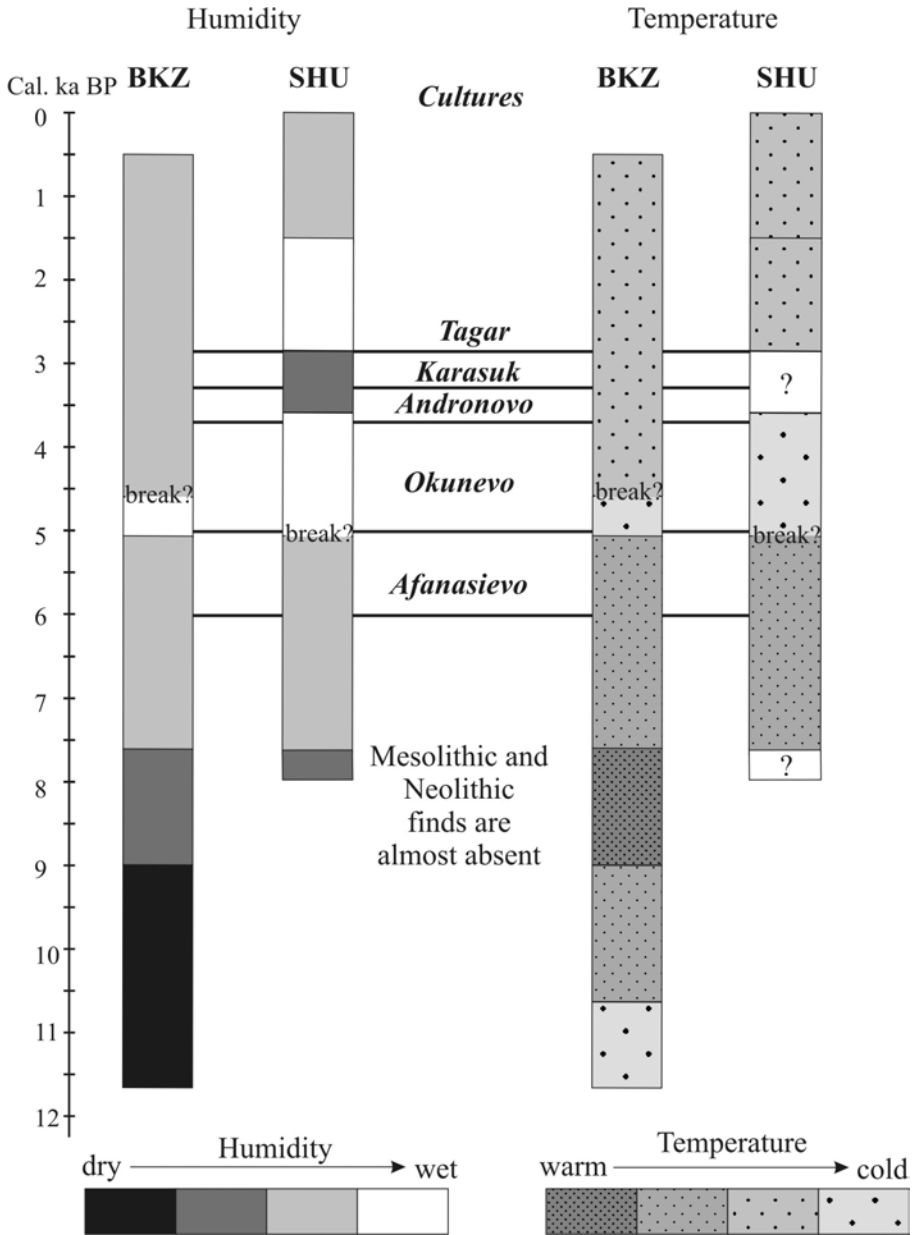


Figure 7 Relationship between Holocene climate changes and cultural dynamics in the Minusinsk depression. Reconstructed climatic events and their age limits correspond to zones in diagrams for the Big Kyzykul Lake (BKZ) and Shushenskoe (SHU) sites (Figures 2 and 4). Question marks indicate a lack of data.

of the Minusinsk depression. We suggest that the environmental change caused by a shift to drier climate at ~3.6 cal kyr BP could be one of the limiting factors. Most probably, the degree of aridity and continentality increased progressively from the northern part of the depression to the south, preventing successful occupation of this entire area.

The best represented Late Bronze Age culture in the Minusinsk depression is the Karasuk culture (14th to 10th century BC; ~3.3–2.9 cal kyr BP; Görsdorf et al. 2001, 2004). Thousands of burial mounds belonging to this culture were discovered in the steppe area of the depression. The influence of the Karasuk culture extends over a huge area from Kazakhstan to Mongolia and China (Chlenova 1972). The archaeological artifacts show that horseriding became important in this period and the transition to a nomadic stockbreeding economy occurred. According to our data, the Karasuk culture appeared and started to develop at the end of a dry period, and the return to a wetter climate may have provided more favorable living conditions than those in the Andronovo period.

The Tagar culture of the Early Iron Age follows the Karasuk culture and is related to the Scythian cultures spreading over other parts of the Eurasian steppe zone. The Tagar was one of the most impressive nomadic cultures, with stockbreeding and complicated burial traditions, types of weapons, and arts. The earlier Tagar cultural artifacts suggest both connections with the preceding Karasuk culture and contacts with Kazakhstan and Central Asia regions. The transition from the Karasuk to the Tagar culture occurred around the 9th century BC or ~2.8 cal kyr BP (Alekseev et al. 2001; Zaitseva et al. 2005). This fits well with the beginning of the 2.8–1.5 cal kyr BP period, when the humidity greatly increased in a relatively warm and less continental climate. We suggest that climatic conditions at this time were optimal for both higher productivity of the steppe vegetation and for establishment of forests at the depression's outer edges. This change in the lowland environments provided an attractive living area for the stockbreeding nomads and, consequently, may have triggered the development and blooming of the Tagar culture.

CONCLUSION

Summarizing the archaeological evidence, climate proxy, and ^{14}C data, we suggest that the cultural dynamics in Southern Siberia appear to be related to past climate variability. The change in moisture availability was the most important factor for these sensitive semi-arid environments, determining biological productivity of ecosystems, and eventually, influencing human occupation of the area. Thus, during the early and mid-Holocene aridity, the vast area of the Minusinsk depression was almost uninhabited. Since ~7.6 cal kyr BP, enhanced effective moisture provided a large environmental change that may have launched the Bronze Age and later, Iron Age cultural expansions.

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