LLNL-JRNL-404036

LAWRENCE LIVERMORE NATIONAL LABORATORY

Late Glacial and Early Holocene Climatic Changes Based on a Multiproxy Lacustrine Sediment Record from Northeast Siberia

H. D. Kokorowski, P. M. Anderson, R. S. Sletten, A. V. Lozhkin, T. A. Brown

May 21, 2008

Arctic, Antarctic and Alpine Research

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Late Glacial and Early Holocene Climatic Changes Based on a Multiproxy Lacustrine Sediment Record from Northeast Siberia

Kokorowski, H.D.,[1] Anderson, P.M.,[2] Sletten, R.S.,[3] Lozhkin, A.V.,[4] and Brown, T.A.[5]

[1] Corresponding author; Department of Earth and Space Sciences and the Quaternary Research Center, University of Washington, Box 351310, Seattle, WA 98195, USA; Email: hkokorowski@gmail.com; Tel.: 206.543.6223; Fax: 206.543.0489

[2] Department of Earth and Space Sciences and the Quaternary Research Center, University of Washington, Box 351310, Seattle, WA 98195, USA; Email: pata@u.washington.edu; Tel.: 206.685.7682

[3] Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195, USA; Email: sletten@u.washington.edu; Tel.: 206.543.0571

[4] North East Interdisciplinary Research Institute, Far East Branch, Russian Academy of Sciences, 16 Portovaya Street, Magadan, 685000, Russia; Email: lozhkin@neisri.ru

[5] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA, 94550, USA; Email: tabrown@llnl.gov; Tel.: 925.423.8507

Abstract

Palynological (species assemblage, pollen accumulation rate), geochemical (carbon to nitrogen ratios, organic carbon and biogenic silica content), and sedimentological (particle size, magnetic susceptibility) data combined with improved chronology and greater sampling resolution from a new core from Elikchan 4 Lake provide a stronger basis for defining paleoenvironmental changes than was previously possible. Persistence of herb-dominated tundra, slow expansion of *Betula* and *Alnus* shrubs, and low percentages of organic carbon and biogenic silica suggest that the Late-Glacial transition (ca. 16,000-11,000 cal. yr BP) was a period of gradual rather than abrupt vegetation and climatic change. Consistency of all Late-Glacial data indicates no Younger Dryas climatic oscillation. A dramatic peak in pollen accumulation rates (ca. 11,000-9800 cal. yr BP) suggests a possible summer temperature optimum, but finer grain-sizes, low magnetic susceptibility, and greater organic carbon and biogenic silica, while showing significant warming at ca. 11,000 cal. yr BP, offer no evidence of a Holocene thermal maximum. When compared to trends in other paleo-records, the new Elikchan data underscore the apparent spatial complexity of climatic responses in Northeast Siberia to global forcings between ca. 16,000-9000 cal. yr BP.

Introduction

Post-glacial climatic shifts initially described in the Blytt-Sernander sequence (Blytt, 1876; Sernander, 1908) often are presumed to be similar and synchronous across the Northern Hemisphere, if not the globe, even though data forming this classic climatostratigraphy originated from sites located solely in the North Atlantic sector (e.g., Von Post, 1946; West, 1970; Walker, 1995). That spatial patterns of climatic change may be complex was subsequently demonstrated by general circulation models (GCMs), whose simulations show that strong regional responses to global forcings are at least physically feasible (e.g., COHMAP, 1988). Recent regional-scale, systematic examinations of paleo-records add further support that past climates have greater spatial complexity than once presumed (e.g., Bond et al., 1997; Steig, 1999; Anderson et al., 2003). For example, the Holocene thermal maximum (HTM), resulting from a post-glacial high in Northern Hemisphere summer solar insolation ca. 12,000-10,000 cal. yr BP, warmed the western Arctic in a time-transgressive manner, with sites in northwestern Canada and Alaska experiencing optimal temperatures 4000 yr before sites in northeastern North America (Kaufman et al., 2004). The Younger Dryas (YD: ca. 13,000-11,500 cal. yr BP), characterized by abrupt cooling likely caused by a slow-down or cessation of North Atlantic thermohaline circulation (Broecker and Denton, 1989; Alley et al., 1993), is another event considered to be global in extent. However, the magnitude and duration of the supposed YD oscillation are variable in different regions, and correlation of sites beyond the North Atlantic is often based on records with poor chronologies or ambiguous shifts in paleoenvironmental data (e.g., Mayle and Cwynar, 1995; Rutter et al., 2000; Hu and Shemesh, 2003).

Northeast Siberia is one region whose Late-Glacial and Early Holocene climatic history seems to differ from that defined for the North Atlantic and vicinity, particularly as regards the classic HTM and the YD. The most direct support for warmer-than-present temperatures in the Northeast are macrofossils of tree *Betula* and high shrub *Alnus* and *Salix* found beyond modern limits and dated to ca. 11,000-9000 cal. yr BP (Lozhkin, 1993; see also Edwards et al., 2005). Although these range extensions are possibly from increased summer insolation, coastline at the time was 200-500 km farther north, causing more continental conditions and lessened influences of the cool East Siberian and Chukchi seas (Anderson and Lozhkin, 2002). Determining a thermal optimum in the interior and areas bordering the northern Okhotsk Sea (Priokhot'ye) is more elusive, as interpretations depend on palynological spectra alone (e.g., Lozhkin et al., 1995; Lozhkin et al., 1998). Well-constrained intervals of high pollen accumulation rates (PARs) at Taloye and Goluboye lakes (Fig. 1) suggest vegetation changes associated with warmer-than-modern conditions during the Early to Mid-Holocene (Lozhkin et al., 2000). Similarly high PARs are found at Elgennya Lake, although this record is less robust due to large sampling intervals and relatively few radiocarbon dates (Lozhkin and Anderson, 1996; Anderson et al., 1997). Other pollen diagrams do not display such peaks, nor is there evidence for incursion of more southerly taxa (e.g., Anderson and Lozhkin, 2002).

The YD, like the HTM, is not well defined in Northeast Siberia. The majority of pollen diagrams show no indications of any climatic reversals once post-glacial amelioration has begun (e.g., Lozhkin et al., 1993; Anderson et al., 1996). The exceptions are Smorodinovoye (upper Indigirka valley; Fig. 1) and Dolgoe (west bank of Lena River; Fig. 1) lakes, where there is a brief interval of high herb pollen percentages within the Late-Glacial *Betula* zone (Pisaric et al., 2001; Anderson et al., 2002). Although this change clearly implies cooler conditions, the chronologies are inadequate to unquestionably label it as the YD. In contrast, palynological and plant macrofossil analyses of a well-dated buried peat on Wrangel Island (Fig. 1) suggest that effective moisture and summer temperatures were greater than present during YD times (Lozhkin et al., 2001). A spatially complex response to a YD cooling is not inconsistent with GCM results (e.g., Rind et al., 1986; Mikolajewicz et al., 1997; Peteet et al., 1997), although the models do not simulate the particular patterns inferred from the Northeast Siberian data.

The variations in climatic histories within the Northeast perhaps are real, or they may be the result of inadequacies in the current paleo-records. Many sites have sampling intervals that are too broad or radiocarbon chronologies that are too coarse to determine short-term events, like the YD. For these reasons, examination of additional sedimentological and geochemical proxies in lake sediments may help improve understanding of past landscapes and climatic changes.

To this end, we decided to re-core a previously analyzed site to assess whether additional data would confirm or refute the earlier defined climatic history. We chose Elikchan 4 Lake (60°45´N, 151°53´E; 810 m asl; Fig. 1), which was first cored in 1991, because it lies in a climatically-sensitive area near the boundary of Okhotsk Sea maritime influences and the more continental conditions of the upper Kolyma interior (Lozhkin and Anderson, 1996). The post-glacial record in the initial investigation showed an abrupt warming ca. 14,600 cal. yr BP and no evidence of the YD or HTM. Although the chronology and sampling resolution of the 1991 core were insufficient to define short-term oscillations, marine records show a decrease in sediment organic matter at the time of the YD (Gorbarenko, 1996), suggesting that changes in North Atlantic circulation were transmitted to the marginal seas of the North Pacific and presumably would be evident in the Elikchan 4 record. Thus, a more detailed, multiproxy study at Elikchan 4 Lake should clarify paleoclimatic trends and help assess the strength of palynological data in paleoclimatic interpretations in Northeast Siberia.

Site Description

Elikchan 4 (3.9 km long, 0.9-1.3 km wide) is the largest of four lakes occupying a tectonic valley located in northern Priokhot'ye ca.180 km north of Magadan. Underlying bedrock is early Cretaceous granodiorite and late Triassic shale and sandstone (Lozhkin and Anderson, 1996). The outlet flows southward to the Okhotsk Sea, while inlets are limited to seasonal runoff streams. The three smaller lakes in the valley discharge northward to the Kolyma River and ultimately to the East Siberian Sea. Bathymetry of Elikchan 4 Lake indicates two large, flat-bottomed basins (20-22 m water depth) separated by an underwater ridge (10-15 m water depth). The eastern third of the lake is shallow (<2 m water depth), and a similar but more restricted shelf is found on the lake's western end.

Regional vegetation is open *Larix dahurica*-Bryales forests at low to mid-elevations with an understory of *Pinus pumila, Betula middendorffii, B. exilis, Duschekia fruticosa, Salix*, and Ericales (Lozhkin and Anderson, 1996). A band of high-shrub tundra, typically dominated by *P. pumila,* occupies areas immediately above altitudinal treeline. Beyond this zone is *B. exilis*-Ericales low-shrub tundra. The highest elevations are characterized by high-angled rocky slopes that support little to no vegetation. *Populus suaveolens, Chosenia macrolepis*, *Salix*, *B. middendorffii,* and *B. exilis* are common floodplain species. Local vegetation at Elikchan 4 Lake mirrors the regional plant communities with open *Larix* forests at low to mid-elevations, a narrow zone of *P. pumila* high-shrub tundra beyond altitudinal treeline, and unvegetated mountain tops.

Methods

In summer, 2005, a 285-cm-long sediment core (E4-5) was raised with a modified Livingstone piston sampler (Wright et al., 1984) from the central basin of Elikchan 4 Lake (19.2 m water depth). A volcanic ash, originally named the Elikchan tephra (Anderson et al., 1998), was found between 185-187 cm. Tephra chemistry indicates that it is the KO tephra (V. Borkhodoev, personal communication 2006) from the Kuril Lake-Iliinsky caldera on Kamchatka Peninsula (Ponomareva et al., 2004). The KO tephra has been dated between 7600-7700 ^{14}C yr BP, based on multiple ^{14}C dates on soils, peat, wood, and charcoal from under and above the tephra (Braitseva et al., 1997; Lozhkin et al., 2004). The E4-5 analyses focused on 185-280 cm, which captures the transition from the full glaciation (as indicated by herb-dominated pollen spectra) through the Early Holocene (as constrained by the tephra).

Magnetic susceptibility (MS) was measured along the intact core with a Bartington MS2C Sensor with a 7-cm-diameter, 2-cm-thick loop (Bartington Instruments, Oxford, England). Values are reported without correction for sediment bulk density. Cores were sliced lengthwise and photographed. One half of the core was kept intact and archived. The other half was sectioned continuously at 0.25 cm intervals using a custom-made sampler. Subsamples of the slices were taken every 2-5 cm for multiproxy analysis.

Palynological samples were prepared according to standard procedures for arctic sediments (PALE, 1994) and counted at 400x and 1000x magnification. Pollen accumulation rates (PARs) were calculated based on the cal. yr age model (Fig. 2). Five pollen zones were defined by visual inspection of changes in the pollen percentages of the major taxa.

Percent organic carbon (%C) and carbon to nitrogen (C:N) ratios were measured by vacuum-drying, homogenizing with a mortar and pestle, and then combusting sediment samples to oxidize carbon to CO_2. The CO_2 was measured using coulometric titration (Hu et al., 2002). Because carbonates are absent in the lake catchment and palynological samples processed from multiple Elikchan cores have not reacted to HCl washes (Lozhkin and Anderson, 1996), carbon values reported here likely represent organic sources. Biogenic silica was extracted by alkaline dissolution and percent biogenic silica (%$BSiO_2$) was determined with a spectrophotometer (Spectronic Genesys5; Mortlock and Froelich, 1989). Bulk sediment grain-size was determined with a Laser Diffraction Particle Size Analyzer (Beckman Coulter LS 13 320), and grain-sizes were divided into eight classes (USDA, 1993).

One sediment sample (Table 1) was processed to concentrate pollen for AMS ^{14}C analysis following the methods of Brown (1994), with slight modifications to account for the small pollen size-class and the high proportion of inorganic material in the sample. A twig fragment was pretreated using a standard acid-base-acid protocol. The sharp rise in *Betula* pollen percentages, which has been radiocarbon dated to 12,250 +/- 250 ^{14}C yr BP at multiple sites in Northeast Siberia (Anderson and Lozhkin, 2002) and the KO/Elikchan tephra provide additional chronological control. The midpoints of each age range (*Betula* rise: 12,250 ^{14}C yr; KO/Elikchan tephra: 7650 ^{14}C yr) were used for calibration. All radiocarbon dates were calibrated using CALIB 4.3, method B, which uses probability distributions to calculate the most likely age and provides an associated 1σ age-range (http://depts.washington.edu/qil.calib/calib.html; Table 1, Fig. 2). The choice of a simple linear regression for the E4-5 age model reflects the relatively consistent core sedimentology, which argues for a generally constant sedimentation rate (0.012 cm cal. yr^{-1}).

Results

PALYNOLOGICAL ANALYSIS

Zone E1 (280-262 cm; Fig. 3) is dominated by Poaceae, *Artemisia,* and Cyperaceae pollen with PARs <300 grains cm^2 yr^{-1} (Fig. 4). Zone E2 (262-241 cm) is characterized by an increase in *Betula* pollen percentages, although PARs do not increase significantly until zone E4 (219-211 cm). *Larix* pollen appears for the first time in zone E2. Herb pollen percentages decrease to moderate levels (<15%), although PARs remain similar to zone E1 values. *Alnus* percentages rise in zone E3 (241-219 cm), but like *Betula*, PARs do not increase until zone E4. Maximum PARs (ca. 12,000 grains cm^2 yr^{-1}) occur in zone E4, and herb taxa decline to near trace percentages. Zone E5 (211-197 cm) marks the first consistent appearance of *Larix* pollen in the record. Pollen accumulation rates (ca. 2600 grains cm^2 yr^{-1}) decrease from the previous highs. Percentages of *Pinus* subg. Haploxylon pollen increase to co-dominate with *Betula* and *Alnus* in zone E6 (197-185 cm).

SEDIMENT CHARACTERISTICS

Between 280-269 cm, grain-sizes are relatively fine, with high percentages (ca. 65-80%) of clays and very fine silts (Fig. 5). From 269-218 cm, grain-size variability and percentages of medium-to-coarse silts and sands increase (>50%), whereas very fine silts and clays decrease (<50%). Above 218 cm, grain-sizes are dominated by clays and very fine to fine silts (ca. 80%). Below 218 cm, %C is low (1-3%). A distinct shift occurs between 224-214 cm, where carbon content increases from one of its lowest (1.4%) to its highest (6.2%) value. Although variable, %C remains above 3% from 218-185 cm. Carbon to nitrogen ratios are low (8-13) throughout the core, although they show very slight step-like increases at 262, 244, and 214 cm, roughly paralleling the E1/E2, E2/E3, and E4/E5 pollen zone transitions, respectively. Biogenic silica percentages fluctuate, but are relatively low (2.5-8.5%) between 280-224 cm and relatively high (6.5-14%) between 223-185 cm.

Paleoenvironments of the Elikchan Valley

Pollen zones identified in the E4-5 record are similar to those presented in the 1991 record (Lozhkin and Anderson, 1996). However, the addition of other paleoenvironmental proxies and the finer-scale sampling resolution permit a more complete description of the transition from full-glaciation to the Early Holocene in the upper Kolyma-northern Okhotsk region. For ease of discussion, we have grouped the data into three general periods: Last Glacial Maximum (LGM; defined here as ca. 16,000-14,500 cal. yr BP); Late Glaciation (LG; ca. 14,500-11,000 cal. yr BP); and Early Holocene (EH; ca. 11,000-8500 cal. yr BP). Please note that only two pollen samples are illustrated for the LGM because pollen concentrations are extremely low, making counting difficult. Furthermore, LGM pollen percentages from E4-5 are similar to those previously reported by Lozhkin and Anderson (1996).

LGM: 280-262 cm; ca. 16,000-14,500 cal. yr BP

The high percentages of herbaceous taxa in zone E1 (Fig. 3), particularly Poaceae, Cyperaceae, and *Artemisia*, and extremely low PARs (Fig. 4) are characteristic of full-glacial pollen assemblages from Northeast Siberia (Anderson and Lozhkin, 2002). The variety of herb pollen taxa implies a local mosaic of moist and xeric habitats (e.g., snowbed communities as indicated by *Salix*, Ranunculaceae, and *Thalictrum*; dry, disturbed, or rocky habitats as suggested by Compositae, Brassicaceae, and *Selaginella rupestris*) in otherwise discontinuous, graminoid-dominated tundra (Lozhkin and Anderson, 1996). The LGM was colder and drier than present.

Geochemical and sedimentological analyses agree with this paleoclimatic interpretation. Low %C and %$BSiO_2$ argue for limited aquatic productivity. An extended duration of seasonal ice-cover, resulting from cooler late-spring or early autumn temperatures, would lower organic production and diatom abundance. Sparse vegetation cover and cold summers likely reduced the production and decomposition of organic material, restricting the availability to aquatic organisms of N and other organically-derived nutrients. Low C:N ratios also suggest limited input of terrestrial carbon. Increasing grain-sizes towards the end of the LGM imply greater mobilization of coarse silt and sand particles, perhaps reflecting increases in wind intensity, the rate of snowmelt, and/or larger runoff events. Sediment MS often is used to infer relative cool/warm conditions, or greater/lesser mineral input depending on the extent of vegetation cover (Thompson and Oldfield, 1986). However, MS fluctuations during the LGM seem to depend more on grain-size, and hence on the cohesive force of magnetic minerals, than on paleoenvironmental factors.

LG: 262-219 cm; ca. 14,500-11,000 cal. yr BP

Increases in pollen percentages of *Betula* (zone E2) and *Alnus* (zone E3) indicate the expansion of woody taxa near the lake by ca. 14,500 cal. yr BP and ca. 12,800 cal. yr BP, respectively. While certainly more abundant than during the LGM, the relatively low PARs suggest that shrubs probably were restricted to lower mountain slopes and lake shores. The continued importance of herbaceous communities is supported by: 1) graminoid and *Artemisia* PARs in zones E2 and E3 that are similar to the LGM; and 2) pollen percentages of *Salix* and herb taxa that, although less than during the LGM, have moderate values. Trace amounts of *Larix* pollen, beginning ca. 13,200 cal. yr BP, mark the establishment of local woodlands, which probably were limited to south-facing slopes where surface temperatures were relatively warm. The improved core chronology and high sampling resolution, resulting in more trustworthy PARs, suggest that the LGM-LG transition was more gradual than thought originally (Lozhkin and Anderson, 1996). The expansion of *Betula* or *Betula-Alnus* shrub tundra, even if not extensive, and the appearance of *Larix* imply greater effective moisture during the LG as compared to the LGM. The presence of *Larix* further argues for at least local mean July temperatures of 12°C (Kozhevnikov, 1981; Andreev, 1980).

Increases in medium to coarse silts and sands are often cited as evidence of discontinuous vegetation (e.g., Hughen et al., 1996). Although the percent of larger grain-sizes is relatively high in zones E2 and E3, total PARs suggest that the LG vegetation was not as sparse as during the LGM, when finer grain-sizes dominate the sediments. If vegetation was more extensive, larger grain sizes would likely reflect elevated precipitation, where higher energy runoff would bring coarser sediments to the lake. The absence of *Pinus pumila*, which requires deep snow-cover to survive harsh winter temperatures (Andreev, 1980), suggests an increased intensity of summer rainfall rather than greater spring melt as the cause of the additional runoff.

Terrestrial input continued to be nutrient-poor during the LG as indicated by small %C and %$BSiO_2$. These proxies, like the low PARs, suggest a limited vegetation cover. Because the rise in C:N ratios is so slight, the increase probably reflects microbial denitrification of organic matter and not a strengthening in terrestrial carbon sources (Meyers and Lallier-Verges, 1999). High MS values denote greater mineral input, perhaps resulting from higher precipitation, but fluctuations appear to correspond to grain-size changes.

In contrast to earlier interpretations, the vegetation shift from LGM herb-dominated tundra to a mix of shrub tundra and woodland was gradual as indicated by the differential expansion of key species (*Betula*, *Larix*, and *Alnus* at 14,500, 13,200, and 12,800 cal. yr BP, respectively) and moderate PARs. Coarser grain sizes and low %C and %$BSiO_2$ lend further support for relatively sparse vegetation. The multiproxies suggest a continued increase in summer temperature and rainfall during the LG, with no evidence of a YD climatic reversal.

EH: 219-185 cm; ca. 11,000-8500 cal. yr BP

Betula and *Alnus* dominate the pollen spectra at the beginning of the EH (zone E4; 11,000-10,400 cal. yr BP), although PARs indicate graminoids continued to be important on the landscape until the end of zone E4. Large spikes in *Betula* and *Alnus* PARs imply a rapid expansion of shrub tundra beginning shortly after 11,000 cal. yr BP. Although inferring extent of vegetation cover from PARs can be problematic (Seppä and Hicks, 2006), the fivefold increase in total PARs seen in zone E4 strongly suggests a more continuous vegetation cover than during the LG. *Larix* achieves highest percentages and PARs in zone E5 (ca. 10,400-9200 cal. yr BP). While these changes are not dramatic, they hint that trees may have moved up nearby slopes, perhaps replacing *Alnus*, whose pollen percentages decline in this zone. No tree *Betula* pollen was identified, indicating that like today, *Larix* dominated the local forest. Modern vegetation established ca. 9200 cal. yr BP (zone E6), with the arrival of *Pinus pumila*.

Sedimentological and geochemical data indicate a major change in vegetation and climate beginning ca. 11,000 cal. yr BP. The shifts to relatively fine grain-sizes and low MS are consistent with increasing vegetation cover as inferred from the palynological data. Although perhaps partially a function of smaller grain-sizes, low MS may also denote reducing conditions at the sediment-water interface (Thompson and Oldfield, 1986). Such conditions would be associated with higher rates of aquatic productivity and decomposition, a conclusion supported by greater %C and %$BSiO_2$. The latter proxies suggest increases in summer temperatures and/or winter snow depths. Warmer summers would reduce the period of ice-cover, whereas wetter winters might lessen ice thickness, thereby enhancing aquatic productivity and diatom abundance. However, if winter snow deepened in the earliest Holocene, it was insufficient to support *Pinus pumila*. Carbon to nitrogen ratios are slightly higher than previously but continue to reflect aquatic carbon sources.

After the shift ca. 11,000 cal. yr BP, the geochemistry and sedimentology vary little throughout the EH, indicating relative climate stability ca. 11,000-8500 cal. yr BP. In contrast, palynological data evoke two climatic events between ca. 11,000-9200 cal. yr BP. The most unambiguous evidence is an increase in snow depth (and possibly warmer winters) associated with the arrival of *Pinus pumila* ca. 9200 cal. yr BP. The high PARs 11,000-10,400 cal. yr BP imply a fundamental change in the vegetation and by extension climate. However, the nature of that change is more difficult to interpret. Because they depart so much from modern PARs (as represented by zone E6 values), the zone E4 and possibly E5 vegetation probably differed from the mid-to-low shrub tundra occupying areas of the valley today. The slight increase in *Larix* pollen in zone E5 perhaps is a faint indication of higher altitudinal treeline. If the PARs are indeed indicative of the above vegetation changes, then summer temperatures were probably warmer than present ca. 11,000-10,400 cal. yr BP, and possibly to ca. 9800 cal. yr BP (see following section for further discussions of interpretive limits associated with *Larix* pollen and PARs).

Multiproxies vs. Palynological Data for Reconstructing Paleoclimate

Late Quaternary climates of Northeast Siberia have been inferred principally from changes in paleovegetation (e.g., Shilo, 1970). As valuable as the paleobotanical data are, they have certain innate limitations: 1) arctoboreal pollen flora are simple as compared to more temperate regions, providing fewer paleoclimatic indicators; 2) many key pollen types have only coarse taxonomic resolution and can not resolve tree vs. shrub forms; 3) plant macrofossils are rare in lake sediments, thus preventing their widespread use to complement pollen records; and 4) paleoenvironmental work in many areas of the Northeast is still in the pioneering stages, resulting in records with insufficient dating control or sampling resolution for identifying brief climatic oscillations. The situation is further confounded by having *Larix*, a pollen taxon that is so under-represented it is essentially equivalent to a macrofossil, as the main boreal indicator. Even with stomate identification in a core (e.g., Hansen, 1995), establishing the local presence of *Larix* is a challenge, much less inferring relative tree densities on the landscape. Thus, the addition of nonpalynological proxies and the improved sampling resolution at Elikchan 4 Lake is a much-needed experiment that allows us to revisit regionwide paleoclimatic patterns.

Edwards et al. (2005) used plant functional types inferred from pollen data and plant macrofossils to hypothesize the existence of a deciduous boreal forest across Northeast Siberia and Alaska ca. 13,000-10,000 cal. yr BP. Based on the diameters of woody macrofossils, they postulated that moderate-sized shrubs, which are characteristic of present-day tundra, achieved tree-equivalent heights while retaining their shrubby growth forms. This possibility is supported in Northeast Siberia by the presence of large stumps and branches of *Alnus* and *Salix* found in sites that are now beyond latitudinal treeline that are dated to ca. 11,000-9000 cal. yr BP (Lozhkin, 1993). The presence of such a biome, which is absent on the modern landscape, occurs at times of increased summer insolation and suggests that the spread of northern deciduous trees or large shrub species is the result of warmer-than-present temperatures.

Although not without problems, PARs have been used in high latitudes to infer past changes in northern plant communities and related climatic causes (e.g., dramatic increases in arboreal PARs suggesting greater tree density or a more widespread forest cover with inferences drawn to increased summer temperatures). Prior to the E4-5 study, only two sites from northern Priokhot'ye and the upper Kolyma region showed evidence of increased PARs (Taloye Lake at ca. 10,000-10,200 cal. yr BP and ca. 7900-4500 cal. yr BP and Goluboye Lake at ca. 9000-6750 cal. yr BP; Lozhkin et al., 2000; Fig. 1), peaks in PARs that are modest in comparison to Elikchan 4. Highest values at Elikchan 4 Lake occur ca. 11,000-9800 cal. yr BP. This latter interval overlaps the HTM, as defined by northern coastal macrofossils and biome reconstruction (Edwards et al., 2005), but shows little correspondence to times of maximum warmth inferred from the Taloye and Goluboye data. Although PARs are sensitive to core chronology, the discrepancies among the three lake records are unlikely to be artifacts of the age models. For example, linear interpolation was used in the Taloye and Goluboye diagrams, and shifts in PARs are not associated with the placement of radiocarbon dates. Furthermore, experiments with various age models in E4-5 suggest the PAR peak is not a function of the chosen dating scheme. The sedimentology and geochemistry from Elikchan 4 show no variations that correspond to the increases in PAR. If climate was the main driver of change, parallel changes in all biotic and nonbiotic data would be expected as the lake and terrestrial ecosystems and pathways of sediment input to the basin react to the shifting climate. Thus, the lack of synchronous response of the various proxies from Elikchan 4, the inconsistent timing in PARs peaks in the Taloye, Goluboye and Elikchan 4 records, and constant PARS in other lakes in the region suggest that variations in PARs at these three lakes are reflecting changes in local ecology rather than regional climate.

Like the HTM, the YD presents its own puzzle. Obtaining bracketing dates for this interval has proved difficult because of the highly inorganic lake sediments, the lack of macrofossils, and low sedimentation rates in many cores. Despite these drawbacks, a YD-type oscillation is clearly recorded at Smorodinovoye and Dolgoe lakes, suggesting high-latitude pollen spectra can be sufficiently sensitive to short-term cooling. The increased sampling resolution of core E4-5, which has a sample every 150 cal. yr for the YD, shows no changes in palynological, sedimentological, or geochemical data. To date, these results provide the strongest evidence that a YD cooling was not experienced across all of Northeast Siberia. The Elikchan data also contrast with warmer and/or wetter than modern conditions inferred for Wrangel Island.

The transition from the LGM to the LG has traditionally been interpreted as abrupt and dramatic (e.g., Lozhkin et al., 1993). Pollen percentages in E4-5 mirror those conclusions. However, improved chronology and PAR calculations suggest a more gradual transition. Sedimentological and geochemical data also imply a more measured shift in past environments. PARs from other sites provide somewhat ambiguous results caused by poor chronology. If the trend at Elikchan 4 Lake is indicative of the broader region, then fundamental paleovegetation and paleoclimatic interpretations as related to post-glacial climatic amelioration need to be reconsidered.

Although this multiproxy approach is of great value, the sedimentology and geochemistry remain indirect evidence for climatic fluctuations. Like the palynological data, reasons for change may either be climatic or due to variations in the local catchment. These sediment data do not provide quantitative paleoclimatic estimates and thus do not improve upon previous qualitative estimates of past conditions. Unfortunately, the noncalcareous terrain in Northeast Siberia limits applications of more quantitative proxies such as the isotopic analysis of ostracodes (e.g., Leng and Marshall, 2004; Anderson et al., 2005). The interpretive discrepancy among the various data types argues that future research must rely on the compilation of multiproxies as well as on newly developing techniques (e.g., oxygen isotope analyses of diatoms; Shemesh and Peteet, 1998; Rioual et al., 2001) for assessing the Late-Glacial and Early Holocene climate history of Northeast Siberia.

Acknowledgements

This work was supported by the National Science Foundation (ATM-00-117406) and the Russian Foundation for Fundamental Research (Grant 06-05-64129). The authors would like to thank Pavel Minyuk and Vladimir Borkhodoev of the North East Interdisciplinary Science Research Institute, Magadan, and Linda Brubaker, Alecia Spooner and Philip Higuera at the University of Washington for their help in this study. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

TABLE 1. Radiocarbon and calibrated dates for Elikchan 4 Lake, core E4-5.

FIGURE 1. Map showing the location of Elikchan 4 Lake and other relevant sites.

FIGURE 2. (A) ^{14}C age-depth curve; and (B) calibrated age-depth curve for core E4-5; midpoint with error bars indicate 1σ maximum and minimum ages.

FIGURE 3. Select pollen and spore taxa (%) for Elikchan 4 Lake, core E4-5. Palynological data are presented as a percentage of the sum of identified and unidentified tree, shrub, and herb pollen.

FIGURE 4. Total and select taxa pollen accumulation rates (PARs: grains/cm^2 yr^{-1}) for core E4-5. Note changes in scale.

FIGURE 5. Grain size, organic carbon (%C), C:N ratio, biogenic silica (%$BSiO_2$), and magnetic susceptibility (MS) for core E4-5. Note changes in scale.

References Cited

Alley, R. B., Meese, D. A., Shuman, C. A., Gow, A. J., Taylor, K. C., Grootes, P. M., White, J. W. C., Ram, M., Waddington, E. D., Mayewski, P. A., and Zielinski, G. A., 1993: Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature,* 362: 527-529.

Anderson, L., Abbott, M. B., Finney, B. P., and Burns, S. J., 2005: Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. *Quaternary Research,* 64: 21-35.

Anderson, P. M., Lozhkin, A. V., and Brubaker, L. B., 1996: A lacustrine pollen record from North Priokhot'ya: new information about late Quaternary vegetational variations in western Beringia. *Arctic and Alpine Research,* 28: 93-98.

Anderson, P. M., Lozhkin, A. V., Belaya, B. V., Glushkova, O. Y., and Brubaker, L. B., 1997: A lacustrine pollen record from near altitudinal forest limit, Upper Kolyma Region, northeastern Siberia. *The Holocene,* 7: 331-335.

Anderson, P. M., Lozhkin, A. V., Belaya, B. V., and Stetsenko, T. V., 1998: New data about the stratigraphy of late Quaternary deposits of northern Priokhot'ye. *In* Simakov, K. V. (ed.), *Environmental Changes in Beringia During the Quaternary*. Magadan: North East Interdisciplinary Science Research Institute, Far East Branch, Russian Academy of Sciences, 69-87. In Russian.

Anderson, P. M. and Lozhkin, A. V., 2002: Palynological records and radiocarbon data from late Quaternary deposits of the Yana-Kolyma Lowland, the Kolyma Basin, and Northern Priokhot'ye. *In* Anderson, P. M. and Lozhkin, A. V. (eds.), *Late Quaternary Vegetation and Climate of Siberia and the Russian Far East (Palynological and Radiocarbon Database)*. Magadan: U.S. National Oceanic and Atmospheric Administration and the Russian Academy of Sciences, Far East Branch, 80-163.

Anderson, P. M., Lozhkin, A. V., and Brubaker, L. B., 2002: Implications of a 24 000-yr palynological record for a Younger Dryas cooling and for boreal forest development in northeastern Siberia. *Quaternary Research,* 57: 325-333.

Anderson, P. M., Edwards, M. E., and Brubaker, L. B., 2003: Results and Paleoclimate implications of 35 years of paleoecological research in Alaska. *Development in Quaternary Science,* 1: 427-440.

Andreev, A. A., 1980: *Vegetation and Soils of Subarctic Tundra*. Nauka: USSR Academy of Sciences, Siberian Branch, Yakutia Subdivision, Biological Institute, Novosibirsk.

Blytt, A., 1876: Essay on immigration of the Norwegian flora during alternating rainy and dry periods. (proposed: Arctic Subarctic Boreal Atlantic Subboreal Subatlantic).

Bond, G., Showers, W., Cheseby, M., Lotti-Bond, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G., 1997: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science,* 278: 1257-1266.

Braitseva, O. A., Ponomareva, V. V., Sulerzhitsky, L. D., Melekestsev, I. V., and Bailey, J., 1997: Holocene key-marker tephra layers in Kamchatka, Russia. *Quaternary Research,* 47: 125-139.

Broecker, W. S. and Denton, G. H., 1989: The role of ocean-atmosphere reorganizations in glacial cycles. *Geochimica et Cosmochimica Acta,* 53: 2465-2501.

Brown, T. A., 1994: Radiocarbon dating of pollen. PhD, College of Forest Resources, University of Washington, Seattle.

COHMAP, 1988: Climatic Changes of the last 18,000 years: observations and model simulations. *Science,* 241: 1043-1052.

Edwards, M. E., Brubaker, L. B., Lozhkin, A. V., and Anderson, P. M., 2005: Structurally novel biomes: A response to past warming in Beringia. *Ecology,* 86: 1696-1703.

Gorbarenko, S., 1996: Stable isotope and lithologic evidence of late-glacial and Holocene oceanography of the northwestern Pacific and its marginal seas. *Quaternary Research,* 46: 220-250.

Hansen, B. C. S., 1995: Conifer stomate analysis as a paleoecological tool: An example from the Hudson Bay Lowlands. *Canadian Journal of Botany,* 73: 244-252.

Hu, F. S., Lee, B. Y., Kaufman, D. S., Yoneji, S., Nelson, D. M., and Henne, P. D., 2002: Response of tundra ecosystems in southwestern Alaska to Younger-Dryas climatic oscillation. *Global Change Biology,* 8: 1156-1163.

Hu, F. S. and Shemesh, A., 2003: A biogenic silica ^{18}O record of climatic change during the last glacial-interglacial transition in southwestern Alaska. *Quaternary Research,* 59: 379-385.

Hughen, K. A., Overpeck, J. T., Anderson, R. F., and Williams, K. M., 1996: *The potential for palaeoclimate records from varved Arctic Lake sediments: Baffin Island, Eastern Canadian Arctic*. Geological Society Special Publication No. 116, London.

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., Brubaker, L. B., Coats, L. L., Cwynar, L. C., Duvall, M. L., Dyke, A. S., Edwards, M. E., Eisner, W. R., Gajewski, K., Geirsdottir, A., Hu, F. S., Jennings, A. E., Kaplan, M. R., Kerwin, M. W., Lozhkin, A. V., MacDonald, G. M., Miller, G. H., Mock, C. J., Oswald, W. W., Otto-Bliesner, B. L., Porinchu, D. F., Ruhland, K., Smol, J. P., Steig, E. J., and Wolf, B. B., 2004: Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Science Reviews,* 23: 529-560.

Kozhevnikov, Yu.P., 1981: Ecology-floristics in the middle part of the Anadyr River basin. *In* Mazurenko, M.T. (ed.), *Biology of Plants and Flora of Northern Far East*. Vladivostok: Institute of Biological Problems of the North, Far Eastern Branch, USSR Academy of Sciences, 65-78.

Leng, M. J. and Marshall, J. D., 2004: Paleoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews,* 23: 811-831.

Lozhkin, A. V., 1993: Geochronology of late Quaternary events in northeastern Russia. *Radiocarbon,* 35: 429-433.

Lozhkin, A. V. and Anderson, P. M., 1996: A late Quaternary pollen record from Elikchan 4 Lake, northeast Siberia. *Geology of the Pacific Ocean,* 12: 609-616.

Lozhkin, A. V., Anderson, P. M., Eisner, W. R., Ravako, L. G., Hopkins, D. M., Brubaker, L. B., Colinvaux, P. A., and Miller, M. C., 1993: Late Quaternary lacustrine pollen records from southwestern Beringia. *Quaternary Research,* 39: 314-324.

Lozhkin, A. V., Anderson, P. M., Brubaker, L. B., and Prokhorova, T. P., 1995: The first results of palynological analyses of lacustrine sediments from Chukotka. *Doklady Akademii Nauk,* 342: 540-542.

Lozhkin, A. V., Anderson, P. M., Brubaker, L. B., Kotov, A. N., Kotova, L. N., and Prokhorova, T. P., 1998: The herb pollen zone from sediments of glacial lakes. *In* Simakov, K. V. (ed.), *Environmental Changes in Beringia During the Quaternary*. Magadan: North East Interdisciplinary Research Institute, Far East Branch, Russian Academy of Sciences, 96-111.

Lozhkin, A. V., Anderson, P. M., Belaya, B. V., Glushkova, O. Y., and Stetsenko, T. V., 2000: Vegetation change in northeast Siberia at the Pleistocene-Holocene boundary and during the Holocene. *In* Simakov, K. V. (ed.), *The Quaternary Period of Beringia*. Magadan: North East Interdisciplinary Research Institute, Far East Branch, Russian Academy of Sciences, 53-75.

Lozhkin, A. V., Anderson, P. M., Vartanyan, S. L., Brown, T. A., Belaya, B. V., and Kotov, A. N., 2001: Reconstructions of late Quaternary paleo-environments and modern pollen data from Wrangel Island (northern Chukotka). *Quaternary Science Reviews,* 20: 217-233.

Lozhkin, A.V., Anderson, P.M., and Matrosova, T.V., 2004: Volcanic ash in lake sediments from Northeast Siberia. *In* Onoprienko, Yu.I. and Lozhkin, A.V. (eds.), *Climate Records from Quaternary Sediments of Beringia*. Magadan: North East Interdisciplinary Research Institute, Far East Branch, Russian Academy of Sciences, 108-112.

Mayle, F. E. and Cwynar, L. C., 1995: Impact of the Younger Dryas cooling event upon lowland vegetation of maritime Canada. *Ecological Monographs,* 65: 129-154.

Meyers, P. A. and Lallier-Verges, E., 1999: Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *Journal of Paleolimnology,* 21: 345-372.

Mikolajewicz, U., Crowley, T. J., Schiller, A., and Voss, R., 1997: Modeling teleconnections between the North Atlantic and North Pacific during the Younger Dryas. *Nature,* 387: 384-387.

Mortlock, R. A. and Froelich, P. N., 1989: A simple method for the rapid determination of biogenic opal in pelagic marine sediments. *Deep Sea Research,* 36: 1415-1426.

PALE, 1994: *Research Protocols for PALE: Paleoclimates of Arctic Lakes and Estuaries.* PAGES Workshop Report Series, Bern.

Peteet, D. M., Del Genio, A., and Lo, K. K. W., 1997: Sensitivity of northern hemisphere air temperatures and snow expansion to north Pacific seat surface temperatures in the Goddard Institute for Space Studies general circulation model. *Journal of Geophysical Research,* 102: 23,781-723,791.

Pisaric, M. F. J., MacDonald, G. M., Velichko, A. A., and Cwynar, L. C., 2001: The late-glacial and post-glacial vegetation history of the northwestern limits of Beringia based on pollen, stomates, and tree stump evidence. *Quaternary Science Reviews,* 20: 235-245.

Ponomareva, V., Kyle, P. R., Melekestsev, I. V., Rinkleff, P. G., Dirksen, O. V., Sulerzhitsky, L. D., Zaretskaia, N. E., and Rourke, R., 2004: The 7600 (C-14) year BP Kuril Lake caldera-forming eruption, Kamchatka, Russia: stratigraphy and field relationships. *Journal Of Volcanology And Geothermal Research,* 136: 199-222.

Rind, D., Peteet, D. M., Broecker, W. S., McIntyre, A., and Ruddiman, W., 1986: The impact of cold North Atlantic sea surface temperatures on climate: Implications for the Younger Dryas cooling. *Climate Dynamics,* 1: 3-33.

Rioual, P., Andrieu-Ponel, V., Rietti-Shati, M., Batterbee, R., deBeaulieu, J. L., Cheddadi, R., Reille, M., Svobodova, H., and Shemesh, A., 2001: High-resolution record of climate stability in France during the last interglacial period. *Nature,* 413: 293-296.

Rutter, N. W., Weaver, A. J., Rokosh, D., Fanning, A. F., and Wright, D. G., 2000: Data-model comparison of the Younger Dryas event. *Canadian Journal of Earth Sciences,* 37: 811-830.

Seppä, H. and Hicks, S., 2006: Integration of modern and past pollen accumulation rate (PAR) records across the arctic tree-line: a method for more precise vegetation reconstructions. *Quaternary Science Reviews,* 25: 1501-1516.

Sernander, R., 1908: On the evidence of postglacial changes of climate furnished by the peat-mosses of northern Europe. *Geol. Foren,* 30: 456-478.

Shemesh, A. and Peteet, D., 1998: Oxygen isotopes in fresh water biogenic opal- Northeastern US Allerod-Younger Dryas temperature shift. *Geophysical Research Letters,* 25: 1935-1938.

Shilo, N. A., 1970: *The North of the Far East*. Moscow: Nauka, 488 pp.

Steig, E. J., 1999: Paleoclimate: mid-Holocene climate change. *Science,* 286: 1485-1487.

Thompson, R. and Oldfield, F., 1986: *Environmental Magnetism*. London: Allen and Unwin, Ltd.

USDA, 1993: Soil Survey Manual: Soil Survey Division Staff, U.S. Department of Agriculture.

Von Post, L., 1946: The Prospect for Pollen Analysis in the Study of the Earth's Climatic History. *New Phytologist,* 45: 198-203.

Walker, M. J. C., 1995: Climatic changes in Europe during the last glacial/interglacial transition. *Quaternary International,* 28: 63-76.

West, R. G., 1970: Pollen zones in the Pleistocene of Great Britain and their correlation. *New Phytologist,* 69: 1179-1183.

Wright, H. E. J., Mann, D. H., and Glasner, P. H., 1984: Piston corers for peat and lake sediments. *Ecology,* 65: 657-659.

Table 1.

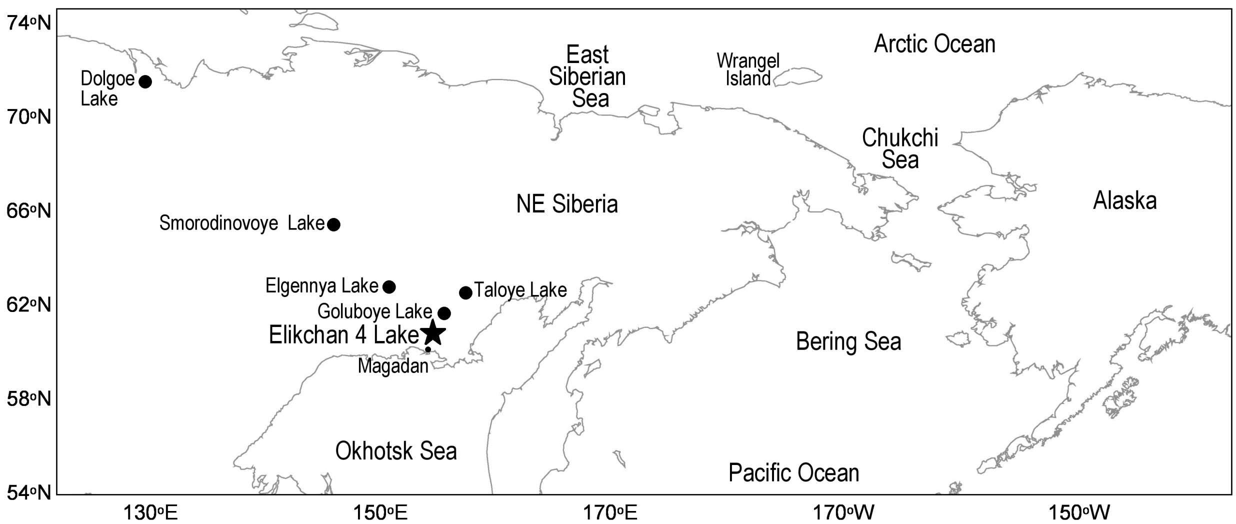
RADIOCARBON DATES

Depth (cm)	Laboratory Number	^{14}C age (yr BP)	Calibrated age (cal. yr BP; midpoint & 1σ range)	Dated material
206	CAMS 94637	8990 +/- 40	10218 (10096.5) 9975	Twig (AMS ^{14}C)
229.5	CAMS 100066	10040 +/- 190	11933 (11581) 11229	Pollen concentrate (AMS ^{14}C)
259	N/A	12250 +/- 250	15145 (14496) 13847	Pollen stratigraphy

TEPHRACHRONOLOGY

Depth (cm)	Tephra Name	Associated ^{14}C age (yr BP)	Calibrated age (cal. yr BP; midpoint & 1σ range)
187	KO/Elikchan Tephra	7650 +/- 50	8535 (8459.5) 8384

Figure 1.



74°N
70°N
66°N
62°N
58°N
54°N
130°E
150°E
170°E
170°W
150°W
Dolgoe Lake
East Siberian Sea
Wrangel Island
Arctic Ocean
Chukchi Sea
NE Siberia
Alaska
Smorodinovoye Lake
Elgennya Lake
Taloye Lake
Goluboye Lake
Elikchan 4 Lake
Magadan
Bering Sea
Okhotsk Sea
Pacific Ocean

Figure 2.

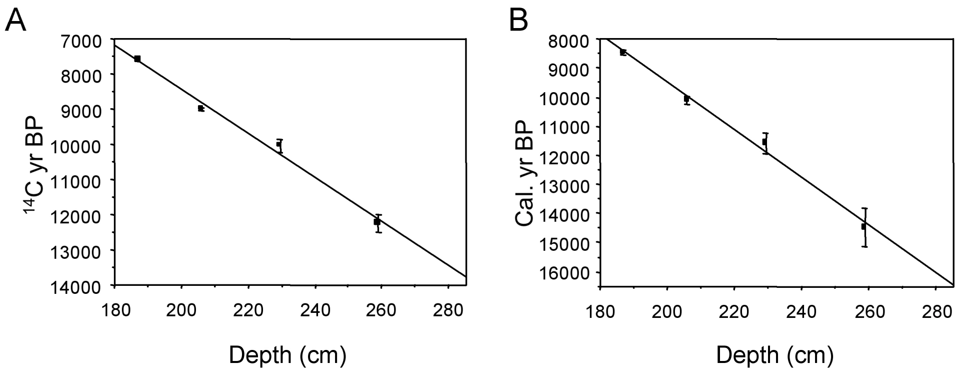

A
^{14}C yr BP
7000
8000
9000
10000
11000
12000
13000
14000
180
200
220
240
260
280
Depth (cm)
B
Cal. yr BP
8000
9000
10000
11000
12000
13000
14000
15000
16000
180
200
220
240
260
280
Depth (cm)

Figure 3.

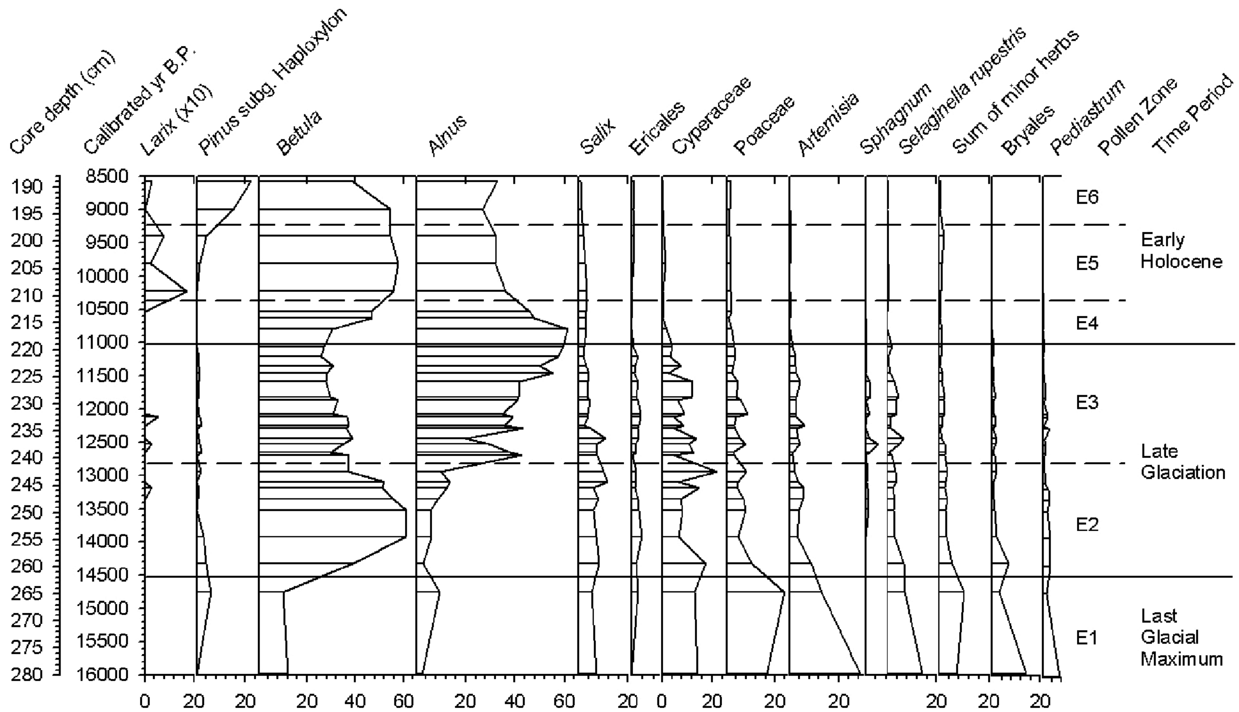
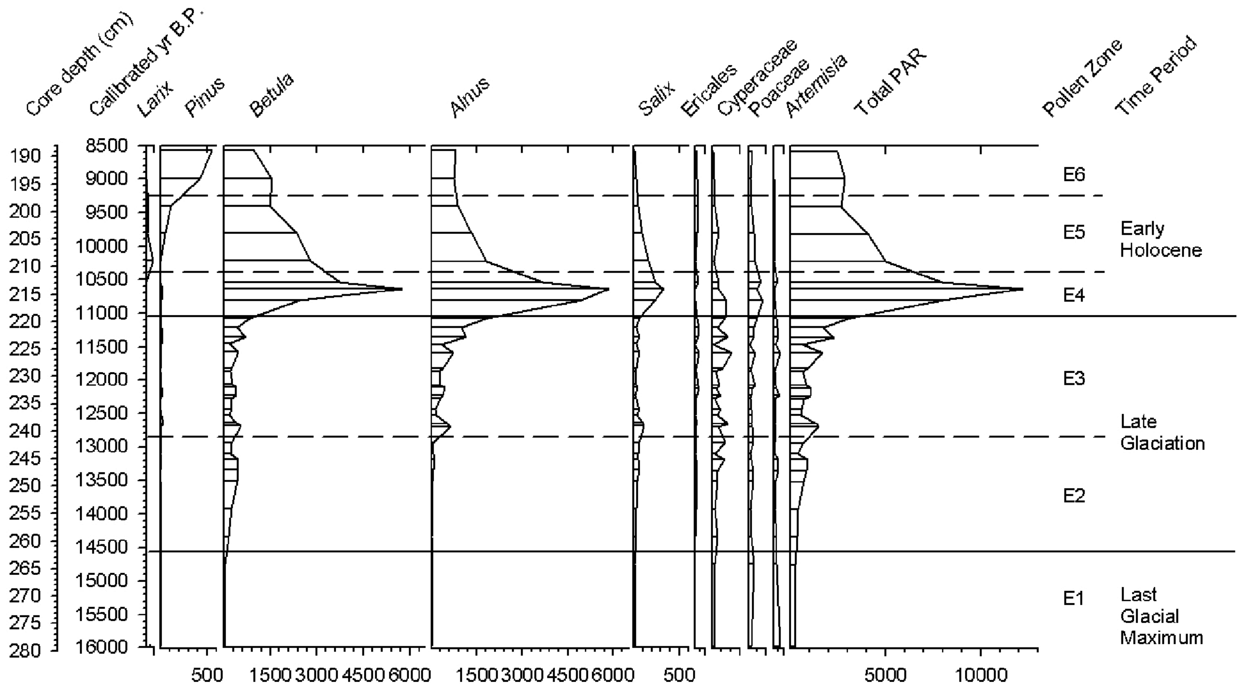
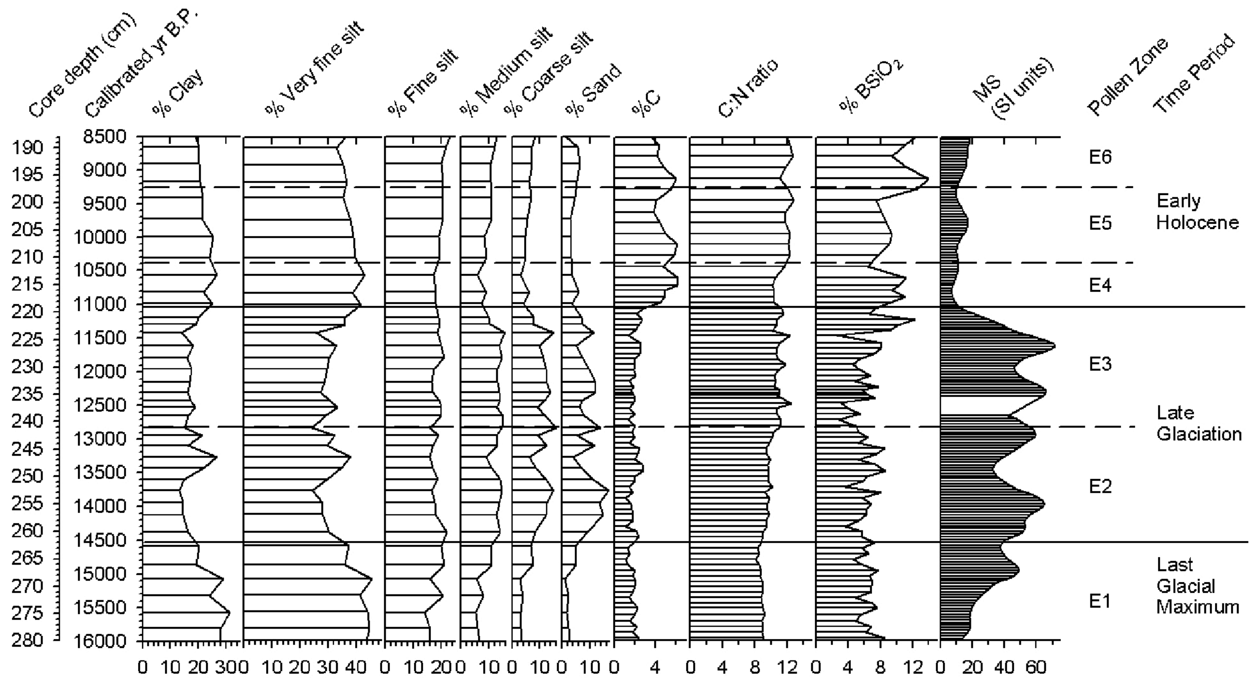

Core depth (cm)
Calibrated yr B.P.
Larix (x10)
Pinus subg. Haploxylon
Betula
Alnus
Salix
Ericales
Cyperaceae
Poaceae
Artemisia
Sphagnum
Selaginella rupestris
Sum of minor herbs
Bryales
Pediastrum
Pollen Zone
Time Period
E6
E5
E4
E3
E2
E1
Early Holocene
Late Glaciation
Last Glacial Maximum

Figure 4.



Core depth (cm)
Calibrated yr B.P.
Larix
Pinus
Betula
Alnus
Salix
Ericales
Cyperaceae
Poaceae
Artemisia
Total PAR
Pollen Zone
Time Period
190
195
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
8500
9000
9500
10000
10500
11000
11500
12000
12500
13000
13500
14000
14500
15000
15500
16000
500
1500 3000 4500 6000
1500 3000 4500 6000
500
5000
10000
E6
E5
E4
E3
E2
E1
Early Holocene
Late Glaciation
Last Glacial Maximum

Figure 5.



Core depth (cm)
Calibrated yr B.P.
% Clay
% Very fine silt
% Fine silt
% Medium silt
% Coarse silt
% Sand
%C
C:N ratio
% BSiO2
MS (SI units)
Pollen Zone
Time Period
E6
E5
E4
E3
E2
E1
Early Holocene
Late Glaciation
Last Glacial Maximum