Géographie physique et Quaternaire

Two Late Quaternary Pollen Records from South-Central Alaska
Deux inventaires polliniques du Quaternaire supérieur en provenance du centre-sud de l'Alaska
Две позднецетвертицные пыдцевые записи иэ южных районв Центральльной Аляски

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Volume 48, Number 2, 1994

URI: https://id.erudit.org/iderudit/032990ar
DOI: https://doi.org/10.7202/032990ar

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Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

Anderson, P. M., Lozhkin, A. V., Eisner, W. R., Kozhevnikova, M. V., Hopkins, D. M., Brubaker, L. B. & Colinvaux, P. A. (1994). Two Late Quaternary Pollen Records from South-Central Alaska. *Géographie physique et Quaternaire*, *48*(2), 131–143. https://doi.org/10.7202/032990ar

Article abstract

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Géographie physique et Quaternaire, 1994, vol. 48, n° 2, p. 131-143, 5 fig., 5 tabl.

TWO LATE QUATERNARY POLLEN RECORDS FROM SOUTH-CENTRAL ALASKA*

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ABSTRACT Pollen records from Wonder and Ten Mile lakes, located at altitudinal treeline to the north and south of the Alaska Range respectively, document the vegetation history of a portion of the southern Alaskan boreal forest. The new pollen diagrams indicate a *Betula* shrub tundra, preceded at Wonder Lake by a sparse herb tundra, which characterized these two areas during latest Wisconsinan times. *Populus* was in the vicinity of Ten Mile Lake *ca.* 10,000 BP, but was apparently absent from Wonder Lake. *Picea glauca* grew at or near Ten Mile Lake by 9100 BP, with *P. mariana* becoming important *ca.* 7000 BP. The first forests at Wonder Lake were also dominated by *P. glauca* and followed by increased numbers of *P. mariana*. The timing of forest establishment at Wonder Lake is uncertain due to problematic radiocarbon dates. *Alnus* appears to be common in both regions by *ca.* 7000 BP. These records suggest that paleovegetational reconstructions are more difficult for the southern than northern boreal forests in Alaska because of greater topographic diversity, difficulties with over-representation of some pollen taxa, and problems with radiocarbon dating. Despite these concerns, available data from south-central Alaska suggest that southern and northern forests differ in their vegetational histories. Such differences, when related to temperature fluctuations that have been postulated for the Holocene, imply that the Alaskan boreal forest may not respond uniformly to future global warming.

RÉSUMÉ *Deux inventaires polliniques du Quaternaire supérieur en provenance du centre-sud de l'Alaska.* Les inventaires polliniques de Wonder Lake et de Ten Mile Lake, situés à la limite altitudinale des arbres au nord et au sud de la chaîne de l'Alaska permettent de reconstituer l'histoire de la végétation d'une portion de la forêt boréale du sud de l'Alaska. Les nouveaux diagrammes polliniques montrent une toundra arbustive à *Betula*, précédée au Wonder Lake par une toundra herbacée clairsemée, à la fin du Wisconsinien. Vers 10 000 BP, *Populus* était dans les environs du Ten Mile Lake, mais était apparamment absent du Wonder Lake. *Picea glauca* croissait autour du Ten Mile Lake à 9100 BP et *P. mariana* prenait de l'importance vers 7000 BP. Au Wonder Lake, les premières forêts ont également été dominées par *P. glauca*, puis par un nombre croissant de *P. mariana*. La chronologie de l'afforestation est incertaine en raison de datations au radiocarbone douteuses. *Alnus* semble être une espèce courante dans les deux régions vers 7000 BP. Les inventaires indiquent que la reconstitution de la paléovégétation est plus difficile à faire pour les forêts méridionales que septentrionales de l'Alaska, en raison de la plus grande diversité topographique, la sur-représentation de certains taxons et des problèmes de radiodatation. Les données indiquent tout de même que l'histoire de la végétation des forêts diffèrent au nord et au sud. Ces différences, mises en relation avec les fluctuations de températures présumées de l'Holocène, laissent croire que la forêt de l'Alaska ne répondra pas nécessairement de facon uniforme à un réchauffement climatique éventuel.

РЕЗЮМЕ Две позднечетвертичные пыдьцевые записи из южных районов Центральньной Аляски. Пыльцевые диаграммы осадков озер Ваеде и Тенмайл, расположенных вблизи верхней границы леса на севере и юге Аляскинского хребта, отражают историю растительности южной части бореального леса Аляски. Новые пыльцеье диаграммы показывают, что кустарниковой бергзовой тундре, характерной для зтих двух территорий в течение позднего висконсина, предшествовада в отдожениях оз. Ванде бедная травянистяа тундра. Populus пропзрагтал в окрестностях оз. Тенмайл 10000 л.н., но, ло-видимому, отсутствовад в районе оз. Ванае. 9100 л.н. в районе оз. Тенмайл или в непосредственной близости от него произрастала Picea glauca, которая вмерте с Picea mariana играет значительную роль в составе растительности около 7000 л.н. В первых лесах в районе оз. Ванде также доминировала Picea glauca, но затем роль Picea mariana начинает возрасастать. Время появления лесов в районе оз. Ванде иокане устанавливается надежно радиоуглеродным методом. Alnus образует сообщества в обоих районах около 7000 л.н. Полученные данные свидетельствуют о том, что реконструкция растительности будет более сложной для южных, чем для северных бореальных лесов Аляски из-за значительного топографического несходства, затруднения в интерпретации некоторых пыльцевых таксонов, проблем с радиоуглеродным датирванием. Несмотря на зти проблемы, полфченные данные показыают, что бореальные леса на юге и севере южной части Центальной Аляски имеют разлчную историю. Такие различия, связханные с измененлями землератур в теченле голоцена, свидетельствуют, что бореальный лес Аляски может не отвечать сченарию глобального потепления в будущем.

Manuscrit reçu le 15 juin 1993; manuscrit révisé accepté le 6 décembre 1993

* PALE Contribution No. 11

INTRODUCTION

Palynologists often focus on the history of late Quaternary vegetation boundaries to improve the understanding of plant-climate interactions, since such ecotones are particularly sensitive to environmental change caused by variations in temperature and effective moisture. The record of the northern Alaskan boreal forest, representing the ecotone between the boreal forest and tundra, is well documented (Anderson and Brubaker, 1993; Lamb and Edwards, 1988; Ager and Brubaker, 1985) and indicates that the development of the modern forest was strongly affected by variations in seasonal insolation (Barnosky *et al.*, 1987). However, the response of the southern boreal forest to postglacial climatic fluctuations is poorly known (Ager and Brubaker, 1985; Ager, 1983). The probability that subarctic environments will change profoundly due to increased levels of anthropogenic gases makes such information vital for evaluating the possible effects of climatic change on boreal ecosystems (Schlesinger and Mitchell, 1987; Pastor and Post, 1988, Emanuel *et al.*, 1985).

Paleovegetational interpretations for the southern Alaskan boreal forest are limited, because the published pollen records are poorly dated and are from widely scattered localities (Ager, 1983; Ager and Brubaker, 1985). To improve these interpretations, it will be necessary to both sample sites in areas where the vegetation history is unknown and sites near previously sampled lakes so that the trends in the published pollen records can be verified. Pollen and macrofossil records from Eightmile and Tangle Lakes (Ager, 1983; Ager and Sims, 1981; Schweger, 1981) currently provide the only published information about the Holocene-late Pleistocene vegetation of the Alaska Range, the major geographic feature of south-central Alaska (*i.e.*, the region between the northern foothills of the Alaska Range and the northern coast of the Gulf of Alaska). To confirm the vegetational histories from these two key Alaska Range sites, we recovered sediments from Ten Mile and Wonder Lakes, located in the altitudinal forest-tundra ecotone of the Gulkana Uplands and northern Alaska Range, respectively (Figs. 1 and 2A). Comparison of the Ten Mile and Wonder results to sites from the Alaska Range and other parts of south-central Alaska (Table I), while far from definitive, do suggest regional differences in the development of the southern and northern boreal forest.

THE SITES

TEN MILE LAKE

Ten Mile Lake (informal name; 63°04′N 145°42′W; 1000 m) lies on the southeastern edge of the Gulkana Uplands in a broad trough confined by mountains of *ca.* 1400 m summits. Approximately 20 km to the north, the towering peaks of the heavily glaciated eastern Alaska Range rise to altitudes of 4000 m. Today the lake is part of a complex drainage flowing into the Gulkana River (Fig. 2B). Ten Mile Lake contains two basins of 14 m and 6 m depth. Although both basins were sampled, we chose to analyze the core from the shallower one, because its sedimentology suggested a more complete postglacial record.

Altitudinal treeline (*ca.* 900 m), comprised of *Picea glauca*, occurs *ca.* 5 km to the east of Ten Mile Lake with the main body of the forest, dominated by *Picea mariana*, occupying the nearby Delta and Copper River valleys (Fig. 2A). *Betula glandulosa* and *Salix* spp. dominate the shrub tundra surrounding the lake, but a variety of ericaceous species (*e.g.*, *Vaccinium uliginosum*, *Ledum decumbens*, *Vaccinium vitis-idaea*, *Empetrum nigrum*) are common locally. Graminoids and lichens are typical in less favorable sites.

Ten Mile Lake lies well within the limits of former large, piedmont ice tongues of Late Wisconsinan age (Donnelly or Denali II glaciation of Péwé, 1975; Péwé and Reger, 1975) that spread southward from the Alaska Range (Fig. 2B). Several hundred meters of glacial ice likely covered the site, as attested to by the southwest-oriented roches moutonnées (glacier-scoured streamlined hillocks) on the adjoining mountain sides and ribbed moraines in the immediate vicinity of the lake. A series of dry gorges crossing the northern crest of Paxson Mountain indicates a history of slow downwasting of this ice cover.

Though Ten Mile Lake presently drains to the south, an esker complex surrounding the lake records a former northward subglacial drainage. An outwash train leading toward the Delta River shows that this northward drainage persisted for at least a short time after the glacial ice disappeared. Ten Mile Lake, itself, was confined when tilting caused by postglacial isostatic recovery shifted the drainage divide *ca.* 6.5 km to the north.

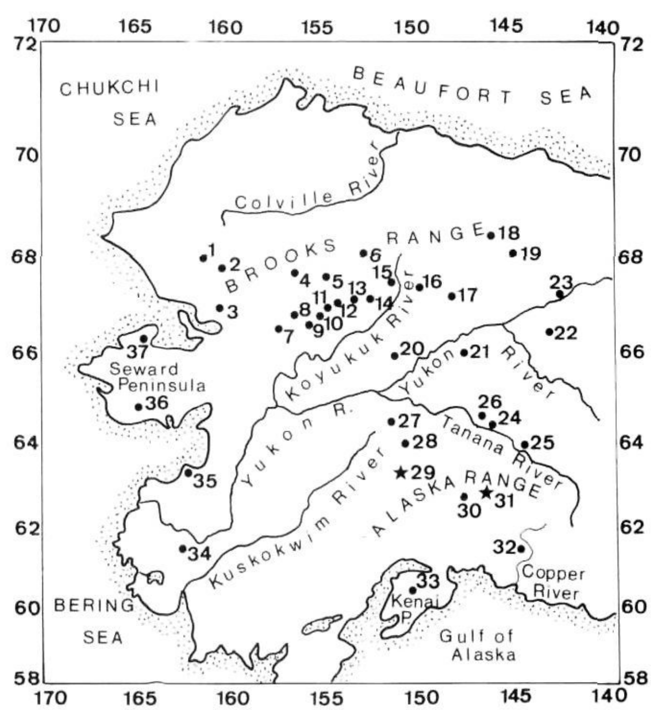
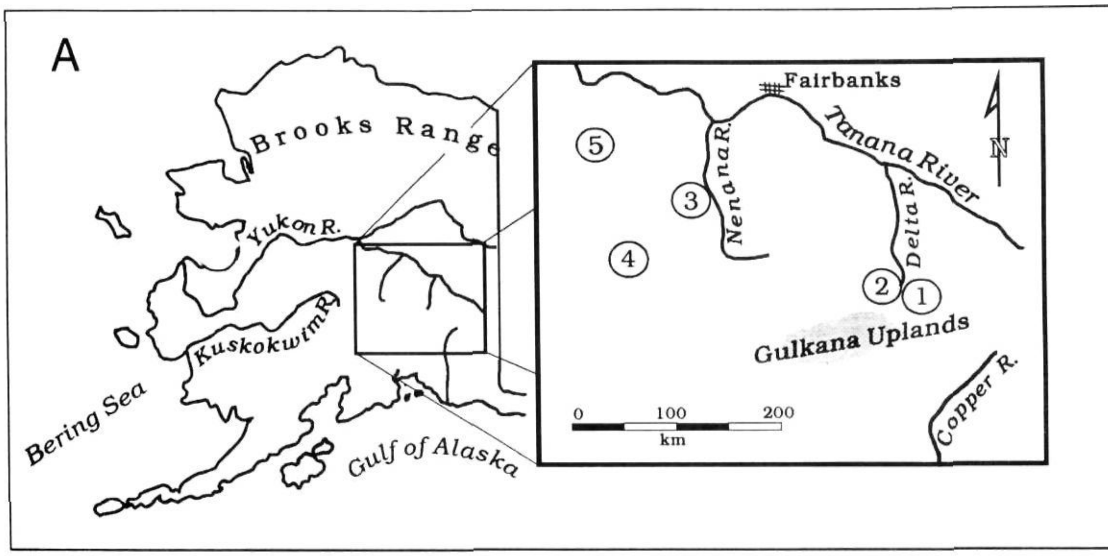
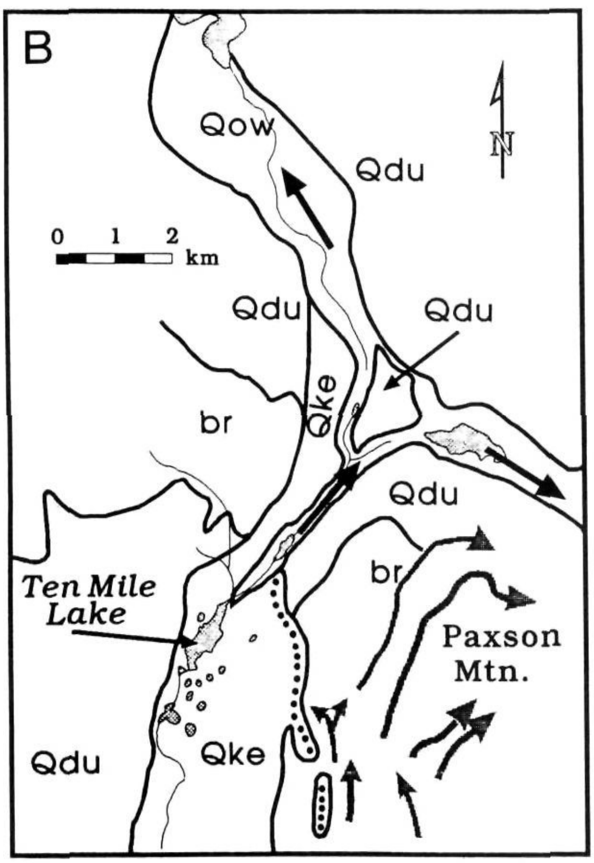


FIGURE 1. Map of Alaska with sites discussed in text. See Table I for site information.

Carte de l'Alaska montrant les sites dont on parle dans le texte (voir tabl. I).





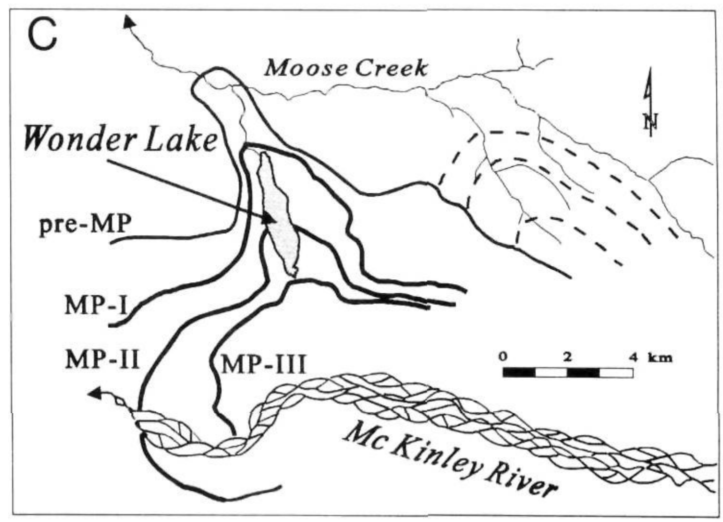


FIGURE 2. A) Locations of Ten Mile (1), Tangle (2), Eightmile (3), and Wonder (4) lakes. B) Quaternary geology of the Ten Mile Lake area. Qke: kame-esker complex; Qow: outwash; Qdu: undifferentiated glacial drift; br: bedrock. Light arrows on Paxson Mountain are dry canyons carved in bedrock by ice-marginal channels; lines of dots on lower flank of Paxson Mountain is a major esker; heavy arrows in outwash area indicate direction of paleo-drainage. C) Glacial moraines of Wonder Lake vicinity. MP-I, MP-II, and MP-III are moraines marking stades of the McKinley Park Glaciation (Late Wisconsinan?); the pre-MP moraine is of uncertain but relatively late Pleistocene in age; the dashed lines to the east mark apparent moraines of much greater age.

Localisation des lacs à l'étude: Ten Mile (l), Tangle (2), Eightmile (3), et Wonder (4). B) Géologie du Quaternaire de la région du Ten Mile Lake. Qke: complexe kame-esker; Qow: épandage fluvio-glaciaire; Qdu: dépôts glaciaires non différencié; br: roche en place. Les flèches qui parcourent Paxson Mountain identifient des canyons secs surcreusés dans la roche en place par des chenaux de contact glaciaire; le pointillé sur les flancs inférieurs de Paxson Mountain donne la direction du paléodrainage. C) Les moraines dans les environs du Wonder Lake. Les moraines MP-I, MP-II et MP-III représentent les différents stades de la Glaciation de McKinley Park (Wisconsinien supérieur?). La moraine « pre-MP », bien qu'étant d'un âge incertain, date probablement du Pléistocène supérieur. Les tiretés à l'est montrent des moraines beaucoup plus anciennes.

TABLE I

Site information and key to figures 1 and 5

Site #	Site Name	Location	Elev. (m)	Rank*	Reference
1	Kaiyak	68°09'N 161°25'W	190	1	Anderson, 1985
2	Niliq	67°52'N 160°26'W	274	2	Anderson, 1988
3	Squirrel	67°06'N 160°23'W	91	2	Anderson, 1985
4	Etivlik	68°08'N 156°02'W	631	1	Anderson, unpub.
5	Headwaters	67°56'N 155°02'W	820	1	Brubaker *et al.*, 1983
6	Chandler	68°15'N 152°42'W	950	0	Livingstone, 1957
7	Joe	66°46'N 157°13'W	183	4	Anderson, 1988
8	Kollioksak	66°58'N 156°27'W	213	1	Anderson, unpub.
9	Selby	66°51'N 155°43'W	145	3	Anderson, unpub.
10	Minakokosa	66°55'N 155°02'	122	3	Anderson, unpub.
11	Ruppert	67°04'N 154°15'W	210	4	Brubaker *et al.*, 1983
12	Angal	67°08'N 153°54'W	820	1	Brubaker *et al.*, 1983
13	Ranger	67°09'N 153°39'W	820	1	Brubaker *et al.*, 1983
14	Redstone	67°15'N 152°36'W	914	1	Edwards *et al.*, 1985
15	Screaming Yellowlegs	67°35'N 151°25'W	650	1	Edwards *et al.*, 1985
16	Rebel	67°25'N 149°48'W	914		Edwards *et al.*, 1985
17	Sakana	67°26'N 147°51'W	640	4	Brubaker, unpub.
18	Crowsnest	68°20'N 146°29'W	881	1	Anderson, unpub.
19	Seagull	68°16'N 145°13'W	637	1	Brubaker, unpub.
20	Sithylemenkat	66°07'N 151°26'W	213	3	Anderson *et al.*, 1990
21	Sands of Time	66°02'N 147°31'W	250	3	Lamb and Edwards, 1988
22	Tiinkdhul	66°35'N 143°09'W	189	4	Anderson *et al.*, 1988
23	Ped	67°12'N 142°04'W	211	2	Edwards and Brubaker, 1987
24	Birch	64°19'N 146°50'W	274	0	Ager, 1975
25	George	63°47'N 144°30'W	389	0	Ager, 1975
26	Harding	64°26'N 146°52'W	217	3	Ager, 1983
27	Wein	64°20'N 152°16'W	305	4	Hu *et al.*, 1993
28	Eightmile	63°53'N 149°15'W	646	2	Ager, 1983
29	Wonder	63°29'N 151°05'W	610	0	—
30	Tangle	63°02'N 146°04'W	850	1	Schweger, 1981
31	Tenmile	63°04'N 145°42'W	1000	1	—
32	70 Mile	61°30'N 145°14'W	548	3	Ager and Brubaker, 1985
33	Hidden	60°29'N 150°17'W	91	2	Ager, 1983
34	Tungak	61°23'N 164°01'W	122	0	Ager, 1982
35	Puyuk	63°29'N 160°02'W	14	1	Ager, 1982
36	Glacial	64°53'N 165°42'W	119	1	Eisner, unpub.
37	Whitefish	66°04'N 165°03'W	12	1	Anderson, unpub.

* Rank based on percentage of *Populus* pollens from 9000 to 11,000 BP (see also Fig. 5).

WONDER LAKE

Wonder Lake (63°29'N 151°05'W; 610 m) occupies the lowland that connects the broad valley of the McKinley River to the south and the canyon of Moose Creek to the north (Fig. 2C). The lake is *ca.* 4.5 km long and 0.8 km wide with an outlet to Moose Creek. Maximum depths are greater than 60 m in the central basin (A. Werner, unpub.). Because this exceeds our coring abilities, we sampled a shallower platform (*ca.* 11 m) in the northern part of the lake.

The vegetation in the Wonder Lake catchment consists of a mosaic of alpine and shrub tundra and open *Picea glauca* forest. Alpine tundra occurs in the highest areas of the surrounding mountains. Tall *Betula-Alnus* shrub tundra is restricted to lower elevation mountain slopes and cooler sites in the valley where it is interspersed with *Carex* marsh in local wetlands. *Picea glauca* is present below altitudes of 800 m and is most dense on warm, south-facing slopes. Relatively dense *Picea* forests also grow along the floodplains of the McKinley River and Moose Creek. *Populus balsamifera* and, more rarely, *P. tremuloides*, comprise the broadleaf deciduous component of the vegetation.

Wonder Lake lies within a broad belt of morainal topography evidently of Late Wisconsinan age (Fig. 2C; McKinley Park glaciation of Werner, 1982, 1992). The lake is confined to the north by the outermost morainal ridge in this complex (MP-I), and it is blocked to the south by a broad moraine (MP-III) marking either a readvance or a major surge. Midway between these two moraines is a pair of morainal ridges (MP-II) that apparently record a minor readvance or a surge; they slope northward along either side of Wonder Lake and seem to be connected by a minor submarine ridge that bisects the lake's deepest basin (Werner, unpub.).

Although the Wonder Lake area has been free of glacial influence since some time in the Late Wisconsinan, it was repeatedly glaciated at earlier times (Ten Brink and Waythomas, 1985; Werner, 1982, unpub. data). Air photos suggest that a glacial advance recorded by what appears to be a massive and very ancient moraine and outwash complex

(Fig. 2C) displaced Moose Creek into its present canyon, but previously the open valley of upper Moose Creek was a tributary to the McKinley River. These ancient deposits are transected farther west by a series of younger moraines that wrap around Wonder Lake. (Note: Werner (unpub.) suggests that glacial erosion may have gouged the lake basin itself from a pre-existing bedrock fault zone extending north from Moose Creek.) The outermost moraine extends beyond Wonder Lake for a short distance down Moose Creek; its subdued appearance suggests that it may correspond to the pre-Wisconsinan Healy moraine of the Nenana Valley (Wahrhaftig, 1958).

METHODS

Cores were collected in summer, 1990, with a modified Livingstone piston sampler (Wright *et al.*, 1984). Undisturbed uppermost sediments were collected with a plexiglass corer, although samples from these cores were used only in the Ten Mile diagram (see Results). The Ten Mile core was analyzed at the Ohio State University, whereas Wonder Lake pollen counts were done at the North East Interdisciplinary Institute. One cubic centimeter samples from all of the Ten Mile Lake and some of Wonder Lake cores were prepared following standard procedures for North American arctic lakes (Faegri and Iversen, 1989; Cwynar *et al.*, 1979; Stockmarr, 1971). Because of limitations of chemical availability, other Wonder Lake samples were prepared following the heavy-liquid method of Grichuk and Zaklinskaya (1948). A minimum of 300 known terrestrial pollen grains form the pollen sum. Spores and aquatics are calculated as percent of pollen sum. Pollen zones were defined qualitatively from pollen percentage diagrams. Pollen accumulation rates (PAR) for Ten Mile Lake were calculated by simple linear interpolation between radiocarbon dated levels (Table II). A PAR diagram was not constructed for Wonder Lake because of questionable radiocarbon dates (see Radiocarbon below). Proportions of *Picea glauca* to *Picea mariana* pollen grains (theta values; Table III) were calculated for select samples by a maximum likelihood technique (Brubaker *et al.*, 1987). Percent loss on-ignition was determined by ashing samples at 550°C after oven drying at 90°C (Table IV).

TABLE II

Radiocarbon Dates

Depth (cm)	Date	Lab No.
Ten Mile Lake:		
70-86	3270 ± 90	BETA-42704
178-188	7330 ± 110	BETA-42705
214-224	9140 ± 80	BETA-42706
276-288	11540 ± 120	BETA-42707
Wonder Lake:		
74-84	5330 ± 120	BETA-43474
115-125	7000 ± 100	BETA-42589
166-175	9820 ± 110	BETA-42590
195-205	11270 ± 280	BETA-42591
215-225	12760 ± 110	BETA-43475
250-260	13550 ± 140	BETA-42592

RESULTS

POLLEN DIAGRAMS

Ten Mile Lake

Three pollen zones were defined at Ten Mile Lake (Fig. 3). TM-1, which includes subzones TM-1A and TM-1B, is dominated by *Betula* pollen (40-60%; 61-422 grains cm^{2}yr^{-1}) with relatively high percentages of *Salix* (7-15%) and Gramineae (3-11%) as compared to the rest of the core. *Populus, Juniperus*, and Ericales pollen are present in trace amounts in this and other zones. Percentages of Cyperaceae pollen (10-37%) are highest in TM-1A, although PARs (40-80 grains cm^{2}yr^{-1}) imply Cyperaceae was more abundant in TM-1B. The highest *Artemisia* PARs in the core occur in TM-1B.

TM-2 is characterized by a sharp increase in *Picea* pollen percentages (23-41%) and PARs (83-118 grains cm^{2}yr^{-1}). *Salix* (3-4%) and *Betula* (31-44%) pollen percentages decrease, as do PARs for *Salix* (7 grains cm^{2}yr^{-1}), *Betula* (172 grains cm^{2}yr^{-1}), Gramineae (3-14 grains cm^{2}yr^{-1}) and Cyperaceae (30-49 grains cm^{2}yr^{-1}).

The beginning of TM-3 is marked by an increase in percentages and PARs of *Alnus* pollen (15-30%; 18-170 grains

TABLE III

Theta Values for Ten Mile and Wonder Lakes

Depth (cm)	Theta [1]	Standard Error
Ten Mile Lake:		
0	0.619	0.134
4	0.748	0.123
8	0.552	0.137
10	0.665	0.131
18	0.494	0.137
28	0.642	0.133
38	0.937	0.083
48	0.523	0.137
68	0.277	0.127
88	0.277	0.127
103	0.422	0.136
108	0.831	0.111
126	0.669	0.134
154	0.318	0.131
163	0.052	0.080
172	0.818	0.113
196	1.000	*
201	1.000	*
216	0.930	0.079
Wonder Lake		
100	0.001	*
120	0.167	0.112
140	0.407	0.136
161	0.998	0.038
180	0.775	0.120
200	0.917	0.091

[1] Theta values greater than 0.8 are interpreted to indicate a dominance of *Picea glauca* trees on the landscape (Anderson and Brubaker, 1986).

* Convergence criteria not met, suggesting samples that are nonanalogous to modern *Picea* populations.

TABLE IV

Percent loss-on-ignition

Wonder Lake		Ten Mile Lake	
Depth (cm)	% Orqanic	Depth (cm)	% Organic
12	9.8	0	5.7
23	12.3	10	5.5
35	11.1	20	5.2
50	11.6	30	5.5
67	11.9	40	3.6
72	12.2	50	5.8
82	3.5	60	7.6
92	14.6	70	6.5
100	11.4	80	6.6
115	12.1	90	6.5
129	12.0	100	6.2
149	11.0	110	7.7
152	8.1	120	5.1
161	11.6	125	2.1
172	9.7	130	8.3
180	6.5	140	9.7
189	6.3	150	8.8
200	10.8	160	7.4
205	9.9	170	13.1
213	9.2	180	8.2
240	7.7	190	8.4
252	4.3	200	7.6
271	3.6	210	8.8
283	2.9	220	9.8
290	6.1	230	12.9
297	1.1	240	12.9
300	6.0	250	10.6
306	6.4	260	9.0
308	7.1	270	4.8
		280	6.2

cm^2yr^{-1}). Percentages of *Picea* pollen remain high (>20%) throughout TM-3, with a slight increase in the uppermost samples. *Picea* thetas are generally below 0.8, indicating a predominance of *P. mariana* from 0 to 163 cm (Table III).

Wonder Lake

The Wonder Lake core has four pollen zones (Fig. 4). The oldest, WL-1, is dominated by Cyperaceae pollen (up to 70%) with substantial representation of *Salix* (up to 9%), Gramineae (up to 13%), *Artemisia* (up to 9%), and other herbaceous (up to 12%) pollen.

WL-2 is characterized by high percentages of *Betula* pollen (53-78%). WL-2A has low but consistent amounts of *Salix* (*ca.* 2%), Gramineae (3-15%), and *Artemisia* (<5%) pollen, and within-zone variations in Cyperaceae percentages (6-32%). WL-2B is distinguished from WL-2A by slight rises in *Picea* (*ca.* 8%) and *Alnus* (*ca.* 5%) pollen. *Picea* grains were measured in two samples and thetas indicate a predominance of *P. glauca* pollen (Table III).

Increased percentages of *Alnus* pollen (35-43%) with low but significant *Picea* percentages (7-13%) and moderate *Betula* percentages (35-44%) define WL-3. This pollen assemblage contrasts to the Ten Mile core, where the *Picea* pollen rise is rapid and precedes the major increase in *Alnus* pollen. A lower theta at 140 cm (*cf.* 161 cm) indicates a shift from primarily *P. glauca* pollen to *P. mariana* pollen within WL-3.

Pollen spectra in WL-4 are similar to WL-3 except *Picea* percentages (>25%) are greater, resulting in a slight decrease in *Alnus* and *Betula* pollen percentages (generally (<30%). *Picea* pollen percentages (<30%) decrease in the uppermost samples in WL-4 and low thetas suggest the continued importance of *P. mariana* pollen. A 32 cm plexiglass core (not illustrated here) could not be correlated with the Livingstone core, because of differences in pollen assemblages between the two cores (*e.g.*, *Picea* percentages exceed 50% in all plexiglass samples). This dissimilarity is difficult to explain, because the cores were taken side-by-side. Because of this ambiguity, we are reluctant to interpret the uppermost changes in *Picea* percentages at Wonder Lake as actual shifts in treeline.

RADIOCARBON DATES

Bulk sediment samples from both lakes were submitted for radiocarbon analyses (Table II). We think the Ten Mile dates are correct, because they are consistent with the regional chronostratigraphy (see Discussion). For the same reasons, the dates of the 166-175 cm, 195-205 cm, and possibly 215-225 cm samples from Wonder Lake seem suspiciously old. The presence of nearly 10% *Picea* at depths corresponding to ages of *ca.* 11,000 to 10,000 BP suggest an unusually early presence of trees within the Wonder Lake watershed (Anderson and Brubaker, 1986). The earlier arrival of *Picea* at Wonder Lake than at sites in eastern Alaska, where *Picea* is present *ca.* 9000 to 9500 BP, is unlikely, given Wonder Lake's greater distance from presumed postglacial source areas in northwestern Canada (Edwards and Brubaker, 1986). The presence of Late Wisconsinan piedmont glaciers in the proximity of Wonder Lake makes it equally difficult to imagine the presence of a full-glacial *Picea* refugium in nearby valleys. However, it must be noted that the 215-225 cm date at Wonder Lake is not completely unreasonable, and the 250-260 cm date corresponds to similar pollen stratigraphic changes at Eightmile Lake (Ager, 1983).

Sediment contamination by old carbon may be the cause of the apparent dating anomalies at Wonder Lake (MacDonald *et al.*, 1991). Bedrock within the Wonder Lake catchment includes small belts of carbonate rocks (Reed, 1961). A wide belt of Tertiary coal-bearing sediments, which extends below the McKinley valley just south (*i.e.*, up-glacier) from Wonder Lake, is perhaps a more significant contamination source. Finely ground lignite and/or carbonate from glacial scouring could have been easily redeposited in the moraines surrounding the lake. As postglacial erosional processes continued, these materials eventually would wash into the Wonder basin. The error associated with the input of dead carbon could vary throughout the core, depending on amount of vegetation cover, degree of soil development, and the proportion of contemporary carbon (*i.e.*, larger amounts of old carbon are required in younger sediments to produce comparable errors), thereby accounting for some dates that seem reasonable and some that seem too old.

VEGETATION HISTORY OF WONDER AND TEN MILE LAKES

The Wonder Lake catchment during latest glacial times was a treeless landscape dominated by herbs and *Salix* shrubs. The variety of minor herb taxa (Table V) indicate a mosaic of xeric and mesic communities (*e.g.*, Compositae, Cruciferae, Ranunculaceae). *Picea*, *Betula*, and *Alnus* were probably absent from the watershed, with the small amounts of their pollen representing long-distance transport. Given the proximity of Late Wisconsinan glaciers to the lake, the predominance of Cyperaceae and *Salix* pollen may reflect very local shoreline vegetation, with much of the bordering hillsides supporting sparse xeric communities. The low organic content of the sediment further suggests a non-productive lake system and minimal overland flow of organic material

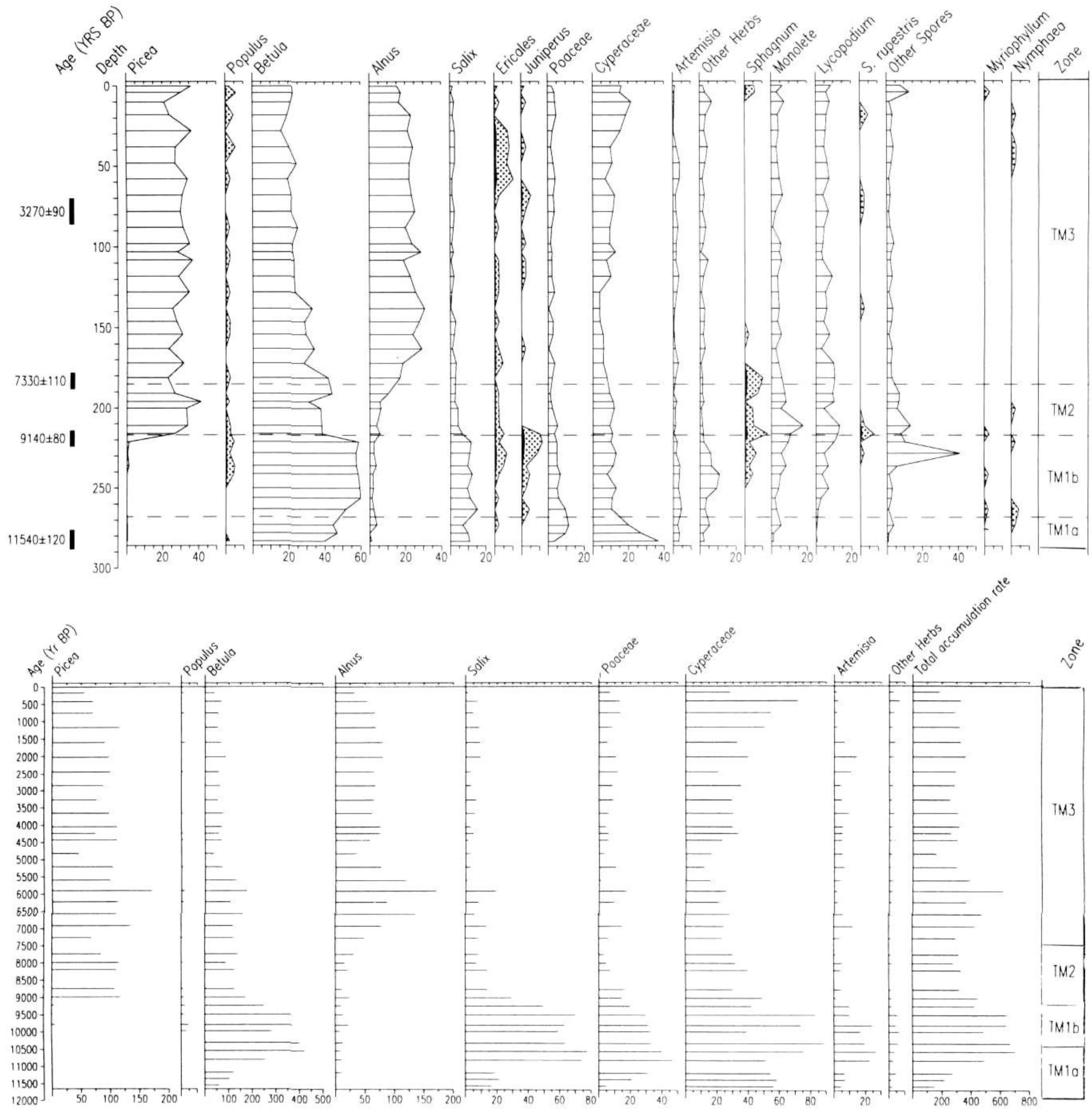


FIGURE 3. Pollen diagrams from Ten Mile Lake. A) Percentage diagram of major taxa. Percents are calculated based on all identified and unindentified pollen. Stippled pattern indicates 7x exaggeration. B) Accumulation rate diagram. Rates are expressed as number of grains deposited per cm^2 per yr.

Diagrammes polliniques du Ten Mile Lake. A) Diagramme en pourcentages des principaux taxons. Les pourcentages sont calculés sur la base de tout le pollen identifié et non identifié. Il y a eu exagération de 7x là où la trame est en pointillé. B) Diagramme du taux d'accumulation. Les taux sont fondés sur le nombre de grains déposés par cm^2/a.

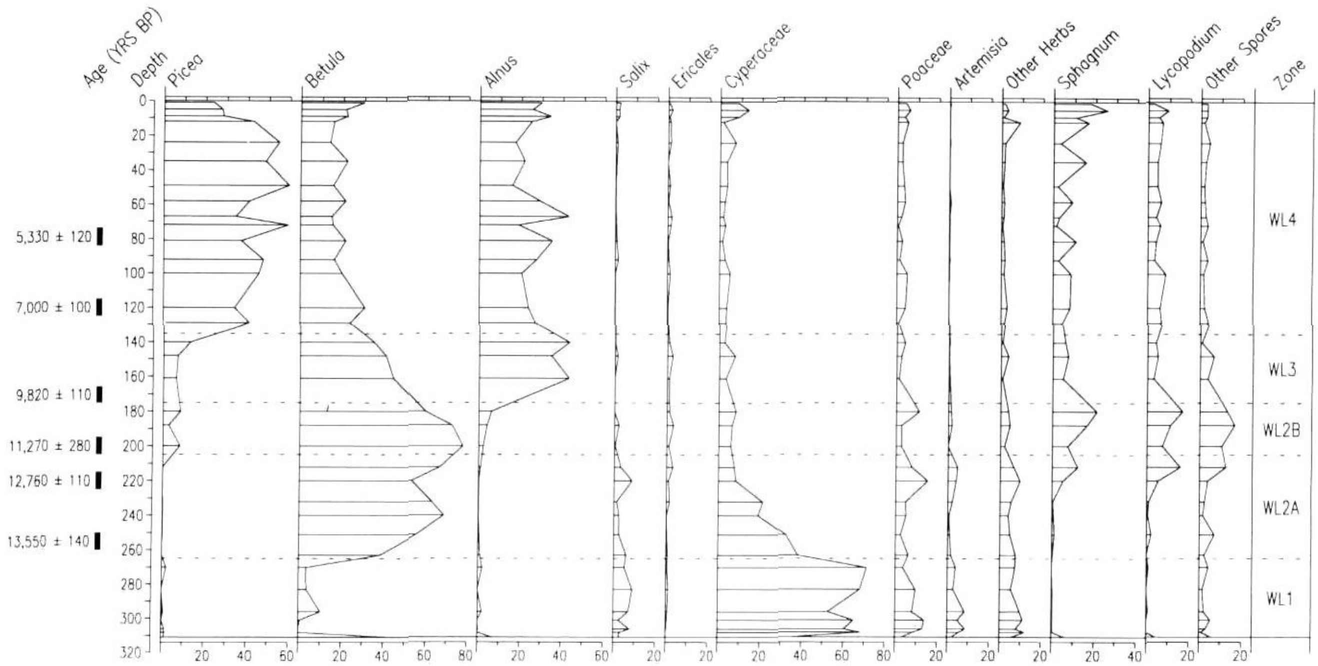


FIGURE 4. Percentage diagram of major taxa for Wonder Lake. Percents are calculated based on all identified and unidentified pollen.

Diagramme en pourcentages des principaux taxons du Wonder Lake. Les pourcentages sont calculées sur la base de tout le pollen identifié et non identifié.

into the basin. Probably the most favorable hillsides and lowlands supported a mesic graminoid tundra. *Salix* probably dominated scattered riparian and snowbed communities.

Betula shrubs established near Wonder Lake possibly as early as 13,500 BP. Pollen percentages at Ten Mile Lake suggest *Betula* was present by at least 11,500 BP, but PARs imply it was most abundant between 10,700 to 9300 BP. The vegetation during this period near Ten Mile Lake, and possibly Wonder Lake, may have been similar to the high *Betula* shrub tundra found in the forest-tundra ecotone of the modern Gulkana Uplands (Viereck *et al.*, 1992).

Populus pollen is absent from Wonder Lake, suggesting the tree was never present in the watershed. In contrast, *Populus* pollen occurs in trace amounts throughout the Ten Mile record beginning *ca.* 10,000 BP. A slight rise in *Populus* pollen at *ca.* 10,000 BP is also reported for nearby Tangle Lake (Schweger, 1981; Fig. 1). Interpretation of such minor but consistent percentages of *Populus* is difficult. Similar percentages occur in samples of modern pollen rain from lakes that have *Populus* growing along the shore as well as lakes located within the tundra hundreds of kilometers from *Populus* groves (Anderson and Brubaker, unpub. data). The similarity of ancient with modern percentages at Ten Mile, where *Populus* is currently absent, suggests that the tree probably never grew near the lake and that the pollen likely blew in from nearby populations (*e.g.*, the Delta or Copper River valleys; Ager and Brubaker, 1985; see also Discussion).

The *Picea* curve from Wonder Lake is unusual for, unlike other Alaskan diagrams, the main *Picea* increase is preceded by a period of constant, moderately high percentages (*i.e.*, between 150 and 205 cm). These *Picea* percentages, which are primarily *P. glauca*, are below the 10% threshold conventionally used to infer *Picea* presence, but well above the trace (<2%) amounts typical for sites receiving *Picea* pollen from long distance wind transport (Anderson and Brubaker, 1986). However, Hu *et al.* (1993), based on pollen and macrofossil data from Wein Lake, conclude that *Picea* trees can occur in a watershed when pollen percentages are as low as 5%. These results suggest that *Picea* may have existed in low numbers near Wonder Lake for some time prior to the establishment of larger forested areas. If the radiocarbon dates are correct, *Picea* could have established *ca.* 11,300 BP, which would be the earliest postglacial date for *Picea* in Alaska. Alternatively, the moderate *Picea* percentages could reflect a long distance source. Both interpretations are problematic, because the presence of a full-glacial *Picea* refugium at high elevation near alpine glaciers is unlikely, and a distant source area is difficult to define given the apparent arrival of *Picea* from northwestern Canada between 10,000 and 9000 BP (Edwards and Brubaker, 1986). We think that significant *Picea* populations were absent in the Wonder Lake region until *ca.* 7000 to 7500 BP, when the pollen spectra approximate the modern ones and *P. mariana* is the dominant *Picea* taxon.

The *Picea* curve from the upper 140 cm of the Wonder Lake core is equally problematic. Percentages generally exceed 40%, except for the uppermost 10 cm. Few modern pollen spectra in Alaska have such high *Picea* percentages, but those that do are from lakes in closed *P. mariana* forests (Anderson and Brubaker, 1986). In contrast, modern sites near treeline typically have 10% *Picea* pollen. The presence of a closed boreal forest in the Wonder Lake area during much of the Holocene seems doubtful (see Discussion), and

TABLE V

Taxa Included in Other Herb Category

Depth (cm)	Taxa
Wonder Lake	
12	Lamiaceae, Polygonaceae, Rosaceae, Saxifragaceae, Scrophulariaceae, Tubliflorae, *Thalictrum*,
35	Saxifragaceae, *Thalictrum*
58	Liliaceae, Onagraceae, Polemoniaceae, Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*
81	Ranunculaceae, Saxifragaceae, Rosaceae
100	Rosaceae, Saxifragaceae, Tubliflorae, Valerianaceae, *Polygonum* sect. *Bistorta*
120	Caryophyllaceae, Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*, *Thalictrum*
140	Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*
161	Rosaceae, Saxifragaceae
180	Saxifragaceae, Tubliflorae, *Polygonum* sect. *Bistorta*, *Thalictrum*,
200	Liliaceae, Ranunculaceae, Saxifragaceae, Tubliflorae
220	Cruciferae, Polygonaceae, Rosaceae, Ranunculaceae, Saxifragaceae, Scrophulariaceae, Umbelliferae, *Polygonum* sect. *Bistorta*
240	Liliaceae, Polygonaceae, Rosaceae, Saxifragaceae, Valerianaceae, *Polygonum* sect. Bistorta, *Thalictrum*
263	Chenopodiaceae, Onagraceae, Polygonaceae, Ranunculaceae, Tubliflorae, Saxifragaceae, Scrophulariaceae, *Polygonum* sect. *Bistorta*, *Thalictrum*,
283	Chenopodiaceae, Liliaceae, Gentianaceae, Ranunculaceae, Rosaceae, Saxifragaceae, Scrophulariaceae, Tubliflorae, *Rumex*
301	Caryophyllaceae, Polemoniaceae, Polygonaceae, Ranunculaceae, Rosaceae, Rubiaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*, *Thalictrum*
Ten Mile Lake	
0	Cruciferae, Ranunculaceae, Rosaceae
4	Rosaceae, Polemoniaceae, Tubliflorae, Valerianaceae, *Polygonum* sect. *Amphibium*
8	Rosaceae, Tubliflorae, Saxifragaceae
10	Rosaceae, Tubliflorae, Saxifragaceae, Valerianaceae, *Rumex*
18	Rosaceae, Saxifragaceae, Tubliflorae, *Saxifraga tricuspidata*
28	Cruciferae, Rosaceae, Umbelliferae, Saxifragaceae, *Rumex*
38	Ranunculaceae, Rosaceae, Saxifragaceae, Valerianaceae, *Polygonum* sect. *Amphibium*
48	Onagraceae, Rosaceae, Saxifragaceae, *Rumex*
58	Rosaceae, Saxifragaceae, Tubliflorae
68	Caryophyllaceae, Rosaceae, Saxifragaceae, Valerianaceae, *Rumex*
78	Cruciferae, Rosaceae, Saxifragaceae, Umbelliferae, Valerianaceae
88	Cruciferae, Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*, *Saxifraga tricuspidata*
98	Rosaceae, Saxifragaceae
103	Rosaceae, Saxifragaceae,
108	Ranunculaceae, Rosaceae, Saxifragaceae, Tubliflorae, Umbelliferae, Valerianaceae, *Rumex*
118	Rosaceae, Saxifragaceae, Tubliflorae, Valerianaceae
128	Rosaceae, Saxifragaceae
138	Cruciferae, Onagraceae, Polemoniaceae, Rosaceae, Saxifragaceae
146	Rosaceae, Valerianaceae, *Polygonum* sect. *Bistorta*
154	Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*, *Saxifraga tricuspidata*
163	Cruciferae, Ranunculaceae, Rosaceae, *Polygonum* sect. *Bistorta*
172	Caryophyllaceae, Rosaceae
181	Onagraceae, Rosaceae, *Rumex*
191	Rosaceae
196	Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*
200	Rosaceae
211	Rosaceae, Valerianaceae
216	Caryophyllaceae, Rosaceae, Saxifragaceae
221	Rosaceae, *Rumex*
228	Caryophyllaceae, Rosaceae, Saxifragaceae, *Polygonum* sect. *Bistorta*, *Rumex*
236	Ranunculaceae, Rosaceae, Saxifragaceae, Tubliflorae, Umbelliferae, *Saxifraga tricuspidata*
241	Caryophyllaceae, Ranunculaceae, Rosaceae, Saxifragaceae, Tubliflorae
250	Chenopodiaceae, Onagraceae, Ranunculaceae, Rosaceae, Saxifragaceae
256	Caryophyllaceae, Rosaceae, Saxifragaceae, Tubliflorae, *Rumex*
263	Chenopodiaceae, Polemoniaceae, Rosaceae, Saxifragaceae
273	Chenopodiaceae, Ranunculaceae, Rosaceae, Saxifragaceae, Valerianaceae
278	Chenopodiaceae, Rosaceae, Tubliflorae, *Rumex*
283	Chenopodiaceae, Rosaceae, Saxifragaceae, Tubliflorae
288	Rosaceae

the high *Picea* percentages probably reflect over-representation of lowland species as documented for other mountainous regions (Gaudreau and Webb, 1985). A recent change in *Picea* populations, as suggested by a decline of *Picea* percentages in the uppermost part of the core, is also questionable, because *Picea* percentages from a plexiglass core taken adjacent to the Livingstone site do not show a similar pattern. Additional data will be needed before conclusions can be made about recent treeline behavior near Wonder Lake.

The *Picea* percentages (*ca.* 20-30%) in the Ten Mile core are more typical of forested areas, although these data may reflect the effects of wind dispersal from *Picea* populations in nearby valleys. *Picea* measurements suggest the early Holocene population was predominantly *P. glauca* with *P. mariana* becoming important *ca.* 7000 BP. Although *Picea* percentages do not vary greatly in this core, slight fluctuations in PARs provide some tantalizing evidence for shifting treeline positions during the Holocene. *Picea* PARs are highest (>100 grains $cm^2 yr^{-1}$) between *ca.* 9000 to 8000 BP and 7000 to 5900 BP, with lowest values *ca.* 8000 to 7000 BP and near core top. These data may indicate that treeline was at higher elevation during the early Holocene followed by a retreat between 8000 and 7000 BP. The decline in *Picea* PARs over the last 1000 years is probably spurious, reflecting use of water-rich samples from the plexiglass corer. These inferences concerning changing treeline location must be taken very skeptically, but the data are not inconsistent with the regional patterns discussed later.

Alnus is the last major pollen taxon to appear at both sites. *Alnus* establishes *ca.* 7300 BP at Ten Mile Lake. The time of arrival of *Alnus* in the Wonder catchment is less certain, but probably occurred before 7000 BP and possibly as early as 9800 BP. Although the radiocarbon results suggest that *Alnus* may have been present as early as 9800 BP, such an early age is unlikely because pollen records from other sites indicate *Alnus* spread throughout most of Alaska between 8000 and 7000 BP (Anderson and Brubaker, in press; Hu *et al.*, 1993). Although *Alnus* percentages are high in both the Ten Mile and Wonder diagrams, the shrubs probably were restricted to riparian thickets, lake-shore communities, and/or mountain draws.

DISCUSSION

FOREST DEVELOPMENT IN SOUTH-CENTRAL ALASKA

The earliest evidence of trees in south-central Alaska is from Hidden Lake, central Kenai Peninsula (Fig. 1), where scattered stands of *Populus* occurred *ca.* 10,300 BP (Ager and Brubaker, 1985). *Populus* established near Ten Mile, Tangle, and Eightmile Lakes by *ca.* 10,000 (Schweger, 1981; Ager, 1983). The 70 Mile Lake (Fig. 1) record indicates that *Populus* arrived in or near the uplands bordering the Copper River some time prior to 9100 BP, but inadequate dating prevents more precise estimates of the time of establishment. These results suggest that *Populus* expanded quickly throughout much of south-central Alaska during the earliest Holocene. Ager (1983) inferred that the trees were restricted to interfluves or warm, well-drained upland sites but that the regional vegetation was predominantly a *Betula-Salix* shrub tundra.

The above records also indicate that *Picea* (probably *P. glauca*) arrived in south-central Alaska at least 1000 years after *Populus*, *Picea glauca* macrofossils from Tangle Lakes, which today is *ca.* 25 km beyond treeline, are dated to 9100 BP and document an extension of *Picea* treeline during the early Holocene (Schweger, 1981). *Picea* was also present in the Copper River lowlands by 9000 BP, but did not arrive in the central Kenai Peninsula until *ca.* 8000 BP and at Eightmile Lake until *ca.* 7500 BP (Ager, 1983). The early coniferous forests, dominated by *P. glauca*, were probably restricted to warm, well-drained low and mid-elevation sites. The forest composition changed during the middle Holocene to include large numbers of *P. mariana*, and the landscape cover of forests probably became more extensive at this time. The shift in *Picea* dominance almost certainly reflects a regional increase in cool, moist, nutrient-poor soils.

THE POPULUS FORESTS OF ALASKA

The period 9000 to 11,000 BP has been inferred to be a time of maximum summer warmth in northern Alaska (Brubaker *et al.*, 1983; Anderson *et al.*, 1988). This conclusion is based on expanded populations of *Populus* (most likely *P. balsamifera*), other plants (*e.g.*, *Myrica*, *Typha latifolia*), and animals (*e.g.*, McCulloch and Hopkins, 1966; Edwards and Brubaker, 1986; Anderson, 1988; Anderson *et al.*, 1988). Anderson *et al.* (1988) suggested that for the southern flanks of the Brooks Range, *Populus* populations were restricted to gallery forests and nearby south-facing hillslopes but were absent at mid- to high elevations. However, Ager (1983) and Hu *et al.* (1993) postulated that rather extensive *Populus-Salix* forests characterized large areas of lowland Alaska at this time.

Because the pollen spectra from the *Populus* period lack modern analogs (Anderson *et al.*, 1989), vegetation reconstructions are particularly difficult. Consequently, Anderson and Brubaker (in press) have suggested that *Populus* pollen data should only be interpreted as a simple presence or absence of the trees within the region. This approach, however, may be too simplistic. Large variations in *Populus* percentages (from trace amounts to greater than 40%) exist in the fossil records, suggesting significant variation in the landscape. The possibility of regional differences in the abundance of ancient *Populus* populations is also suggested by the range of interpretations of the *Populus* pollen records (*i.e.*, relatively abundant forest *vs.* restricted interfluvial populations). If regional patterns in *Populus* occurred, some spatial coherency would be expected if the fossil pollen data were mapped.

Standard isopoll maps are difficult to interpret because of the large variation in pollen percentages (Anderson and Brubaker, in press). However, an interesting pattern emerges when the pollen data are summarized by ranking *Populus* percentages on a scale of 0 to 4 and the sites are classified by elevation (Fig. 5; Table I). We interpret rank 0 (0% *Populus* pollen) to indicate absence or extreme scarcity of trees in the catchment, with higher rankings reflecting increasing importance of *Populus* trees in the local and regional landscapes.

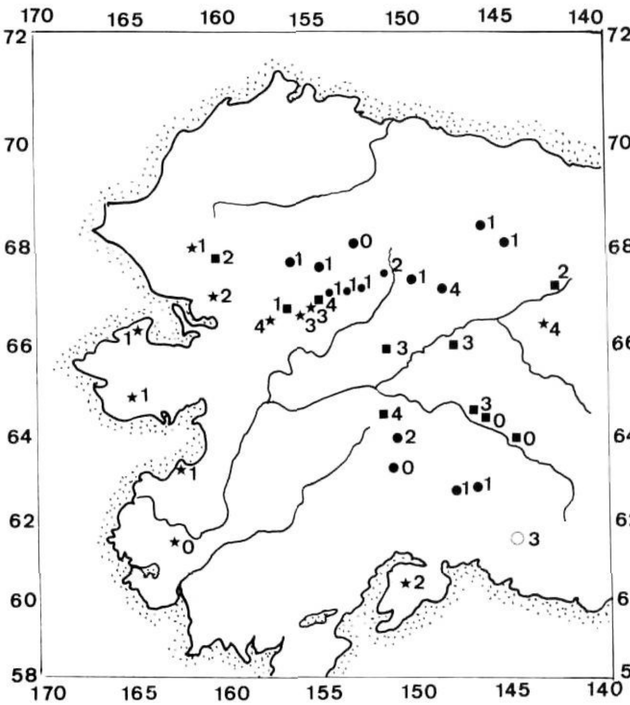


FIGURE 5. Map of lacustrine pollen records indicating *Populus* rank and elevation. The key to the *Populus* ranks is: 0 =absent, 1 = trace to 5%, 3 = 5 to 10%, 4 >15%. The key to elevation classes is: ★= 0-200 m, ■= 200-400 m, ○= 400-600 m, ●= 600 m.

Carte des inventaires polliniques lacustres de Populus *illustrant les pourcentages et les altitudes. Pourcentages: 0 = absent, 1 = trace à 5%, 3 = 5 à 10%, 4 >15%. Classes d'altitude: ★= 0-200 m, ■= 200-400 m, ○ = 400-600 m, ● 600 m.*

Ranks reflect the highest percentage recorded at a site during the *Populus* period. Sites are referred to as low to mid-elevation (<400 m) and high elevation (>400 m).

All sites except Wonder, Birch, George, Tungak, and Chandler Lakes have at least minor amounts of *Populus* pollen during the *Populus* interval. High elevation sites tend to have lowest and low elevations highest percentages. The major patterns in the *Populus* data suggest that extensive populations occurred in the lowlands with isolated stands or clones restricted to upland settings. These data also suggest that a broadleaf forest may have covered much of what is now *Picea mariana-P. glauca* forest.

THE PICEA FORESTS OF ALASKA

Holocene pollen records from lakes in the forest and forest-tundra ecotone of northern Alaska indicate the presence of open *P. glauca* forests in northeastern and north-central Alaska 9500 to 8000 BP, a decline in *P. glauca* populations between 8000 and 7000 BP, and a rapid establishment at *ca.* 6000 BP of *P. mariana-P. glauca* forests across most of the region. The modern composition and distribution of boreal forest was in place 5000 to 4000 BP (Anderson and Brubaker, in press). There is insufficient evidence to suggest that *Picea* populations extended beyond latitudinal or altitudinal treelines during the postglacial.

Pollen records in south-central Alaska are too sparse and poorly dated to examine *Picea* history with similar detail as for the north. Nonetheless, these records can be used to infer general Holocene migrational patterns of *Picea*; insufficient sites exist to document altitudinal fluctuations in treeline. As in the north, postglacial *Picea* populations first appeared in the east and then spread westward. For example, *Picea* percentages increased prior to 9000 BP at Ten Mile, Tangle, and 70 Mile Lakes, but did not rise until *ca.* 7500 BP at Eightmile Lake. Unfortunately, the poor chronological control for Wonder Lake and the lack of data from the upper and middle Kuskokwim drainage (Fig. 1) do not permit the dating of its spread farther to the west or southwest. However, Ager (1983) inferred that *Picea* populations probably were present in the Yukon-Kuskokwim delta by 5500 BP, based on low *Picea* pollen percentages at Tungak and Puyuk Lakes (Fig. 1). *Picea* populations also moved rapidly southward in south-central Alaska during the early Holocene, establishing in the central Kenai Peninsula by 8000 BP.

The similarity in the arrival times of *Picea* in south-central and northern Alaska (*i.e.*, *ca.* 9000 BP in the eastern portion of the state and *ca.* 5000 BP in western Alaska) suggests that the northern and southern coniferous forests did not differ significantly as regards an east-to-west migration across the state. Yet the forest histories of south-central and northern Alaska do vary. The southern pollen diagrams, with the exception of a discontinuous record from Tangle Lakes, do not imply a fluctuation in the size of early Holocene *Picea* populations, as found in northern Alaska. *Picea* percentages in the southern sites (except Wonder Lake) increase sharply to greater than 20% in the early Holocene and remain high throughout the remainder of the record, suggesting that population densities have been similar to today during most of the Holocene. In northern Alaska, the reduction in *P. glauca*-dominated forests has been attributed to cooling of middle Holocene climates (Anderson and Brubaker, 1993; Hu *et al.*, 1993). The early Holocene *Picea* forests of south-central Alaska (presumed to be *P. glauca* based on extrapolation of the Ten Mile and Wonder lakes data) evidently were unaffected by this climatic change. If tree density was high, as suggested by the high percentages of *Picea* pollen, the forests could have created their own microenvironment, which is less susceptible to decreasing temperatures, thereby permitting the continuation of well developed forests throughout the Holocene. The only clear evidence of a fluctuation in *Picea* populations is from Tangle Lakes, where *P. glauca* macrofossils indicate the tree's presence by 9100 BP, with an apparent decline in the population, as indicated by low *Picea* pollen percentages in a 4700 year core, some time after 9100 BP. Because Tangle Lakes is at a higher elevation, it is possible that the vegetation during the early Holocene was a forest-tundra with a relatively sparse tree cover. In this situation, a decline in *Picea* near Tangle Lakes would be conceivable, even though lower elevation populations remained unchanged.

CONCLUSIONS

Available data from south-central Alaska clearly are too meager to evaluate the role of climate in the development of the southern boreal forest. Consequently, we lack sufficient data to postulate how this forest may respond to global warming and whether it will respond differently than the northern boreal forest. The above data, however, hint at possible variations in the forest development, even though the northern and southern Alaskan forests share the same species composition. A dense grid of well-dated fossil records must be collected before the preliminary vegetation history presented here can be evaluated and any "working climatic hypotheses" can be formulated. As illustrated by the Wonder Lake core, reliable dating is often a problem in Alaskan lakes, which typically have low organic content and lack plant macrofossils, and therefore require large bulk sediment samples for dating. Steps must be taken to improve dating control by less reliance on bulk dates (*e.g.*, greater use of terrestrial macrofossils and development of techniques to concentrate sufficiently clean samples of pollen for radiocarbon assays). Other problems must also be addressed in order to understand the history of climate-vegetation interactions in south-central Alaska. One is the apparent over-representation of certain pollen taxa, in particular *Picea*, at forest-tundra sites. Long distance dispersal of low elevation taxa is not a significant factor for the interpretation of pollen records from the Brooks Range, but the greater topographic variability of the Alaska Range may result in greater transport of valley taxa to higher elevations making the interpretation of local vegetation more difficult than in northern Alaska. A detailed study of altitudinal variation in modern samples is vital to help interpret the fossil records. In addition, *Picea* pollen must be differentiated in both modern and fossil samples to compare the histories of these species with that described for northern Alaska. Finally, multiple proxy data sets (*e.g.*, pollen, macrofossil, sediment geochemistry, diatoms) will be especially important to describe the development of the modern boreal forest of south-central Alaska and its relationships to late Quaternary climatic changes.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation (ATMS-8915415) and the Far Eastern Branch of the Russian Academy of Science. We especially appreciate the help of Al Werner who shared unpublished data and ideas with us about Wonder Lake. We also would like to thank V. Davydov, L. Kotova, I. Gushina, M. Miller, A. Polujan, and T. Wheeler for their help in the field. The National Park Service and the Bureau of Land Management kindly granted permission to core the lakes. We also thank T. Anderson and an unnamed reviewer for comments on an earlier version of the manuscript and P. Heiser and L. Carlson for help in manuscript preparation.

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