Pollen records, postglacial/Northern Asia☆

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This is an update of A.A. Andreev, P.E. Tarasov, Pollen records, postglacial | Northern Asia, Editor(s): Scott A. Elias, Cary J. Mock, Encyclopedia of Quaternary Science (Second Edition), Elsevier, 2013, Pages 164–172, ISBN 9780444536426, https://doi.org/10.1016/B978-0-444-53643-3.00194-1.

Abstract

The article is an overview of postglacial vegetational and climate changes in northern Asia based on pollen records with reliable chronology. The presented pollen records demonstrate spatially—and temporally—coherent patterns of environmental changes. Open *Artemisia*- and Poaceae-dominated communities were widely spread in northern Asia during the Late Glacial. A significant increase of shrub pollen registered in a number of records may be correlated with the Bølling/Allerød warming, ca. 13.7 cal ka BP. The subsequent increase in nonarboreal pollen contents reflects a cooling/drying of the Younger Dryas age. Many records show that the Late Glacial/Holocene transition occurred at about 11.5 cal ka BP and was characterized by a significant increase in tree and shrub pollen. Records from geographically different sites demonstrate different patterns of vegetation changes connected with local environmental conditions and migration history of boreal tree species.

Key points

- The climate of northern Asia is cold and continental and the spatial distribution of vegetation shows the clear response to the westerlies and the Asian monsoon circulation.
- There were fundamental changes in the strength and extent of the westerlies and the Asian monsoon in response to changes in insolation, global sea level and glacial boundary conditions during the Late Glacial and Holocene.
- Here, we review the postglacial vegetation and climate changes in northern Asia based on pollen records with reliable chronologies.

Introduction

The territory of northern Asia represents approximately 15% of the Earth's land surface and includes a wide variety of climatic and vegetation zones. It is situated between the Ural Mountains (ca. 60° E) in the west and the Pacific Ocean in the east (ca. 180° E) and between the Arctic Ocean in the north and ca. 47° N in the south (Fig. 1). The latter boundary corresponds to the southern limit of boreal coniferous forests in Kazakhstan and Mongolia. West of 90° E the topography is relatively flat. Elevations of the West Siberian Lowland do not exceed 200 m, and hilly plains and low-elevation (up to 1500 m) mountains occur in northern Kazakhstan. East of 90° E the topography is more complex. Lowlands occupy a 50–600-km-wide band along the Arctic coast, while central and southern regions consist of high plateaus and mountains above 1000 m. The highest elevations occur in the Altai (4506 m) and Hangai (3905 m) mountains and on the Kamchatka Peninsula (4750 m).

☆*Change History:* May 2023. PE Tarasov and AA Andreev prepared the update. Fig. 1 and the following sections (Introduction, The Ural Mountains, East Siberia, References, and Key points) have been updated.

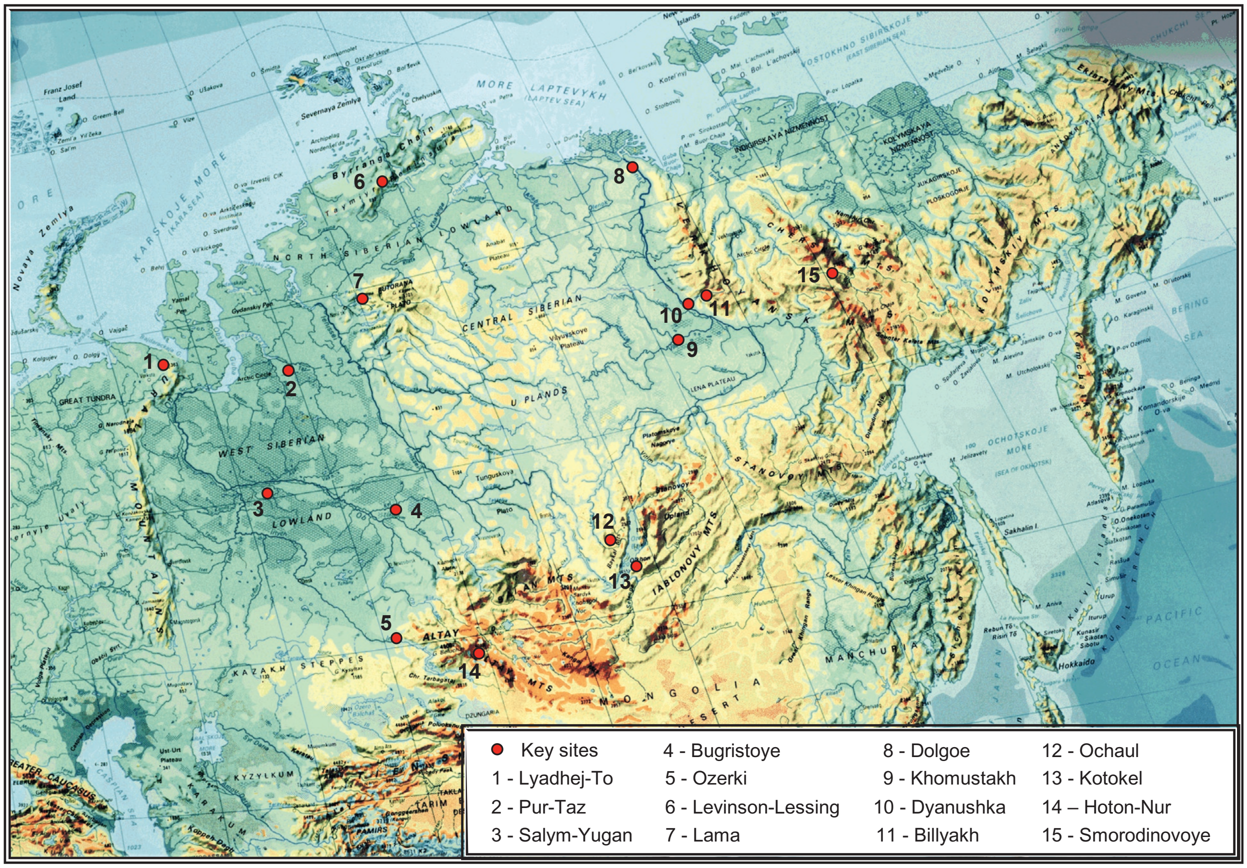

Fig. 1 Map of northern Asia showing the location of cited sites.

The climate of northern Asia is cold and continental. A strong Siberian anticyclone controls winter weather. The mean January temperatures vary from −16 °C in the south to −48 °C in the interiors of East Siberia. The absolute temperature minima registered in the Verkhoyansk Mountains is −68 °C. July temperatures (T_{VII}) decrease northward from ca. 20 °C to less than 4 °C. More than 65% of the annual precipitation (*P*) falls during the warm season, when the weather is controlled by the westerlies and the Pacific monsoon. *P* reaches 600 mm in the Ural Mountains and ca. 1000 mm in the Far East. In Kazakhstan, Central Yakutia, and Mongolia, situated far from oceanic influence, *P* is less than 300 mm.

The spatial distribution of vegetation shows the clear influence of climate. In the mountains it is complicated by altitude and slope orientation. Various moss, grass, dwarf shrub, and shrub tundra types (tundra zone) occupy arctic lowlands and the upper belt of the mountains and high plateaus. Southward, this is gradually replaced with boreal cold deciduous and evergreen conifer forests (taiga) dominated by larch (*Larix*), Siberian spruce (*Picea obovata*), Scots pine (*Pinus sylvestris*), Siberian pine (*P. sibirica*), and fir (*Abies sibirica*). Broad-leaved trees are represented mostly by cold- and drought resistant birch (*Betula pubescens* and *B. pendula*) and aspen (*Populus tremula*). Temperate deciduous taxa, such as elm (*Ulmus*) and lime (*Tilia*), play minor roles in the modern vegetation. *U. glabra* and *T. sibirica* trees sporadically occur in the West Siberian Lowland and Altai Mountains, and *U. pumila* may grow in the floodplain forests south of Lake Baikal.

Since Dokturovskii and Kudryashov (1923) have provided pollen identification keys for the main arboreal taxa in Russia, scientists from the former Soviet Union published numerous articles and monographs reconstructing postglacial changes in northern Eurasian vegetation by means of pollen analysis (for a comprehensive synthesis, see Neishtadt (1957), Khotinskii (1977), Grichuk (1984), Peterson (1993), and Velichko et al. (1997)). The collapse of the USSR intensified the level of international cooperation, resulting in the appearance of extensive compilations of existing northern Eurasian pollen data (e.g., Tarasov et al. (1998), Lozhkin et al. (1993), Gunin et al. (1999), Edwards et al. (2000), Williams et al. (2011), Binney et al. (2017), Cao et al. (2019) and references therein) and in publications of new high-resolution and better dated pollen records from different parts of northern Asia (e.g., Clarke et al., (2020), Andreev et al. (2021), Kobe et al. (2022), Yuzhanina et al. (2022)). Since the late 1970s, there has been a rapid increase in the number of published pollen diagrams from northern Asia. Khotinskii (1977) had used 26 pollen sequences to reconstruct the Holocene vegetation history of northern Asia, but now there are 10 times as many records archived in the Global and European Pollen databases (e.g., Tian et al. (2018), Cao et al. (2019) and references therein).

In this article, we review the postglacial vegetation and climate changes in northern Asia based on pollen records with reliable chronologies, rather than attempting to synthesize a complete northern Asia-wide picture of postglacial environmental changes, which requires further refinement of site spatial coverage and chronologies.

The Ural Mountains

The pollen record from Lake Lyadhej-To (68°15′N, 65°45′E, 150 m a.s.l., site 1 in Fig. 1), situated in the shrub-herb tundra zone at the northwestern rim of the Polar Ural, provides information on the Holocene environmental history of this area (Andreev et al., 2005). Pollen of sedges (Cyperaceae), grasses (Poaceae), and dwarf birches (*Betula* sect. *Nanae*) (Fig. 2) from the lowermost sediments suggests sparse tundra-like vegetation around the lake ca. 10.7–10.55 cal ka BP. Approximately 10.55–8.8 cal ka BP birch forest with some shrub alder grew around the lake, reflecting the warmest climate of the Holocene with T_{VII} 11–13 °C. Pollen records from the adjacent areas also reflect a major spread of birch at that time in what is now treeless tundra (Andreev et al. (2005) and references therein). Higher values of dwarf birch and sedge pollen and significantly lower pollen concentrations point to climatic deterioration during 8.8–5.5 cal ka BP. Birch forests completely disappeared from the lake vicinity at ca. 6 cal ka BP, and shrub and herb tundra communities became dominant in the regional vegetation after ca. 5.5 cal ka BP. Pollen-based reconstruction suggests significant cooling between 5.5 and 3.5 cal ka BP with T_{VII} up to 8 °C leading to establishment of the shrub–herb tundra vegetation similar to the modern one.

Further south, in the eastern part of the Polar Ural, Svendsen et al. (2014) reconstructed the Late Glacial and early Holocene vegetation history using the pollen record from Lake Gerdizty (66°50′N, 66°00′E, 213 m a.s.l.). Their record reflects a first significant increase of dwarf-shrub willow and birch communities occurred at around 15 cal ka BP or shortly after, which is similar to the records from the Arctic regions in the east (Tarasov et al., 2021). The first dramatic change in vegetation cover happened soon after the Late Glacial/Holocene transition when birch and spruce trees reached the area around Gerdizty (Svendsen et al., 2014).

The establishment of shrub-tundra communities probably with some *Betula pubescens* trees at ca. 15 cal ka BP was also reconstructed from the pollen record of Lake Bolshoye Shchuchye (67°53′24″N, 66°18′36″E, 187 m a.s.l.) located in the central part of the Polar Ural (Clarke et al., 2020). *Picea* established near the lake ca. 10 cal ka BP, followed by *Larix* trees from ca. 9 cal ka BP. However, spruce began to decline from ca. 7 cal ka BP and a complete withdrawal of trees occurred by ca. 4 cal ka BP due to decreasing summer temperatures, allowing the expansion of dwarf-shrub tundra and a diverse herb community similar to the present-day vegetation mosaic (Clarke et al., 2020).

West Siberia

Pollen diagrams from the West Siberian Lowland are quite numerous (e.g., Volkova and Mikhailova (2002) and references therein). The Pur-Taz peat section from the flat watershed between the Pur and Taz Rivers (66°42′N, 79°44′E, site 2 in Fig. 1) is one of the better-studied sequences from the forest-tundra transitional zone with *L. sibirica* as a dominant tree. It provides pollen and macrofossil records of vegetation and climate history at the Arctic tree line ca. 10.4–5.1 cal ka BP (Peteet et al., 1998). The presence of larch and tree birch pollen in the Late Glacial/early Holocene indicates that regional summer temperatures were warm enough to support the growth of trees. An increase in spruce pollen between 10 and 5.1 cal ka BP suggests a movement of spruce into the north as the result of warmer-than-present early Holocene climate. Quantitative pollen-based climate reconstruction (Andreev and Klimanov, 2000) shows that the warmest period (T_{VII} 2.5 °C higher than today) occurred in the area ca. 6.8–5.6 cal ka BP. This is approximately the same time as the dominance of *Picea* macrofossils at the Pur-Taz site. The decrease in evergreen conifer tree pollen and macrofossils registered in the uppermost peat layer suggests a late Holocene shift toward colder environments similar to today (Peteet et al., 1998).

Pollen data from the Salym-Yugan area (60°10′N, 72°50′E, site 3 in Fig. 1) help to trace the Holocene vegetation history in the southern part of West Siberia (Pitkänen et al., 2002). The modern vegetation of the area consists of forests (mainly Scots pine) and open mire communities. Pollen data suggest that open sedge associations dominated the vegetation between ca. 10.9 and 9.9 cal ka BP and trees, such as larch, spruce, and birch, were poorly represented in the regional vegetation. On the other hand, the pollen sequence from Bugristoye Mire (58°15′N, 85°20′E, site 4 in Fig. 1) demonstrates that larch (up to 40%), spruce (up to 25%), and birch (up to 60%) absolutely dominated the pollen spectra as early as 11.4–10.8 cal ka BP, suggesting significant afforestation of the Ket′-Chulym watershed at that time (Blyakharchuk and Sulerzhitsky, 1999). This conclusion agrees with other West Siberian pollen data (Volkova and Mikhailova, 2002). In the Salym-Yugan area, birch and pine forests established shortly after 9.9 cal ka BP, but spruce was rather abundant until ca. 4.3 cal ka BP, while the Bugristoye record demonstrates a decrease in spruce abundance shortly after 6.3 cal ka BP, reflecting climate deterioration. Peat accumulation at the Bugristoye stopped shortly after ca. 4 cal ka BP. After 4 cal ka BP, modern birch-pine forest dominated the vegetation in southern West Siberia, while large regions were covered with open mire vegetation.

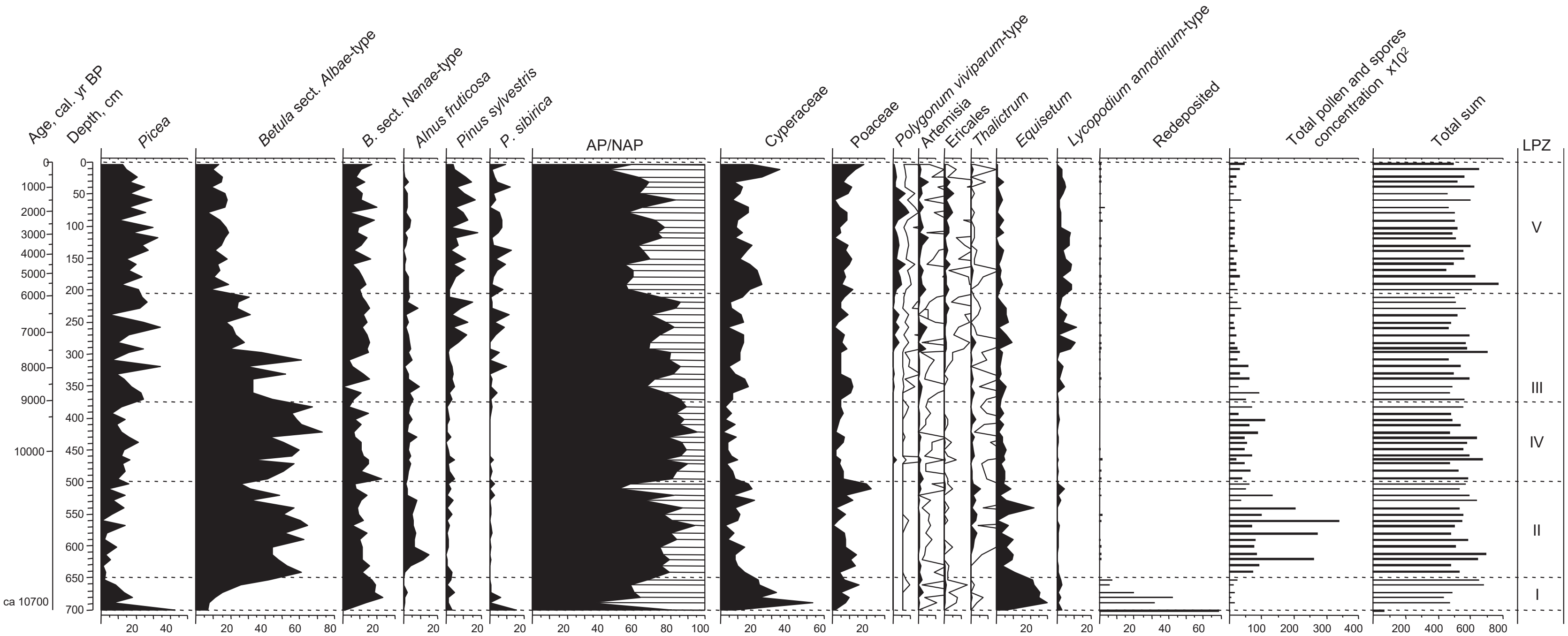

Fig. 2 Percentage palynological diagram of selected taxa from Lake Lyadhej-To record. Pollen zonation is according to Andreev et al. (2005).

Kazakhstan

Reliable records of the Holocene vegetation and climate dynamics in the vast area of northern and central Kazakhstan were not available until the 1990s (Kremenetski et al. (1997) and references therein). Ozerki Swamp (50°25′N, 80°28′E, 210 m; site 5 in Fig. 1) located in the Irtysh River valley provides the most complete postglacial pollen record from the forest-steppe transition zone in northern Kazakhstan. In this area, steppe vegetation is dominated by grasses and *Artemisia* (sage) species and Chenopodiaceae and *Ephedra* grow on hardened soils (Tarasov et al., 1997). High summer temperatures and low precipitation limit the spread of patchy birch and pine forests to the river valleys and low mountains. The Ozerki record suggests that an oxbow depression currently occupied by a swamp was filled with water at about 15 cal ka BP, suggesting amelioration of the very dry and cold 'glacial' climate. The lowermost pollen zone (Fig. 3) reveals the highest percentages of non-arboreal pollen (NAP) taxa (up to 85%), suggesting rather dry environments and steppe vegetation. However, the occurrence of *Hippophae* (sea-buckthorn), spruce, and larch pollen in this pollen zone can be interpreted as the spread of sea buckthorn shrubs and trees along the Irtysh River between 15 and 12 cal ka BP. These taxa can be found today in the Altai Mountains, southeast of the study site. Since 12 cal ka BP, the vegetation composition has been similar to that found today in the Kazakhstan steppe. Around 8.5 cal ka BP, birch pollen exceeded 70%, suggesting expansion of birch forest in the area and probably wetter-than-present climate conditions. After 6.5 cal ka BP, the pollen spectra reflect the spread of pine from the south Ural and West Siberia to northern and central Kazakhstan. Regional pollen data (Kremenetski et al., 1997; Tarasov et al., 1997) suggest that Scots pine was already established in northern Kazakhstan by 7 cal ka BP, but did not reach its modern limit in central Kazakhstan until after 2 cal ka BP. Thus, the afforestation of the steppe zone reached a maximum only during the last millennium (Tarasov et al., 2005). Because none of these changes in vegetation can be attributed to human activities, a climatic explanation should be invoked.

Central Siberia

Environmental changes since about 32 ^{14}C ka BP from northern Central Siberia are recorded in the sediments of Levinson-Lessing Lake (74°28′N, 98°38′E, site 6 in Fig. 1) in the northeastern Taymyr (Andreev et al., 2003). The lake is situated in the tundra zone. Pollen spectra (Fig. 4) contain large amounts of herbaceous taxa, including grasses and sage, reflecting severe continental climate and scarce, steppe-like vegetation until ca. 13.7 cal ka BP. Dwarf shrub and sedge tundra vegetation had limited coverage and survived only in wet habitats. Dramatic increases in shrub birch and willow pollen and in total pollen concentration, associated with a significant decrease in sage, grasses, and other herb taxa pollen, reflect a climatic amelioration after 13.7 cal ka BP corresponding with the Allerød in Europe. This was followed by an increase in herbaceous taxa pollen, likely indicating a cooling associated with the Younger Dryas (YD). Pollen spectra from the Pleistocene/Holocene transition dated to ca. 11.5–11.2 cal ka BP reflect a shift in vegetation from herb-dominated to shrubby birch-willow tundra. Shrub alder occurred in the area approximately 10 cal ka BP and disappeared after 3.8 cal ka BP. Dwarf birches broadly distributed in the region during the early and middle Holocene also almost disappeared after 3.2 cal ka BP, when the vegetation became similar to the modern herb tundra. Quantitative paleoclimatic interpretation of the pollen spectra suggests that T_{VII} was 2–4 °C higher than present during the early Holocene and became similar to present after 6.3 cal ka BP.

A continuous pollen record from Lama Lake, from western Taymyr (69°32′N, 90°12′E, site 7 in Fig. 1) provides detailed environmental information for the Late Glacial and Holocene in central Siberia (Andreev et al., 2004). At present, the vegetation cover in the region varies, depending on altitude: dense spruce-larch-birch taiga dominated on the lower elevations, while shrub and herb tundra cover the higher mountains. The pollen data suggest that scarce steppe-like plant communities dominated the vegetation around the lake during the Late Glacial (Fig. 5). Tundra-like communities with arctic dwarf shrubs, sedges, and Brassicaceae species grew in wetter habitats. Reconstructed climate fluctuations may be correlated with the Bølling/Allerød warming and YD cooling. The Late Glacial/early Holocene transition occurred at about 11.5 cal ka BP. It is characterized by a significant increase in shrub birch (*B.* sect. *Nanae*) and willow pollen accompanied with a relatively high NAP content suggesting a broad distribution of shrubby and meadow associations. Abundant spores of *Sphagnum* and Polypodiaceae indicate wet habitats around the lake. High contents of larch and alder pollen in the early Holocene sediments indicate that larch occurred in the area as early as 11 cal ka BP, while shrub alder came to the area 200 yr later. Spruce did not reach the area before ca. 10.3 cal ka BP. The spruce pollen content and the total pollen concentration increase dramatically in the deposits dated to ca. 10.1–8.8 cal ka BP, indicating the broad distribution of spruce under the warm summer conditions. Our paleoclimatic reconstruction from the Lake Lama pollen record suggests that T_{VII} during the early Holocene were ca. 1.5–3.5 °C above modern values. Other paleobotanical records (Andreev et al. (2004) and references therein) also confirm the broad distribution of spruce in the western Taymyr during this interval. A gradual decrease in spruce pollen in the sediments younger than 5.2 cal ka BP reflects a gradual deterioration of the regional climate. A significant increase in birch pollen percentages in the upper part of the core likely mirrors the increased role of birches in the local forests after 2.5 cal ka BP. The sharp decrease in the arboreal pollen (AP) content and the increase in sage pollen content at 30-15 cm depth may be correlated with the Little Ice Age.

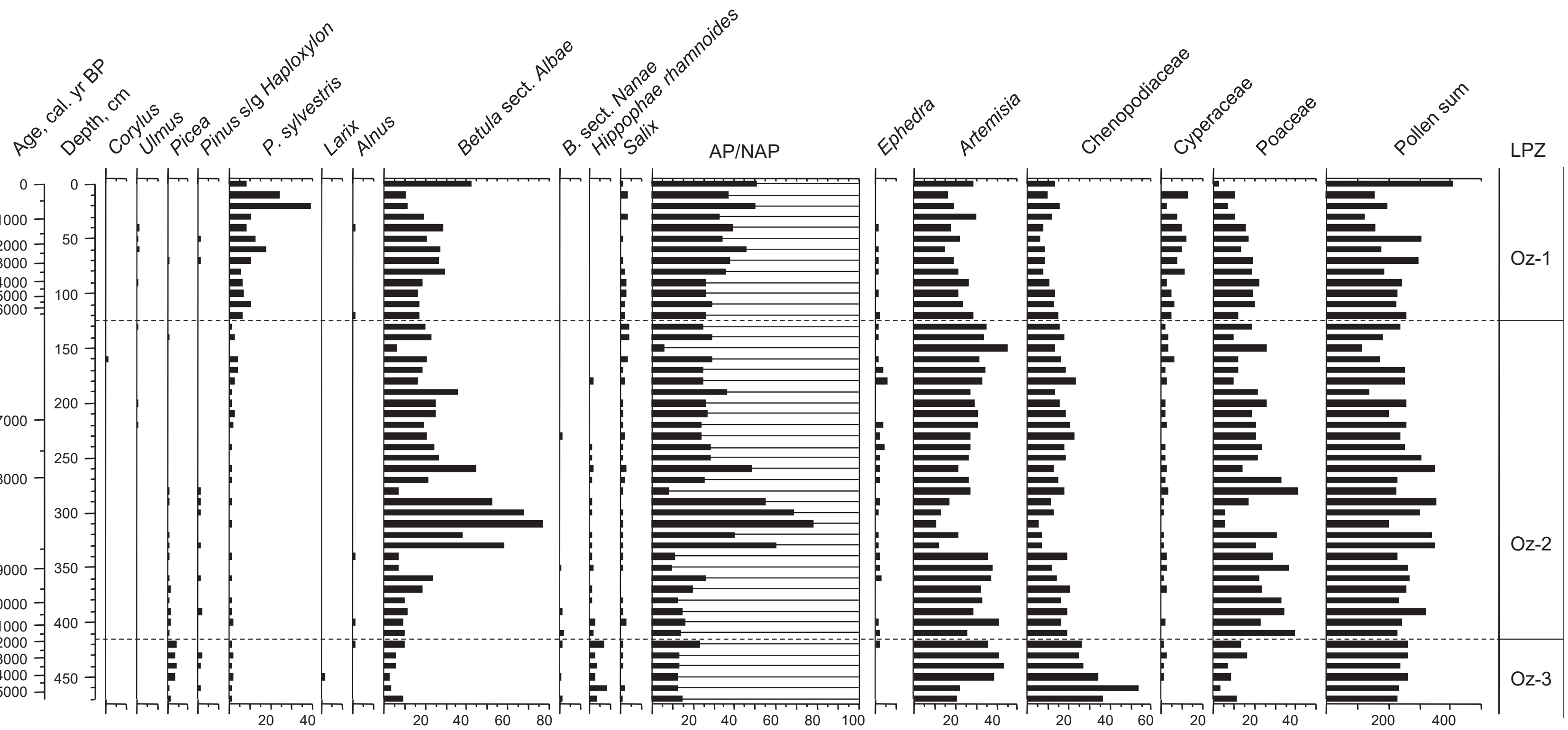

Fig. 3 Percentage palynological diagram of selected taxa from Ozerki Swamp record. Pollen zonation is according to Tarasov et al. (1997).

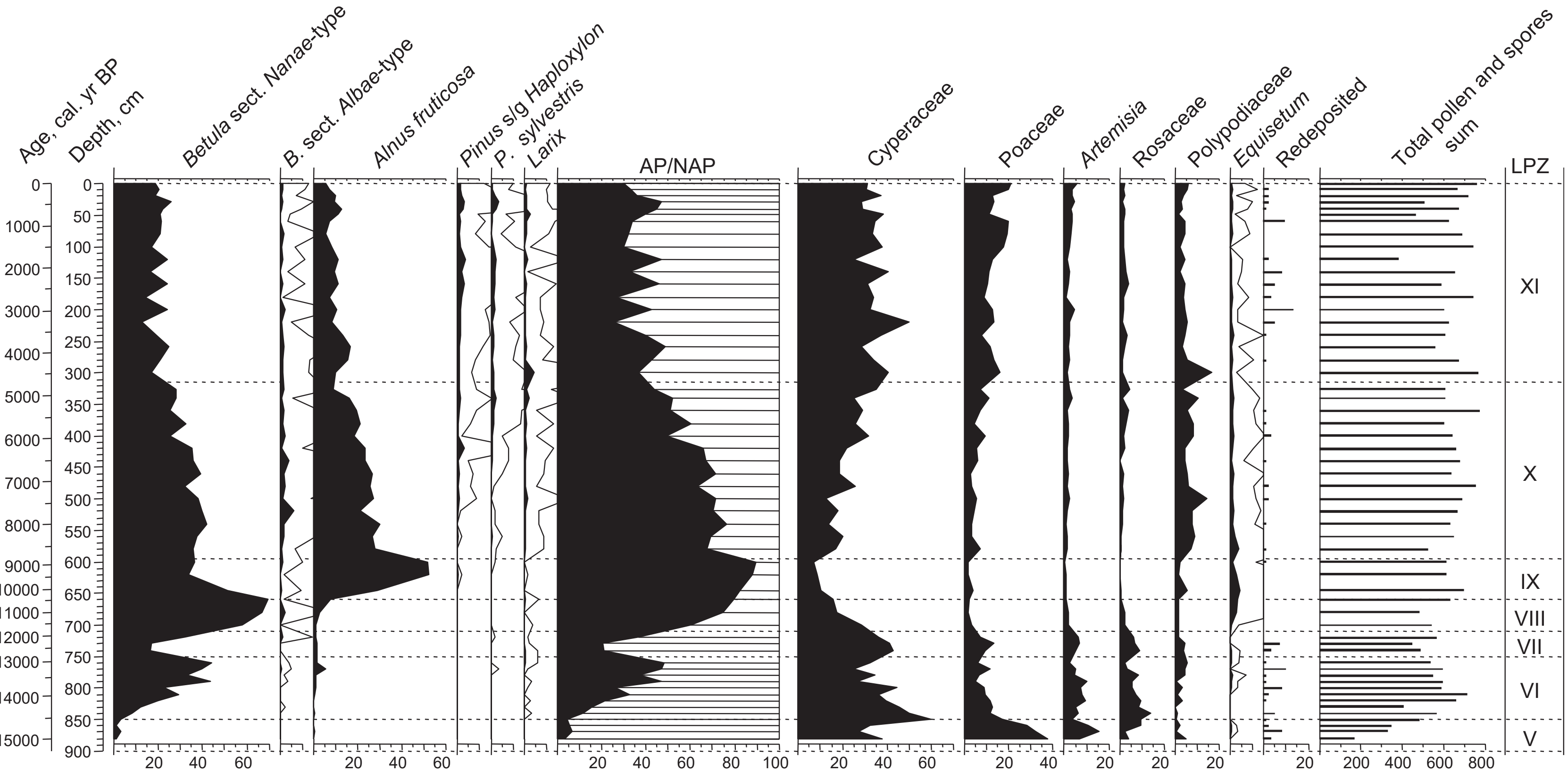

Fig. 4 Percentage palynological diagram of selected taxa from Lake Levinson-Lessing record. Pollen zonation is according to Andreev et al. (2003).

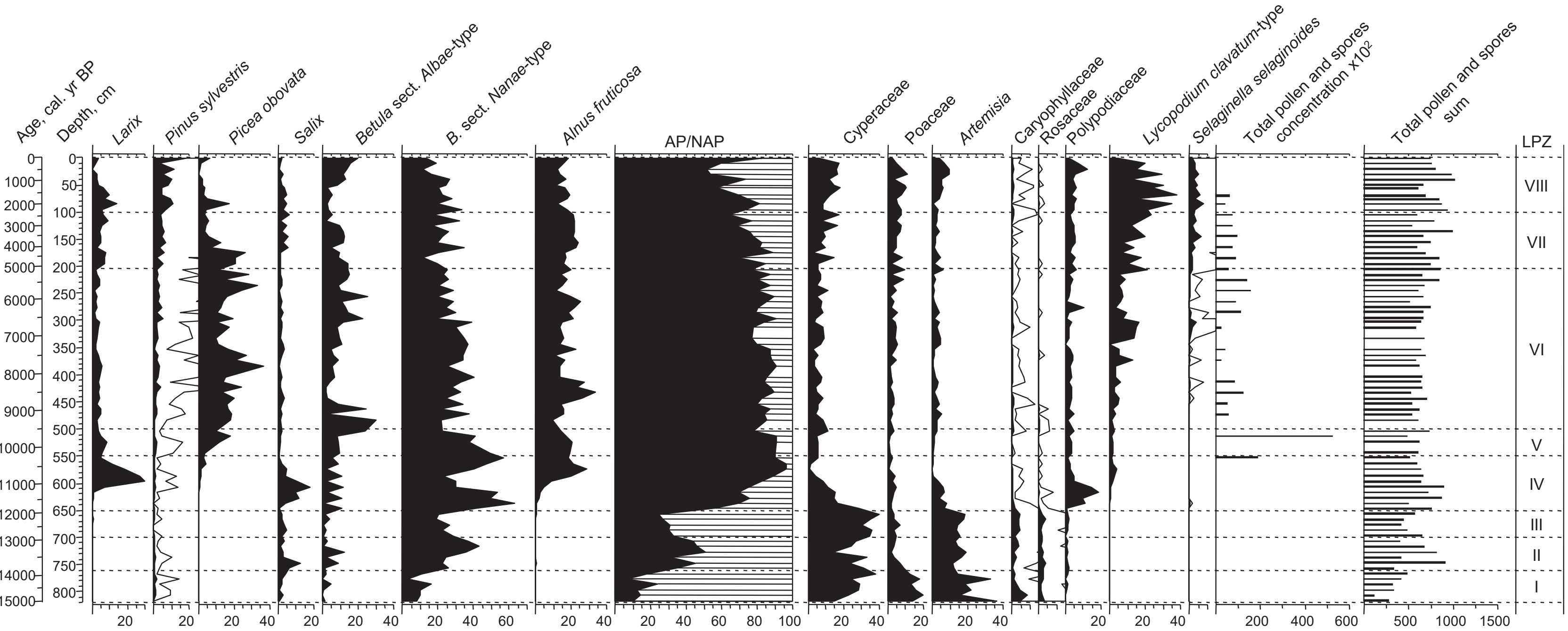

Fig. 5 Percentage palynological diagram of selected taxa from Lake Lama record. Pollen zonation is according to Andreev et al. (2004).

East Siberia

The pollen record from Dolgoe Lake, situated in the lower Lena River (71°52′N, 127°04′E, site 8 in Fig. 1), is valuable for the reconstruction of paleoenvironments in the present-day larch forest-tundra, dominated by dwarf birch and shrub alder (Pisaric et al., 2001). Sedges, grasses, and sage dominate pollen spectra deposited shortly before 14.5 cal ka BP, reflecting open vegetation with only a sparse cover of herbs and grasses around the lake. An increase of shrub birch pollen higher in the sequence points to establishment of shrub birch tundra between 14.5 and 13 cal ka BP. A sharp decrease in shrub birch pollen and rise in herbaceous pollen percentages between 13 and 11.5 cal ka BP suggests a return to a more open vegetation cover. The timing of this vegetation shift is synchronous with the YD oscillation. After 11.5 cal ka BP, shrub birch pollen percentages rise, associated with the onset of the Holocene. Around 11 cal ka BP, birch was replaced as the dominant taxon by alder, likely by a shrub alder (*A. fruticosa*). The increase in larch pollen percentages after 9.5 cal ka BP, coupled with the presence of larch in the stomata and macrofossil record, suggests that it grew north of Dolgoe Lake between 9.5 and 3.8 cal ka BP. At ca. 7.6 cal ka BP, spruce increased in abundance in the pollen record. Today, spruce grows 350 km to the south. However, the presence of its pollen and stomata in the lake record indicates that spruce occurred in the local vegetation between 7.6 and 3.8 cal ka BP. Low AP percentages and AP concentrations in the sediments dated younger than 3.8 cal ka BP suggest a change in the environment and a shift from predominantly woodland vegetation to the modern shrub tundra with isolated larch stands.

Khomustakh Lake (63°43′N, 121°36′E, site 9 in Fig. 1) has been selected as a key site for the study of postglacial vegetation in the central part of eastern Siberia (Velichko et al., 1997). At present, pine forests cover sandy soils in the area, whereas clayey soils are occupied by larch forests. Sedimentation and pollen accumulation in the lake started about 12 cal ka BP (Fig. 6), probably as a consequence of the Allerød climate amelioration. Rather high levels of dwarf birch, sage, grasses, and other herbaceous pollen taxa point to their important role in the local vegetation, co-dominated by open herb and shrub tundra-like vegetation. A subsequent increase in sage and other herb pollen contents likely reflects the YD cooling. The transition to the Holocene is dated to ca. 11.5 cal ka BP and is marked by a dramatic increase in tree birch pollen. During the early Holocene interval, birch dominated the vegetation; however, the permanent presence of larch in the pollen spectra indicates that it also was an important component in the local forests until ca. 6.8 cal ka BP. After 7 cal ka BP, Scots pine migrated to the area and quickly occupied sandy habitats in central and southern Yakutia. Quantitative climate reconstruction based on the Khomustakh pollen record suggests that T_{VII} was up to 1.5 °C warmer than present in the middle Holocene, causing degradation of the permafrost and facilitating the spread of pine. Since 6.8 cal ka BP, forests composed of pine started to dominate in these regions. Recent paleoecological records from Lake Billyakh (Müller et al., 2009, site 11 in Fig. 1) and from the Dyanushka peat section (Werner et al., 2010, site 10 in Fig. 1) revealed similar vegetation changes.

Kobe et al. (2022) presented a very detailed Late Glacial–Holocene pollen record from Lake Ochaul (54°14′ N, 106°28′ E, 641 m a.s.l., site 12 in Fig. 1) situated in the Upper Lena region at the border to South Siberia. The ratios of tree, shrub and herbaceous pollen and the biome reconstruction demonstrate that during the Allerød interstadial the region around Lake Ochaul was dominated by sparse taiga forests. The YD cooling led to the spread of boreal shrubs and dwarf shrubs and a more open, tundra landscape, although trees did not disappear, but formed patchy forest stands in climatically favorable environments. This facilitated a rapid spread of forests at the onset of the early Holocene, although forest density was still below modern levels until ca.8 cal ka BP, likely due to seasonally dry climate, controlled by the interplay of higher than present summer insolation, lower global sea levels and remaining ice sheets in the North Atlantic region. During the middle Holocene, the region saw thermal and moisture optimum conditions and a maximum spread of forests. The climate continuously cooled during the late Holocene, paralleled by a trend toward slightly more open forest landscapes. In addition to these long-term trends, the Ochaul pollen record also indicates several relatively short episodes of vegetation change, which coincide with centennial-scale cooling/drying phases recorded in the Greenland ice cores (Kobe et al., 2022).

South Siberia

This area is extremely important from the paleobotanical viewpoint, as it appears likely that during the last glaciation, the hills and mountains of southern Siberia provided refuges for the tree species that make up the present boreal forest belt (Grichuk, 1984). Postglacial pollen records from this region mainly come from Lake Baikal and its close vicinity (Tarasov et al., 2002; Demske et al., 2005 and references therein). The pollen diagram (Fig. 7) from Lake Kotokel (52°46′N, 108°46′E, 458 m, site 13 in Fig. 1), situated near the eastern coast of Lake Baikal, illustrates changes in vegetation since the Last Glacial (Tarasov et al., 2002, 2009; Bezrukova et al., 2010). At present, the lake is surrounded by boreal forest dominated by Scots and Siberian pine, larch, and birch trees. Shrub pine (*P. pumila*), birch, and alder are abundant in the mountain tundra belt, above tree line. The interval prior to ca. 14.7 cal ka BP was very dry and cold, as indicated by high percentages for steppe herbs and woody coverage below 5% (Fig. 7). After 14.7 cal ka BP climate became warmer and wetter, as marked by a gradual increase in tree and shrub pollen percentages and in woody coverage to 20–30% ca. 14.5–14 cal ka and ca. 13.3–12.8 cal ka BP. These two intervals correspond to the Meiendorf and Allerød interstadials, which were interpreted as part of the undivided Bølling-Allerød interval in the Lake Baikal region (Bezrukova et al., 2005). The increase in tundra shrubs and sedge pollen percentages indicates the YD in the Lake Baikal region between 12.7 and 11.65 cal ka BP, in agreement with the formal definition and dating of this cold oscillation based on the Greenland NGRIP ice core records. The maximal spread of the taiga communities in the region is associated with a warmer and wetter climate than the present prior

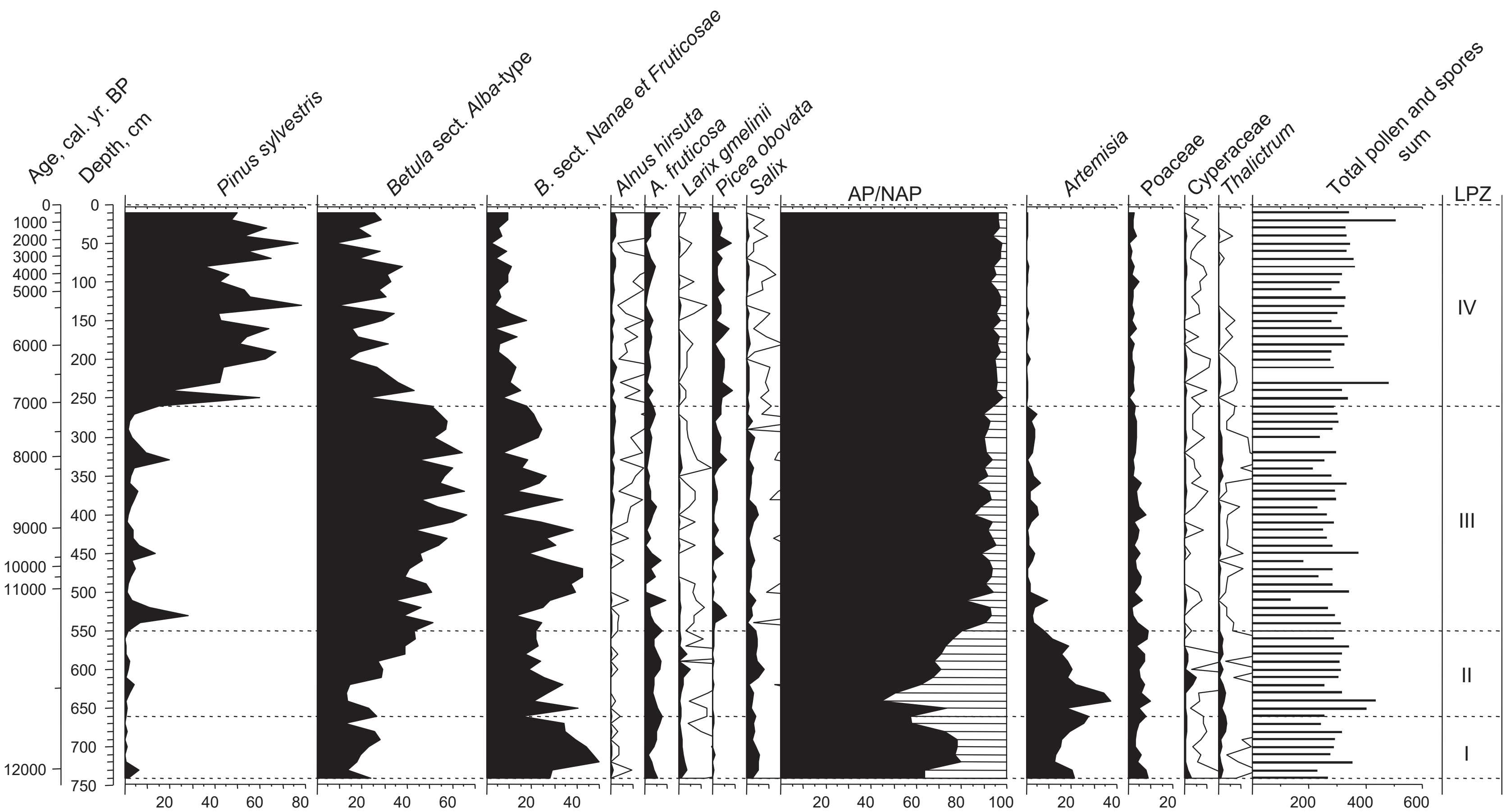

Fig. 6 Percentage palynological diagram of selected taxa from Lake Khomustakh record. Pollen zonation is according to Velichko et al. (1997).

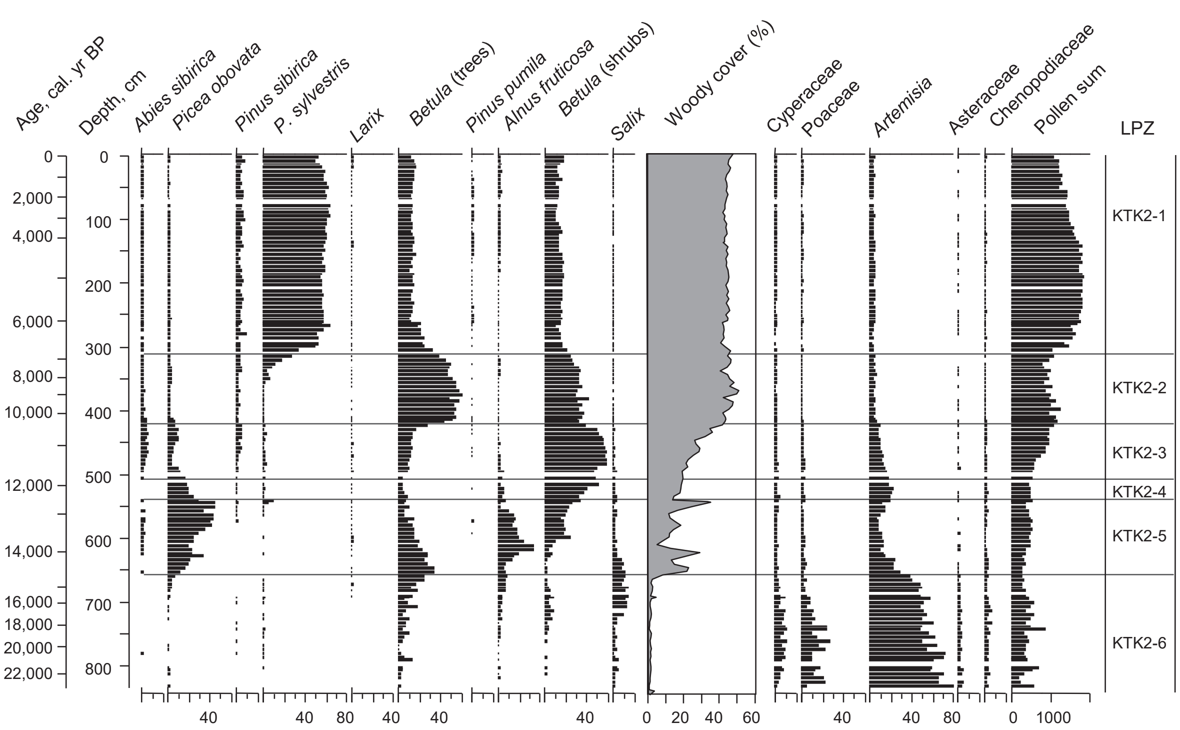

Fig. 7 Percentage palynological diagram of selected taxa from Lake Kotokel record. Pollen zonation and quantitative changes in woody cover percentages within a 21×21 km window are according to Bezrukova et al. (2010).

to ca. 7 cal ka BP. This was followed by a wide spread of Scots pine, indicating the onset of modern environments. Since that time pollen spectra show very little change, likely indicating that vegetation composition and distribution patterns became similar to that of today.

Mongolia

A comprehensive synthesis of pollen and plant macrofossil records from Mongolia is presented in Gunin et al. (1999). This paper presents reconstructions of Late Glacial and Holocene vegetation dynamics. Several other papers discuss vegetation and environmental changes at the regional scale (Tarasov et al. (2000, 2004), Fowell et al. (2003), Rudaya et al. (2009) and references therein). A ^{14}C-dated pollen record from Hoton-Nur (48°40′N, 88°18′E, 2083 m), a large freshwater lake in the northern Mongolian Altai (site 14 in Fig. 1), spans the whole Holocene interval (Fig. 8). Pollen concentration and preservation in the lower part of the 9.2-m record from Hoton-Nur was extremely poor, suggesting severe 'glacial' conditions and scarce vegetation around the lake. Pollen spectra of the Ho-3 pollen zone showed relatively high frequencies of pollen of Arctic-Alpine taxa, including shrub alder and shrub birch, sedges, and grasses (Gunin et al., 1999). This suggests a slight amelioration of the Late Glacial climate and the spread of tundra vegetation at higher elevations and river valleys. At the same time, high percentages of sage and Chenopodiaceae pollen in the Ho-3 zone suggest that before ca. 10.1 cal ka BP the dominant vegetation close to the lake was dry steppe (Tarasov et al., 2000). In the Ho-2 pollen zone dated to ca. 10.1–4.5 cal ka BP, the dominance of spruce, pine (most probably *P. sibirica*), and larch pollen likely indicates that patches of boreal conifers played a more important role in the local vegetation than they do today. Expansion of boreal evergreen conifers in the region would require noticeably wetter conditions than those prevailing today. However, the presence of relatively high percentages of herbaceous pollen suggests quite an open mosaic of forest-steppe-like vegetation. Pollen from the uppermost zone demonstrates that vegetation around the lake became drier and similar to the modern steppe with small forest patches of larch and Siberian pine, for example; taxa less sensitive to the water stress than spruce. Quantitative reconstruction of the Holocene vegetation and climate dynamics in the semiarid Mongolian Altai (Rudaya et al., 2009) suggests that boreal woodland replaced the primarily open landscape of northwestern Mongolia at about 10 cal ka BP in response to a noticeable (from 200–250 mm/yr to 450–550 mm/yr) increase in precipitation. A decline of the forest vegetation and a return to a predominance of open vegetation types occurred after 5 cal ka BP when precipitation sums decreased to 250–300 mm/yr.

Based on the pollen and geochemical records from Hoton-Nur, Rudaya and Li (2013) suggested some refinements to the Holocene climatic history of the region. According to their reconstruction, the early Holocene humid and warm phase continued until ca. 6 cal ka BP. It was interrupted by a cold/dry episode dated to ca. 7.75–7.6 cal ka BP and followed by a transition to drier environments between ca. 6 and 4 cal ka BP.

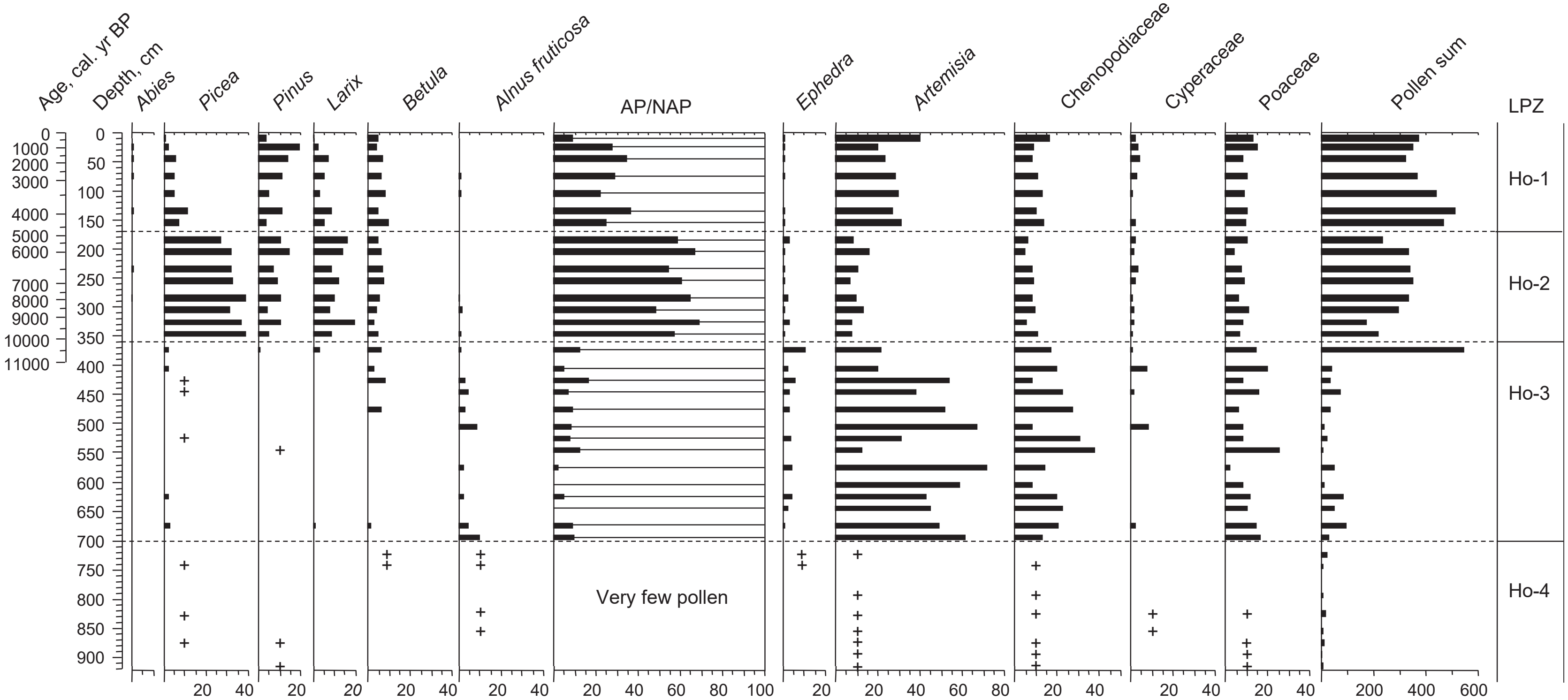

Fig. 8 Percentage palynological diagram of selected taxa from Lake Hoton-Nur record. Pollen zonation is according Tarasov et al. (2000).

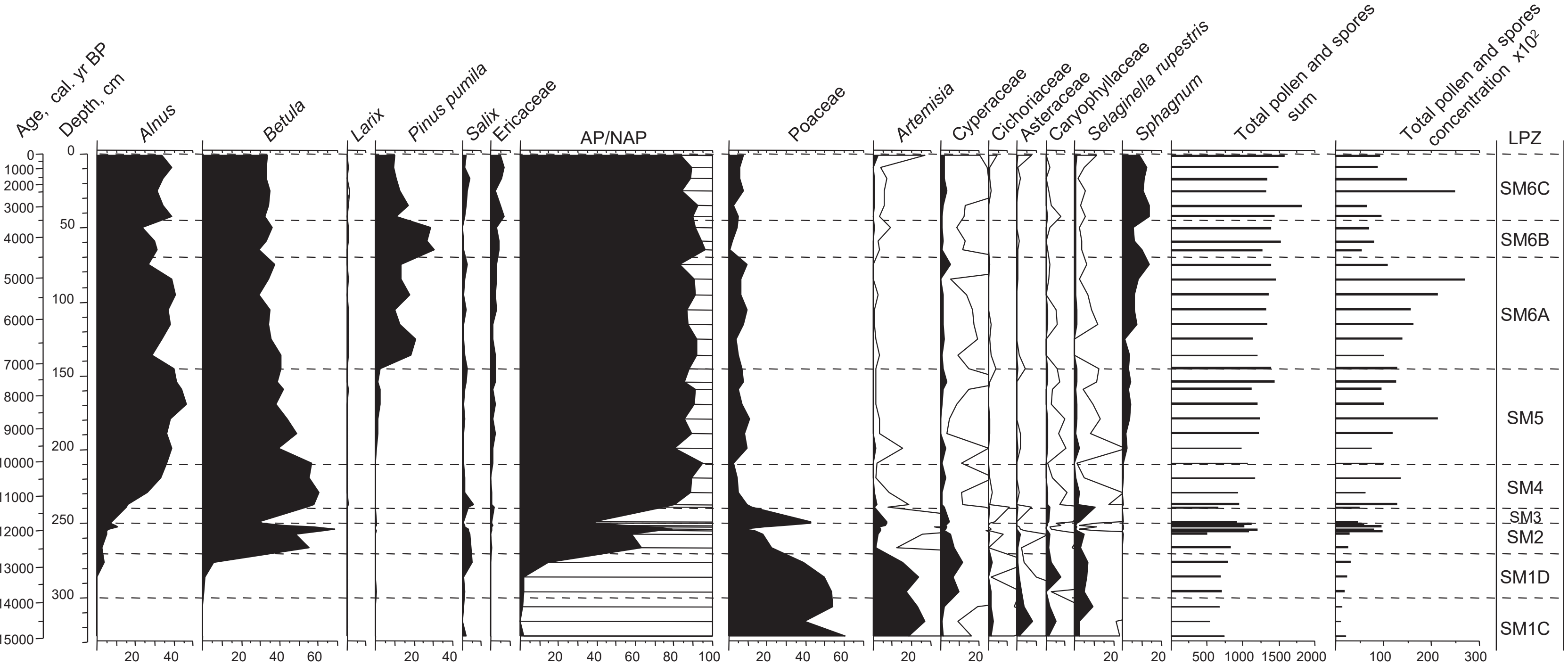

Fig. 9 Percentage palynological diagram of selected taxa from Lake Smorodinovoye record. Pollen zonation is according to Anderson et al. (2002).

Northeast Asia

A sediment core from the Smorodinovoye Lake (Anderson et al., 2002) in the Upper Indigirka region (64°46′E, 141°06′E, site 15 in Fig. 1) provides a ca. 15 cal ka record of vegetation changes from northeastern Siberia (Fig. 9). High percentages of grasses and sage pollen and the variety of xeric taxa such as *Selaginella rupestris* (Fig. 9) suggest that open grass-sage vegetation dominated the landscape during the Late Glacial. A dramatic rise in birch percentages ca. 12.8 cal ka BP implies rapid establishment of shrub tundra in response to postglacial warming. Birch–willow shrub tundra dominated the vegetation between ca. 12.8 and 11.8 cal ka BP. A decline in shrub birch and an increase in grasses and sage pollen percentages indicate that the vegetation reverted to herb-dominated tundra shortly after 11.8 cal ka BP. The vegetation change suggests that summer temperatures and precipitation became lower than during the previous interval (12.8–11.8 cal ka BP), but not as extreme as during the Late Glacial. This short-term episode most likely represents the YD cooling. An increase in birch and willow pollen from ca. 11.3–9.5 cal ka BP suggests that shrub tundra again became dominant with the onset of the Holocene. Alder percentages increased at ca. 11 cal ka BP, but alder was not widespread until ca. 10 cal ka BP. The presence of a larch needle and single larch pollen grains indicates that larch was present in the area as early as by ca. 10.9 cal ka BP. During 9.5–7 cal ka BP, birch and alder continued to dominate the pollen assemblage, indicating that shrub tundra with isolated larch trees dominated the vegetation. Shortly after 7 cal ka BP, shrubby *P. pumila* occurred in the area, as suggested by the composition of the pollen assemblages. Pollen spectra reflect that since that time birch, alder, and heath shrubs were common on the landscape and, along with the dwarf Siberian pine, were abundant in the understory of the larch forest. High shrub tundra, dominated by shrub pine, also became established on the mountain slopes above the altitudinal tree limit.

Conclusions

Generally, pollen records discussed above demonstrate spatially and temporally coherent patterns of environmental changes. Open sage- and grass-dominated communities were widespread in northern Asia during the Late Glacial. A significant increase of shrub pollen registered in a number of records may be correlated with the Bølling/Allerød warming, ca. 13.7 cal ka BP. The subsequent increase in NAP reflects the cooling/drying of the YD interval. Many records show that the Late Glacial/early Holocene transition occurred at about 11.5 cal ka BP and was characterized by a significant increase in birch, shrub alder, and willow pollen and in woody cover percentages (Tarasov et al., 2007; Williams et al., 2011). Records from geographically different sites demonstrate different patterns of vegetation changes connected with local environmental conditions and migration history of the arboreal species. However, the interval from ca. 10.5 to ca. 8.8 cal ka BP was the warmest postglacial episode (the Holocene climatic optimum) in the Arctic regions of northern Asia (e.g., Andreev et al. (2005) and Velichko et al. (1997)). In contrast, records from the more southerly sites, within the boreal forest and forest–steppe zone, show an early Holocene climate amelioration that is less pronounced than that of the middle Holocene. The explanation of these phenomena can be found in the unequal influence of the lower-than-present sea level and higher-than-present summer insolation during the Late Glacial and early Holocene.

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Relevant websites

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http://www.ncdc.noaa.gov—National Climatic Data Center, NOAA Satellite and Information Service, for access to pollen databases.
https://www.neotomadb.org—Neotoma Paleoecology Database.
https://www.pangaea.de/—PANGAEA. Data Publisher for Earth & Environmental Science.
https://stratigraphy.org/chart—International Stratigraphic Chart.