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Thermokarst Formation and Vegetation Dynamics Inferred from a Palynological Study in Central Yakutia, Eastern Siberia, Russia

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Abstract

Thermokarst formation and vegetation change in central Yakutia, eastern Siberia, were reconstructed based on newly obtained AMS radiocarbon data and pollen records from four typical thermokarst depressions (alases). Radiocarbon ages of wood fragments, which are good indicators of the development of thermokarst depressions, suggest that they formed during the early Holocene. The result of dating at various locations implies that thermokarst in central Yakutia developed synchronously, at a time that regional paleoclimate records indicate warm and moist conditions prevailed. Major trends in pollen records from the four thermokarst deposits were similar. The predominant vegetation type during the thermokarst active phase was open larch and birch forest with herbaceous taxa. Grassland developed on areas exposed by a decrease in water levels of thermokarst lakes during the late Holocene.

Introduction

Thermokarst depressions, locally called "alases," are distributed throughout the continuous permafrost zone in central Yakutia, eastern Siberia. Typical features of alases are a depression with a steep slope, flat bottom, grassland vegetation and a central lake (e.g., Czudek and Demek, 1970; French, 1996). In the lowland of central Yakutia, approximately 17% of land area is covered with alases (Bosikov, 1991). Thermokarst depressions range in size from ca. 0.1 to 15 km in diameter, and 3 to 40 m in depth relative to the surrounding terrain (Soloviev, 1962). Thermokarst is formed by thermal disturbance of the ice-rich permafrost surface and an increase in depth of the active layer (annually freezing-thawing layer). Alas is one of the stages of the thermokarst phenomenon (e.g., Czudek and Demek, 1970; Soloviev, 1973; French, 1996). In the initial stage, thawing of the permafrost surface and ground subsidence occurs. Subsequently, water pools emerge that result in further permafrost thawing and ground subsidence, causing the toppling of trees. Finally, in the alas stage, ground subsidence releases salts that were formerly trapped in the permafrost. Owing to dry conditions in this region, salts are brought up to the upper layers (Lopez et al., in press), hindering forest re-establishment (Desyatkin, 1993). An understanding of past thermokarst formation and environment changes is essential for predicting future ecological trajectories of boreal forests in permafrost regions subject to global warming.

Both increased temperature in the surface layer of permafrost and increasing thaw depth have recently been observed in northern subarctic regions (e.g., Osterkamp and Romanovsky, 1999; Jorgenson et al., 2001). The magnitude of the temperature increase in high-latitude regions is greater than that of the global mean value (IPCC, 2001). This temperature increase may lead to deepening of the active layer (e.g., Anisimov et al., 1997; Izrael et al., 1999) and result in changes in permafrost distribution (e.g., Zoltai and Vitt, 1990; Anisimov and Nelson, 1996). Temperature increases in permafrost may also trigger thermokarst initiation or expansion.

Vegetation and climate history inferred from pollen records of lake sediments has been documented for central Yakutia (e.g., Andreev and Klimanov, 1989; Andreev et al., 1989, 1997, 2002; Velichko et al., 1997). From these records, it has been established that Late Glacial vegetation was dominated by steppe elements (e.g., *Artemisia* and Gramineae), followed by a gradual increase in larch (*Larix cajanderi*) and tree birch (*Betula platyphylla*) forest after ca. 11,500 cal yr BP. Scots pine (*Pinus sylvestris*) expanded its range on sandy soil about 6800 cal yr BP. Warm conditions prevailed during ca. 6800–5200 cal yr BP. After the expansion of Scots pine, there were no major compositional changes in the region.

Kachurin (1962) suggested that thermokarst in Siberia started to develop in the Middle Holocene period, and was inhibited in the late Holocene period. According to French (1996), many alases in central Yakutia developed during the Holocene climatic optimum at ca. 5700–4500 cal yr BP. Andreev (2000) proposed that thermokarst development in central Yakutia began ca. 13,500–12,500 cal yr BP, based on dating of lake sediments. Thus, the

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TABLE 1

Site descriptions.

	Latitude N	Longitude E	Area of depression (ha)	Depth of depression (m)
Ulakhan Sykkhan Alas	62°09′	130°31′	64	10
Uinakh Alas	62°09′	130°39′	15	15–20
Ulu Maaly Alas	61°49′	130°13′	97	15–20
Maralay Alas	63°07′	130°36′	121	15–20

history of thermokarst formation that leads to alas grassland in central Yakutia remains unclear. These uncertainties make it difficult to understand the thermokarst phenomenon in relation to climate or vegetation changes.

Pollen records from thermokarst deposits may provide data for reconstructing the history of thermokarst formation. For example, changes in herbaceous pollen percentages may indicate lake-level (area) changes, because lake level fluctuation influences grassland area within the thermokarst depression. In this study, sedimentary records from four typical thermokarst deposits were used to reconstruct the process of thermokarst formation, together with a modern pollen study to elucidate the relationship between modern pollen presence and vegetation distribution.

Study Area

Central Yakutia is located in the inland region of eastern Siberia, where permafrost thickness can reach 500 m near Yakutsk (Ivanov, 1984). In central Yakutia lowland, there are approximately 16,000 alases, with a total area of 4410 km^2 (Bosikov, 1991). At Yakutsk (62°05′N, 129°45′E; 103 m a.s.l.), the mean annual temperature is −10.0°C, and mean monthly temperatures in January and July are −41.2°C and 18.7°C, respectively. Mean annual precipitation is 237 mm (National Astronomical Observatory, 2001). The study sites (Table 1), Maralay Alas, Uinakh Alas, Ulakhan Sykkhan Alas, and Ulu Maaly Alas, are located on the middle terrace (approximately 140–200 m a.s.l.) of the eastern bank of the Lena River (Fig. 1). The middle terrace, where thermokarst is widely distributed (Bosikov, 1991), consists of Quaternary alluvial deposits (Soloviev, 1973).

The vegetation types in central Yakutia are forest and alas grassland. Forests consist primarily of larch, Scots pine, and tree birch (Takahashi, 1994). Open larch forests compose 90% of the boreal forest in central Yakutia. Scots pine dominates on well-drained sites, that is, thick-active-layer sites such as river banks, slopes, and areas with sandy soil. Birch dominates on the borders between forest and alas grassland, and on burned sites. Siberian spruce (*Picea obovata*) is rare but occurs along the river. *Vaccinium vitis-idaea* Mayr and *Ledum palustre* dominate the larch forest floor. Willow (*Salix* spp.), alder (*Alnus fruticosa*), and rose (*Rosa* spp.) dominate the larch forest understory. Alas grasslands are characterized by halophytic species, as saline soils in the alases inhibit the growth of trees (Desyatkin, 1993).

Ulakhan Sykkhan Alas is located approximately 45 km east-northeast of Yakutsk (Fig. 1), with a lake at the center. The depression depth relative to the terrace surface is approximately 10 m. A detailed vegetation map had been made previously (Desyatkin et al., 2000). Figure 2 shows the major vegetation types of alas grasslands (forest-edge meadow, steppe meadow, real meadow, shoreline), indicating a concentric pattern from the center of the lake to the forest margin, with soil moisture decreasing outward. The forest-edge meadow is dominated by Gramineae (e.g., *Elytrigia repens*) and Cyperaceae (e.g., *Carex* spp.). The Steppe meadow is dominated by Gramineae (e.g., *Elytrigia repens, Hordeum brevisubulatum*) and Compositae (e.g., *Artemisia commutata*). The real meadow, which occupies the majority of the grassland area, is dominated by Gramineae (e.g., *Puccinellia tenuiflora*), and the shoreline is characterized by Cyperaceae (e.g., *Bolboschoenus* spp., *Carex* spp.) and Gramineae (e.g., *Poa* spp., *Hordeum brevisubulatum*, *Alopecurus* spp.). Rosaceae, Chenopodiaceae, Caryophyllaceae, Compositae, Brassicaceae, and Ranunculaceae are also present in alas vegetation. The vegetation surrounding the alas is larch forest, with birch at the forest edge, particularly on the south-facing slope. Sediment samples were taken from the southern lakeshore. Surface pollen samples were taken along a north–south transect across the alas (Fig. 2). Plant communities within and around each studied alas were similar.

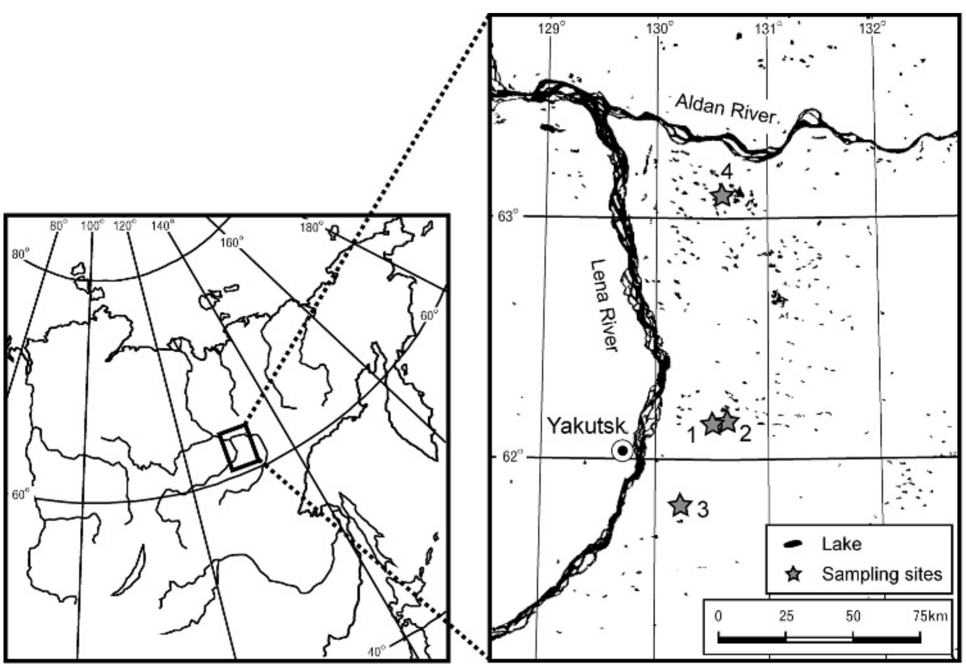

FIGURE 1. Map of eastern Siberia with sites marked as follows: (1) Ulu Maaly Alas; (2) Ulakhan Sykkhan Alas; (3) Uinakh Alas; (4) Maralay Alas.

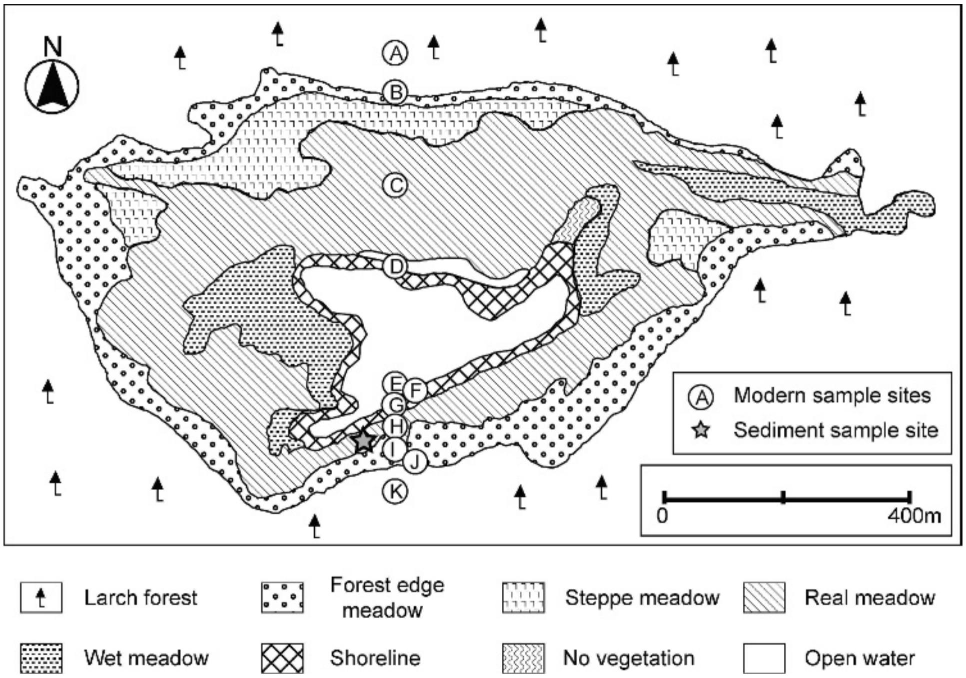

FIGURE 2. Map of Ulakhan Sykkhan Alas surface sample locations and major vegetation zones (after Desyatkin et al., 2000).

Uinakh Alas is located approximately 50 km east-northeast of Yakutsk and 5 km from Ulakhan Sykkhan Alas. The alas depression is 0.5 km wide and 0.3 km long, with a shallow lake at its center. The depth of the depression is approximately 15 to 20 m. Distribution patterns of vegetation within the alas are similar to those of Ulakhan Sykkhan Alas. Sediments were sampled from the northern lakeshore.

Ulu Maaly Alas is approximately 1.5 km wide and 0.5 km long, and is located 36 km southeast of Yakutsk. The depression depth is approximately 15 to 20 m, and there are two shallow lakes within the alas. The vegetation surrounding the lakes consists of open larch forest with Scots pine. Sediment samples were taken near the smaller of the two lakes.

Maralay Alas is located approximately 125 km north-northeast of Yakutsk. The alas is approximately 2.4 km wide and 0.6 km long, with a depression depth of approximately 15 to 20 m and a small lake at its center. The vegetation surrounding the lake consists of open larch forest. Sediment samples were taken from the southern lakeshore (Maralay B) and from the central part of the lake (Maralay A, ca. 50 m from Maralay B).

Methods

SAMPLING

All the sediments, except for those of Maralay Alas A, were sampled from the walls of pits dug during the summers of 2001 and 2002. A motorized auger was used to collect frozen sections of sediments. The Maralay A sediment core was collected from the central part of the lake during the spring of 2004 using a piston corer. Surface pollen samples from Ulakkan Sykkhan Alas (Fig. 2) were analyzed. Eleven surface sediment samples were taken from areas of distinct vegetation types (larch forest, forest-edge meadow, real meadow, shoreline, open water).

RADIOCARBON DATING

Plant macrofossils and charcoal particles were picked out of the sediments and subjected to accelerator mass spectrometry (AMS) radiocarbon dating at Nagoya University Center for Chronological Research and Beta Analytic Inc. Samples were pretreated using the acid-alkali-acid (AAA) method. Radiocarbon dates were converted to calendar dates using the CALIB 5.0.1 program (Stuiver and Reimer, 1993), with a 2σ confidence interval (95.4% probability) (Table 2).

POLLEN ANALYSIS

Surface material and fossil sediment samples of 1.0 cm^3 were prepared using standard procedures for pollen analysis (10% KOH, HF, acetolysis) (Faegri and Iversen, 1989; Moore et al., 1991) and mounted with silicon oil. A minimum of 300 pollen grains were counted per sample. Percentages were calculated based on the sum of tree, shrub, and herb pollen. *Sphagnum* and aquatic taxa were excluded from the pollen sums. Pollen and spores were identified by reference to published keys (Faegri and Iversen, 1989; Moore et al., 1991). The local pollen zones were determined by visual inspection.

Results

STRATIGRAPHY AND RADIOCARBON DATING

The stratigraphy and 13 radiocarbon dates for the four study sites are shown on Figures 3 and 4. Ulakhan Sykkhan Alas sediments consisted of organic-rich silt (0–117 cm) and sand (117–132 cm). Radiocarbon dates of charcoal, twig and wood were 2126–1992 cal yr BP (2085±25 ^{14}C BP), 6469–6316 cal yr BP (5625±29 ^{14}C BP), and 8995–8660 cal yr BP (7975±32 ^{14}C BP) at depths of 16, 67, and 123 cm, respectively.

Uinakh Alas sediments consisted of organic-rich silt (0–87 cm) and silty sand (87–98 cm). Charcoal and plant remains from 10 to 12 cm depth yielded dates of 460–0 cal yr BP (260 ± 40 ^{14}C BP). Wood fragments found in lower layers, at 87 and 95 cm, were dated to 9487–9304 cal yr BP (8388 ± 33 ^{14}C BP) and 9527–9436 cal yr BP (8453 ± 33 ^{14}C BP), respectively.

Ulu Maaly Alas sediments consisted of organic-rich silt (0–108 cm) and silty sand (108–130 cm). Plant fragments at 70 cm

TABLE 2

AMS (accelerator mass spectrometry) radiocarbon dates and their calibrated ages.

Site	Depth (cm)	Material	^{14}C age BP	Calendar age BP (2 sigma range)	Lab. no.
Ulakhan Sykkhan Alas	16	Charcoal	2085±25	2126–1992	NUTA2-4697
	67	Twig	5625±29	6469–6316	NUTA2-4696
	123	Wood	7975±32	8995–8660	NUTA2-4692
Uinakh Alas	10–12	Charcoal/plant remains	260±40	459–0	Beta-206675
	87	Wood	8388±33	9487–9304	NUTA2-4691
	95	Wood	8453±33	9527–9436	NUTA2-4690
Ulu Maaly Alas	70	Plant remains	4641±28	5465–5309	NUTA2-4699
Maralay Alas A	84–86	Aquatic moss	8050±40	9079–8772	Beta-204929
	126–128	Aquatic moss	8980±50	10,238–9918	Beta-204930
	182	*Larix* cone	9390±50	10,742–10,499	Beta-204931
	206	Wood	9610±40	11,161–10,774	Beta-201140
Maralay Alas B	10–12	Charcoal/plant remains	1090±40	1070–928	Beta-206674
	80	Wood	8258±33	9402–9126	NUTA2-4698

depth were dated to 5465–5309 cal yr BP (4641 ± 28 ^{14}C BP). Organic material for radiocarbon dating was not found in the lower section.

Maralay Alas A (central lake) sediments consisted of gyttja (0–34 cm), clay (34–62), organic-rich silt (62–192 cm), and fine sand (192–270 cm). A wood-fragment-rich zone occurs between 182 and 206 cm. Four radiocarbon dates were obtained from this core (Fig. 4). Radiocarbon dating of aquatic moss remains from depths of 84–86 and 126–128 cm yielded dates of 9079–8772 cal yr BP (8050 ± 40 ^{14}C BP) and 10,238–9918 cal yr BP (8980 ± 50 ^{14}C BP), respectively. *Larix* cone and wood fragments yielded dates of 10,742–10,499 cal yr BP (9390 ± 50 ^{14}C BP) and 11,161–10,774 cal yr BP (9610 ± 40 ^{14}C BP), at 182 and 206 cm, respectively.

Maralay Alas B (lakeshore) sediments consisted of organic-rich silt (0–80 cm) and fine sand (80–85 cm). Charcoal and plant remains from a depth of 10 to 12 cm yielded dates of 1070–928 cal yr BP (1090 ± 0 ^{14}C BP). Many wood fragments found in the uppermost sand layers were dated to 9402–9126 cal yr BP (8258 ± 33 ^{14}C BP).

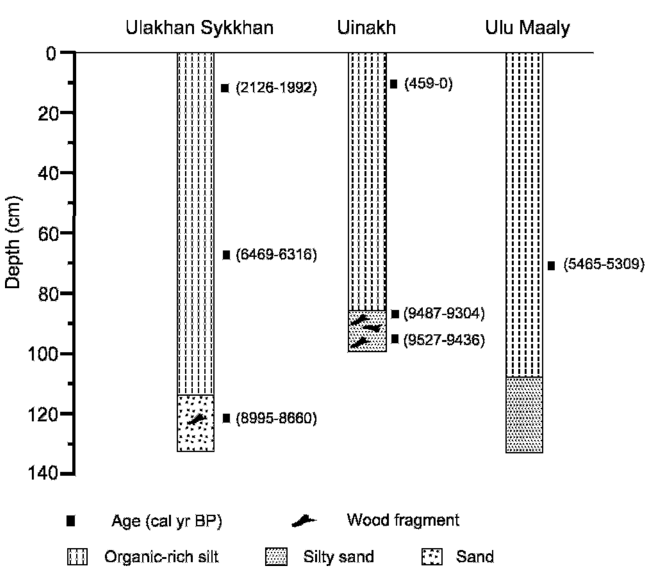

FIGURE 3. Sediment stratigraphy of Ulakhan Sykkhan Alas, Uinakh Alas, and Ulu Maaly Alas with calibrated AMS dates.

POLLEN ANALYSIS

Surface Samples

The pollen spectra of the 11 surface samples from Ulakhan Sykkhan Alas are shown in Figure 5. *Pinus* subg. *Diploxylon* (~27%) and *Betula* (~82%) were the dominant arboreal taxa. *Betula* was dominant at forest sites (sites A and K). *Larix* pollen was comparatively rare (2%–11%) in spite of a high stand density around the alas. Gramineae percentages were the highest (~61%) in real meadow sites (sites C and H). *Artemisia* was more abundant in dry sites than in wet sites.

Ulakhan Sykkhan Alas

The pollen diagram was divided into four local pollen zones: US–1 (118–98 cm), US–2 (98–59 cm), US–3 (58–15 cm), and US–4 (15–0 cm) (Fig. 6). Pollen spectra from below 118 cm are not shown in the figure because pollen concentrations were extremely low. Zone US–1 was dominated by *Betula* (~70%) with Gramineae (~32%) and *Artemisia* (~4%). Zone US–2 was

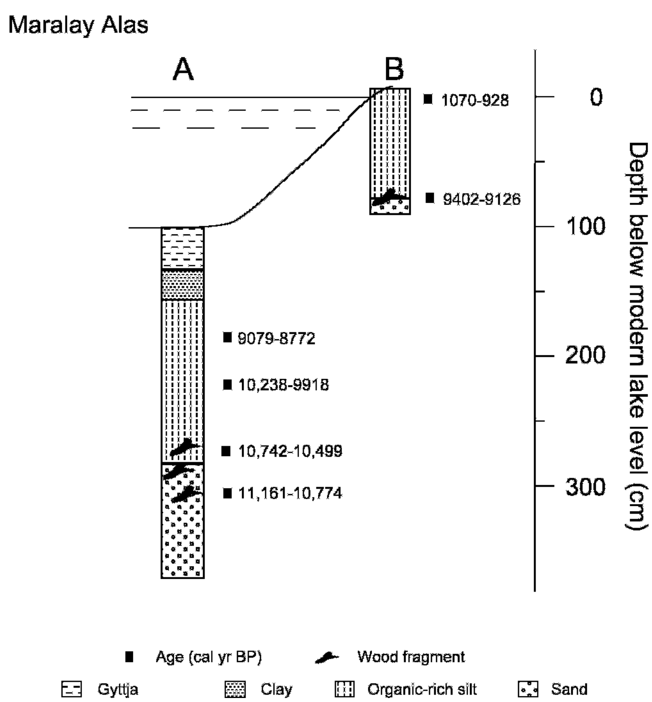

FIGURE 4. Sediment profile stratigraphy in Maralay Alas.

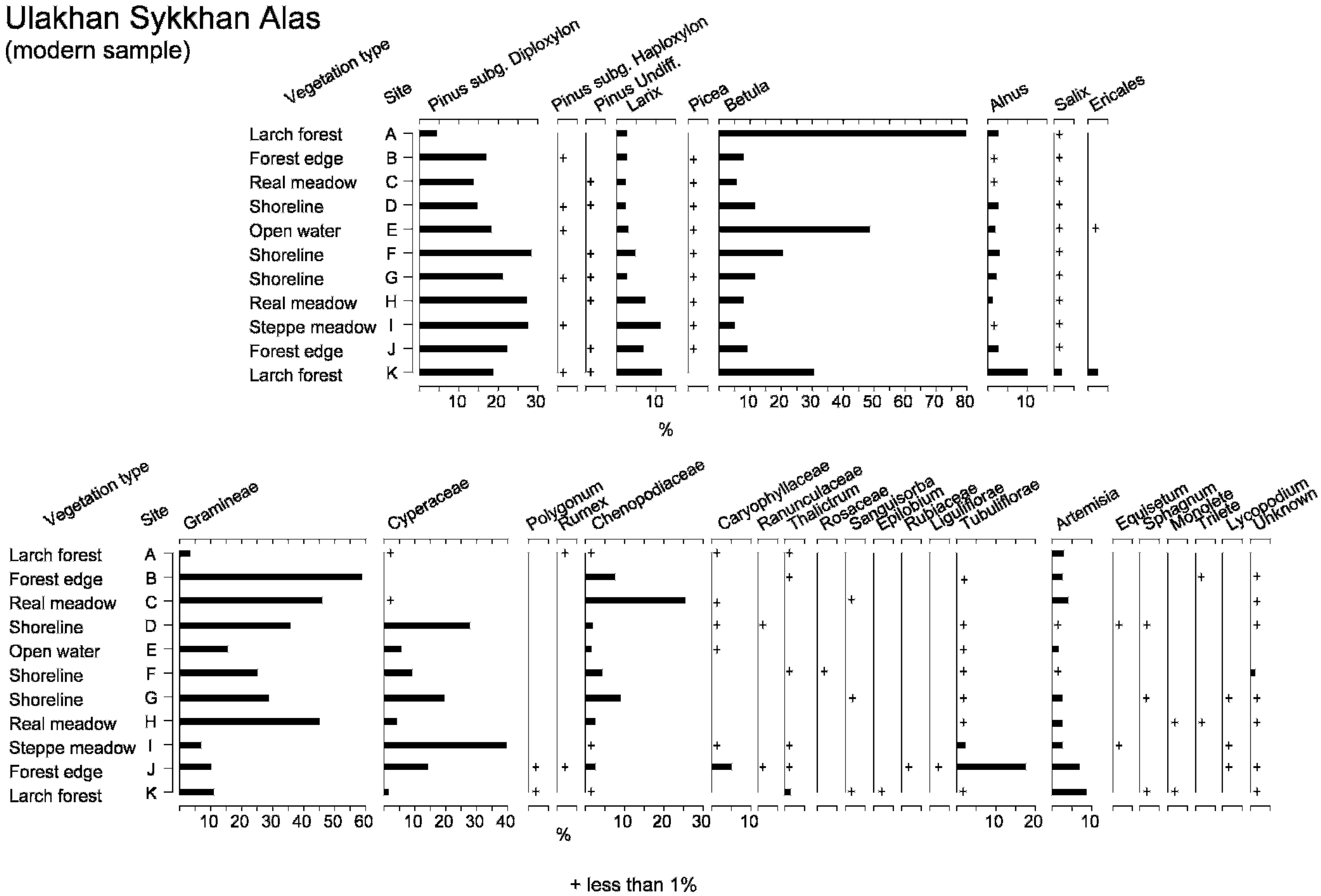

FIGURE 5. Pollen percentage diagram of Ulakhan Sykkhan Alas surface samples.

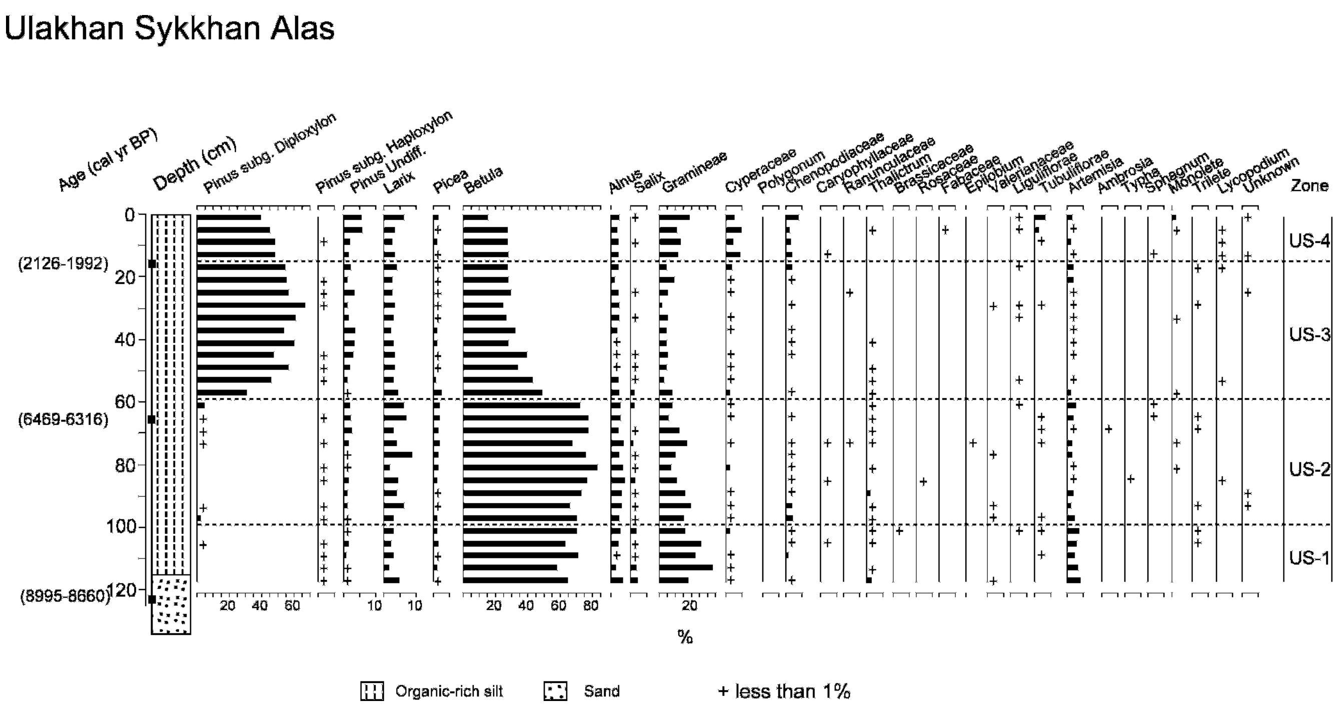

FIGURE 6. Pollen percentage diagram of Ulakhan Sykkhan Alas.

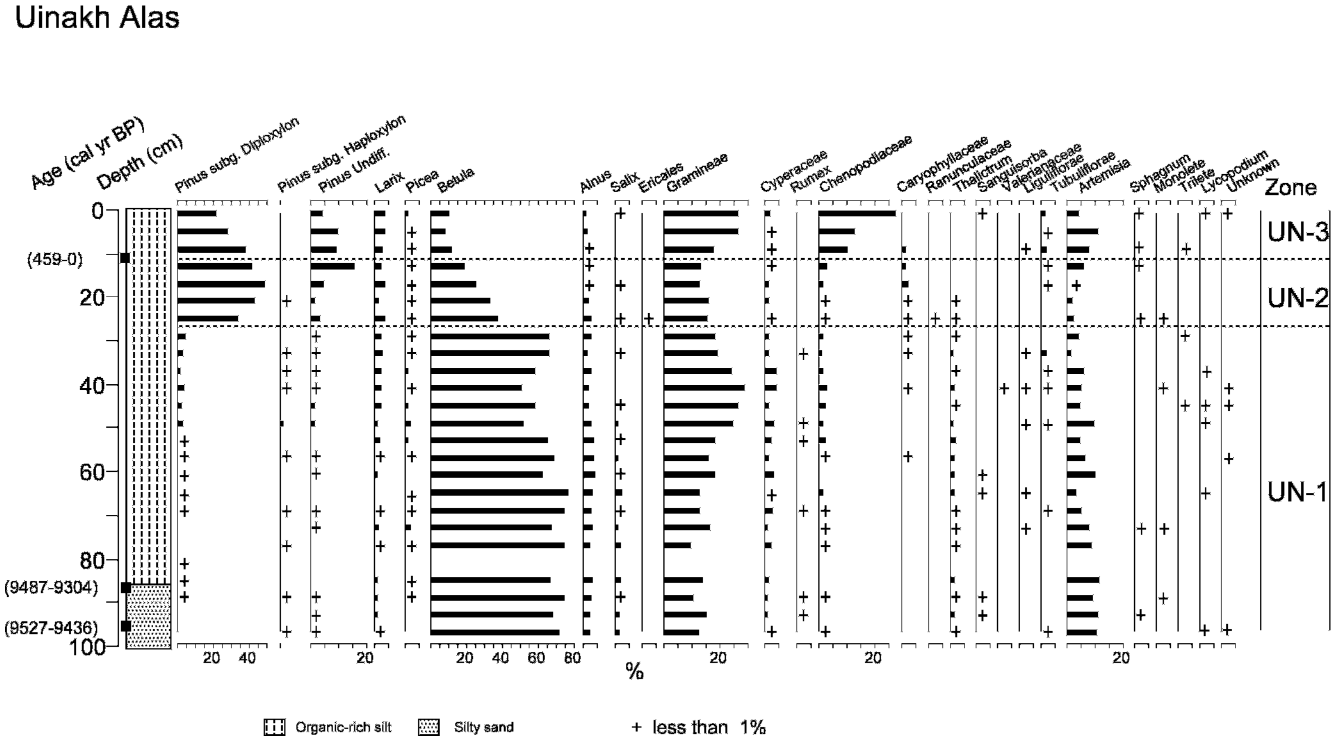

FIGURE 7. Pollen percentage diagram of Uinakh Alas.

marked by high percentages of *Betula* (65%–82%) and a decrease in the amounts of Gramineae and *Artemisia*. *Larix* and *Picea* increased slightly, and reached their maximum frequency in this zone. Zone US–3 was characterized by a high percentage of *Pinus* subg. *Diploxylon* (~66%) and a decrease in the amount of *Betula* (24%–48%). Herbaceous taxa such as Gramineae, Cyperaceae, and Chenopodiaceae increased in zone US–4.

Uinakh Alas

The pollen diagram was divided into three local pollen zones: UN–1 (98–28 cm), UN–2 (28–11 cm), and UN–3 (11–0 cm) (Fig. 7). UN–1 was characterized by an extremely high percentages of *Betula* (~76%), whereas other tree taxa, *Pinus*, *Larix*, and *Picea*, were rare. Gramineae, Cyperaceae, and Chenopodiaceae increased in frequency at around 40 cm depth. Zone UN–2 was characterized by a sharp increase in the presence of *Pinus* subg. *Diploxylon* (~48%) and a gradual decrease in *Betula*. Gramineae (~26%), Chenopodiaceae (~26%), and *Artemisia* (~11%) increased in zone UN–3.

Ulu Maaly Alas

Three local pollen zones were identified in the diagram: UM–1 (113–78 cm), UM–2 (78–13 cm), and UM–3 (13–0 cm) (Fig. 8). UM–1 was marked by an abundance of *Betula* (~68%) with Gramineae (~25%) and *Artemisia* (~8%). UM–2 was characterized by a sharp increase in the amount of *Pinus* subg. *Diploxylon* and a decrease in *Betula*. In zone UM–3, the frequencies of Gramineae (~16%), Cyperaceae, Tubuliflorae, and *Artemisia* increased.

Maralay Alas A

The pollen diagram was divided into three local pollen zones: MC–1 (188–62 cm), MC–2 (62–30 cm), and MC–3 (30–0 cm) (Fig. 9). Pollen spectra from below 188 cm are not shown in the figure because pollen concentrations were extremely low. Zone MC–1 was characterized by the dominance of *Betula* (~71%) with lesser amounts of Gramineae (~20%) and *Artemisia* (~16%). *Artemisia* decreased in zone MC–2. Zone MC–3 was characterized by increases in *Pinus* subg. *Diploxylon* (~14%) and Gramineae (~30%).

Maralay Alas B

Four local pollen zones were identified in the diagram: MR–1 (82–65 cm), MR–2 (65–38 cm), MR–3 (38–15 cm), and MR–4 (15–0 cm) (Fig. 10). MR–1 was dominated by *Betula* (~71%), with Gramineae (~12%), *Thalictrum*, and *Artemisia* (~10%). *Betula* (79%–83%) continued to dominate while Gramineae, *Thalictrum*, and *Artemisia* decreased in zone MR–2. MR–3 was characterized by an increase in *Pinus* subg. *Diploxylon* and a gradual decrease of *Betula*. Gramineae (~71%), Cyperaceae, and *Artemisia* increased in zone MR–4.

Discussion

INTERPRETATION OF MODERN POLLEN SAMPLES

Although data are from a single study site, modern pollen analysis of Ulakhan Sykkhan alas shows features that allow us to understand the fossil record of thermokarst sediments. *Pinus* subg. *Diploxylon* pollen dominates the modern pollen samples, whereas pine trees do not grow around the alas. It is more likely that the presence of pine pollen results from long distance wind transportation, a characteristic of *Pinus*. The amount of *Larix* pollen underestimates the importance of larch in the vegetation assemblage, which has also been documented in other reports (e.g., Clayden et al., 1996; Andreev et al., 1997; Pisaric et al., 2001; Igarashi et al., 2003). Different values of herbaceous pollen such as Gramineae, Cyperaceae, and Chenopodiaceae represent

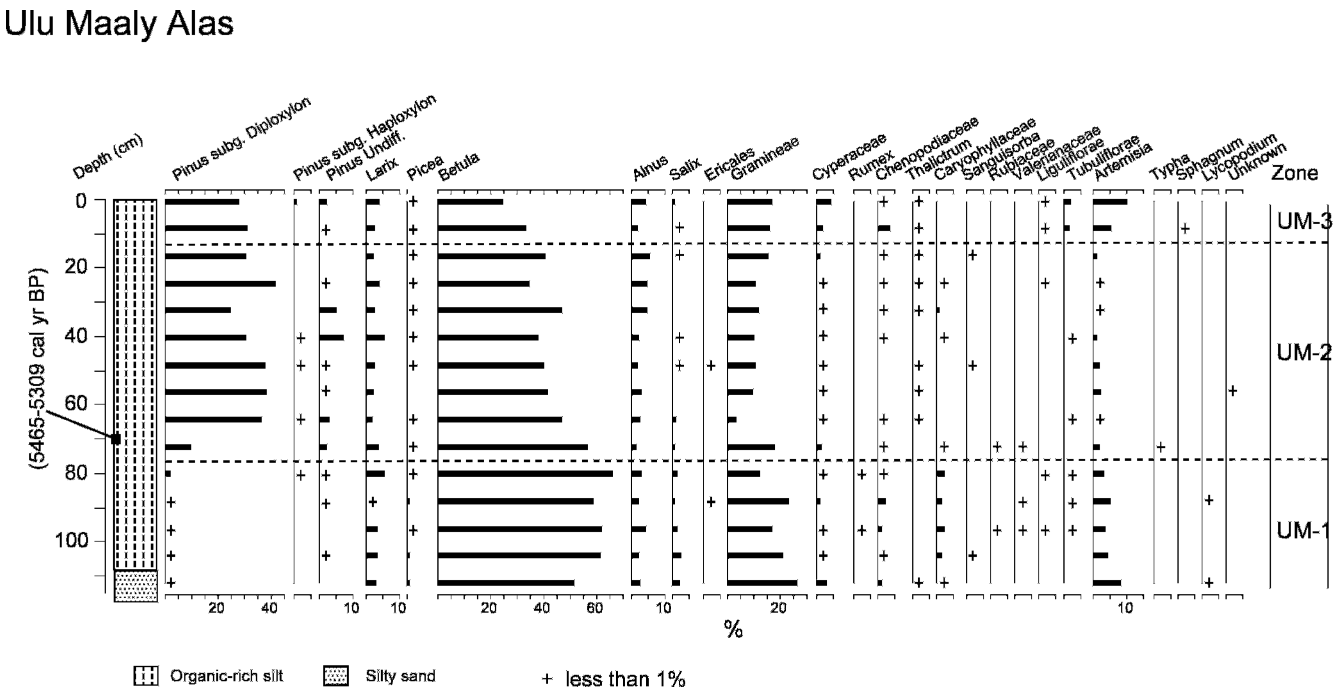

FIGURE 8. Pollen percentage diagram of Ulu Maaly Alas.

differences between sampling sites. These pollen from herbaceous taxa reflect *in situ* grassland vegetation, which is a good representation of the local vegetation type in the thermokarst depression. Further studies are necessary to more accurately interpret the relationship between modern pollen and surrounding vegetation. Furthermore, it is possible that depositional environments of fossil records are different from present ones, because basin pollen accumulation changes along with thermokarst development.

THERMOKARST DEVELOPMENT

Thermokarst sediments show that the there is less organic sandy or silty sediments at the bottom portion of the stratigraphy. These sediments are considered the initial component of the terrace, that is, Quaternary alluvium deposits. The upper rich-organic sediments suggest that these sediments were deposited and preserved in a thermokarst lake after subsidence. During the early development of thermokarst depressions, nearby standing trees

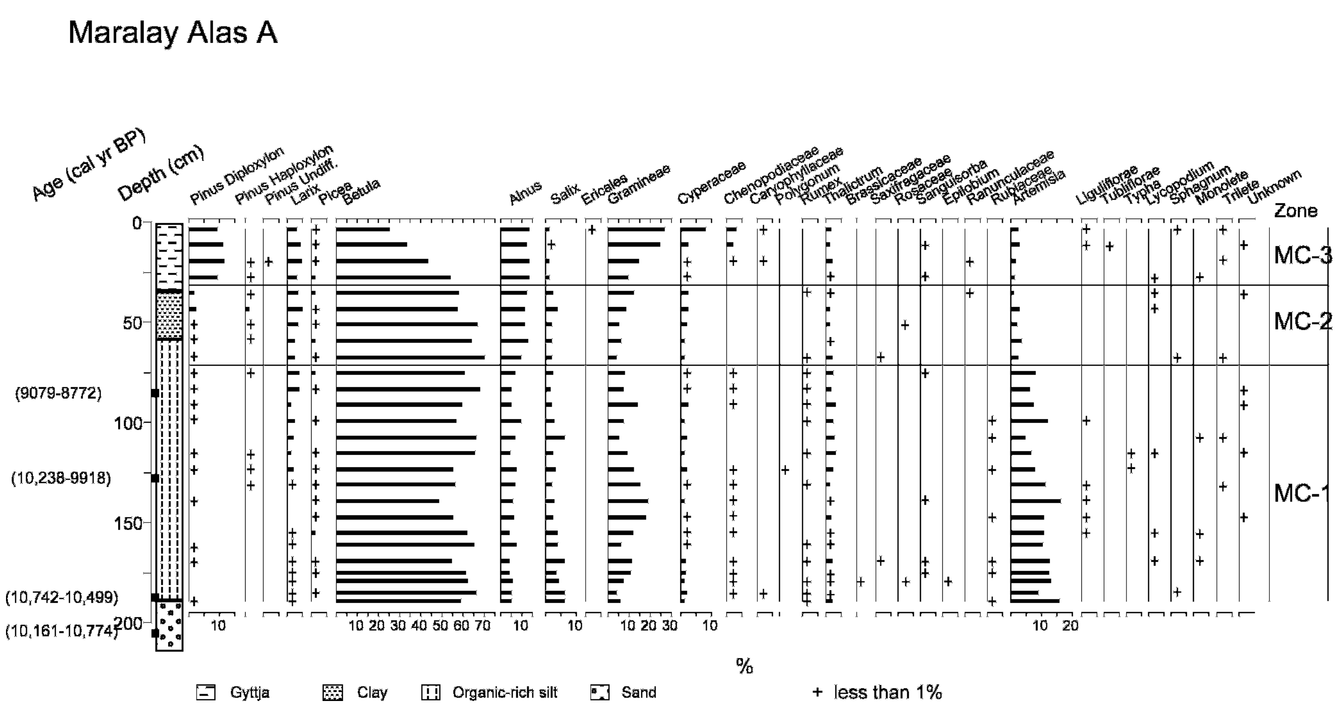

FIGURE 9. Pollen percentage diagram of Maralay Alas A (central lake sediments).

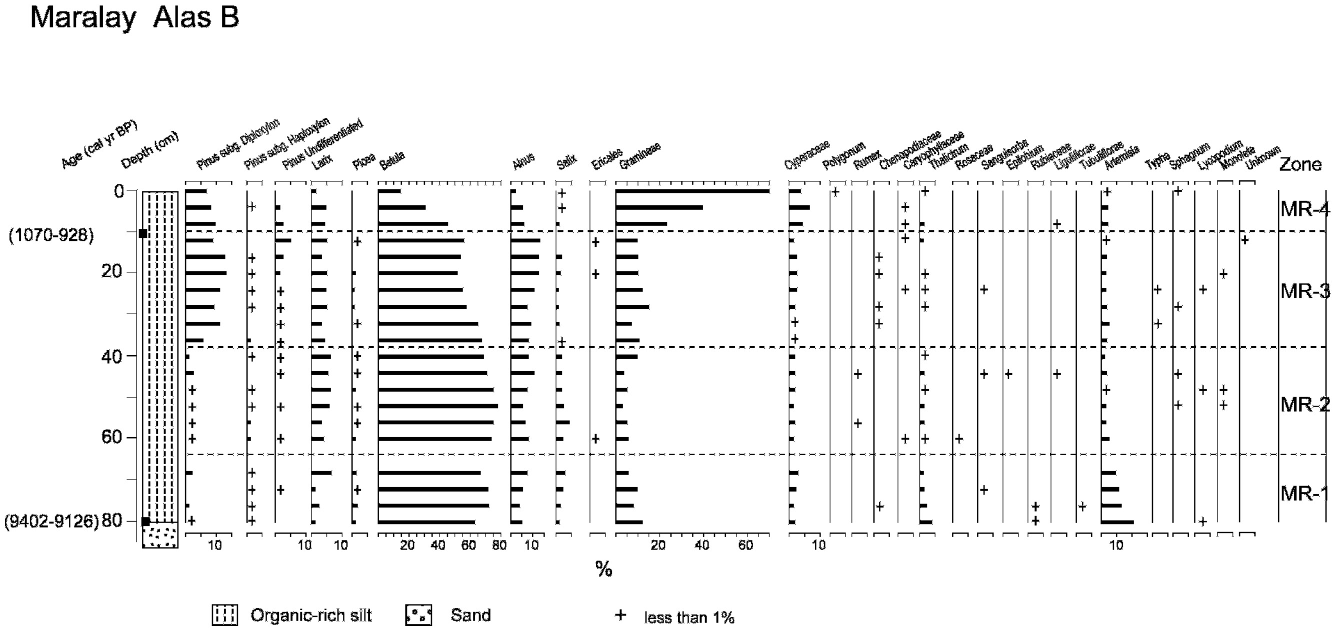

FIGURE 10. Pollen percentage diagram of Maralay Alas B (lakeshore sediments).

are submerged (Czudek and Demek, 1970; French, 1996; Vitt et al., 2000). According to Brouchkov et al. (2004), the active phase of thermokarst subsidence is a short-term catastrophic event, occurring over a few hundred years. The age of wood fragments between sandy and organic sediments of alases thus indicates the age of the early stage of thermokarst development. At Maralay Alas, wood fragments between sandy and organic sediments in the central core (Maralay Alas A) were dated at 10,700–10,500 cal yr BP and 11,200–10,800 cal yr BP, suggesting that thermokarst development started at this time. In contrast, the macrofossil wood interface between organic material and basal sands in the lakeshore sediments (Maralay Alas B) yielded an age of 9400–9100 cal yr BP, suggesting that the lake area had increased and the area of the thermokarst depression had expanded at this time. Other macrofossil woods from the interface between organic material and basal sands in the lakeshore sediments of Ulakhan Sykkhan Alas and Uinakh Alas were dated to between 9500 and 8700 cal yr BP (Fig. 4), suggesting that these lakes expanded during this period. Thus, the early studied alases began to form in the early Holocene, and the thermokarst depressions probably expanded during 8600–9500 cal yr BP. Expansion of the thermokarst occurred at a similar time at different sites 5 to 200 km apart, suggesting that thermokarst development in central Yakutia may have been synchronous in the early Holocene.

Pollen-based reconstruction of central Yakutia climate indicates that both temperature and precipitation increased gradually during the early Holocene (e.g., Velichko et al., 1997; Andreev et al., 1989, 2002). Pisaric et al. (2001) suggested that larch and spruce forests in northern Yakutia advanced into the present tundra zone at ca. 9500 cal yr BP, on the basis of fossilized pollen, stomata, and wood macrofossils. Based on macrofossil wood taken from north of the present treeline, MacDonald et al. (2000) estimated that mean temperatures were 2.5 to 7.0°C higher than at present during ca. 10,200–7900 cal yr BP. Pollen- and chironomid-based reconstructions indicate that the climate was 2 to 3°C warmer than that of today during ca. 10,300–9200 cal yr BP (Andreev et al., 2004).

Thermokarst develops from thermal disturbances of ice-rich ground (French, 1996). Regional thermal disturbances are caused by changes in climate parameters such as temperature and precipitation. Snow or rainfall increases the active-layer thickness in ice-rich ground (e.g., Pavlov, 1996; Agafonov et al., 2004). Thus, the thermokarst development observed in this study was possibly caused by warm and moist climate conditions that prevailed in central Yakutia during the early Holocene.

In the upper portion of each alas sediment sequence, percentages of herbaceous pollen such as Gramineae, Cyperaceae, Chenopodiaceae, and *Artemisia* were high. The modern pollen samples indicate that derived the origin of these herbaceous pollen taxa from within the grassland area. At present vegetation in the forest floor is less than in alas grassland, suggesting that herbaceous pollen is derived mostly from within each alas depression. It is likely that this represents the expansion of the grassland area in each alas as the lake decreased in size during the late Holocene. Herbaceous pollen increased during 1000–900 cal yr BP in Maralay Alas, 2100–2000 cal yr BP in Ulakhan Sykkhan Alas, and 500–0 cal yr BP in Uinakh Alas. Previous pollen analyses suggest that temperature and precipitation were lower than present at ca. 1400 cal yr BP (e.g., Andreev et al., 2002). Perhaps dry conditions in the region caused lake decrease and a corresponding expansion of grasslands within the closed alas system.

REGIONAL VEGETATION HISTORY

Between 10,700 and 8800 cal yr BP, when thermokarst formation was in its active phase, pollen assemblages at Maralay Alas A (Fig. 9) were dominated by *Betula*, Gramineae, and *Artemisia* with trace amounts of *Larix*, suggesting an open larch and birch forest. The presence of *Larix* pollen indicates that larch forests have occurred in this area since at least 10,700–10,500 cal yr BP. In our study, *Betula* pollen grains were not discriminated as shrub or tree taxa; however, other evidence shows that tree birches were dominant at this time in central Yakutia (e.g., Andreev et al., 1989, 1997, 2002).

After thermokarst expansion (ca. 9500–8500 cal yr BP), fossil pollen assemblages from the four alases exhibited similar trends. Pollen percentages of herbaceous taxa such as Gramineae and *Artemisia* gradually decreased except in Uinakh Alas. In central

Yakutia, the disappearance of herbaceous taxa in the forest varies between 11,200 and 6800 cal yr BP (e.g., Andreev et al., 1989, 1997, 2002). At Uinakh Alas, Gramineae and Cyperaceae reached their maximum frequency at 40 cm depth, which probably reflects the expansion of grassland in the alas due to local hydrological changes.

Sediments from all studied alases indicate an increase of *Pinus* subg. *Diploxylon*, suggesting expansion of Scots pine forest. This expansion occurred between 6400 and 5300 cal yr BP, based on radiocarbon dates from Ulakhan Sykkhan Alas and Ulu Maaly Alas. Several other studies in central Yakutia have shown that the expansion occurred about 6800 cal yr BP, during a warm, moist period (e.g., Andreev, 2000; Andreev et al., 1989, 2002). A rapid Scots pine expansion during the mid-Holocene was also observed in the Baikal region in central Siberia (e.g., Takahara et al., 2000; Demske et al., 2005), which suggests that Scots pine expanded synchronously across eastern Eurasia. In the Baikal region, its expansion corresponded to lower moisture and a warmer climate (Demske et al., 2005). Under these conditions in central Yakutia, the distribution of Scots pine forest was probably limited to areas with a thick active layer because Scots pine needs to extend its roots deep into the ground.

Conclusion

In our study, pollen analysis of radiocarbon-dated thermokarst deposits clarified thermokarst dynamics that lead to alas formation. Similar trends were observed at different sites that were many kilometers apart, and those trends are consistent with results from other paleoenvironmental studies. Radiocarbon dating of basal thermokarst deposits indicates that the development of thermokarst activity occurred during the early Holocene in central Yakutia. The timing of thermokarst expansion is consistent with a warm and moist period in the region. Grassland expansion and the corresponding lake area decreasing in the late Holocene are indicated by the increase in herbaceous pollen. Our results provide information for a better understanding of changes in boreal forest response to past and future climate change in permafrost underlain region.

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