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Late Glacial and Holocene vegetational changes on the Ulagan high-mountain plateau, Altai Mountains, southern Siberia

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Abstract

Three well-dated pollen diagrams from 1985 m, 2050 m, and at the tree line at 2150 m asl show the vegetational succession in the central Altai Mountains since 16 cal ka BP. Pioneer vegetation after deglaciation was recorded first at the lowest site. Subsequently, dense dry steppe vegetation developed coincident with the change from silt to organic sediments at the two lower sites, but silt lasted longer at the highest site, indicating the persistence of bare ground there. Forests of *Pinus sibirica*, *Pinus sylvestris*, *Picea obovata*, *Larix sibirica*, *Abies sibirica*, and *Betula pendula* started to develop about 12 cal ka BP with the change to a warmer and wetter climate at the beginning of the Holocene. Results indicate that the timberline did not rise above the highest site. Mesophilous dark-coniferous forests were fully developed by 9.5 cal ka BP. The role of *Abies* and *Picea* decreased by about 7.5 cal ka BP suggesting cooler climate, after which the forests changed little until today. The vegetational development in this portion of the central Altai Mountains is compatible with that described in neighbouring areas of the Altai, southern Siberia, Mongolia, and Kazakhstan.

Keywords: Altai; Late Glacial; Holocene; Pollen; Vegetation; Climate

1. Introduction

The Altai Mountains of southern Siberia (48–59°N, 82–90°E) are located where major cyclonic and anticyclonic air masses meet, so they have been especially sensitive to shifts in atmospheric circulation during the Late Glacial and Holocene. The Ulagan high-mountain plateau is in the central Altai near the transition between the more humid forests on the west and the drier steppe region on the east (Fig. 1). Sediments of three lakes in this area were investigated by pollen analysis: Uzunkol in the forest zone at 1985 m, Kendegelukol at 2050 m, and Tashkol near the upper tree line at 2150 m.

The complex relationships among montane forest, subalpine scrubland, high-mountain vegetation, and

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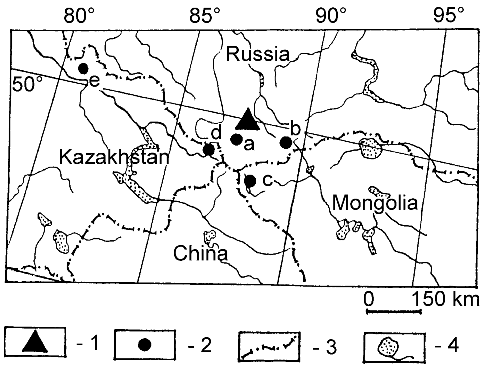


Fig. 1. Location of the area investigated and other published pollen data in the Altai Mountains and adjacent areas. (1) Ulagan high-mountain plateau (on which the study sites lie). (2) Location of published pollen diagrams referred to in text: (a) Yeshtykkol depression (Butvilovsky, 1993); (b) Dzhulukul plateau (Butvilovsky, 1993); (c) Hoton-Nur in Mongolia (Tarasov et al., 2000); (d) mire in Verkhnekarakabinskaya depression, southwestern Altai (Chernova et al., 1991); (e) Ozerki in northern Kazakhstan (Tarasov et al., 1991). (3) National boundaries. (4) Large lake basins.

steppe depend on both regional and local climatic conditions. Regionally, the Altai Mountains are situated at the latitude of steppe and forest–steppe zones, but locally, increased precipitation caused by the mountain relief promotes the dominance of forests. In this work, we use pollen diagrams from three lakes at different elevation to discuss first the local development of the altitudinal belts of vegetation under a changing climate and then the regional geographic relation of forest to steppe.

Previous pollen data from the Altai are scarce and hardly sufficient for a general overview. Pollen diagrams covering the Holocene but from geobotanical subprovinces (as classified by Kuminova, 1960) other than the Ulagan sites studied here, include one diagram from a former lake in the Kuraiskaya steppe (Butvilovsky, 1993) and another from a frozen mire in the Verkhnekarakabinskaya depression 170 km to the south (Chernova et al., 1991). Other pollen diagrams, mostly of the second half of the Holocene and with very poor radiocarbon dating, are from terrace sediments of the Ulagan River (28 km to the northeast) and the Karakudyur River (20 km northeast) and of a former lake in the Karakudyur Valley (Butvilovsky, 1993). Finally, separate pollen spectra and descriptions exist of sediments of interest (Chernova, 1988; Mikhailov et al., 1989; Mikhailov and Chernova, 1995; Baryshnikov, 1996). In order to supplement these data for integration with our Ulagan pollen diagrams, we use the more distant but more representative pollen diagrams from Lake Hoton-Nur in northwestern Mongolia (Tarasov et al., 2000) and Ozerki in northern Kazakhstan (Tarasov et al., 1997) (c and e in Fig. 1). Although these areas have different landscapes and climate, it is clear that any change in regional atmospheric circulation controlling the climate in the Eurasian midcontinent should be reflected in some way in these neighbouring regions.

2. Study sites

The three freshwater lakes studied in the Ulagan high-mountain plateau, central Altai Mountains, are situated 1.5–4 km apart at different elevations (see Figs. 7–9): Uzunkol (50°29′N, 87°6′30″E, 5.9 m water depth) at 1985 m, Kendegelukol (50°30′20″N, 87°38′30″E, 5–6 m water depth) at 2050 m, and Tashkol (50°27′N, 87°40′15″E, 6.25 m water depth at the coring site) at 2150 m. Tashkol lies at the timberline (upper limit of continuous forest), but below the upper limit of groups of trees.

3. Climate

In winter, the Altai is in the high-pressure area of the Siberian anticyclone centred in Mongolia; in summer, it is close to the thermal low-pressure zone formed over Asia (Rudsky, 1996). This results in a gradient from a moderate (cyclonic) type of climate in the western and northern Altai to a markedly more continental climate in the central areas and to the east (Kuminova, 1960). The Ulagan high-mountain plateau lies in the central Altai Mountains on this gradient and has a diverse climate. The upper courses of the Bashkaus and Chulyshman Rivers are influenced by dry southeastern winds, with average annual temperature of −3.7 °C and annual precipitation of 271 mm. The lower course of the Chulyshman River is influenced by warming from Teletskoye Lake (ca. 100 km north of study area), and average annual temperature is +4 °C and annual precipitation is 460 mm.

Three zones of altitudinal climate exist in the Altai: a steppe climate in intermontane depressions and the western piedmont, a forest climate on the mountain slopes, and a high-mountain climate on the highest slopes and mountaintops.

4. Vegetation

Most of the Altai is covered by forests and above it by alpine meadows and tundra, but steppe penetrates into the southeastern Altai along intermontane depressions and river valleys as extensions from the dry areas of Mongolia (Kuminova, 1960). This is reflected by the general altitudinal zonation of vegetation as described by Rudsky (1996) and Shumilova (1962). A lower tree limit at ca. 400 m is caused by drought. The forest zone covers elevations of approximately 700–2100 m with groups of trees up to 2200 m. Forests occupy almost half of the Altai and consist of *Betula pendula* and *Pinus sylvestris* mostly on the western low mountain areas, *Larix sibirica* and *Pinus sibirica* in the central Altai, and *Picea obovata*, *Abies sibirica*, and *Pinus sibirica* in the northern and southwestern areas (Fig. 2).

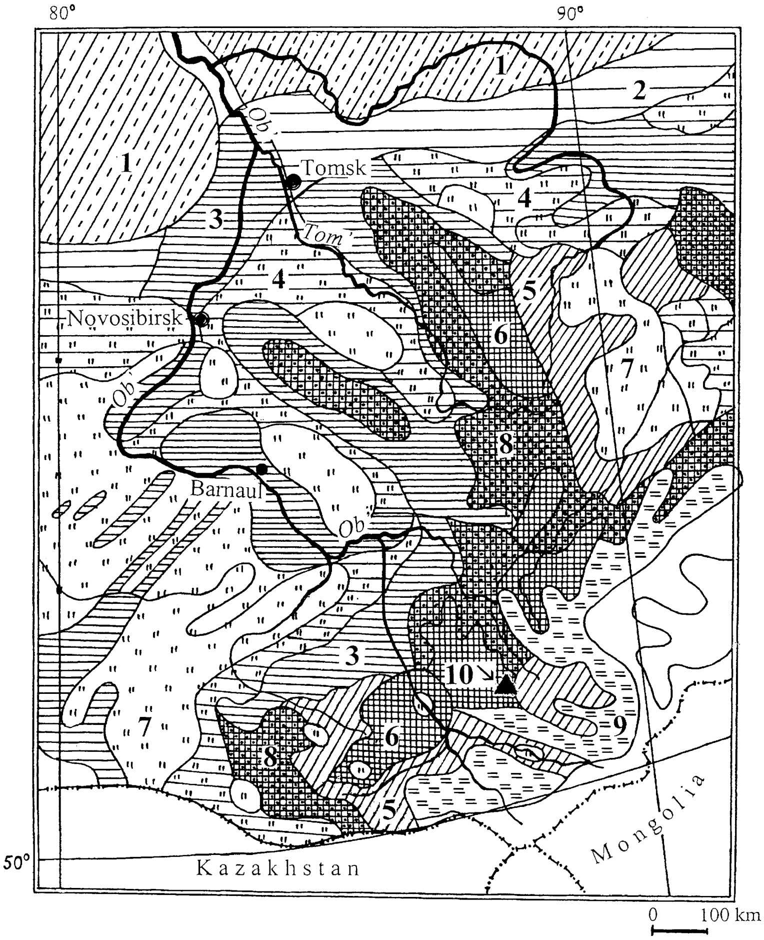


Fig. 2. Map of vegetation of the Altai Mountains and adjacent areas of Western Siberia and Kazakhstan. Redrawn from Krylov (1955). (1) *Betula pendula–Pinus sylvestris* dark-coniferous taiga (with *Pinus sibirica*, *Picea obovata*, and *Abies sibirica*) of the West Siberian plain. (2) *Pinus sylvestris–Betula pendula* forest. (3) *Pinus sylvestris* or *Pinus sylvestris–Larix sibirica* forest. (4) *Betula pendula* and *Betula pubescens* forest–steppe. (5) *Larix sibirica* forest. (6) *Pinus sibirica* and *Pinus sibirica–Larix sibirica* forest. (7) Steppe vegetation. (8) Dark-coniferous mountain taiga with *Abies sibirica*, *Picea obovata*, and *Pinus sibirica*. (9) High-mountain vegetation (alpine meadows, tundra, shrubs). (10) Area of investigation (Ulagan high-mountain plateau).

The forest zone disappears completely in the southeastern Altai, and there the steppe is in direct contact with with high-mountain vegetation.

According to Kuminova (1960), the Ulagan high-mountain plateau is situated in the Chulyshman mountain-forest district of the Central Altai geobotanical subprovince. Morphologically, it is a plateau with elevations from 1500 to 2500 m, deeply eroded by rivers. *Larix* forest covers most of the area, whereas the upper limit of continuous forest is formed of *Larix–Pinus sibirica* open woodlands at about 2100-m elevation. Steppe is extensive below 1400-m elevation in the valleys of the Karakudyur, Kubardu, and Ulagan Rivers near Ust'-Ulagan, 20 km northeast of the study area. Dark-coniferous taiga with *Abies*, *Picea*, and *Pinus sibirica* occurs near Teletskoye Lake (north of the study area), in the lower valley of the Chibitka River, and on the slopes around Cheibekol Lake. *Picea* grows locally admixed in the *Larix* forest on northern slopes, but it generally predominates in river valleys and gorges.

The mountains directly around the two lower-lying lakes (1985 and 2050 m) have open *Larix–Pinus sibirica* forests and on steep slopes xerophytic steppe communities. Gentle slopes around Uzunkol (1985 m) have locally subalpine shrub communities with *Betula humilis*, *Betula rotundifolia*, *Potentilla fruticosa*, and *Spiraea alpina*, which are also widespread along the upper valley of the Chibitka River and in some other areas between 2000 and 2100 m elevation. Gentle slopes around Kendegelukol (2050 m) have high-mountain herb–sedge–moss tundra, which may be connected with temperature inversion in winter causing permafrost in low wet places. Around the highest site Tashkol (2150 m), high-mountain shrub–moss–lichen and sedge tundra are present, and above this are stone lichen and stone tundra.

5. Methods

Long cores for pollen analysis were taken from the middle of the lakes with a square-rod piston sampler (Wright, 1991) in July 1999. The uppermost sediment from Uzunkol was taken with a transparent plastic tube fitted with a piston and subsampled in the field while vertical. The main core segments were transported in 1-m plastic tubes to the Institute of Plant Sciences in Bern (Switzerland), where they were subsampled for pollen analysis at intervals of 8 cm. Chemical preparation of samples for pollen analysis included the use of HCl, KOH, HF where needed, and acetolysis. Pollen analysis of samples was carried out in the Institute of Biology and Biophysics in Tomsk (Russia) under 400 × magnification. For identification of pollen and spore types, the works of Kupriyanova and Aleshina (1972, 1978), Bobrov et al. (1983), Kupriyanova (1965), and Moore et al. (1997) were used. In agreement with Kupriyanova (1965), *Betula nana*-type pollen includes pollen of all shrubby birches in the Altai: *Betula nana* and *Betula humilis*. Nomenclature of pollen and spore types follows the conventions of the European Pollen Database (EPD, Arles, France). The type "Bryales/Algae" as an informal name is discussed in Blyakharchuk (2003).

A total of 300–500 pollen grains of trees plus all other pollen and spore taxa was counted in each analysed level. Percentages of all taxa were calculated based on a pollen sum (100% by definition) including all pollen and spore types of vascular plants except those of water plants, wetland plants, and types redeposited or of long-distance transport (Figs. 3, 4, 6). For easier interpretation of pollen data, the pollen taxa were grouped in the categories Trees, Long-distance transported and redeposited (not shown), Shrubs, High elevation plants, Dry-soil plants, Ruderal plants, Mesophilous herbs, Wetland plants, and Aquatics. These groups are not perfect, because some pollen types can represent plants of different ecological groups. Charcoal particles and conifer stomata (Trautmann, 1953; Ammann and Wick, 1993) were also counted. Pollen diagrams were constructed with the program TILIA (Grimm, 1991). Chronostratigraphic zones in the sense of Mangerud et al. (1974) were not applied to pollen diagrams, because they are defined for northern Europe. Instead, Pollen Assemblage Zones (PAZ) similar for all three diagrams were distinguished and used for interpretation. This was possible because of the great similarity among the three pollen diagrams. Local and regional pollen assemblages are thus identical.

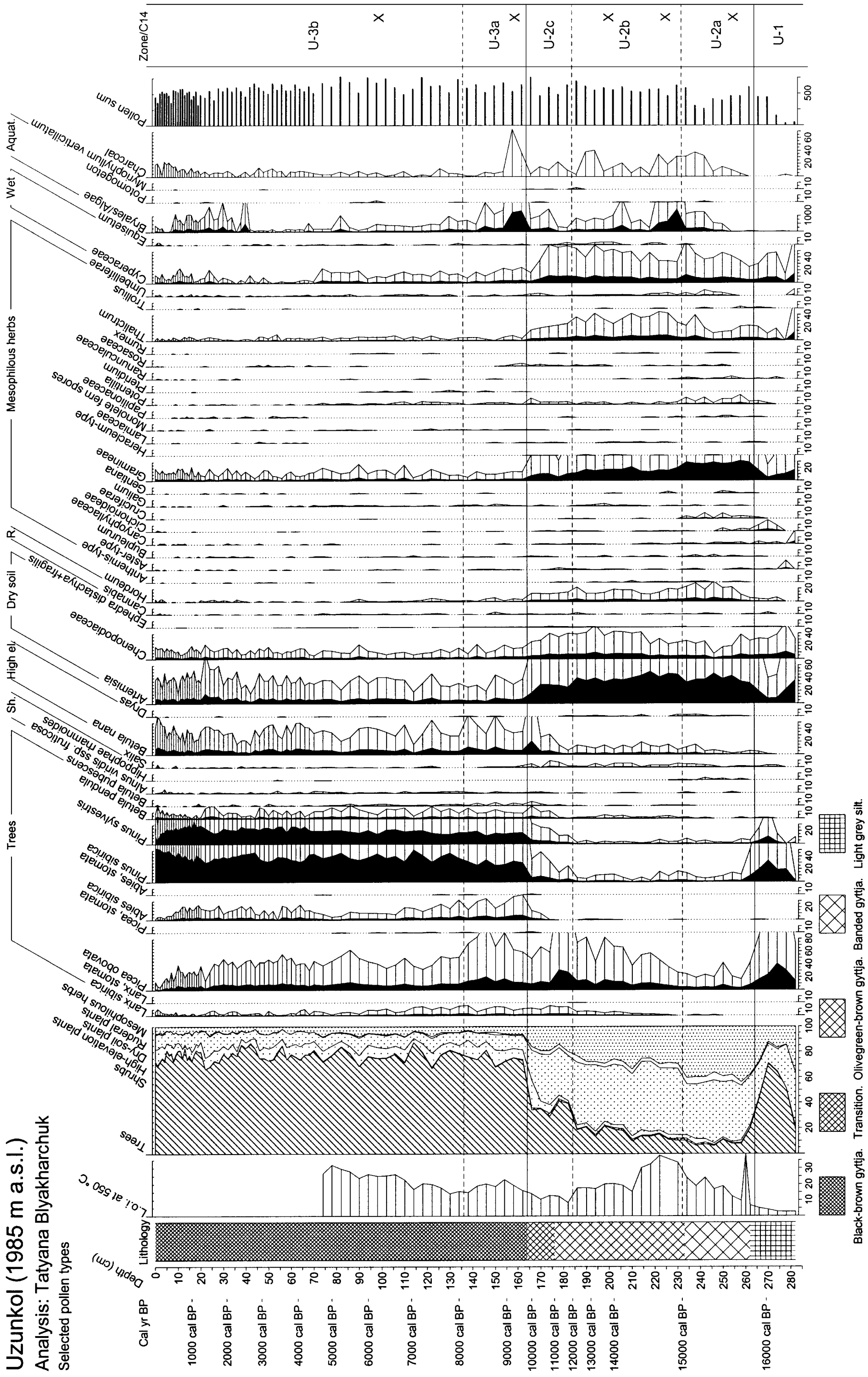


Fig. 3. Pollen percentage diagram for Uzunkol. The time scale (left) follows the depth–age model in Fig. 5. Positions of radiocarbon samples are shown with X in the right-hand column. No loss-on-ignition was determined in the top 70 cm.

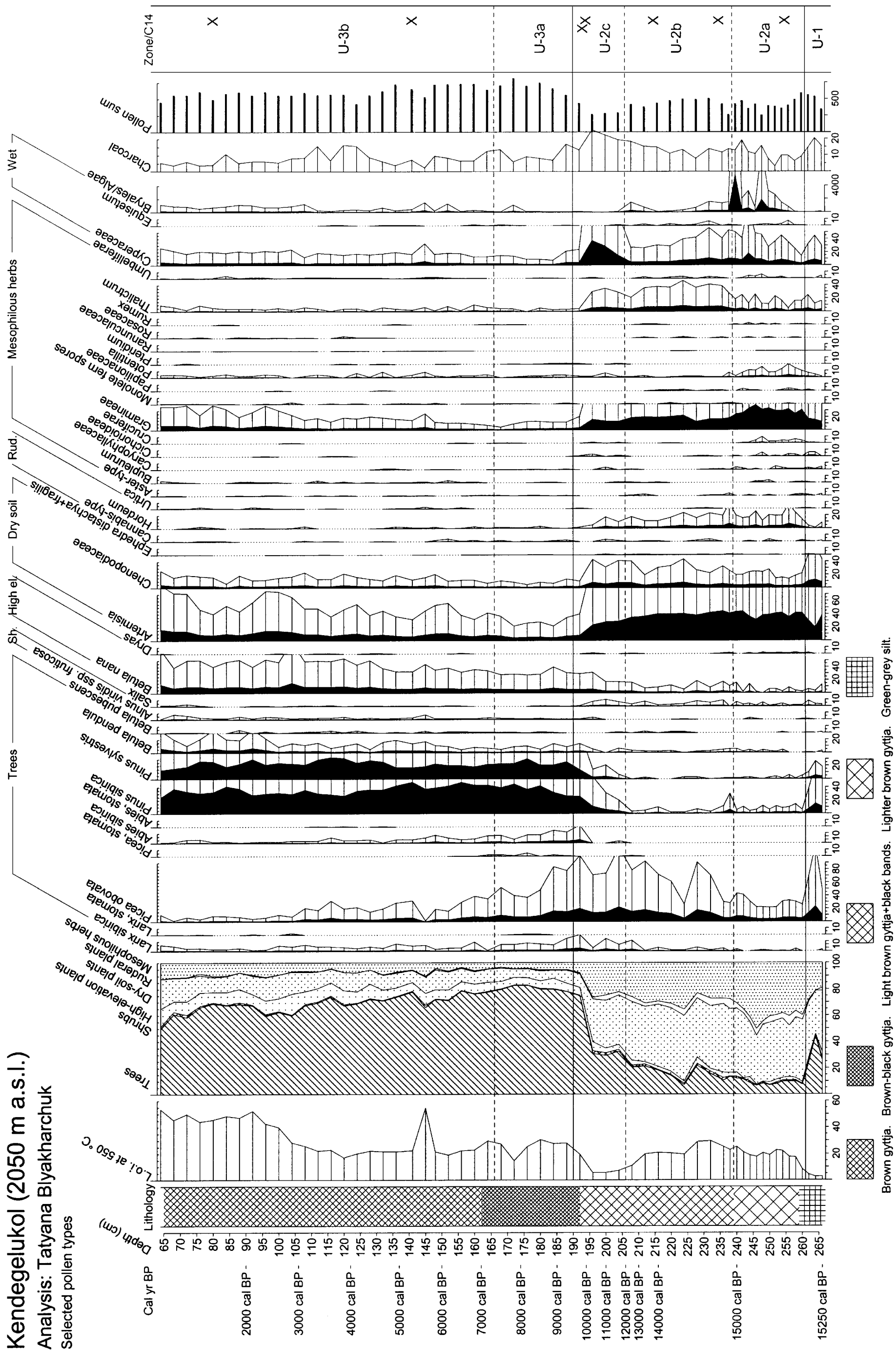


Fig. 4. Pollen percentage diagram for Kendegelukol. The time scale (left) follows the depth–age model in Fig. 5. Positions of radiocarbon samples are shown with X in the right-hand column.

Numerical zonation was carried out according to recommendations by Bennett (1996) by the method of optimal sum of squares partition (Birks and Gordon, 1985), and the number of statistically significant splits was determined with the broken-stick model (MacArthur, 1957). However, this resulted in only one or two statistically significant zone limits, the first separating the basal zone U-1 from the rest, the second one in the middle of the rapid change during reforestation. We prefer, however, to separate this important transitional zone of reforestation, termed here zone U-2c. Within some pollen assemblage zones, subzones were separated by eye.

Radiocarbon ages were determined by accelerator mass spectrometry (AMS) at the University of Colorado and are listed in Table 1. Terrestrial macrofossils constitute the most suitable material for radiocarbon dating, but they were not found. Instead, the humic acid fractions of gyttja were dated, which may be supposed to derive from terrestrial plant material at least for the greater part. No local geological information is available for estimating possible reservoir effects in the radiocarbon dates. Except where noted, all dates used in the text and on the diagrams were calibrated to calendar ages before present (Stuiver et al., 1998), including those from the literature. Core depths on the diagrams are measured from the sediment surface. The depth–age models are shown in Fig. 5.

Maps of local vegetation for different time intervals were constructed for the Pollen Assemblage

Table 1
Radiocarbon dates in study sites[a]

Depth	^{14}C BP uncalibrated	• ^{13}C	NSRL-No.	Calibrated age cal yr BP
Tashkol				
56 cm	3740±50	−27.9	11231	4101±114
98 cm	6480±50	−29.0	11232	7375±54
134 cm	9760±65	−28.7	11233	11,175±52
150 cm	10,460±60	−27.3	11234	12,481±307
168 cm	11,520±65	−27.3	11235	13,503±292
186 cm	12,710±100	−27.4	11236	14,979±607
Kendegelukol				
80 cm	1520±40	−32.1	11219	1426±80
141 cm	4620±70	−29.0	11220	5275±190
193 cm	8720±90	−28.0	11222	9709±155
194 cm	8820±55	−27.9	11221	9912±199
215 cm	11,970±110	−26.7	11223	13,967±150
235 cm	12,690±75	−28.0	11224	14,965±596
255 cm	12,880±130	−29.3	11225	15,155±693
Uzunkol				
99 cm	5590±75	−28.6	11226	6369±69
159 cm	8220±65	−28.2	11227	9155±122
200 cm	11,890±60	−29.5	11228	13,941±125
225 cm	12,500±70	−28.5	11229	14,808±538
255 cm	13,000±95	−27.5	11230	15,635±345

[a] Material dated is humic acids extracted from gyttja.

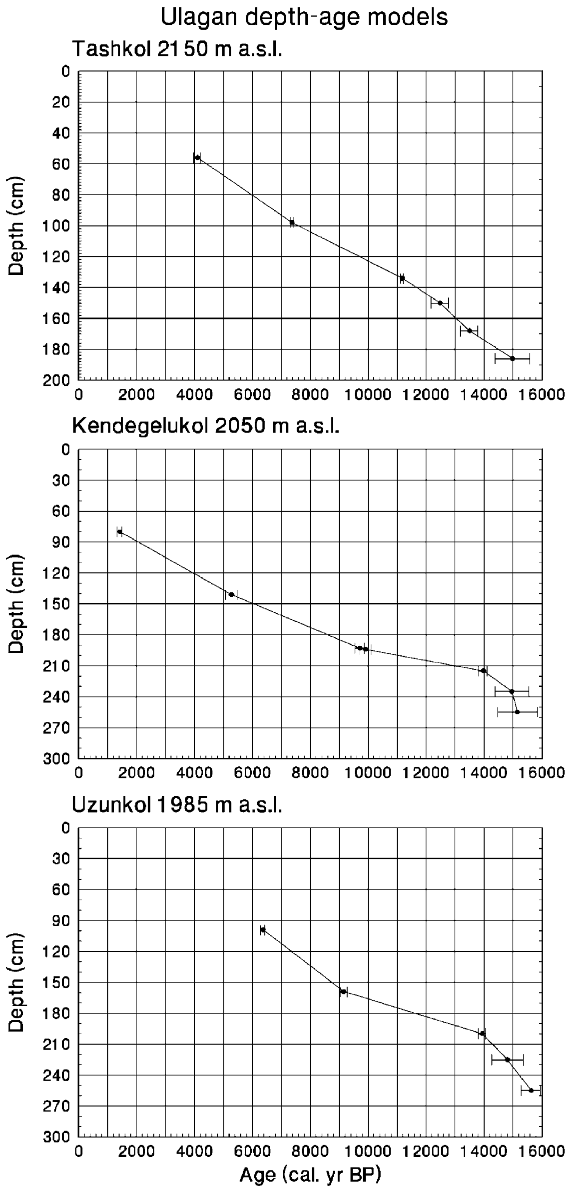


Fig. 5. Depth–age models of the three pollen sites on the Ulagan Plateau.

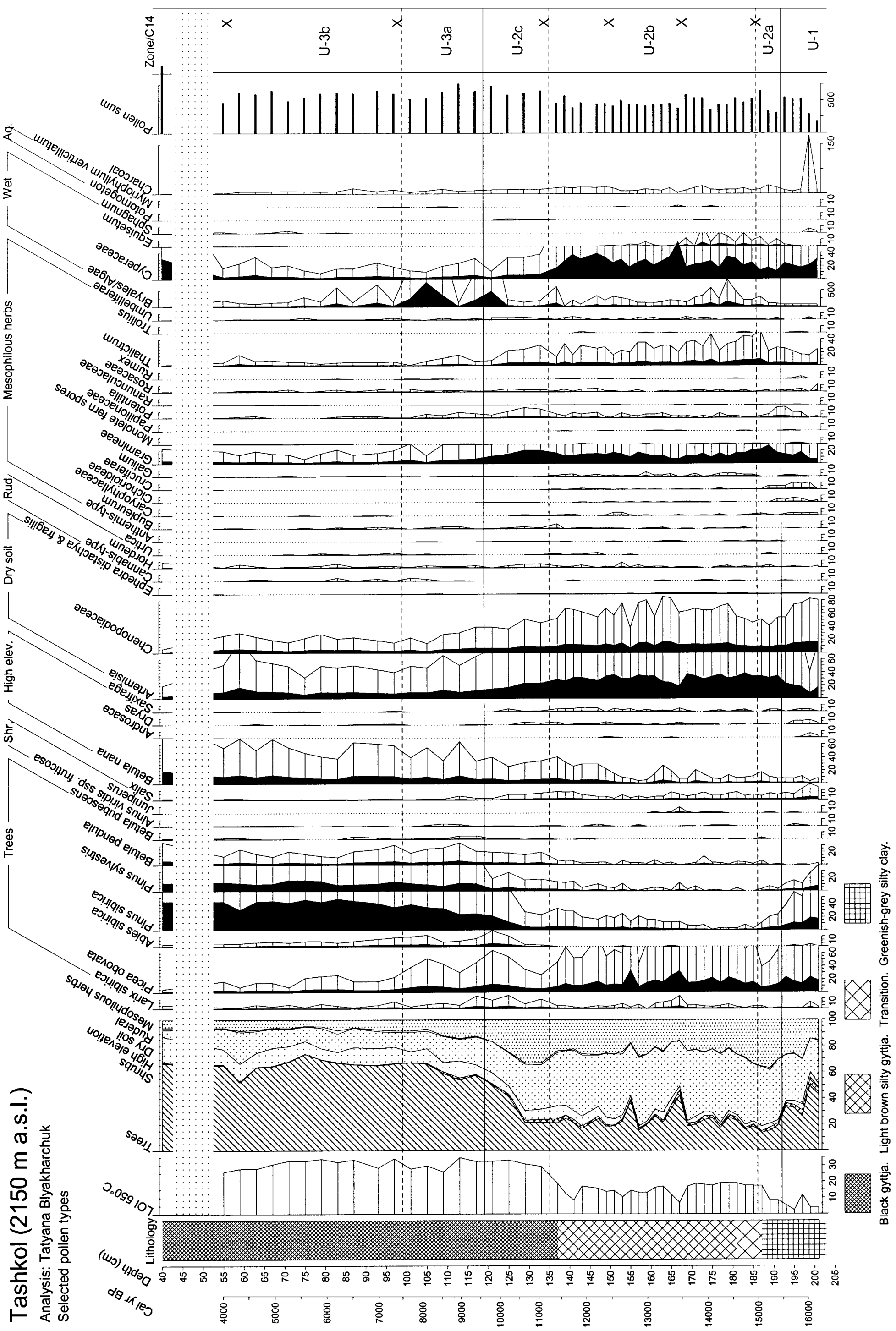


Fig. 6. Pollen percentage diagram for Tashkol. The time scale (left) follows the depth–age model in Fig. 5. Positions of radiocarbon samples are shown with X in the right-hand column. Top 20 cm is short core subsampled in the field.

Zones (Figs. 7, 8 and 9) based on the calibrated time scale and the topographic map of the area of investigation, taking into account the modern altitudinal distribution of vegetation in central Altai (Yelenevsky, 1939; Kuminova, 1960; Shumilova, 1962).

6. Description and interpretation of pollen diagrams

Because of the great similarity of the pollen diagrams (Figs. 3, 4 and 6), we identify with the label U

Table 2
Description of pollen diagrams[a]

Zone	Uzunkol		Kendegelukol		Tashkol		Transition	Description of zone limits and zones
	Depth	cal BP	Depth	cal BP	Depth	cal BP		
U-3b								AP: decreasing *Abies sibirica*, *Picea obovata*, and *Larix sibirica*.
	136 cm	**8100 yr**	166 cm	**7400 yr**	99 cm	**7500 yr**	**Gradual**	
U-3a								AP: increasing *Pinus sibirica, Pinus sylvestris*, *Abies sibirica*, and *Betula pendula*, and in Uzunkol and Kendegelukol presence of stomata of *Abies*, *Picea*, and *Larix*; shrubs: increasing *Alnus viridis* ssp. *fruticosa* and *Betula nana*-type and decreasing *Salix* and *Potentilla*; NAP: sharply decreasing *Artemisia*, Chenopodiaceae, Gramineae, *Hordeum*, *Thalictrum*, and Cyperaceae. Maximum of Bryales/Algae in two sites.
	164 cm	**9740 yr**	190 cm	**9454 yr**	117 cm	**9380 yr**	**Sharp**	
U-2c								Transitional phase. AP: beginning increase of *Pinus sibirica*, *Pinus sylvestris*, *Abies sibirica*, and *Betula pendula*, and at Uzunkol and Kendegelukol modest maxima of *Picea* and *Larix* and first stomata. NAP: at Tashkol temporary maxima of Gramineae, *Hordeum,* and *Potentilla*.
	184 cm	**12,075 yr**	206 cm	**12,230 yr**	137 cm	**11,420 yr**	**Gradual**	
U-2b								AP: gradually increasing *Picea* and *Larix* but no stomata. NAP: decreasing Gramineae, *Potentilla*, Cruciferae, and Umbelliferae; Bryales/Algae show maximum at base of zone.
	232 cm	**15,000 yr**	239 cm	**15,004 yr**	186 cm	**14,980 yr**	**Gradual**	
U-2a								AP: sharp decline of *Picea obovata* to 10%, *Pinus sibirica*, and *Pinus sylvestris*, no stomata, very low *Betula*, and nearly continuous *Larix*. Shrubs: increase of *Betula nana*-type, *Salix*, and *Ephedra*. NAP: increase up to 90% dominated by *Artemisia*, Gramineae, Chenopodiaceae, Cyperaceae, and *Thalictrum*.
	264 cm	**15,880 yr**	261 cm	**15,212 yr**	192 cm	**15,470 yr**	**Sharp**	
U-1								AP: predominance of *Picea obovata*, *Pinus sibirica*, and *Pinus sylvestris*. Shrubs: presence of *Salix* and *Betula nana*-type. Main NAP: *Artemisia*, Chenopodiaceae Gramineae, Cyperaceae, and *Thalictrum*. Minor NAP: maxima of Caryophyllaceae, Cichorioideae, Cruciferae, *Potentilla*, and *Dryas*. Complete absence of Bryales/Algae.

[a] AP = Tree pollen. NAP = High-elevation + Dry-soil + Ruderal + Mesophilous herb pollen. Pollen sum = AP + shrubs + NAP.

for Ulagan the three regional Pollen Assemblage Zones (PAZ) common for all diagrams. The pollen zones are described in Table 2; they are biozones and their limits may be time transgressive. The subzones have ecological meaning and are probably related to altitudinal peculiarities of the vegetation. Calibrated ages BP of the PAZ limits for the three sites are summarized in Table 2.

6.1. PAZ U-1 *Picea–Pinus–Artemisia*

PAZ U-1 is in the silt that underlies organic lake sediments in all three lakes. This suggests that the landscape was barren and prone to erosion. Pollen concentrations are very low and tree pollen is predominant. Therefore, the tree pollen may represent long-distance transport to a landscape that has very little vegetation and is partly covered by glaciers. Especially, the highest site Tashkol (2150 m) shows a great variety of herbaceous types representing pioneer mountain tundra with low pollen production and dispersal, including the nitrogen-fixing pioneer *Dryas*.

6.2. PAZ U-2 *Artemisia–Gramineae*

Except at Tashkol (2150 m), PAZ U-2 is found entirely in the gyttja that overlies the silt of PAZ U-1. This suggests a decrease in erosion in the surroundings and therefore denser vegetation. The predominance (up to 90%) and high variety of NAP (nonarboreal pollen) with dominance of Gramineae and abundant *Potentilla* and Cruciferae indicates a well-developed pioneer vegetation cover. The sharp drop in conifer pollen percentages indicates that the pollen assemblage records primarily local trees rather than long-distance types, although *Pinus sylvestris* and *Betula* may still be of long-distance origin. Absence of stomata suggests that *Picea* and *Larix* may not have been locally present, although nearly continuous *Larix* pollen at all sites suggests nearby trees, considering the poor dispersal of this pollen type. Higher values of Bryales/Algae imply greater productivity in the lakes. The reconstructed changes in vegetation indicate clearly a more moderate climate.

In subzone PAZ U-2b, higher temperatures are suggested in three ways. First, slightly declining values of Gramineae, *Hordeum*, *Potentilla*, and Cruciferae and increasing *Artemisia*, Chenopodiaceae, *Thalictrum*, *Salix*, and *Betula nana*-type suggest a succession from pioneer vegetation to steppe or tundra–steppe including shrub tundra. Second, *Picea* and *Larix* gradually increase, although no stomata were found to indicate local trees. Third, in the first part of U-2b a maximum of loss-on-ignition suggests decreased erosion and therefore denser vegetation near the lakes, which may reflect on the one hand the succession from pioneer to tundra vegetation, on the other expansion of pioneer vegetation on barren areas. A maximum (in two sites) of Bryales/Algae in the first part of U-2b suggests higher productivity in the lakes. In the second part of U-2b, decreased Bryales/Algae (in all sites) indicates decreased in productivity of microscopic algae. Steppe had reached its maximum altitudinal extent.

Subzone PAZ U-2c shows a transitional phase from treeless to locally forested landscapes in all three pollen diagrams by an increase of arboreal pollen (AP). The slight maxima of *Picea* and *Larix* pollen at Uzunkol and Kendegelukol and the first findings of their stomata are evidence that these tree species began to appear near the lakes. This indicates a shift to more moderate climatic conditions after colder and drier conditions earlier. Absence of stomata in high-elevation Tashkol (2150 m) indicates that these trees were never abundant at that elevation. Nevertheless, the temporary maxima of the NAP types Gramineae, *Hordeum*, and *Potentilla* in Tashkol support the climatic warming. The same NAP types increased at the lower-lying sites already at the beginning of PAZ U-2a, suggesting more moderate climatic conditions.

6.3. PAZ U-3 *Pinus sibirica–Pinus sylvestris*

PAZ U-3 is well expressed in all three pollen diagrams. Stomata of *Abies*, *Picea*, and *Larix* in Uzunkol and Kendegelukol are signs that the pollen of these taxa originated from local tree stands around these sites. More gradually increasing AP curves in Tashkol and a greater amount of *Betula nana*-type pollen (shrub birch) suggest that the tree pollen at this site came from lower elevation. The present-day timberline in the central Altai is formed mostly by *Pinus sibirica*, which is well expressed in the Tashkol diagram. The general decrease in diversity of NAP types may be due to swamping of the pollen assemblage by *Pinus* pollen.

In subzone PAZ U-3b, pollen suggests a decreasing role of *Abies*, *Picea,* and *Larix* in the forests, which indicates slightly decreasing temperatures and less humidity in the second part of the Holocene. Two features are tentatively ascribed to human impact on vegetation. (1) The increased Bryales/Algae from ca. 3 ka BP onwards in Uzunkol and Kendegelukol is possibly related to eutrophication caused by grazing near the lakeshores. (2) During the last few hundred years (covered only in Uzunkol), marked decreases of *Abies* and *Picea* and increases of *Pinus sibirica* and *Larix* are suggested, for which a human cause is likely.

7. Palaeogeographic reconstructions and discussion

7.1. Reconstruction of changes in vegetation and climate

Three maps of reconstructed vegetation are presented for selected time intervals (Figs. 7–9). The maps are based on the topographic map of the area and the reconstructed extent of glaciers. Assumptions are that the vegetation was in equilibrium with the climate of that period, and, as at the present time, elevation and exposure determined the altitudinal zonation in the past.

The palaeogeographic events as reconstructed based on pollen are described below. The available published literature for the Altai Mountains and neighbouring areas (summarized in Fig. 10) is used for correlation and interpretation of these events.

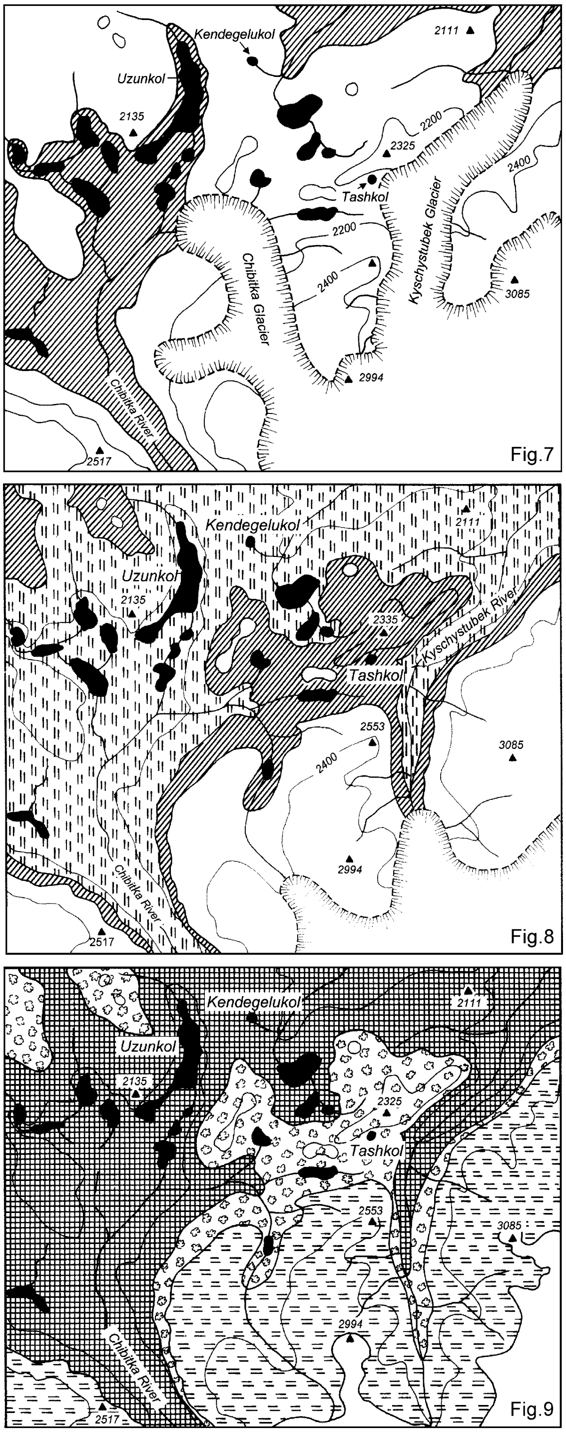
7.2. PAZ U-1

The warming at the end of the glacial maximum caused melting of the ice cap on the Ulagan plateau and an increase of barren areas. Before 15.9 cal ka BP, the Ulagan high-mountain plateau was mostly covered by retreating glaciers and barren areas, and also by high-mountain desert and stone—lichen tundra with open pioneer vegetation. The reconstructed vegetation suggests that the climate was cold and dry but with rather warm summers, which may have caused extensive recession of the glaciers. The ice melted first at the lower elevations, including the depression exposed by the melting glacier of the Chibitka valley in which the primary Uzunkol (1985 m) began to form. The other, higher-lying lakes studied came into existence soon after. The meltwater passed over barren areas and deposited silt in the lakes, and possibly also pollen that had been deposited on the glaciers and accumulated in the ice.

Tree pollen transported from a long distance was dominant in PAZ U-1. One source was presumably woodlands that survived on the piedmont and low mountain areas during glacial times. Several studies confirm the occurrence of such woodlands in this period. Approximately 145 km north of the Ulagan sites at the bottom of a terrace in the Pyzha River valley near Teletskoye Lake, pollen of *Picea*, *Pinus sibirica*, and different herbs were found, and a piece of wood from these sediments was dated ca. 19 cal ka BP (16120 ± 80 ^{14}C year BP; COAN-1864, Baryshnikov, 1996). The pollen diagram from Anui-I cave in the upper Anui River basin in the western low mountain areas of the Altai was the basis for reconstructing a periglacial forest–steppe with *Betula* and *Picea* and vast areas covered by Chenopodiaceae–Gramineae steppe during the period 20–17 cal ka BP (17–14 ^{14}C year BP; Derevyanko et al., 1998). According to this author, it was a rather dry period. Further east near Lake Baikal, forest–tundra and vast areas of Chenopodiaceae–*Artemisia* vegetation dominated the landscape during this interval (Bezrukova, 1998).

7.3. PAZ U-2a (ca. 15.9–15 cal ka BP, Fig. 7)

During the interval of PAZ U-2a, long glaciers probably still filled the upper tributary valleys of the Chibitka and Kyskhystubek rivers, and the remaining areas above 2000 m were barren or marked by stone tundra similar to that of PAZ U-1. Below 2000 m in the Chibitka River valley, the slopes around the lowest-lying study site Uzunkol (1985 m) became occupied by dense and varied pioneer vegetation, and silt accumulation in the lake gave way to gyttja as a result of less erosion and greater organic productivity in the warmer climate. The increased levels of Bryales/Algae also indicate higher productivity in the lakes. Species-rich pioneer vegetation developed around the lowest-lying study site Uzunkol (1985 m) as early as 15.9 cal ka BP, while at the intermediate site Kendegelukol (2050 m) such vegetation and the onset of gyttja deposition



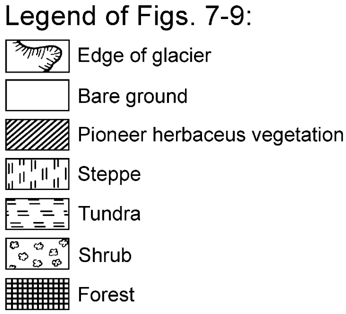


Fig. 7. Map of vegetation on the Ulagan Plateau reconstructed for PAZ U-2a, 15.9–15 cal ka BP. Pioneer herbaceous vegetation has *Artemisia*, Gramineae, Cyperaceae, *Salix*, and *Potentilla*. Bare ground may have very scarce pioneer plants.

Fig. 8. Map of vegetation of the Ulagan Plateau reconstructed for PAZ U-2b, 15–12 cal ka BP. Steppe vegetation is dominated by *Artemisia* and Chenopodiaceae. Pioneer herbaceous vegetation has Gramineae, Cyperaceae, Cruciferae, *Artemisia*, *Salix*, and *Potentilla*. Bare ground may have very scarce pioneer plants.

Fig. 9. Map of vegetation of the Ulagan Plateau reconstructed for PAZ U-3a, 9.5–7.5 cal ka BP. Forest vegetation has *Pinus sibirica*, *Abies sibirica*, *Picea obovata*, and *Larix sibirica*. Shrub vegetation has *Betula rotundifolia* and *Betula humilis* alternating with alpine meadows. Tundra vegetation is sedge–moss and lichen tundra. Bare ground may have very scarce pioneer plants.

started several hundred years later. The sediment at the highest site Tashkol (2150 m) was silt rather than gyttja, which suggests that barren landscapes still existed there. The sharp decrease in the proportions of long-distance tree pollen can be explained by increased pollen production from the denser plant cover. Likely sources of this tree pollen are the woodlands mentioned under PAZ U-1 and other woodlands referred to in literature. Baryshnikov (1996) reconstructs dark-coniferous taiga in the low mountains near Teletskoye Lake 195 km north of the Ulagan sites based on a rich carpological complex found in a terrace of the Lebed' River (basin of Teletskoye Lake), dated ca. 16.5 cal ka BP (13750 ± 70 BP; COAN-576). Derevyanko et al. (1998) reconstruct for this period *Betula* forest–steppe on the low mountains of the western Altai.

The inferred spread of mesophilous herbs, which were abundant along with dry-soil plants, suggests that local moisture was rather high. We may assume that it was not a simple mixture of plants with different ecology, but a structured vegetation cover such as the modern treeless landscapes of the southeastern Altai. A modern analogue may be the high-mountain tundra in the Altai that includes meadow–tundra with patches of cold steppe, turf-grass meadows, and turf-sedge tundra with predominance of *Koeleria cristata*, *Festuca lenensis*, *Helictotrichon krylovii*, *Carex pediformis*, and *Carex duriuscula* (Yelenevsky, 1939; Lavrenko, 1981), or kobresian tundra with predominance of *Kobresia simpliciuscula* and shrub and moss–lichen tundra with such dwarf-shrubs as *Spiraea alpina*, *Potentilla fruticosa*, and *Betula rotundifolia* (Kuminova, 1960). Most of these species are present in the vegetation of the Ulagan high-mountain plateau today. The arctic and the alpine ranges of these species are separated today by the boreal forest zone, but they may have been connected in the past and the extent of such tundra–steppe communities may have been wider in the past than today. In the area of the Ulagan River, Butvilovsky (1993) characterized the Late Glacial pioneer vegetation as tundra–meadow or in more arid places tundra–steppe. Because of weakly developed soils, this pioneer vegetation included species that now play a role as weeds on disturbed soils poor in organic matter. Our data suggest that this was indeed the case on the Ulagan high-mountain plateau, by increased amounts of Cruciferae and Compositae Cichorioideae pollen, to which most local weeds belong today.

The initiation of the warmer and wetter climatic conditions and the start of organic sedimentation may correlate with the beginning of the Late Glacial of western Europe and the Greenland ice cores (ca. 14.7–14.5 ka BP).

7.4. PAZ U-2b (ca. 15–12 cal ka BP; Fig. 8)

The succession from pioneer vegetation to steppe and tundra vegetation suggests a warmer climate (Fig. 8). This succession took place even around the highest site Tashkol (2150 m) and new pioneer vegetation developed on formerly barren areas such as valley bottoms where glaciers were melting away, but the climate may not have been warm enough for rapid expansion of dense vegetation above 2200-m elevation. Meadow–shrub–grass vegetation was widespread including pioneer species, typical arctic–alpine species, dwarf-shrubs, and a great amount of mesophilous herbs and turf grasses and sedges. Steppe reached its maximum altitudinal extent on the Ulagan high-mountain plateau in PAZ U-2b. The lack of woodland vegetation made the Ulagan landscape similar to modern landscapes of the southeastern Altai and Mongolia, where steppe directly contacts high-mountain vegetation (Kuminova, 1960).

Within the 3-ka duration of PAZ U-2b, no trends in the pollen profiles are apparent that could suggest a subdivision of the Late Glacial into Bølling, Allerød, Younger Dryas, etc. Clear signs of Younger Dryas cooling are lacking in the Ulagan pollen diagrams, perhaps because the Ulagan plateau was a treeless landscape during this period. The only published pollen diagram from another treeless mountainous part of the Altai also lacks indications of a Younger Dryas (northern Mongolia; Tarasov et al., 2000). However, pollen records from the forested areas of the Altai are of low temporal resolution and are based on poor radiocarbon dating control (Butvilovsky, 1993; Derevyanko et al., 1998). Consequently, these records are limited in their utility for addressing abrupt climatic oscillations during the Late Glacial.

Elsewhere in Siberia, the impacts of Late Glacial climate oscillations were clearly recorded over a large area. In the steppe of the Barabiskaya plain (northwest of the Altai) in southwestern Siberia, sedimentation in river valleys changed abruptly from periglacial to typically alluvial (Orlova, 1986). In northern Kazakhstan, montane steppe–taiga expanded during the interval 15.5–11.5 cal ka BP under cool and wet climatic conditions (Tarasov et al., 1997). However, Butvilovsky (1993) refers to sharp alternations of dry–warm with cold–wet intervals during the Late Glacial, which caused the formation of three terraces in the Ulagan River valley with signs of solifluction and large naleds (temporary ice covers) on the terraces below scarps. He considers that the last great cooling in the Altai took place at 12.8–11.8 cal ka BP, beginning with a cold–wet phase followed by a cold–dry phase. The start of this temperature decrease coincided approximately with the deposition of the first Altai moraine about 13.2 cal ka BP (Okishev, 1982). However, the dating of the moraines in the Altai is still a matter of debate (Butvilovsky, 1993). Possibly, the influence of the Younger Dryas will be more clearly expressed in pollen diagrams from sediments of modern lakes in the western or northern Altai where forest cover is more extensive. This is a task for future investigation.

Our pollen data from the Ulagan sites do not contradict the interpretation of Butvilovsky (1993) that warm and dry conditions prevailed in the Late Glacial and early Holocene. He reconstructed these conditions based on a rich carpological complex found in the Late Glacial blue clays of the Yeshtykkol site (Dzhangyskol in Kuraiskaya valley) and on the evidence of deep fluvial downcutting of the Karakudyur and Ulagan Rivers during this period. He argues that this would have been unlikely under cold conditions with widespread permafrost. Moreover, he maintains that the warm conditions (sometimes warmer than today) in the Late Glacial are confirmed by presence of saltwater foraminifers and marls in ancient lake sediments in the Karakudyur River valley. Evidence from more distant areas includes a change in the sedimentation in Lake Baikal (Bezrukova, 1998) around 14 cal ka BP.

Information for the Younger Dryas period 13.0–11.5 cal ka BP (11–10 ^{14}C ka BP) comes from large lake basins in the Dzhulukul and Kuraiskaya depressions of the southeastern Altai (Butvilovsky, 1993). According to pollen and diatom data of Levina et al. (1989) from lake sediments in the modern forest—steppe area in the Nizhnii Suzun River basin in the northern Altai piedmonts, *Picea* and *Betula* forest surrounded the lake from 13.6 to 12.7 cal ka BP, whereas the wider surroundings were dry Chenopodiaceae–*Artemisia* steppe. Tarasov et al. (1997) reconstructed for the Kokchetav highland of northern Kazakhstan during the Younger Dryas montane steppe–taiga with groves of *Picea* and *Pinus sibirica* surrounded by vast areas of montane steppe. Deep lakes existed in these landscapes (Davydova et al., 1995). The Younger Dryas landscape east of the Altai near Lake Baikal was occupied by forest–tundra with *Picea*, *Larix*, and *Betula* (Bezrukova, 1998). In northwestern Mongolia, dry steppe with *Artemisia*, Chenopodiaceae, Gramineae, and *Betula nana* was dominant (Tarasov et al., 2000). Thus, in all these areas two contrasting landscape features coexisted: dry steppe and deep water basins that, in some cases, provided sufficient moisture for the growth of tree vegetation along the shores. According to Prentice et al. (1992), pollen evidence of semiarid conditions and geomorphic evidence of high lake levels are compatible under conditions with dry summers and wet winters and with a general reduction of seasonal temperatures. From the south of the West Siberian plain to the south taiga subzone, 13.0–11.5 cal ka BP was the time of degradation of permafrost, which had been widespread in glacial times. Astakhov (1995) considers that numerous thermokarst lakes were formed during this time. With thawing of permafrost, a general lowering of the loess surface occurred, and old periglacial lakes that existed in glacial times and had been filled by sediments were drained and became hills. Thus, an inversion of the relief took place in Western Siberia during this period.

7.5. PAZ U-2c (ca. 12–9.5 cal ka BP)

Afforestation of the steppe–tundra began in the Ulagan area in PAZ U-2c after about 12 cal ka BP, marking the climatic warming at the beginning of the Holocene (10 ^{14}C ka BP, 11.5 cal ka BP). However, unlike the abrupt changes more common in western Europe, it was a slow process lasting about 2 ka. The changes occurring in the steppe–tundra vegetation at Tashkol are similar to those occurring about 4 ka earlier in PAZ-2a at the two lower-lying sites, and similar is also the interpretation of warmer and somewhat moister climatic conditions. The past vegetation marked by increased Gramineae and Cyperaceae may have modern parallels in the high-elevation kobresian and turf-sedge tundra occurring in the region today.

The time of ca. 11.5 cal ka BP (10 ^{14}C ka BP) was marked by palaeogeographic events in many sites (Fig. 10). In the Ulagan high-mountain plateau (our data) and in southwestern Siberia (Orlova, 1986), woodland vegetation began to expand after this time, although steppe vegetation still persisted in the southeastern Altai and in intermontane depressions (Butvilovsky, 1993). In northern Kazakhstan, montane steppe–taiga changed to steppe–*Betula* woodlands, which are associated with increased continentality of climate (Tarasov et al., 1997). After 11.5 cal ka BP, gyttja (sapropel) started to accumulate in the lakes of northern Kazakhstan, with evidence of increased biological productivity on the landscapes due to climatic warming (Davydova et al., 1995). In the Lake Baikal area, forest–tundra changed to closed forest with

Picea and *Betula* and areas of montane shrub vegetation (Bezrukova, 1998).

According to Butvilovsky (1993), the climatic optimum in the Altai was about 10 cal ka BP. Remains of thermophilous aquatic plants were found in the blue clays of an ancient lake in the Kuraiskaya depression (Yeshtykkol area) near modern Dzhangyskol that do not grow in the Altai today (Fig. 10). Butvilovsky (1993) reconstructed an increase in summer temperatures of 5–6 °C and an upward shift of the forest altitudinal belt of 400–500 m in the southeastern Altai near Dzhulukul Lake, enabling *Picea* and *Pinus sibirica* forests to grow in an area that is today a treeless tundra–steppe landscape. All these reconstructions are consistent with the assessment of COHMAP Members (1988) that, at about 10 cal ka BP, the average solar radiation over the Northern Hemisphere was 8% higher in July and 8% lower in January than it is today. It is evident, however, that increased summer insolation cannot be the sole reason for the expansion of forests in former treeless areas. Increased moisture is also a requirement. Steppe persisted for several millennia not only at the Ulagan sites but also in Mongolia (Tarasov et al., 2000), northern Kazakhstan (Tarasov et al., 1997), and the south of the West Siberian plain (Orlova, 1986). This reflects the dominance of cold and dry northeasterly airflow from the Siberian anticyclone (Tarasov et al., 1997), which was strengthened by the supply of circumpolar arctic air north of the ice sheets that persisted on both Eurasia and North America. After 10 cal ka BP, seasonal extremes decreased toward modern values (COHMAP Members, 1988) as the last remnants of the Scandinavian ice sheet disappeared, causing changes in atmospheric circulation and increased moisture in the southeastern and central Altai.

7.6. PAZ U-3a (ca. 9.5–7.5 cal ka BP; Fig. 9)

Full development of forests is registered at all three sites by 9.5 cal ka BP (Fig. 9). Continuous forest reached the elevation of the two lower sites (1985 and 2050 m), but not of the highest site (2150 m). *Pinus sylvestris* pollen was most probably transported from forests at lower elevation in the western Altai, and *Pinus sibirica* was likely at the timberline, as is the case today. *Abies*, *Picea*, *Larix*, and *Betula pendula* were also growing locally. Forest rich in the mesophilous *Abies* and *Picea* is called dark-coniferous taiga, which reached its maximum extent 9.5–7.5 cal ka BP. A modern analogue is the forest in the northern and western Altai. At elevations more than 2100 m, we assume dominance of high-mountain shrub-tundra with thickets of *Betula nana*.

During this time, maximum extent of dark-coniferous forest with *Picea* was also reconstructed for the valley of the Karakudyur River (1420 m elevation), 22 km north of the Ulagan sites, which today is a forest–steppe landscape (Butvilovsky, 1993). In the southwestern Altai, a rapid expansion of *Picea–Abies* forests took place from 8.3 cal ka BP onwards (Chernova et al., 1991). In northern Kazakhstan, *Betula* forest–steppe expanded between 8.9 and 8.1 cal ka BP in place of the former open steppe. Around 10.8–9.5 cal ka BP, roughly synchronous with the spread of forest on the Ulagan high-mountain plateau, *Picea* and *Pinus sibirica* forests spread in the former steppe areas of northern Mongolia (Tarasov et al., 2000).

Evidence for moistening of the climate in central areas of Eurasia is expressed both in the expansion of forest vegetation in former treeless landscapes described above and in the increase of lake levels. Diatom analysis of lake sediments indicates higher lake levels between 8.4 and 7.4 cal ka BP in northern Kazakhstan (Davydova et al., 1995) and between 7.8 and 6.6 cal ka BP in Chany Lake, which is situated in the steppe zone of southwestern Siberia. The combination of climatic moistening and warming was favourable for forest expansion, higher lake levels, and increased biological productivity in lakes. Increased organic matter and diatom productivity are reconstructed for the lakes in the southern Ural Mountains from 8.8 to 6.3 cal ka BP (Davydova et al., 1995). Investigations of Harrison et al. (1996) show that from 8.9 to 5.8 cal ka BP, lake levels in Mongolia were higher than at present, suggesting conditions wetter than at present.

Our data from the central Altai indicate that the Altai Mountains, just as northern Mongolia, came under stronger influence of moist air after about 9.5 cal ka BP. Northern Mongolia was influenced by strengthening and northward displacement of the Pacific monsoon (Tarasov et al., 2000), whereas the Altai Mountains were affected by moisture carried by Atlantic cyclones, which caused greater afforestation in the latter.

According to estimates of COHMAP Members (1988), summer temperatures at 6.8 cal ka BP were 2–4 °C higher than at present throughout the continental interior of Eurasia, and increased July and decreased January insolation between 14 and 7 cal ka BP produced a major strengthening of northern monsoons. From about 14–10 cal ka BP, the Altai and Mongolia were influenced by the dominance of cold and dry northeasterly air flow from the Siberian anticyclone (Tarasov et al., 1997); whereas after 10 cal ka BP, the influence of this anticyclone weakened, and orbitally induced Pacific monsoons penetrated far inland to the mountains. Just as today, the early Holocene Russian Altai and northwestern Mongolia were under the influence of different climatic systems, with the boundary between them situated in the southeastern and partly central Altai.

7.7. PAZ U-3b (ca. 7.5 cal ka BP to the present)

Dark-coniferous species such as *Abies sibirica* and *Picea obovata* declined gradually from 7.5 cal ka BP onwards, and they almost disappeared from the woodlands of the Ulagan high-mountain plateau by about 6 cal ka BP. The decrease of these mesophilous species indicates cooler and more continental climatic conditions in the late Holocene. In the Uzunkol area, which among the study sites is closest to the remnant of present-day dark-coniferous forest near Cheibekol Lake, *Picea* declined less and *Abies* had a second maximum after about 4 cal ka BP. Open *Pinus sibirica* and *Larix* forest became dominant on the plateaus and closed forest on the mountain slopes, and *Pinus sibirica* continued to form the timberline. At elevations above 2100 m, high-mountain shrub and sedge–moss tundra were present.

Picea forests decreased in the valley of the Karakudyur River in the late Holocene (Butvilovsky, 1993) (Fig. 10). According to this author, solifluction and other slope processes in the valleys of the Karakudyur and Ulagan Rivers sharply increased, and forests disappeared from the Dzhulukul depression of the southeastern Altai, where the timberline was lowered by 400–500 m. Cold winter winds began to penetrate westwards along river valleys and intermontane depressions. Thus, islands of permafrost formed in Chuiskaya, Kuraiskaya, and other depressions south and east of the Ulagan high-mountain plateau at 4.5 cal ka BP.

After about 5.7–4.5 cal ka BP, dark-coniferous taiga sharply decreased in the neighbouring southwestern Altai (Chernova et al., 1991). Instead, *Pinus sibirica*, *Betula*, and *Pinus sylvestris* forests and mires expanded. At about 4.5 cal ka BP pingos formed near Dzhangyskol due to permafrost. In the Chuiskaya depression (100 km southeast of the Ulagan high-mountain plateau) near the settlement Tebeler at about 2.25 cal ka BP, a large pingo formed (Butvilovsky, 1993). In northern Mongolia after 4.5 cal ka BP, *Picea* and *Pinus sibirica* forest–steppe was replaced by steppe with small forest patches dominated by *Larix* and *Pinus sibirica*.

In the pollen diagrams of the Ulagan high-mountain plateau, we do not find signs of a marked change of vegetation during the last 5 ka. Permanent forest vegetation existed except in high-mountain areas above 2100-m elevation. It is possible that, during this time interval, strong changes of the moisture regime did not occur in the central Altai due to the persistence of stable atmospheric circulation in this area.

Cooler and more continental climate in the late Holocene is also indicated for other parts of the Altai and neighbouring areas (Fig. 10). It is consistent with the COHMAP scheme of orbitally induced climatic changes, according to which after 6.8 cal ka BP, simulated temperatures over the land decreased in response to decrease in July insolation. Pacific monsoonal winds and rainfall weakened in northwestern Mongolia due to this change and caused disappearance of woodland vegetation in northern Mongolia and in the Dzhulukul depression of the southeastern Altai, whereas Atlantic cyclones supplied enough moisture to the mountain areas of the central Altai to support a belt of mountain forest. The Atlantic cyclones, however, were not strong enough to prevent penetration of the cold air masses of the Siberian anticyclone in winter, producing cold dry winds along intermontane depressions and valleys to the west.

Archaeological evidence shows human presence in the Altai at about 4.5 ^{14}C ka BP (Afanas'evskaya culture), 2.1 ^{14}C ka BP (Pazyrykskaya culture), and 1.4 ^{14}C ka BP (Tyurkski kaganat culture; Rudsky, 1996). However, our pollen diagrams show little or no human impact on the vegetation in these periods.

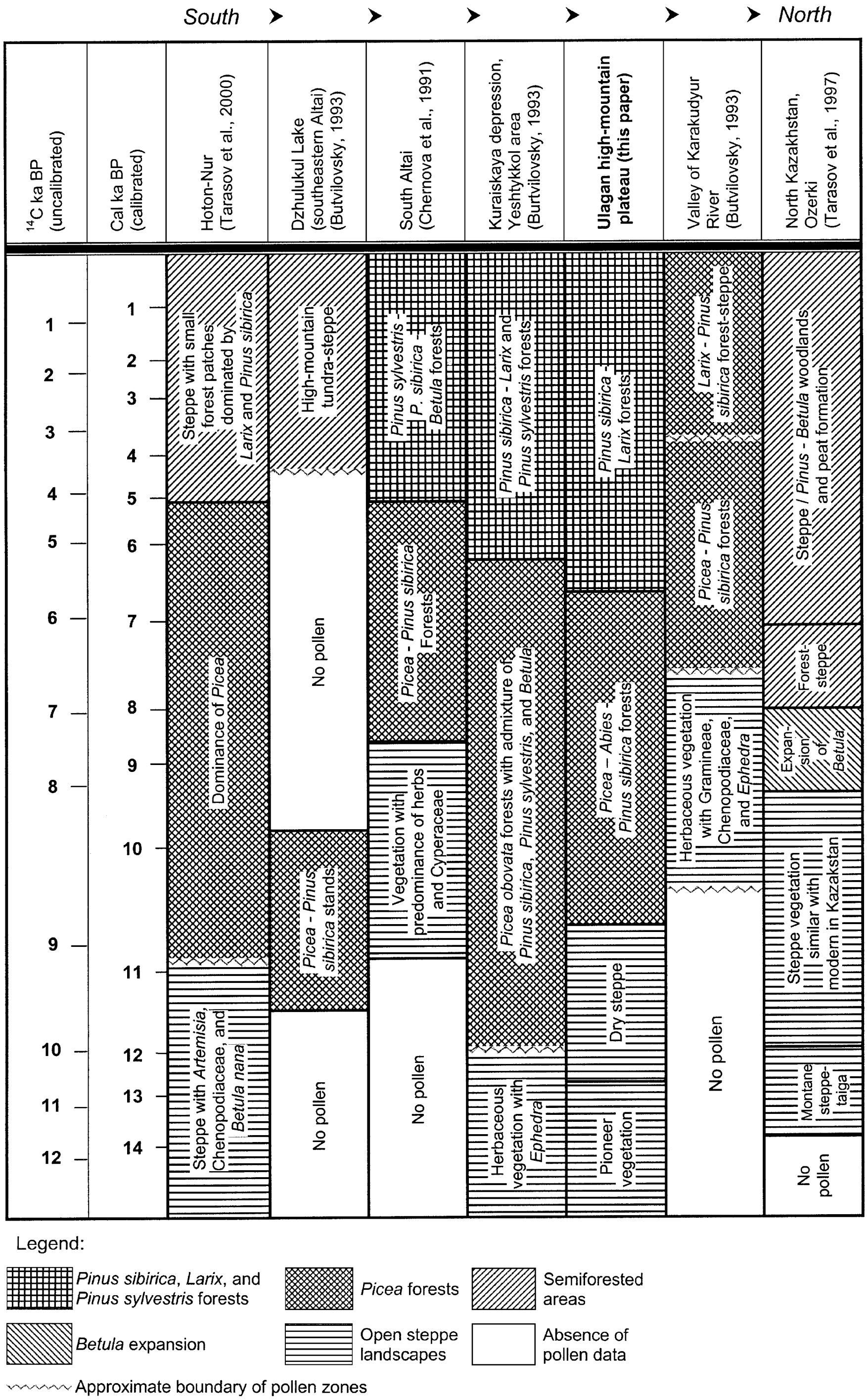


Fig. 10. Correlation of palaeogeographic events of Ulagan sites with neighbouring areas of Altai Mountains and adjacent territories.

Climate is therefore the main driving factor in the vegetation dynamics, until anthropogenic deforestation started a few centuries ago.

8. Discussion and conclusions

8.1. Origin of forests

Very rapid migration of trees into the Altai after deglaciation is recorded. In order to explain this, different points of view exist about the origin of forests in the Altai in relation to the glacial periods. One view (Grosvald, 1965; Butvilovsky, 1993) holds that hardly any sites were available for the survival of the forest vegetation in the Altai during glacial times because of the large extent of ice cover on all the mountains. According to this view, the rapid spread of vegetation, including woodlands, in interglacials is explained by survival of seeds under the glaciers. We do not support this view because the survival of seeds for the entire duration of a glaciation perhaps lasting 100 ka, and under a thick layer of ground moraine, seems totally out of the question. A second view supports the survival of trees in refugia in or close to the Altai. Pollen diagrams from Anui-2 cave and Denisova cave (Derevyanko et al., 1998) in the western low mountains of the Altai indicate that deciduous tree species survived throughout the Quaternary period until 17–15 ^{14}C ka BP. In interglacial intervals, such taxa as *Corylus*, *Tilia*, *Acer*, *Ulmus*, *Juglans*, *Fagus*, and *Quercus* returned to their positions by the local migration of altitudinal belts. Only the last (Sartanian) glaciation caused extinction of the thermophilous tree species. In contrast to these two extreme points of view, a third opinion in the Russian botanical literature is that during glacial times, the trees had their refugia in low mountainous parts of the Altai which due to their diversity of relief provided a variety of sheltered positions. In a sheltered area near Teletskoye Lake (ca. 500 m asl, ca. 100 km north of study area), *Tilia* and *Alnus glutinosa* survived along with dark-coniferous species (Kuminova, 1957; Polozhii and Krapivkina, 1985). Baryshnikov (1996) describes abundant macrofossil remnants of *Picea* and *Pinus sibirica* at a site 200 km north of Ulagan and 1000 m lower dated 13,750 ^{14}C year BP. In Russian palaeogeographic literature, it is accepted that during glacial times, when the high-elevation areas of the Altai were covered with ice, forests occurred at elevations lower than 1000 m with *Larix*, *Betula*, and *Picea* (Malaeva, 1987; Baryshnikov, 1995). Such forests expanded in glacial times in the area of the southern Lake Baikal (Malaeva, 1987; Bezrukova, 1998).

8.2. Past landscapes

During deglaciation of the Ulagan high-mountain plateau before ca. 15.9 cal ka BP, major landscape changes occurred that correlate well with events in the neighbouring sites of the Altai Mountains and in the adjacent more distant areas of Kazakhstan and northeastern Mongolia.

After ca. 15.9 cal ka BP, the formerly barren periglacial landscapes became occupied by varied vegetation similar to the present-day high-mountain shrub, turf-grass, and turf-sedge tundra and meadows and after ca. 15 cal ka BP by dry steppe. The completely treeless steppe–tundra landscape on the Ulagan high-mountain plateau between 15 and 11.5 cal ka BP has its parallel in the present-day landscapes of the southeastern Altai and Mongolia, where steppe directly contacts high-mountain vegetation. Modern analogues of the Late Glacial steppe on the Ulagan plateau may be found in the high-mountain tundra above the timberline (Kuminova, 1960). The Late Glacial vegetation sequence in these central Asian mountains included very few indications of climatic fluctuations such as characterized western Europe. A reason may be that the latter is closer to the Atlantic source of climatic change. Nevertheless, the ubiquitous expansion of temperate broad-leaved forest seen in the Alps and other mountains and lowlands of Europe at the beginning of the Holocene was matched about 2000 years later in the Altai by the expansion of conifers.

The most significant palaeoenvironmental event took place between about 11.5 and 9.5 cal ka BP, when former treeless landscapes gradually changed to closed forests at elevations below 2100 m and high-mountain tundra and shrub thickets expanded above 2100 m. The interpretation of a Late Glacial/early Holocene shift from cold–dry to warm–dry conditions is supported by palaeoclimatic model simulations, which show dominant northeasterly winds at ca. 14 cal ka BP followed by summer temperatures in southern Siberia 2–4 degrees higher than today at ca. 10 ka BP. The continuation of steppe vegetation well into the Holocene, at least at high elevation, can be attributed to warm and dry summers related to the insolation maximum. It also suggests that enhanced monsoonal rains were not able to reach the area during this time. The temporal sequence of Late Glacial steppe persisting in the Altai Mountains into the early Holocene resembles the spatial biogeographic east–west gradient in the Altai Mountains today. Steppe in the dry east, where trees are restricted to patches on north-facing slopes, grades to subalpine forest in the more humid west. The pollen stratigraphy for sediments in glacial lakes in a region farther to the east, now under study, should show whether steppe vegetation has continued from the Late Glacial through the entire Holocene, despite the changing trend in summer insolation. However, cold Late Glacial steppe cannot easily be distinguished palynologically from warm Holocene steppe. Differences are that the Late Glacial pollen assemblage includes more pollen of pioneer plants on barren soils, whereas the Holocene pollen assemblage shows the immigration of warmth-demanding species (both terrestrial and aquatic).

The mesophilous dark-coniferous taiga reconstructed for the period 9.5–7.5 cal ka BP has its modern analogue in the forests of the northern and western Altai. These forests were more mesophilous than those growing at present on the Ulagan high-mountain plateau. Mesophilous trees (*Picea* and *Abies*) started to decline on the Ulagan plateau after 7.5 cal ka BP, surviving only on the wetter northern slopes and in deep river valleys. Modern, more continental forests (with *Pinus sibirica* and *Larix*) began to dominate at elevations from 1500 to 2000–2100 m, with thickets of dwarf birches and sedge–moss and kobresian tundra in an altitudinal belt above this. Human impact on vegetation becomes evident only in recent centuries.

Minor differences among the diagrams are in agreement with the differences in altitude. Thus, pollen abundances indicate that only the highest site (2150 m) lies at the timberline, whereas trees surrounded the other two sites (1985 and 2050 m) during the Holocene. Even slight differences in time boundaries of pollen zones are in agreement with the differences in altitude, in spite of the uncertainties in dating. The sedimentation of gyttja and expansion of steppe vegetation prior to 15 cal ka BP started first in the lowest site (1985 m), then in the site at 2050 m, and last in the highest site (2150 m). Full afforestation around 9.5 ka cal BP was reached first at 1985 m, then at 2050 m, but never at 2150 m.

8.3. Past climate

Palynological investigation of three high-mountain lakes in the central Altai Mountains and comparison with available pollen data from neighbouring areas provide a record of palaeoenvironmental conditions in the region that spans the last 16,000 years. Initially, the records support the existence of the maximum in summer insolation in the Late Glacial and early Holocene. The increase of summer insolation beginning at ca. 17 cal ka BP (COHMAP Members, 1988) caused not only the melting of the Altai glaciers but also the development of tundra–steppe. However, during the subsequent 4 ka, the southern and central areas of the Altai, as well as northeastern Mongolia, were dominated by cold and dry northeasterly airflow from the Siberian anticyclone (Tarasov et al., 1997), which was probably strengthened by the supply of circumpolar arctic air north of the ice sheets that persisted on both Eurasia and North America. During this time, these areas had similar dry steppe conditions and possibly similar floras. After about 10 cal ka BP, this anticyclone weakened and gave way to predominance of Atlantic cyclones in the central Altai (our data) and to moisture-bearing Pacific monsoons in northwestern Mongolia (Tarasov et al., 2000) and possibly the southeastern Altai. This is matched by expansion of trees forming a contiguous forest across the central and southeastern Altai and northwestern Mongolia after about 9.5 cal ka BP. After about 6.8 cal ka BP, as July insolation decreased, temperatures over the land decreased and likely caused the weakening of both the Pacific monsoonal winds (Tarasov et al., 2000) and to a lesser degree the Atlantic cyclones, as a result of a stronger Siberian anticyclone. This is matched by the disappearance of forest in northwestern Mongolia and the southeastern Altai, but not in mountain areas of the central Altai where moisture-supplying Atlantic cyclones were still strong enough to support the belt of mountain forest. They were, however, no longer strong enough to prevent the penetration of cold air masses of the Siberian anticyclone in the winter into intermontane depressions and valleys to the west, resulting in the growth of permafrost.

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