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Late Quaternary vegetation and climate history of the central Bering land bridge from St. Michael Island, western Alaska

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Abstract

Pollen analysis of a sediment core from Zagoskin Lake on St. Michael Island, northeast Bering Sea, provides a history of vegetation and climate for the central Bering land bridge and adjacent western Alaska for the past ≥30,000 ^{14}C yr B.P. During the late middle Wisconsin interstadial (≥30,000–26,000 ^{14}C yr B.P.) vegetation was dominated by graminoid-herb tundra with willows (*Salix*) and minor dwarf birch (*Betula nana*) and Ericales. During the late Wisconsin glacial interval (26,000–15,000 ^{14}C yr B.P.) vegetation was graminoid-herb tundra with willows, but with fewer dwarf birch and Ericales, and more herb types associated with dry habitats and disturbed soils. Grasses (Poaceae) dominated during the peak of this glacial interval. Graminoid-herb tundra suggests that central Beringia had a cold, arid climate from ≥30,000 to 15,000 ^{14}C yr B.P. Between 15,000 and 13,000 ^{14}C yr B.P., birch shrub-Ericales-sedge-moss tundra began to spread rapidly across the land bridge and Alaska. This major vegetation change suggests moister, warmer summer climates and deeper winter snows. A brief invasion of *Populus* (poplar, aspen) occurred ca.11,000–9500 ^{14}C yr B.P., overlapping with the Younger *Dryas* interval of dry, cooler(?) climate. During the latest Wisconsin to middle Holocene the Bering land bridge was flooded by rising seas. Alder shrubs (*Alnus crispa*) colonized the St. Michael Island area ca. 8000 ^{14}C yr B.P. Boreal forests dominated by spruce (*Picea*) spread from interior Alaska into the eastern Norton Sound area in middle Holocene time, but have not spread as far west as St. Michael Island.

Keywords: Alaska; Central Beringia; Land bridge; Pollen; Paleoecology; Paleoclimates

Introduction

This paper presents a pollen record from a 15.2-m sediment core obtained from Zagoskin Lake on St. Michael Island in Norton Sound, western Alaska. Radiocarbon ages from the core indicate that the pollen record spans at least the past 30,000 ^{14}C yr B.P. This site was located near the center of the Bering land bridge at the time of the late Wisconsin maximum, when sea level was about -120 m below its present position (Fig.1).

Most previous investigations of the paleoecology of central Beringia (the Bering land bridge and adjacent areas of western Alaska and Chukotka) suggest that the vegetation of the region during the late Wisconsin maximum was characterized by mostly graminoid herbaceous tundra (e.g., Colinvaux, 1964, 1967, 1981; Colbaugh, 1968; Ager, 1982, 1983, 2002; Anderson and Lozhkin, 2002). Graminoid-herb vegetation implies that the Wisconsin climate of the land bridge and adjacent areas was cold and dry until ca. 15,000–13,000 ^{14}C yr B.P. when birch shrub tundra spread across the region, and more mesic climates prevailed.

More recently, an alternate scenario has been suggested, based on a few samples from sediment cores from the northern Bering Sea shelf. The samples contain pollen, insect fossils, and plant macrofossils of full-glacial age (Elias et al., 1996, 1997). These samples represent terrestrial environments on the former Bering land bridge. The radiocarbon-dated fossil evidence from these cores suggest that wetland habitats and mesic herb-shrub tundra existed in at least one area of the land bridge during full glacial time, before 14,000 ^{14}C yr B.P. Elias et al. (1996, 1997) suggest that mesic shrub-herb tundra may have been the dominant vegetation on the land bridge during full glacial time (late

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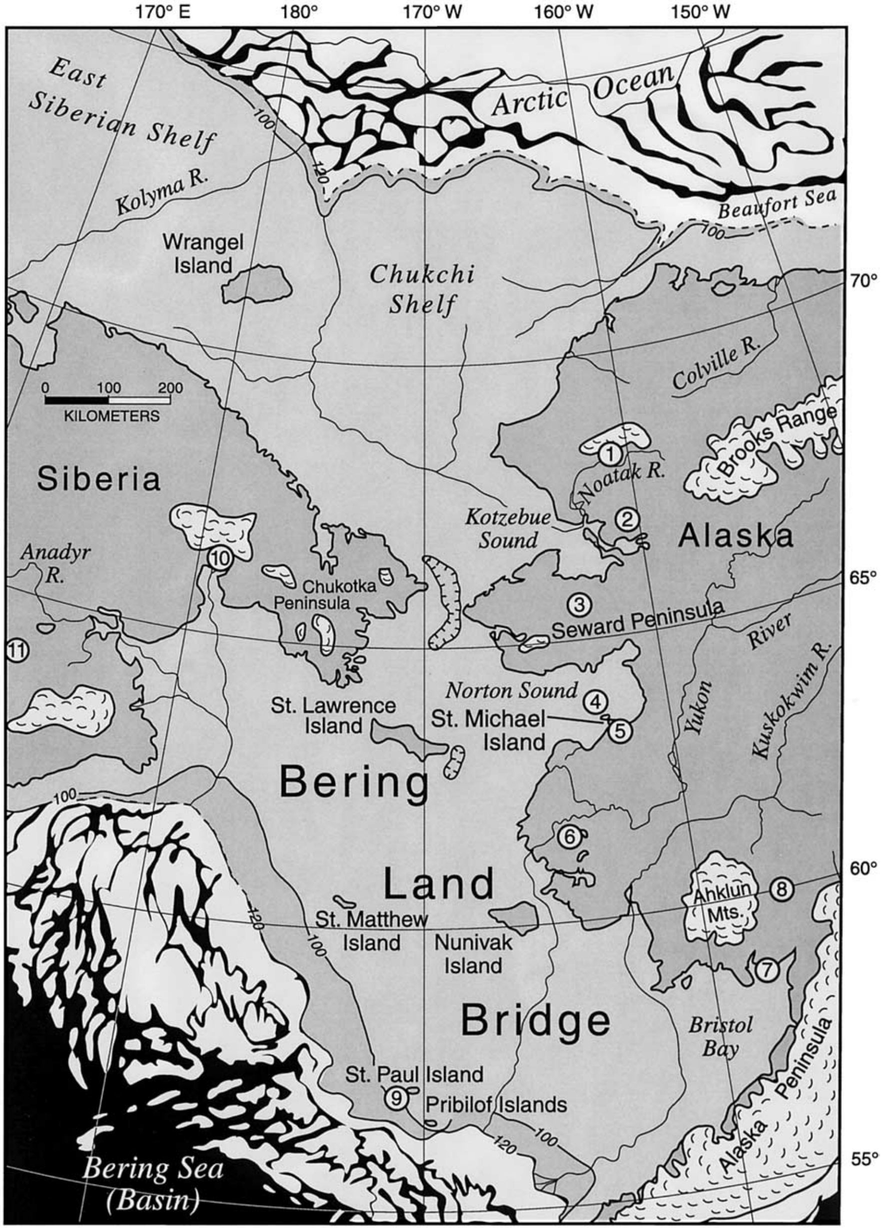


Fig. 1. Map of central Beringia showing approximate position of late Wisconsin shorelines at and near the maximum depression of sea level (−120 to −100 m below present sea level) ca. 20,000–18,000 ^{14}C yr B.P. Glaciers are shown at maximum known limits during the late Wisconsin, based on maps by Hamilton (1994), Kaufman and Hopkins (1986), Manley et al. (2001) and Velichko et al. (1984). Although the figure depicts some open water in the Arctic Ocean, it is likely that thick, perennial sea ice existed year round, with minimal summer melting. In the Bering Sea basin, sea ice was extensive and may have lasted most, or possibly all, of the year during the maximum late Wisconsin (Sancetta and Robinson, 1983). Numbered sites shown on the map correspond to some of the localities in central Beringia where published radiocarbon-dated pollen records have been obtained. Vegetation histories from these sites have been summarized in Figure 6 for comparision with the Zagoskin Lake record. The actual position of site 11 (Patricia Lake) is beyond the western edge of the map at 63° 10′ N, 176° 45′ E. Bathymetric maps used to approximate the −120 m and −100 m shoreline positions on the land bridge are from Sharma (1979) for the Bering Sea, and Perry and Fleming (1990) for the Chukchi Sea and adjacent shelf areas.

Wisconsin), rather than the herb tundra and drier climates previous work had suggested. Elias et al. (1992, 1996, 1997) also present dated fossil data from northern Bering Sea and northeast Chukchi Sea sediment cores that document the existence of mesic shrub-herb tundra on the land bridge after 14,000 ^{14}C yr B.P. (until the marine transgression of the core sites). These latter findings are consistent with previously published onshore records from central Beringia for that time interval.

In this paper, I discuss pollen evidence from the Zagoskin Lake core, which provides the most detailed and well-dated history of vegetation and inferred climate yet obtained from central Beringia for the past ≥30,000 ^{14}C yr B.P. The data presented here test the Elias et al. (1996,

1997) suggestion that mesic habitats and shrubby vegetation may have been widespread on the Bering land bridge vegetation during the late Wisconsin glaciation prior to ca.14,000 ^{14}C yr B.P. At the end of this paper, other vegetation histories from sites scattered across central Beringia are compared in order to place the Zagoskin Lake record into a broader regional context.

An accurate reconstruction of land bridge environments is important for testing and improving climate models for Beringia (e.g., Bartlein et al., 1998), and for evaluating the ecological context for human populations entering the region, whether they entered North America by inland or coastal routes (Dixon, 2001). In addition, the Pleistocene vertebrate fossil records from Beringia suggest that the land bridge may have functioned as a filter through which many, but not all, species of late Pleistocene large mammals passed between Siberia and northwest North America (Guthrie, 2001). The land bridge offered no significant topographic barriers to intercontinental migration of large mammals. Guthrie (2001) suggests that a broad band of mesic vegetation and climate on the Bering land bridge served as an ecological barrier for a few mammal species, preventing them from dispersing between eastern and western Beringia. Did such a band of mesic environments exist on the land bridge during the late Wisconsin prior to 15,000–13,000 ^{14}C yr B.P.? This paper will consider this question in light of new evidence.

Setting

St. Michael Island is located in Norton Sound, in northeastern Bering Sea (Figs. 1, 2 and 3). The island is volcanic in origin, has low relief (120 m), and covers an area of 88 km^2. The island is composed of basalt flows and pyroclastic deposits capped with about a meter of loess and up to several meters of Holocene peat. Reversed polarity of basalt flows on the island suggests that the basalts may be of early Pleistocene age (Hoare and Condon, 1971). Seven maar craters are scattered across the island and are occupied by lakes (e.g., Clear Lakes, Puyuk Lake, Zagoskin Lake, shown in Fig. 3). Several other maar craters have been breached by coastal erosion, and now form marine embayments or contain brackish marshes (Fig. 3; Muhs et al., 2003, Fig. 4). The time of formation of the maar craters is unknown, but a minimum age, based on this study is $\geq$30,000 ^{14}C yr B.P.

St. Michael Island lies beyond the limits of late Cenozoic glaciations in western Alaska (Hamilton, 1994; Kaufman and Hopkins, 1986). The island therefore has the potential for preserving long, continuous, Quaternary sediment records within the ancient lakes that occupy its maar craters.

Zagoskin Lake (63°26.9′ N, 162° 06.3′ W, 7 m altitude) is located near the southeastern shore of St. Michael Island and occupies one of the smallest maar craters on the island (Fig. 3). The area of the crater that encloses the lake is 36 ha; Zagoskin Lake has a surface area of 16 ha and a maximum depth of 19 m.

During a reconnaissance study of the crater lakes on St. Michael Island in the summer of 1978, a sediment core was obtained from Puyuk Lake on the northwest side of the island (Fig. 3). A summary of the ca. 16,000 ^{14}C yr B.P. pollen record recovered from Puyuk Lake was discussed by Ager (1982). In the late winter of 1979, a 15.2-m core was raised from Zagoskin Lake. Preliminary results of pollen analysis of a few key taxa from the upper 5.3 m of that core were discussed briefly in a review of Alaskan Holocene vegetation history (Ager, 1983). The present paper discusses the late Quaternary pollen record from the entire core. In a companion paper, Muhs et al. (2003) present results of geochemical and sedimentological analyses of the Zagoskin Lake core and discusses their implications for understanding the history of loess deposition in the region.

The Norton Sound area of western Alaska lies within a climate zone that is transitional between arctic, continental, and maritime zones (Fig. 4; Joint Federal-State Land Use Planning Commission for Alaska [JFSLUPC], 1973). Climate data from Nome, Unalakleet, and the village of St. Michael (Figs. 2 and 3) are summarized in Table 1. Mean annual temperatures within the entire Norton Sound region are several degrees below freezing and permafrost underlies much of the landscape.

The present vegetation on St. Michael Island and the adjacent mainland is mostly mesic shrub tundra (Fig. 2). The mesic tundra communities are composed of dwarf birch (*Betula nana*), low willows (e.g., *Salix arctica*), blueberry (*Vaccinium uliginosum*), crowberry (*Empetrum nigrum*), bearberry (*Arctostaphylos*), Labrador tea (*Ledum palustre* subsp. *decumbens*), cottongrass (*Eriophorum* spp.), and other sedges (Cyperaceae, e.g., *Carex* spp.). Grasses (Poaceae) and numerous tundra forbs are also common elements of mesic habitats on the island (e.g., *Polemonium, Delphinium, Chrysanthemum, Pedicularis, Castelleja, Mertensia*), along with numerous species of mosses and lichens. Thickets of larger shrub willows (e.g., *Salix alaxensis, S. lanata, S. glauca,* and *S. pulchra*) and alders (*Alnus crispa*) grow mostly in gullies and within the sheltering walls of maar craters on the island. An aquatic and semiaquatic flora of *Equisetum, Carex, Isoëtes, Glyceria, Potentilla palustris,* and *Potamogeton* grow in the many lakes and ponds on the island. Extensive wetlands are common in coastal mudflats south of the island and in the Yukon Delta area of western Norton Sound (Figs. 2 and 3). Sedges, especially *Carex* spp., are the most common vascular plants in these wetlands.

Boreal forest vegetation composed of spruce (mostly white spruce, *Picea glauca*) paper birch (*Betula papyrifera*), and balsam poplar (*Populus balsamifera*) covers some lowlands bordering eastern and northeastern Norton Sound (Fig. 2). Some black spruce (*P. mariana*) can be found on southeastern Seward Peninsula (Hultén, 1968). A few white spruce trees grow in small stream valleys $\geq$35 km east of St.

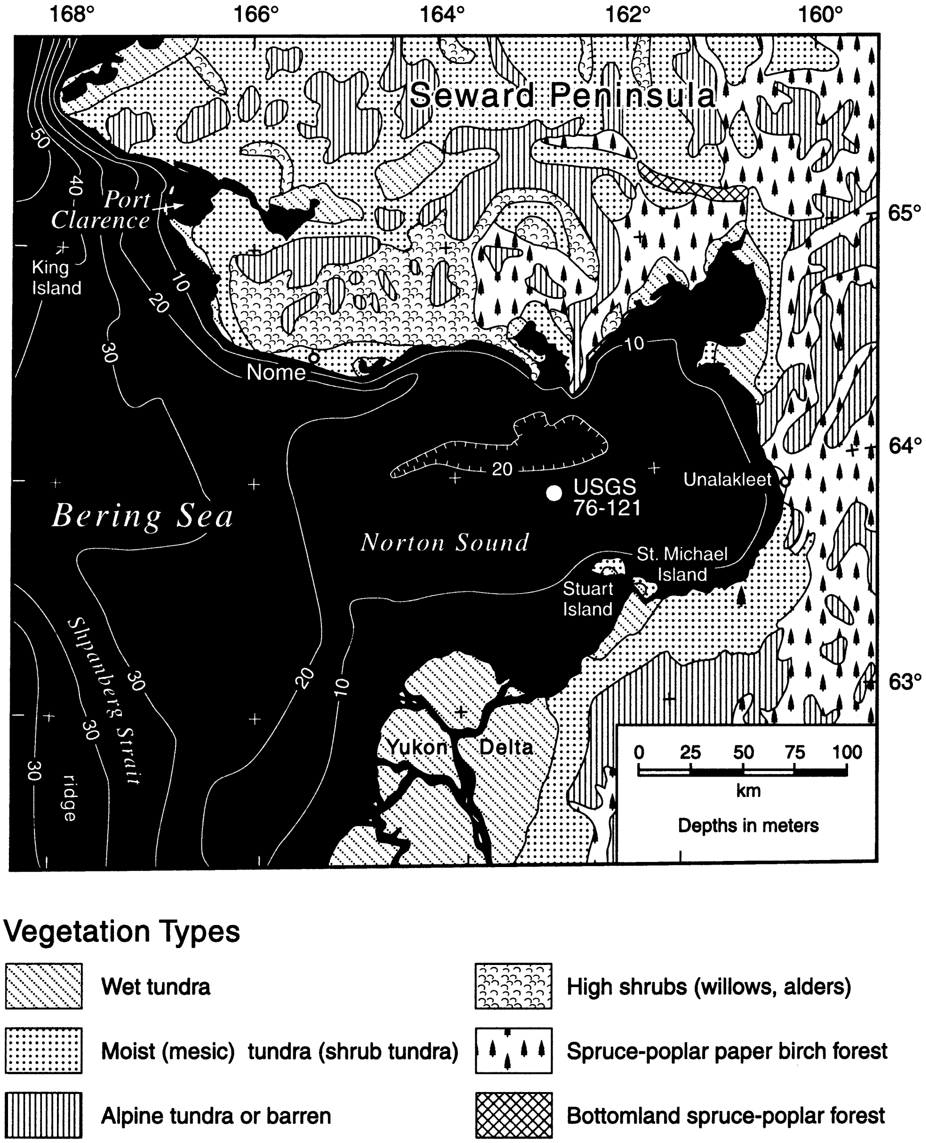


Fig. 2. Map of Norton Sound area showing locations of St. Michael Island and the communities of Unalakleet and Nome. Modern isobaths are shown at 10-m intervals. USGS 76–121 is the collection site for a sediment core discussed in this paper and in Muhs et al. (2003). Present-day vegetation communities surrounding Norton Sound are also shown on this map (JSFUPC, 1973; Viereck and Little, 1972).

Michael Island (Fig. 2). No trees of any kind grow on St. Michael Island today.

Methods

The sediment core discussed in this paper was sampled from near the center of Zagoskin Lake (water depth 18 m) in late winter. The 5-cm-diameter core was obtained with a modified Livingstone piston corer. The coring effort ended when impenetrable silty sediments were encountered. The core was sampled for pollen analysis at 10-cm intervals, and at irregular intervals for geochemical and sedimentological analyses (Muhs et al., 2003), loss on ignition and radiocarbon dating. Bulk sediment core samples were dated by conventional radiocarbon analytical methods at the U.S. Geological Survey Radiocarbon Laboratory in Reston, Virginia. Pollen samples were processed in the U.S. Geological Survey Palynology Laboratory in Reston, Virginia, following procedures modified slightly from Faegri and Iversen (1964). Identification of pollen and spore types was aided primarily by comparisons with modern reference slides. At least 300 pollen grains were counted for each sample.

Results

The Zagoskin Lake core consists primarily of silt, mixed with organic material consisting of plant detritus, freshwater algae (*Pediastrum, Botryococcus*), diatoms, cladocera, and

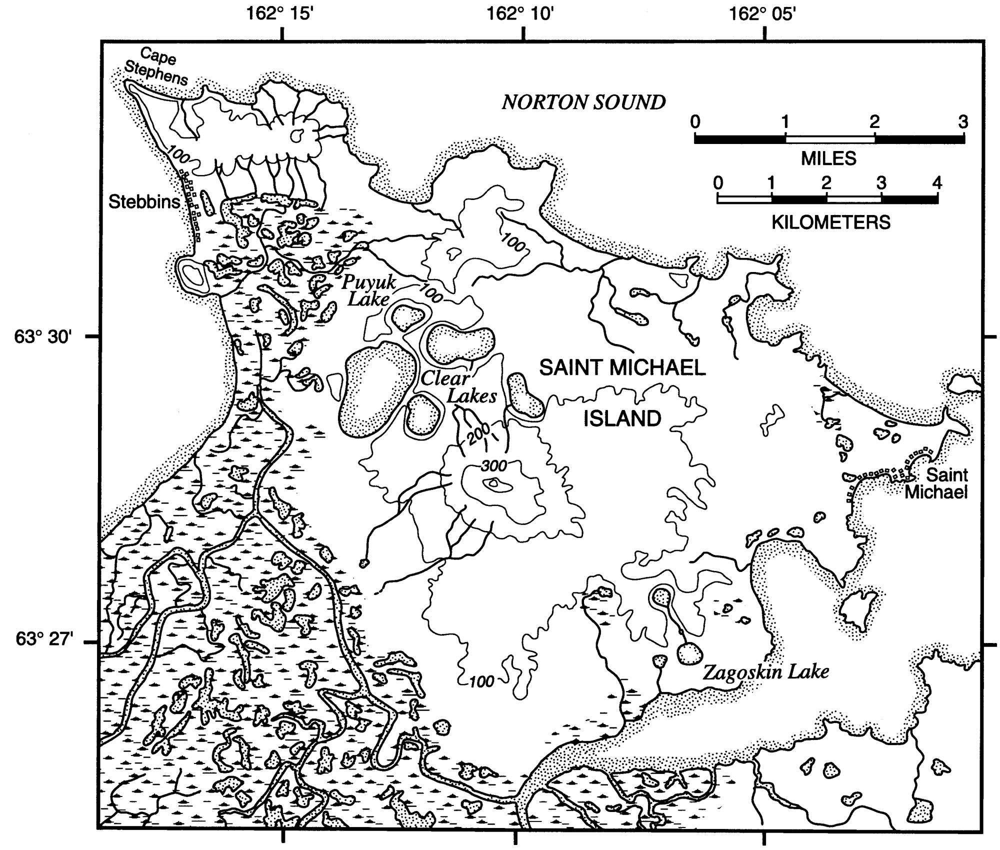


Fig. 3. Map of St. Michael Island in southern Norton Sound. Most of the lakes on St. Michael Island, including Zagoskin Lake occupy maar craters formed within Pleistocene-age basalts. Topographic contours = 100 feet (30.5 m). Larger wetland areas are depicted by swampland symbols, such as shown on the southwestern corner of the map.

occasional insect parts. Loss on ignition analyses (Fig. 5C) indicates that the percentage of organic material accumulating in the lake sediments was relatively low during the MIS 3 and 2 (4.7–6.8%) and increased after ca. 15,000 ^{14}C yr B.P. (7.0–15.3%). Organic material is most abundant in the upper 1.2 m of the core and may be related to the greater influence of maritime climates as Norton Sound was gradually flooded by transgressing seas, a process that continued into the late Holocene.

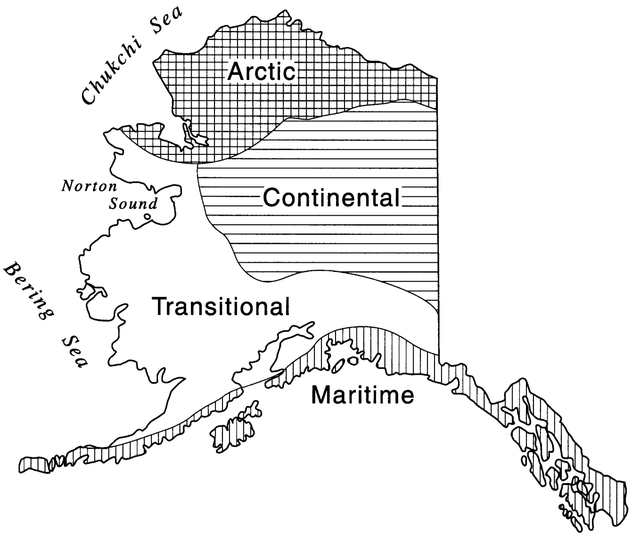


Fig. 4. Modern climate zones of Alaska (JSFLUPC, 1973). The Norton Sound area lies entirely within the transitional climate zone.

Two tephras were recognized in the core. The uppermost tephra (1.4 to 1.6 m depth) is white in color, and has been identified as the ca. 3600 ^{14}C yr B.P. Aniakchak tephra from a major caldera eruption on the Alaska Peninsula (Riehle et al., 1987). The bracketing radiocarbon ages for this tephra in the Zagoskin Lake are older than the previously reported age for the tephra (Fig. 5B). This dating problem might be explained by sinking of this 20-cm-thick, relatively dense tephra through uncompacted, organic-rich sediments at the water-sediment interface until the tephra accumulated on an older, more compact sediment layer (Beierle, 2002). Alternatively, the radiocarbon dates may be older than expected because of reworked older carbon washing into the lake. A second tephra, gray in color, was encountered in the core at a depth of about 5.10–5.15 m. This tephra was also encountered in Puyuk Lake on northwestern St. Michael Island (Fig. 3; Ager, 1982). The source of this tephra is unknown, but its age is less than 15,610 ^{14}C yr B.P. (Fig. 5B; Ager, 1982).

Table 1
Climate data for Norton Sound, Alaska (Leslie, 1989)

Climate Station	Nome	Unalakleet	St. Michael
Latitude	64° 30′ N	63° 53′ N	63° 29′ N
Longitude	165° 26′ W	160° 48′ W	162° 01′ W
Altitude	4 m	5.5 m	15.2 m
Mean January temperature	−14.2°C	−16.0°C	−13.1°C
Mean July temperature	10.4°C	12.5°C	11.9°C
Mean annual temperature	−3.4°C	−3.2°C	−2.3°C
Mean annual precipitation	397 mm	356 mm	184 mm
Years of record	1948–1987	1941–1987	1922–1933

Radiocarbon dates (Fig. 5B) indicate that the Zagoskin Lake core spans the period from the late-middle Wisconsin interstadial to the present (late MIS 3 through MIS 1). Conversions from calendar ages to calendar years ages for the Zagoskin Lake core are presented in Muhs et al. (2003, Table 1). One minor dating reversal occurred in the sequence of dated samples (Fig. 5B), but this does not seriously hinder the interpretation of the pollen or sedimentation records (see Muhs et al., 2003). Although the radiocarbon age of the lowest sample in the core (Fig. 5B) was reported as nonfinite (>39,000 ^{14}C yr B.P.), the age vs depth trend of the other radiocarbon ages in the core suggests that the age of the core base is more likely to be about 30,000 ^{14}C yr B.P. Therefore I assign an age of ≥30,000 ^{14}C yr B.P. to the base of the core, while recognizing the possibility that the reported age might be more correct.

Pollen zonation from Zagoskin Lake

Pollen data from the Zagoskin Lake core are presented in a pollen percentage diagram (Fig. 5). Figure 5C includes minor herb taxa. Some rare pollen and spore taxa have been deleted from the diagram, and percentages of less than 1% are not shown for any pollen or spore types. The complete pollen data set (raw counts) for the Zagoskin Lake core can be obtained from the PARCS pollen data base (http://www.ngdc.noaa.gov/paleo/parcs). The diagram has been divided into five pollen assemblage zones, ZL-1 (youngest) to ZL-5 (oldest). Zone ZL-5 has been divided into subzones A and B.

Zone ZL-5B (15.2 to 12.3 m core depth; ≥30,000–26,000 ^{14}C yr B.P.) is composed predominantly of pollen of Cyperaceae (25–45%), Poaceae (30–50%), *Artemisia* (5–15%), and *Salix* (2–7%). Other taxa that are relatively important contributors to the pollen assemblages in this subzone include Caryophyllaceae (2–6%), Ranunculaceae (2–5%), and *Betula* (2–5%). Other taxa present in low percentages include Asteroideae, Cichorioideae, *Ambrosia, Potentilla,* Ericales, *Thalictrum, Polemonium, Rumex/Oxyria, Valeriana*. Small amounts (<2%) of *Sphagnum* and *Encalypta* moss spores are also present. Polypodiaceae type fern spores are also present in low percentages (<1.5%).

This pollen and spore assemblage represents an herb-dominated tundra with shrub *Salix,* but at least a few other low shrubs and small woody plants such as *Betula* and Ericales were also present in the area. The radiocarbon ages suggest that this subzone was deposited during the latter part of the mid-Wisconsin interstadial. The herb-dominated flora suggests an arid climate in the region during this interval, but the relative abundance of Cyperaceae vs Poaceae and the *Betula* percentages in the 2–7% range suggest that the climate was slightly more mesic and the vegetation was somewhat richer in low shrubs and sedges than during the full glacial interval that followed.

Pollen subzone ZL-5A (12.3–4.9 m core depth; 26,000–15,000 ^{14}C yr B.P.) is also herb dominated, but Poaceae are more abundant (45–65%) than Cyperaceae (10–30%) except near the top of the subzone. Poaceae percentages reach maximum levels (50–65%) between ca. 25,000–20,000 ^{14}C yr B.P. *Artemisia* percentages reach their highest levels in the entire core within this subzone (ca. 10–15%). *Salix* is the shrub type most abundantly represented in the subzone (2–5%). A rich assemblage of herb taxa is represented in this subzone, plants that represent a variety of habitats that existed adjacent to the lake, on the surrounding volcanic upland, and on the immediately adjacent lowlands now submerged by the waters of Norton Sound. The common occurrence of pollen of Caryophyllaceae, Chenopodiaceae, *Papaver, Ambrosia, Plantago,* Fabaceae, and Brassicaceae suggests that some dry habitats and sparsely vegetated, or frost-disturbed soils were probably present nearby (Hultén, 1968).

Mesic habitats (perhaps confined to streambanks, lakeshores, and protected sites along crater walls where deeper snows accumulated) are suggested by the presence of pollen of plants such as *Claytonia,* Ranunculaceae, *Thalictrum, Polemonium, Rumex/Oxyria,* and *Geranium*. Spores of *Sphagnum* moss and of Polypodiaceae type fern spores occur within subzone A, but their very low percentages (0–3%) suggest that these plants were probably very minor components of the nearby vegetation, even within the relatively sheltered crater enclosing the lake. *Encalypta* moss spores appear sporadically within Subzone ZL-5A, suggesting the presence of calcareous soils nearby.

Pollen of *Picea, Pinus, Alnus,* and occasional *Populus* pollen occur in Subzone ZL-5A, but they are represented by low percentages (0–3%) and occur sporadically. Most of these pollen grains of trees and large shrubs probably represent reworked fossils that were carried to the lake by wind. It is uncertain if *Picea* survived in Alaska during the late Wisconsin, but it seems likely. Pollen evidence from the Pribilof Islands (Fig. 1; Colinvaux, 1981) suggests that at least a small population of *Picea* may have grown near those islands during the late Wisconsin glaciation and late glacial. *Picea* may also have survived as small, scattered populations in eastern Beringia (Edwards, 2002), but no conclusive fossil evidence has yet been found to prove this.

Populus pollen is fragile and is unlikely to survive retransport from older sediments. Therefore its presence in Zagoskin Lake sediments, even in low percentages, suggests that *Populus* trees survived in central Beringia during the Wisconsin glaciation. Evidence for *Populus* in sediments of the same age has been reported from northwestern Alaskan sites (e.g., Anderson, 1985). Balsam poplar (*Populus balsamifera*) is the hardiest tree species in Alaska today, often growing beyond the altitudinal and latitudinal limits of other boreal forest tree species (Viereck and Little, 1972). It has also been discovered growing in Chukotka (Yurtsev, 1982). Therefore *P. balsamifera* may account for the Wisconsin-age *Populus* record in Zagoskin Lake and in northwestern Alaskan lakes. Aspen (*P. tremuloides*) grows in many areas of Alaska today, and it too may have survived in eastern Beringia during the late Wisconsin. Evidence for the persistence of any tree species in Beringia during full-glacial time is important, because trees may have provided food and critical habitat for a variety of mammals, birds, and insects. Trees of any kind may have also provided wood for human use, if any humans were present in central Beringia during full-glacial time.

The paucity of pollen and spores of aquatic plants in Subzone 5A suggests that lake level may have been lower than today. The central part of the lake basin has a steep-walled funnel-shaped crater with a broad, fairly flat bottom. If the full-glacial shorelines coincided with the steep inner slopes of the lake basin, habitats for rooted aquatic vegetation would have been very limited.

The pollen assemblages from Subzone 5A suggest that the dominant vegetation on and near St. Michael Island was grassy herbaceous tundra, with probable open patches of loess-derived soils, frost boils, and basalt exposures. The diversity of herbaceous plants suggests that a variety of habitats existed in the area around the lake and on adjacent uplands.

Pollen Zone ZL-4 (4.9 to 3.8 m; ca. 15,000–11,000 ^{14}C yr B.P.) is dominated by pollen of *Betula* (35–60%), Cyperaceae (15–30%), Poaceae (15–30%), and *Salix* (4–10%). Some of the herb taxa that occur in Zone ZL-5, Subzone A also persist in this zone, such as Asteraceae (*Artemisia,* Asteroideae, Cichorioideae), Caryophyllaceae, Brassicaceae, Ranunculaceae, and *Thalictrum*. However, these herbs appear less consistently and in lower percentages than in Zone ZL-5. This may imply a reduction in the area of ground surface occupied by forbs (leafy herbs), as shrubs and peat-forming sedges and mosses began to spread over the landscape.

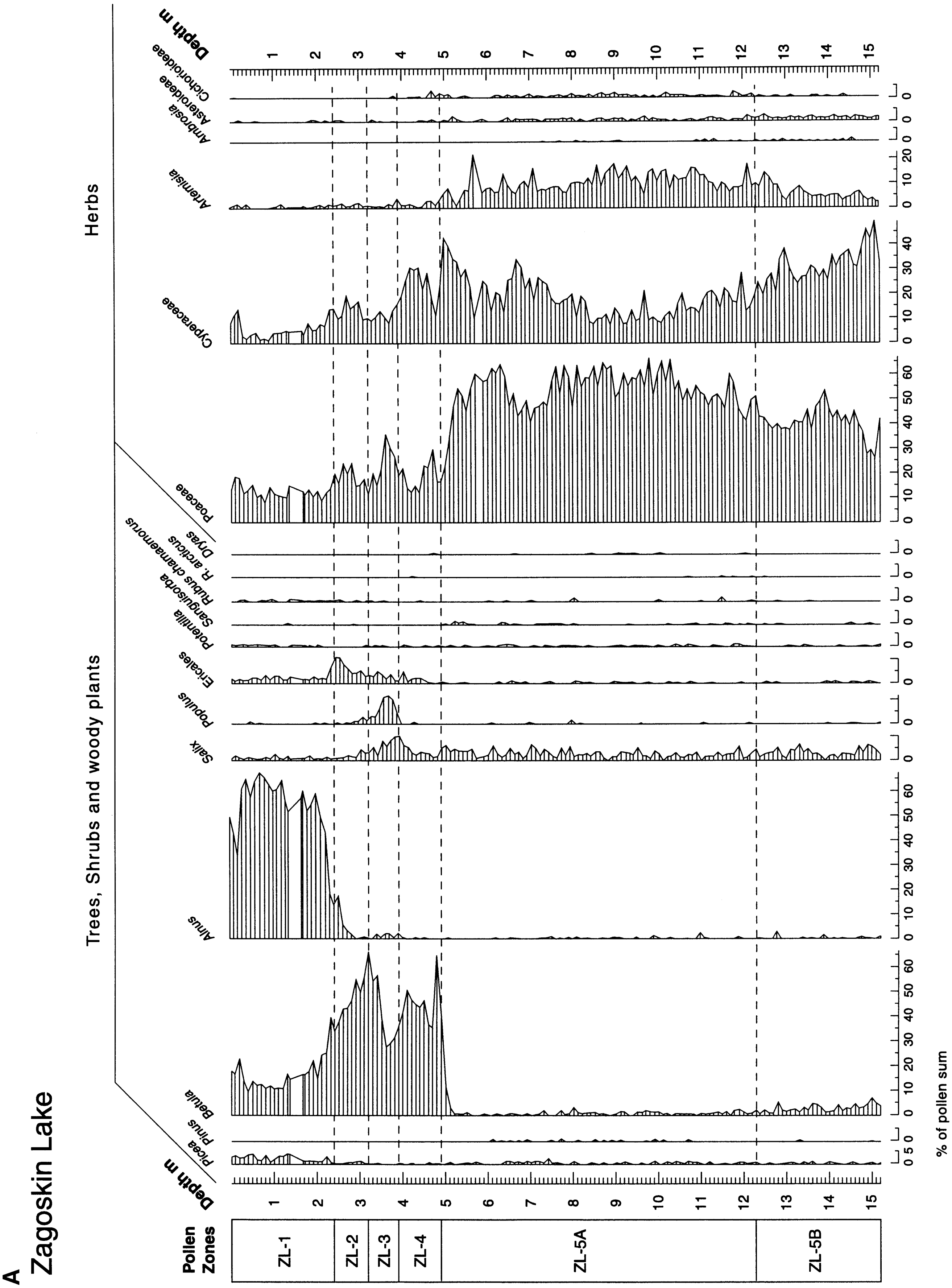
Pollen and spores of aquatic and semiaquatic plants appear in this zone in amounts that often significantly exceed their rare occurrences in Zone 5 (*Hippuris, Myriophyllum, Potamogeton, Equisetum*). This may be a result of rising lake level from inferred increases in precipitation. A rise in lake level beyond the steep inner crater walls would have increased the area of shallow water available to colonizing aquatic vegetation.

Ericales are more abundant in Zone ZL-4 than in Zone ZL-5, and this suggests the spread of peaty, acidic, moist to wet soils and shrubbier vegetation. Once established, the diverse Ericales can constitute a major component of the ground cover (e.g., *Vaccinium, Artostaphylos, Ledum, Empetrum*). Spores of ferns (Polypodiaceae) and *Sphagnum* are also more abundant in this zone, reflecting expansion of mesic and boggy habitats. The pollen and spore evidence from Zone ZL-4 suggests a sudden onset of moister, perhaps warmer, climates, and perhaps deeper snow accumulations in winter after about 15,000 ^{14}C yr B.P. Other sites in western Alaska suggest that this vegetation change to dwarf birch mesic tundra took place about 14,000 ^{14}C yr B.P. or even later (Ager, 1982, 1983; Anderson, 1985, 1988). It is possible that the bulk sediment radiocarbon date from the base of Zone 4 in Zagoskin Lake (Fig. 5B) is too old by perhaps 1000 years.

Global eustatic sea level rise had not yet flooded much of the Bering land bridge at the time of the transition to shrub tundra 15,000–13,000 ^{14}C yr B.P. (Fairbanks, 1989; Bard et al., 1990). Sea level had probably risen to between -110 and -95 m below present sea level during that time interval (Fig. 1; Bard et al., 1990). Therefore the initial shift to mesic climates in central Beringia may have been minimally influenced by encroaching coastlines on the land bridge. Reduced sea ice in the Bering Sea and northwest Pacific Ocean along with warmer sea surface and air temperatures may have been more important factors, permitting more moisture to evaporate and to be transported into central Beringia.

Pollen Zone ZL-3 (3.8 to 3.2 m; ca. 11,000–9500 ^{14}C yr B.P.) is characterized by a peak in *Populus* pollen (5–12%), accompanied by increases in percentages of *Salix* (5–10%), Poaceae (15–35%), and of microspores of the shallow water aquatic plant *Isoëtes* (15–45%), while percentages of *Betula* and *Sphagnum* decline. Similar *Populus-Salix* zones have been documented in other parts of Alaska (e.g., Ager, 1983; Ager and Brubaker, 1985; Anderson, 1985, 1988; Mann et al., 2002) but the chronologies vary somewhat from site to site, ranging between about 11,500 and 8500 ^{14}C yr B.P. At Zagoskin Lake, the time interval for the *Populus-Salix* assemblage overlaps with the Younger *Dryas* interval of colder, drier climate that has been documented in several areas of Alaska (e.g., Peteet and Mann, 1994). It is unclear why an interval of apparently colder, drier climate might favor the expansion of *Populus* and *Salix* populations, even into areas beyond the present day range of *Populus* trees. However, some evidence suggests that the Younger Dryas event was not necessarily both colder and drier everywhere in Alaska (Elias, 2001; Mann et al., 2002). It may have been

Fig. 5. (A–C) Pollen percentage diagram from the Zagoskin Lake sediment core. Panel C shown minor pollen taxa and loss-on-ignition data. Pollen zones Z-1 to Z-5B are shown in the left columns of A and C. Radiocarbon dates (^{14}C yr B.P.) are shown in the right column of B.


A
Zagoskin Lake
Pollen Zones
ZL-1
ZL-2
ZL-3
ZL-4
ZL-5A
ZL-5B
Depth m
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Trees, Shrubs and woody plants
Herbs
Picea
Pinus
Betula
Alnus
Salix
Populus
Ericales
Potentilla
Sanguisorba
Rubus chamaemorus
R. arcticus
Dryas
Poaceae
Cyperaceae
Artemisia
Ambrosia
Asteroideae
Cichorioideae
Depth m
0 5 0
0 10 20 30 40 50 60
0
0 10 20 30 40 50 60
0 10 20 30 40
0 10 20
% of pollen sum

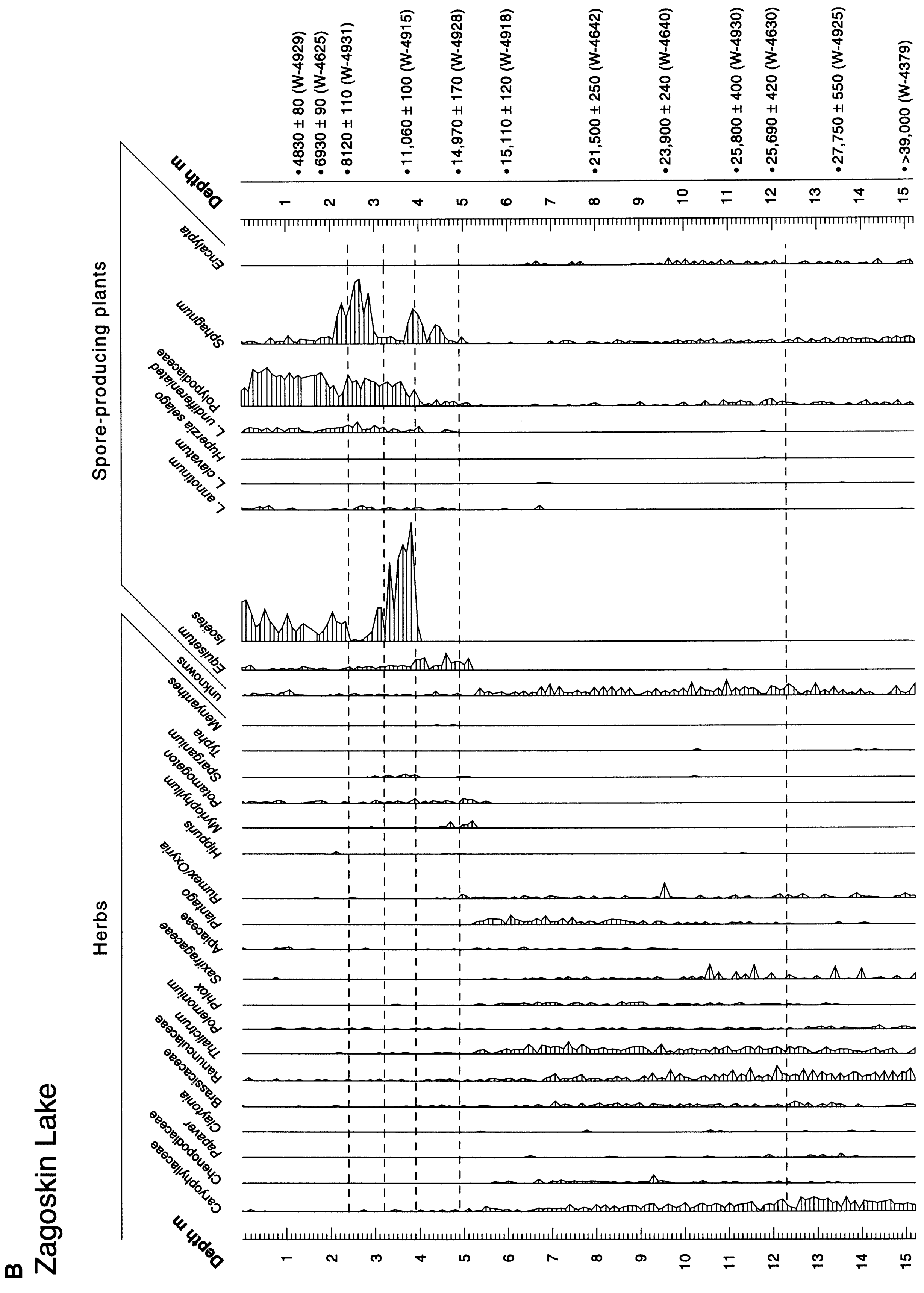


Fig. 5 (*continued*)

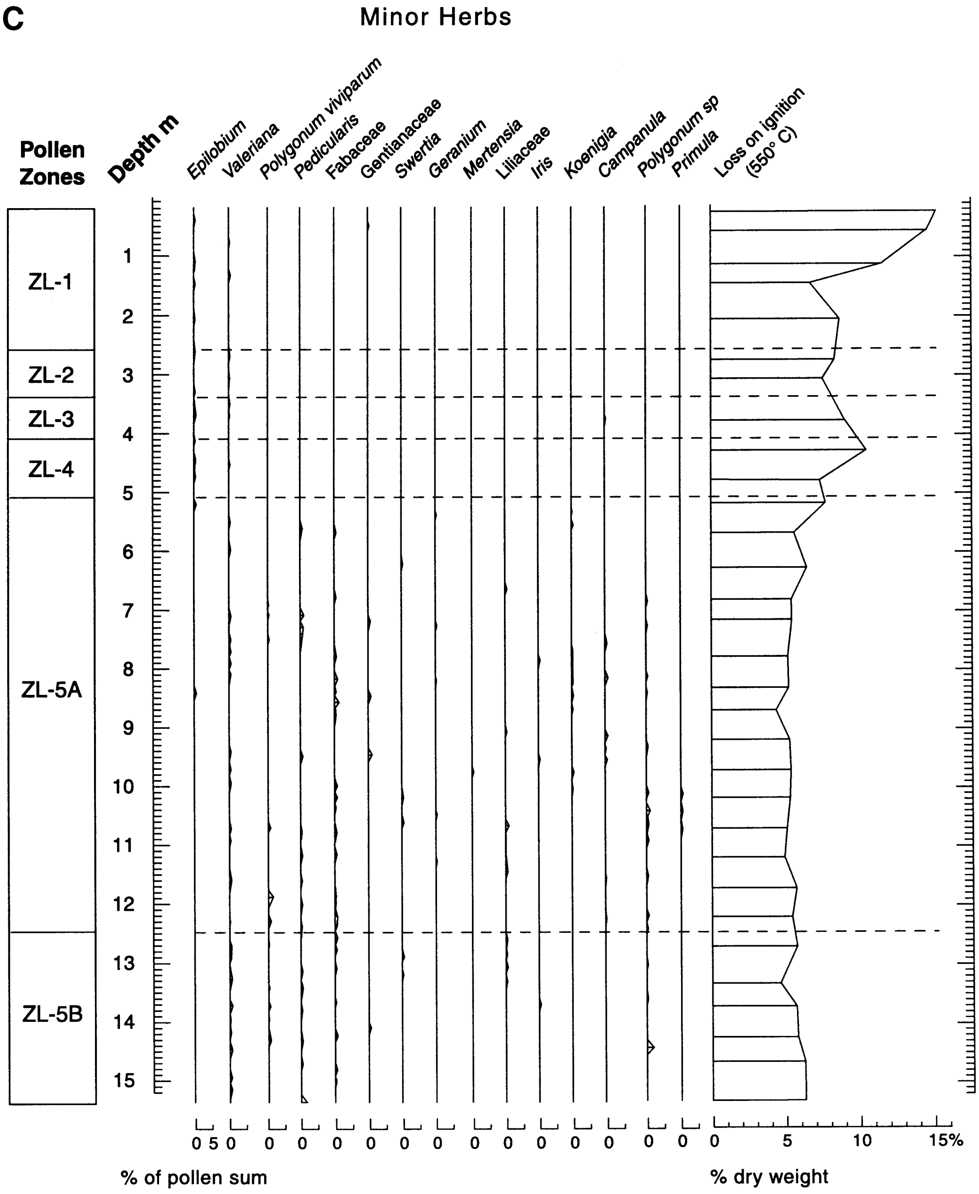


Fig. 5 (*continued*)

drier, but perhaps not colder in northern and northwestern Alaska. A Younger *Dryas* interval of drier climate, coinciding with a peak in July insolation at 65° N (Berger and Loutre, 1991) may explain the increases in *Populus* and Poaceae pollen and a temporary decline in *Betula* and *Sphagnum,* as implied by their lower percentages. The significant increase in percentages of *Isoëtes* microspores may have been caused by a moderate drop in lake level in response to drier climate, creating a larger area of shallows surrounding the central, deep crater. *Isoëtes* continues to grow in the shallows of Zagoskin Lake today.

Pollen zone ZL-2 (3.2–2.4 m; ca. 9500–8000 ^{14}C yr B.P.) is dominated by pollen of *Betula* (35–60%), Ericales (5–10%), Poaceae (15–25%), Cyperaceae (10–20%), and relatively abundant spores of *Sphagnum* (5–25%) and Polypodiaceae-type fern spores (10%). This assemblage suggests a return to a wetter climate, perhaps deeper snow accumulation in winter, and an expansion of Ericales over increasingly peaty, acidic, moist to wet soils. During the deposition of this part of the record, the marine transgression of the Bering land bridge had reached as far east as the western limits of present day Norton Sound (Fig. 2). The transgression of the remnants of the land bridge, including Norton Sound, probably continued until at least mid-Holocene time. Some of the moisture increases implied by the fossil evidence may be related to this increasingly local maritime climate influence.

Pollen Zone ZL-1 (2.4 m to core top; 8000 ^{14}C yr B.P. to present) is dominated by pollen of *Alnus* (25–65%), *Betula* (15–45%), with minor *Picea* (2–5%). This zone spans most of the Holocene and documents the establishment of the vegetation that now covers St. Michael Island and adjacent areas of the mainland. *Alnus crispa* apparently spread quickly into the Norton Sound area, probably from interior or northwestern Alaska, and grows today on the island in gullies, along streams, and within craters and hollows. *Alnus* produces abundant wind-dispersed pollen. Therefore alders tend to be overrepresented in pollen assemblages, especially in a tundra-dominated landscape.

Picea glauca (white spruce) spread west and north from interior Alaska during the early Holocene (Ager, 1983; Ager and Brubaker, 1985) and reached the vicinity of eastern Kotzebue Sound (northeast of Seward Peninsula) by 6000 ^{14}C yr B.P. (Anderson, 1988). Spruce forests probably arrived in eastern Norton Sound during the mid-Holocene, when *Picea* pollen percentages first consistently exceed 2–3% in the Zagoskin Lake core. *Picea* does not now grow on or near St. Michael Island, but the mean July temperature at St. Michael may be warm enough to permit growth and reproduction of *Picea* in sheltered sites (Table 1). The western and northern limits of spruce forests in Alaska coincide approximately with July mean temperatures near 12° C (Muhs et al., 2001), whereas the limit of tree growth generally coincides with the 10° mean July isotherm.

Discussion

The pollen record from Zagoskin Lake shows that an herbaceous vegetation rich in grasses, sedges, *Artemisia,* and numerous tundra forbs dominated the landscapes on and around St. Michael Island during the late-middle Wisconsin interstadial (MIS-3) and the late Wisconsin glacial interval (MIS 2), until about 15,000–14,000 ^{14}C yr B.P. Some present-day herb-dominated tundra communities in far northwest Alaska, Wrangel Island north of Chukotka Peninsula, and Banks Island in the Canadian arctic produce somewhat similar pollen spectra relatively rich in grasses, sedges, and other herbs (Anderson et al., 1989; Lozhkin et al., 2001). Some of the modern and Holocene pollen spectra from Wrangel Island were produced by vegetation that may provide reasonable near-analogs for some late Wisconsin graminoid-herb vegetation in central Beringia (Lozhkin et al., 2001; Yurtsev, 1982, 2001).

Pollen analysis of USGS core 76-121 (Figs. 2 and 6; Muhs et al., 2003; Ager, 2002, and unpublished data) from central Norton Sound indicates that a graminoid-herb tundra grew northwest of St. Michael Island, in a lowland setting on the land bridge during full glacial time. The herb-dominated pollen floras in the Norton Sound core occur in silty sediments that probably represent loess deposits (Muhs et al., 2003). This silt unit occurs in the core between two peaty silt layers dated to 11,570 ± 130 (USGS-358) and 29,500 ± 340 ^{14}C yr B.P. (USGS-158). The emerging evidence from the Norton Sound core suggests that both lowlands and low-relief uplands (such as St. Michael Island) on the land bridge had similar herb-dominated tundra, not mesic shrub-herb tundra during full glacial time.

A comparison of most of the longest available pollen records from central Beringia (Fig. 6) suggests that herb-dominated vegetation covered most of central Beringia, including sites on the former Bering land bridge, during the Wisconsin glacial interval (prior to ca. 15,000–14,000 ^{14}C yr B.P.). Evidence presented by Elias et al. (1996, 1997) indicates that some plant species which grow in mesic and aquatic habitats existed on the land bridge during full glacial time (MIS 2) and were especially common on the land bridge after 14,000 ^{14}C yr B.P. However, their fossil evidence for mesic environments on the land bridge during late Wisconsin time is based on only four radiocarbon-dated samples from one small area west of Port Clarence in the northern Bering Sea (Fig. 2). That small area represents a very small fraction of the ca. 1.4×10^6 km^2 area of the Bering land bridge at its maximum extent (Fig. 1). Other sites discussed in this paper (Fig. 6) cover a much larger area of central Beringia. The pollen data from these widely distributed sites are more likely to represent the dominant full-glacial vegetation types on and adjacent to the land bridge than a few samples from near Port Clarence.

The pollen records from western Alaska provide a north-south transect of central Beringian vegetation history for the late Quaternary (Fig. 1, Fig. 6). These site histories suggest that herb-dominated vegetation covered most of the landscape of central Beringia during at least the latter part of the middle Wisconsin interstadial, and during the late Wisconsin glacial interval. Across central Beringia, dwarf birch shrub tundra developed after 15,000–14,000 ^{14}C yr B.P. Few well-dated and continuous pollen records extending to MIS-2 and 3 are yet available from Chuktoka. The longest and best-dated record from Chukotka (Patricia Lake, Fig. 1 and Fig. 6) suggests that graminoid-herb tundra dominated at least some of the landscapes of the Anadyr River region during full glacial time (Anderson and Lohzkin, 2002, p. 68). Interestingly, radiocarbon dates from Patricia Lake suggest that the transition from graminoid herb-dominated vegetation to birch-herb-ericales tundra occurred early, ca. 16,000 ^{14}C yr B.P. (Fig. 6; Anderson and Lozhkin, 2002). The dominance of herbaceous tundra vegetation in east-central Beringia suggests that an arid climate with a colder mean annual temperature than today persisted from at least 30,000–14,000 ^{14}C yr B.P. Whatever mesic shrub-herb vegetation was present on the land bridge may have been restricted to stream banks and other sheltered sites (Ager, 2002).

Most available evidence suggests that generally cold, arid climates prevailed across Beringia, from north to south and from east to west during the late Wisconsin. A pollen record from St. Paul Island in the Pribilof Islands (Fig. 1, site 9; Fig. 6; Colinvaux, 1981) suggests that even the southern shores of the land bridge were surprisingly arid, cold, and dominated by herb tundra. Full-glacial sediments deposited in the crater lake that Colinvaux (1981) cored

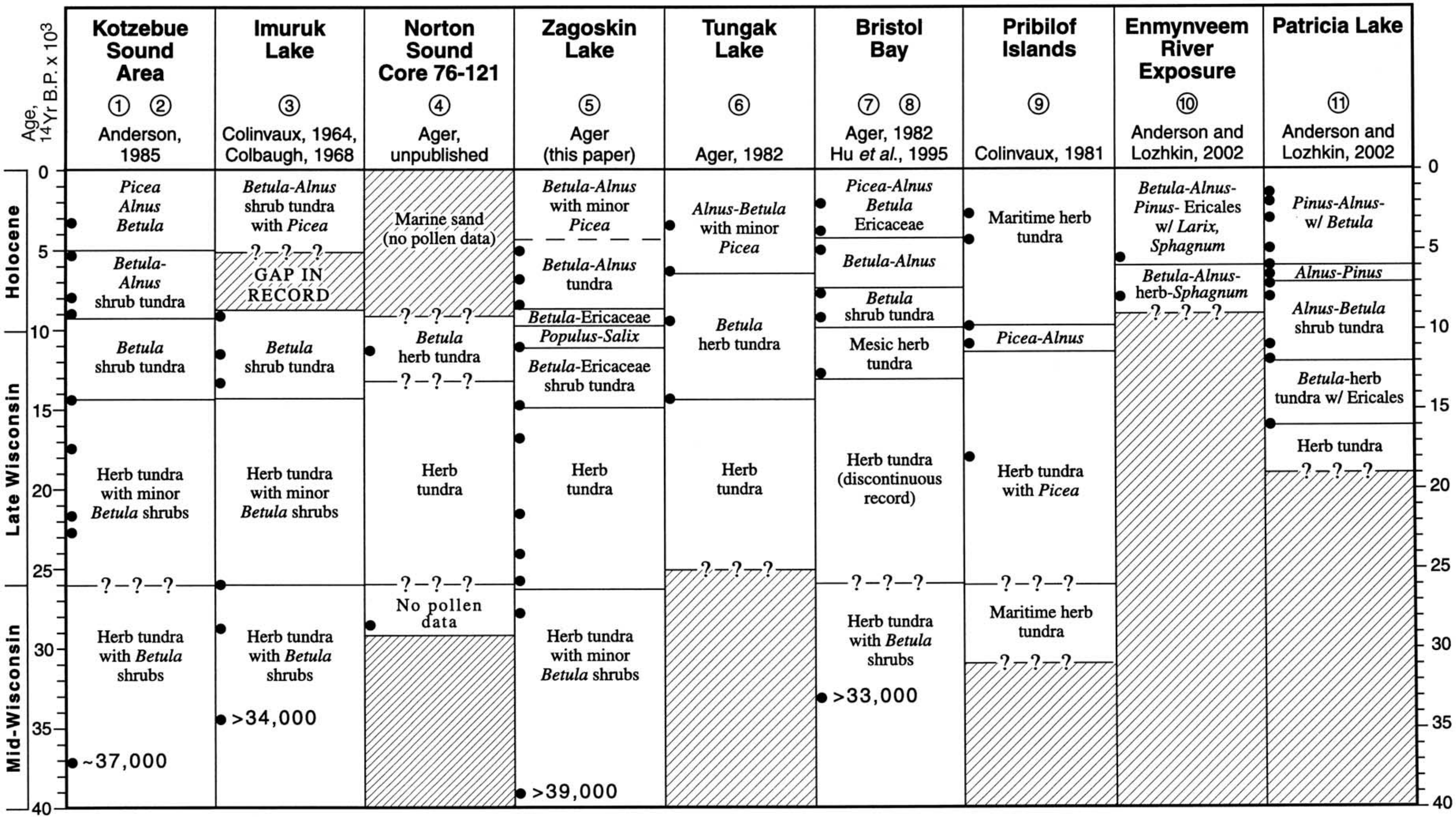


Fig. 6. Chart comparing selected late Quaternary vegetation histories of western Alaska and eastern Chukotka. Numbers shown at the heads of columns correspond to numbered localities shown on Figure 1. Black circles within the columns show the positions of radiocarbon dates within the sequences. Sources of data are cited at the top of each column.

consisted of eolian silt and sand containing little organic matter. However, the presence of spruce pollen in the Pribilof Island pollen record within full-glacial and late glacial sediments suggests that some spruce trees may have survived on the southeastern land bridge. That may indicate the persistence of some mesic environments with some spruce trees near the southern shores of the land bridge, possibly forming gallery forests. If some spruce trees did survive on the southern land bridge during glacial times, they were apparently unable to colonize southwestern Alaska before the late Quaternary marine transgression of the land bridge inundated them (Ager, 1982; Ager and Brubaker, 1985).

The mapped extent of late Wisconsin age glacial deposits on Seward Peninsula, in the Ahklun Mountains, and in the Brooks Range (Fig. 1), indicates that glacier growth in western Alaska was limited by low net snow accumulation. The extent of glacier ice in those mountainous areas was significantly greater during some earlier late Cenozoic glaciations in western Alaska (Kaufman and Hopkins, 1986; Manley et al., 2001; Hamilton, 1994). This suggests that air masses from the northwest Pacific that flowed into central Beringia during late MIS 3 and 2 prior to 14,000 ^{14}C yr B.P. carried limited moisture, less than during some earlier glacial intervals. Air masses entering central Beringia from the south might have been relatively dry because of colder air temperatures, lower evaporation rates from cold seas, and extensive seasonal sea ice cover in the Sea of Okhotsk, southern Bering Sea, and part of the northwest Pacific (Sancetta and Robinson, 1983). Dominant winds from the north and northeast may have persisted through MIS 2 and 3. Such a scenario is supported by the distribution of eolian sediments in western Alaska (Muhs et al., 2003). That scenario differs from the output of some climate models that suggest that relatively warm, moist air masses from the North Pacific should have penetrated into central Beringia during the late Wisconsin (e.g., Bartlein et al., 1998).

Despite evidence for aridity in central Beringia, there is evidence that the region had at least a slightly more mesic climate than in interior Alaska and Yukon, and in Siberia. The persistence of at least some water in some closed-basin lakes in western Alaska (e.g., Imuruk Lake, Zagoskin Lake, Puyuk Lake) contrasts with interior Alaska and Yukon, where most lakes dried up completely during full-glacial time. Some pollen records from central Beringia show somewhat higher percentages of dwarf birch pollen than other sites during MIS 2 (e.g., Colinvaux, 1967; Colbaugh, 1968; Anderson, 1985), reflecting perhaps subtle regional variations in precipitation or depth of winter snow accumulation. Over most of central Beringia, however, wetland and mesic shrub-herb vegetation may have been largely restricted to stream banks, ponds, lakeshores, and sites that trapped windblown snow.

Guthrie (2001) suggests that a broad belt of mesic vegetation and climate covered much of the Bering land bridge during full glacial time, whereas Yurtsev (2001) envisions a narrower band of mesic vegetation in central Beringia. These interpretations appear to be based on fossil evidence described by Elias et al. (1996). Guthrie suggests that a widespread mesic environment in central Beringia may have served as an ecological filter that prevented a few large Pleistocene mammal species from crossing the land bridge from Siberia to Alaska (e.g., woolly rhinos, *Coelodonta*), and other species from crossing from Alaska to Siberia (e.g., short-faced bears, *Arctodus simus*). If such an ecological filter existed in central Beringia, it did not prevent most mammal species from crossing the land bridge between the two continents during the Wisconsin (MIS 2-4). This suggests that whatever environmental differences existed between the land bridge and the adjacent regions were probably subtle, and may be difficult or impossible to detect in the fossil record. Future interdisciplinary studies of well-dated records from some of the many volcanic crater lakes in central Beringia may eventually shed light on this question.

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