PALYNOLOGICAL AND PALEOCLIMATIC STUDY OF THE LATE QUATERNARY DISPLACEMENT OF THE BOREAL FOREST-TUNDRA ECOTONE IN KEEWATIN AND MACKENZIE, N.W.T., CANADA

Harvey Nichols

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INSTITUTE OF ARCTIC AND ALPINE RESEARCH • UNIVERSITY OF COLORADO

PALYNOLOGICAL AND PALEOCLIMATIC STUDY
OF THE LATE QUATERNARY DISPLACEMENTS OF THE BOREAL FOREST-TUNDRA ECOTONE
IN KEEWATIN AND MACKENZIE, N. W. T., CANADA

by

Harvey Nichols

Institute of Arctic and Alpine Research

and Department of Environmental, Population and Organismic Biology

University of Colorado

Boulder, Colorado 80309

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"One area of research that needs to be developed in northern Canada is the study of natural climatic change. If one can understand the mechanics and impact of the natural changes, one is halfway to understanding the implications of man-made changes."

(Dr. F. K. Hare, Director-General, Research Coordination Directorate, Environment Canada, p. 29, in The Natural Environment of the Canadian North. Environment Canada, 1972, mimeo)

"In man's quest to utilize global resources, and to produce adequate supply of food, global climatic change constitutes a first order environmental hazard which must be thoroughly understood well in advance of the first global indications of deteriorating climate."

(Kukla, G. J. and R. K. Matthews, Science, 178, 190-191. 1972)

Second impression 1977

FOREWORD

The historical antecedent of this study is the work by Dr. Nichols on Holocene tree line fluctuations and climatic changes done at the Department of Meteorology (Center for Climatic Research), University of Wisconsin, Madison, in post-doctoral association with Prof. Reid A. Bryson and Dr. J. A. Larsen.

That work produced a preliminary schematic reconstruction of ecotonal displacement and summer paleotemperatures along a section of meridian 100°W in southern Keewatin, which has now been tested and validated in this study along an east-west 1400 km stretch of the ecotone west of Hudson Bay.

This study provides a comprehensible and sensitive paleoclimatic record for the central Canadian sub-arctic and low arctic against which can be evaluated the climatic alterations of the high arctic, where paleoclimatic inferences from sparse palynological studies are presently less clearly made. The related study of contemporary forest pollen influx into the tundra (NSF GB-33497) strongly supports these fossil studies by providing modern analogs for past pollen deposition. It also provides preliminary data for the understanding of paleowind trajectory changes in direction and strength as vectors of exotic pollen into high arctic areas such as Baffin Island, an important consideration in the paleoclimatic reconstructions of that region.

This work, therefore, fits into the context of interdisciplinary research being undertaken by the Institute of Arctic and Alpine Research. Evaluation of climatic fluctuations over the past 10,000 to 1,000,000 years or more, and hence of changing environments, is considered fundamental to an understanding of present cold climate landscapes and processes operating therein. There is a broader concern, however: Over the past two decades world civilization, dependent ultimately on its food producing capacity, has moved from a period of generally favorable climate to one of deteriorating climate coupled with overpopulation. Thus, analysis of climatic and associated ecological changes becomes an occupation that can afford vital contributions to assessment of future resource requirements if predictive models can be developed. Any such model will depend heavily upon understanding past changes and their causes. The Arctic is especially important in this respect because of its long recognized impact on the world's atmospheric circulation at large.

Jack D. Ives

Jack D. Ives
Director, INSTAAR
15th July 1975

ACKNOWLEDGEMENTS

"Seed money" for fieldwork at Coppermine which began this project was provided by the University of Colorado Council for Research and Creative Work. The bulk of the support was then provided by the National Science Foundation, grant GB-25591, with some field support from GB-33497 which studied areas of overlapping interest. The Windy Lakes section from Baffin Island was collected and partly analyzed both under Dr. J. T. Andrews' contract 73-66 from Parks Canada and his Univeristy of Colorado CRCW grant. Dr. J. D. Ives as Director of INSTAAR provided strong support for the establishment of two palynology laboratories (by the University of Colorado Graduate School) in which the analytical work was done.

I am deeply grateful to Margaret F. Nichols and Susan K. Short for their prolonged work on the chemical preparation and pollen analyses on which this project rests. Margaret Nichols was responsible for the development of the computer programming (with Margaret Eccles) which allowed the machine production of publication-ready pollen diagrams. My thanks also go to INSTAAR colleagues: Dr. J. T. Andrews for much stimulus especially as regards to the clustering routines, for providing Baffin Island samples, and for help with radiocarbon dating; Dr. R. G. Barry for climatological comments; Dr. J. D. Ives for tree line discussions; and Dr. P. J. Webber for bryophyte determinations. Dr. R. C. Koeppen kindly identified wood samples. Local assistance in the field was given by G. Baker, T. Hopwood, K. Novak, A. Stevens, and pilots G. McVeagh and R. O'Brien. Kathleen Salzberg edited the manuscript and Cherie Baxley and Eileen Owen typed it.

I thank officers of the Echo Bay Mining Company, Port Radium, for field assistance.

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PREFACE

The aim of this study was to discover the Holocene displacements of the Canadian boreal forest-tundra ecotone resulting from climatic changes. Previous work (Nichols, 1967a, 1967b) had used palynology and peat stratigraphy to extend the initial findings of ecotonal shifts reported by Bryson, Irving, and Larsen (1965). These two studies involved vegetation boundary shifts caused by mean Arctic Front displacement in summer. They related to events along approximately 100^{o}W between 62^{o}N and 65^{o}N, but appeared to have wider applicability (Nichols, 1967b, 1972, 1974). This project extended the earlier studies along the ecotone to test the validity of the schematic models of ecotonal displacement and paleotemperature reconstructions (Nichols, 1967b).

The ecotonal shifts and the associated alterations in paleowind directions were also believed to transport varying amounts of boreal forest pollen into the tundra and two short tundra pollen profiles were analyzed using a modification of routine methods to learn whether exotic pollen influx in the tundra could identify tree line movements.

Six ecotonal pollen diagrams are presented here (in addition to two from the High Arctic) and added to published evidence, they exhibit a cohesive response to climatic changes along the entire length of the ecotone so far examined by me, approximately 1400 km.

NOTES ON DATING

Basal radiocarbon dates were provided free by the Geological Survey of Canada Radiocarbon Laboratory, Ottawa, courtesy of Dr. W. Blake, Jr. and Dr. J. A. Lowdon. Twenty-three other dates were purchased from commercial radiocarbon laboratories and several other dates were obtained without charge.

However, there were numbers of significant vegetational changes which could not at present be dated for lack of funding. Their dates were interpolated from the ^{14}C dated sedimentation graphs, and these estimated dates are distinguished in the text from the ^{14}C assays by their lack of laboratory numbers and standard deviations. Estimated dates on peats which had variable growth rates may involve abnormally large errors, but the interpolated ages are fairly closely controlled by ^{14}C determinations, and these samples are now being submitted for radiocarbon assay to check the estimates.

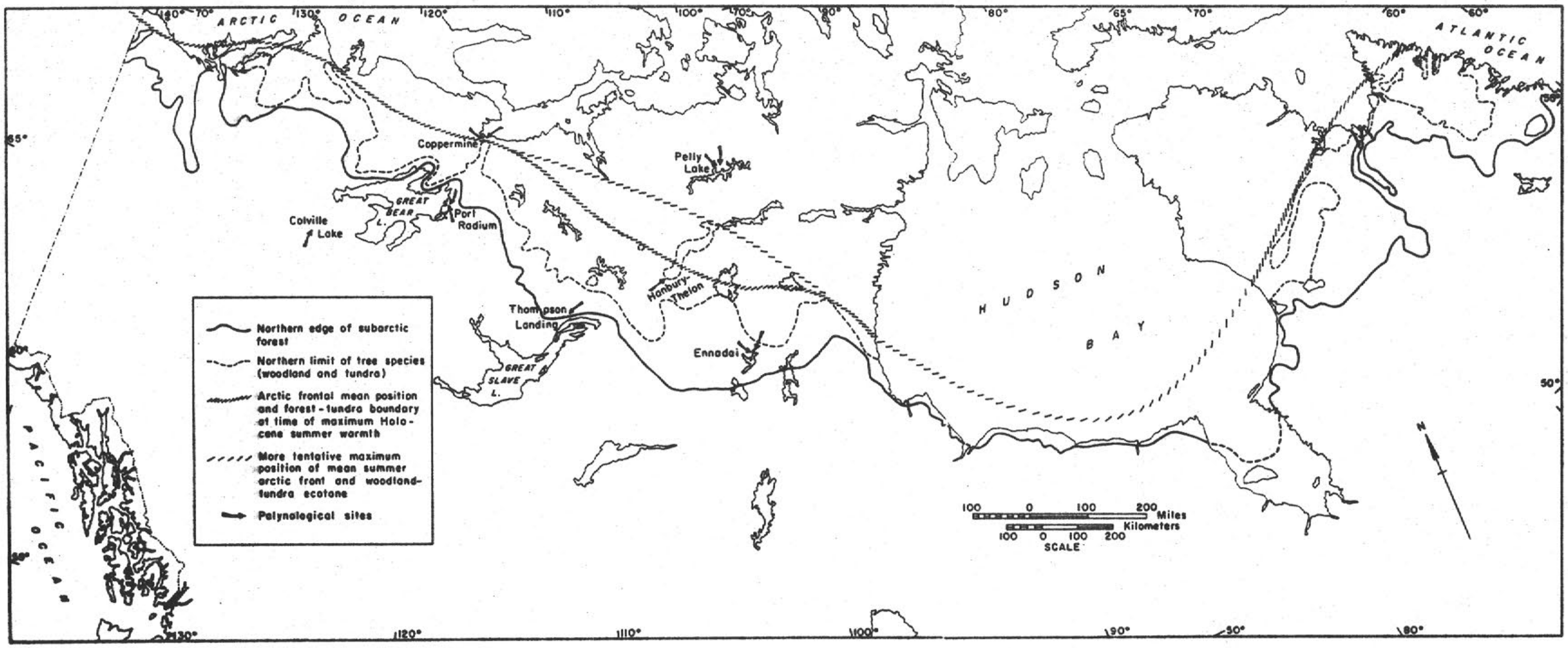

Figure 1: Location map of northern Canada showing the tentative reconstruction of the most northerly mean summer position of the Arctic Front during the hypsithermal. These smoothed curves connect locations of relict spruce clones which are thought to represent the northernmost extension of the forest-tundra ecotone. The palynological sites bracketing the ecotone contain evidence of prolonged Holocene tundra conditions (Pelly Lake, Coppermine) or micro- and macro-fossil proof of substantial northward displacement of the forest.

SUMMARY

A series of six pollen diagrams was prepared from peat profiles from four sites along the Canadian boreal forest-tundra ecotone to detect ecotonal displacements due to climatic changes. Two additional short profiles from the High Arctic tundra were prepared to examine the sensitivity of such analyses to influx of exotic forest pollen due to paleowind shifts and forest displacements. Bryson's (1966) hypothesis of the control of northern forest by the mean summer position of the Arctic Front was used throughout.

Palynological interpretation was assisted by use of "absolute"[1] as well as relative counts, by comparison of fossil data with numerous modern pollen counts from Tauber traps and moss and lichen polsters, by peat stratigraphic analyses, and recognition of plant macrofossils. The palynological data were transferred to punched cards, and computer programs were developed to produce publication-ready pollen diagrams by machine plotter (CALCOMP)(p.81). Clustering routines were used to help distinguish the most significant vegetational changes in the diagrams, and thus the prime levels for radiocarbon dating (p.54). The use of peat profiles involved the comparison of sometimes fragmentary stratigraphic records, compared to lake sediments, but the sensitivity of the peat records amply compensated for that. Rates of peat accumulation of up to 1 cm per 3 years allowed routine sampling at intervals of less than a decade in some profiles. Changes in peat type and rates of growth (involving order of magnitude changes in accumulation rates) were strongly indicative of environmental/climatic changes.

The broad outline of the climatic changes is as follows:

The oldest sediments dated back to 6200 BP in an area deglaciated about 8000 BP (Bryson et al., 1969) and represented a spruce forest environment substantially warmer in summer than now. This hypsithermal warmth continued until 4800 BP, with possible evidence of cooling at 5600 to 5500 BP and a maximum of summer warmth from 5300/5200 BP to 4800 BP.

A cold summer episode from 4800 BP for several centuries expanded tundra almost down to its modern limit, and recovery took place between 4500 and 4250 BP, depending on lag in plant colonization. At 4200 BP there was a brief cooling, followed by a peak of summer warmth around 4000 to 3900 BP. From about 4000 to 3000 BP there were frequent forest fires throughout the northern forest. The forest was able to recover from these until 3500 BP when widespread and broadly synchronous fires swept the ecotone from one end to the other over a period of 100 or 200 years. This was due to summer expansion of cold dry arctic air masses over the northernmost forest, which then

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[1]The quotes around "absolute" are a reminder that present pollen counting methods described as absolute are not truly so. These "absolute" counts relied on modified Jørgensen (1967) dry-weight methods.

changed to tundra until 3300 BP. By 3200 BP some woodland regeneration registered milder summers, but by 3000 BP tundra expanded southwards in a prolonged episode of colder summers. Further cooling at 2500 BP forced another southward ecotonal retreat and damaged the tundra plant cover so that windblown sand was incorporated in peat. Maximum cooling occurred at 2200 to 2100 BP. When warming followed, vegetational recovery was registered at several dates between 2000 and 1500 BP, due probably to plant migrational lag. Brief cooling occurred at 1400 BP. Warming around 1200 to 1000 BP allowed a minor woodland advance, followed by a major cooling after 800 to 600 BP which caused a major forest retreat. Many peat profiles ceased growth and have not regenerated since. Some minor warming may have been registered within the last 150 years at a minority of sites.

A survey of eight ecotonal pollen diagrams spanning 1400 km east-west from the west shore of Hudson Bay to beyond Great Bear Lake demonstrates clear synchrony and parallelism in the movement of this boundary in response to climatic changes over at least the last 6000 ^{14}C years. There is some preliminary evidence which may indicate a greater amplitude of Holocene ecotonal displacement in the continental interior of Keewatin and Mackenzie than in northwest Canada, possibly 400 km as compared to about 250 km. This was presumably due in the northwest to the diminished movement in the upper atmospheric ridge due to compression between the Cordillera and the cold Arctic Ocean. This may imply that the Canadian northwest was less sensitive to paleoenvironmental change than the continental interior.

An apparently normal aspect of the stability of this forest ecosystem was the instability of fairly frequent major fires at intervals of one to two centuries, from which the forest recovered usually within fifty years during the long episodes of favorable climate. It is tentatively deduced from the pollen diagrams that sizable areas of open woodland (e.g., north of Great Bear Lake) may be out of equilibrium with the modern climate and may be overdue for a major fire, after which the trees might be replaced by shrub-tundra.

A schematic reconstruction is presented of the changes in ecotonal location and the deduced summer paleotemperatures, which broadly supports earlier tentative findings (Nichols, 1967a, 1967b).

CHAPTER I

THE MID- AND LATE HOLOCENE HISTORY OF VEGETATION AND CLIMATE AT PORT RADIUM, DISTRICT OF MACKENZIE, N.W.T., CANADA

Topography and Vegetation

Port Radium is a mining camp on the eastern McTavish arm of Great Bear Lake in the northern lichen woodlands, about 80 km (50 miles) south of the forest-tundra ecotone as depicted by Rowe (1972) and as reported by pilots.

Black and white spruce (*Picea mariana* and *P. glauca*) form open woodland on generally thin soils with frequent rock outcrops. The spruces frequently assume the spire habit characteristic of the northernmost forest under climatic stress. Tree birches (*Betula papyrifera*), willows (*Salix* spp.), and alders (*Alnus crispa*) are widespread. Wild roses (*Rosa* sp.) and fireweeds (*Epilobium angustifolium*) are common in areas disturbed by man. Topographically, the region is quite varied, with bare rock hills almost devoid of trees flanked by scree slopes, interspersed with colluvium-filled valleys containing deltaic and beach materials from higher water levels of Great Bear Lake and small rock basin lakes.

Climatic Data (see following table, page 2)

The Sites

The human impact resulting from uranium and later silver mining is considerable; three peat profiles have been exposed beside gravel roads and mining adits. The peat profiles sampled are Port Radium A, at 66° 06' N, 117° 58' W; Port Radium B, at 66° 05' 30" N, 117° 59' W; and Port Radium C, at 66° 05' N, 118° 01' W. The peat profiles were cleaned and excavated by knife, spade, and chainsaw, and the samples wrapped in aluminum foil for transport. The "B" profile was damaged by U.S. Customs inspection and has not been analyzed.

Port Radium, Site A (Figures 2-4)

Peat Stratigraphy: an abbreviated summary

Depth cm	
0 - 9	Very fibrous and unconsolidated, fresh Ericaceae roots and plant litter.
9 - 24	Humified fibrous black peat with charcoal.
24 - 66	Dark brown humified fibrous peat.
66 - 67½	Light brown unhumified *Sphagnum* peat.
67½- 72	Dark brown humified peat.
72 - 74	Light brown unhumified *Sphagnum* peat.
74 - 98	Very dark brown humified peat, with lenses of unhumified

Port Radium: 66° 05' N, 118° 02' W. Elevation 191 m a.s.l. (628 ft)

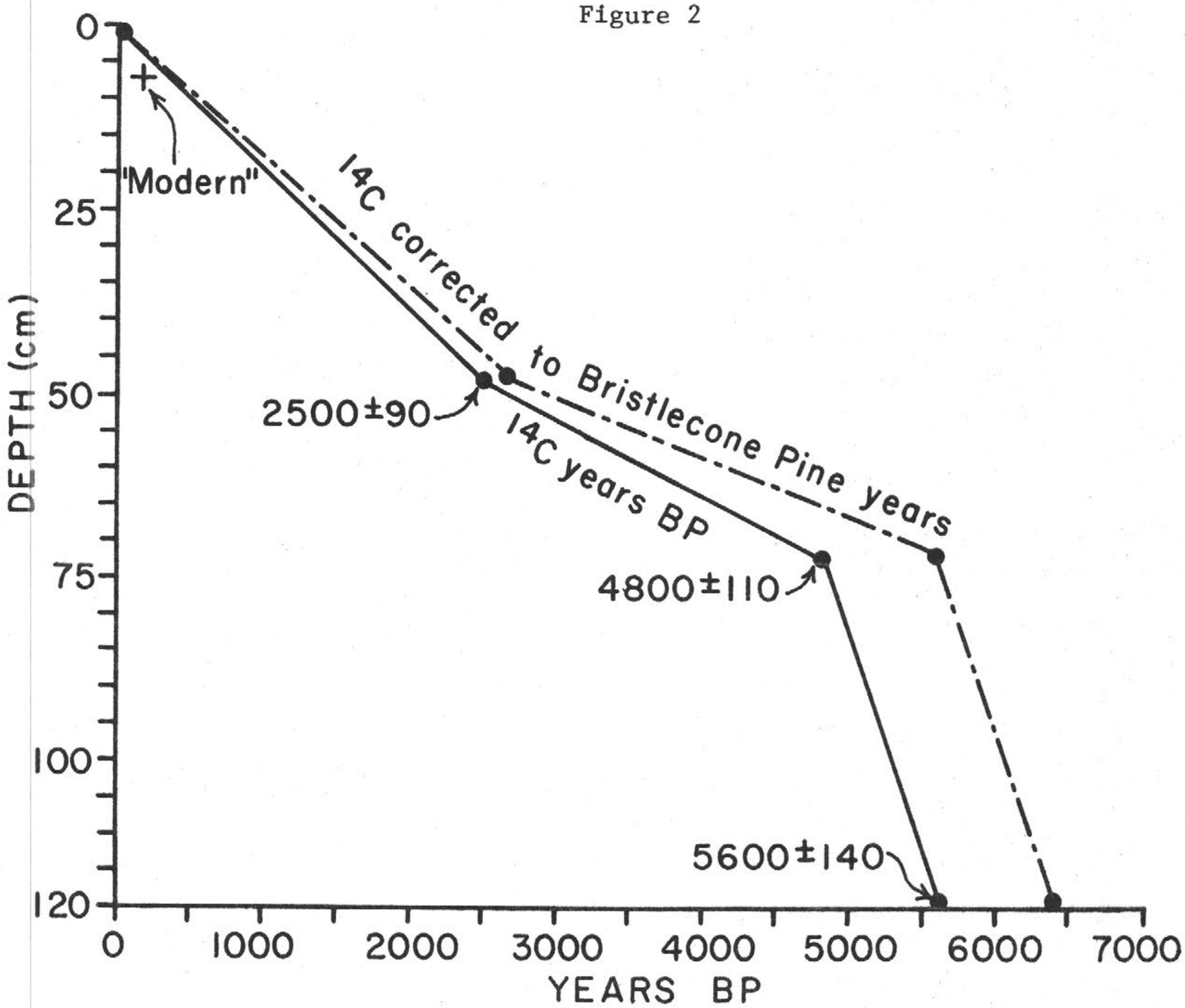
Met. station operated less than last 25 years.

PORT RADIUM — LATITUDE 66 05 N LONGITUDE 118 02 W ELEVATION 628 FT ASL

	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR	
MEAN DAILY TEMPERATURE (DEG F)	-16.1	-16.1	- 3.2	13.7	34.5	48.0	53.5	51.6	41.5	26.2	5.7	- 9.2	19.2	6
MEAN DAILY MAXIMUM TEMPERATURE	-10.0	- 8.7	5.7	23.3	42.6	56.7	61.9	58.4	46.7	30.7	11.0	- 3.3	26.3	6
MEAN DAILY MINIMUM TEMPERATURE	-22.2	-23.5	-12.1	4.1	26.3	39.2	45.1	44.8	36.3	21.6	0.3	-15.0	12.1	6
MAXIMUM TEMPERATURE	28	38	43	58	75	87	86	82	73	62	45	34	87	2
MINIMUM TEMPERATURE	-54	-53	-47	-37	- 9	21	31	27	15	- 4	-42	-43	-54	2
MEAN RAINFALL (INCHES)	0.00	T	0.00	0.01	0.41	0.51	1.37	1.68	0.89	0.28	T	0.00	5.15	6
MEAN SNOWFALL	4.3	3.1	5.6	2.4	1.3	0.5	0.1	T	1.0	7.7	9.9	5.5	41.4	6
MEAN TOTAL PRECIPITATION	0.43	0.31	0.56	0.25	0.54	0.56	1.38	1.68	0.99	1.05	0.99	0.55	9.29	6
NO.OF DAYS WITH MEASURABLE RAIN	0	*	0	*	3	5	7	9	7	3	*	0	34	1
NO.OF DAYS WITH MEASURABLE SNOW	9	8	21	6	3	1	*	*	1	9	12	10	80	1
NO.OF DAYS WITH MEAS PRECIPITATION	9	8	21	7	6	5	7	9	8	11	12	10	113	1
MAXIMUM PRECIPITATION IN 24 HRS	0.30	0.29	0.50	0.30	1.02	0.58	2.05	1.22	1.28	0.82	0.51	0.43	2.05	6

Source: Temperature and precipitation tables for the North - Y.T. and N.W.T. Canada, Department of Transport, Meteorological Branch, Toronto, 1967.

Figure 2



Sedimentation chronology for Port Radium, Great Bear Lake, Site "A", with correction to calendar years by bristlecone pine chronology (Suess, 1970).

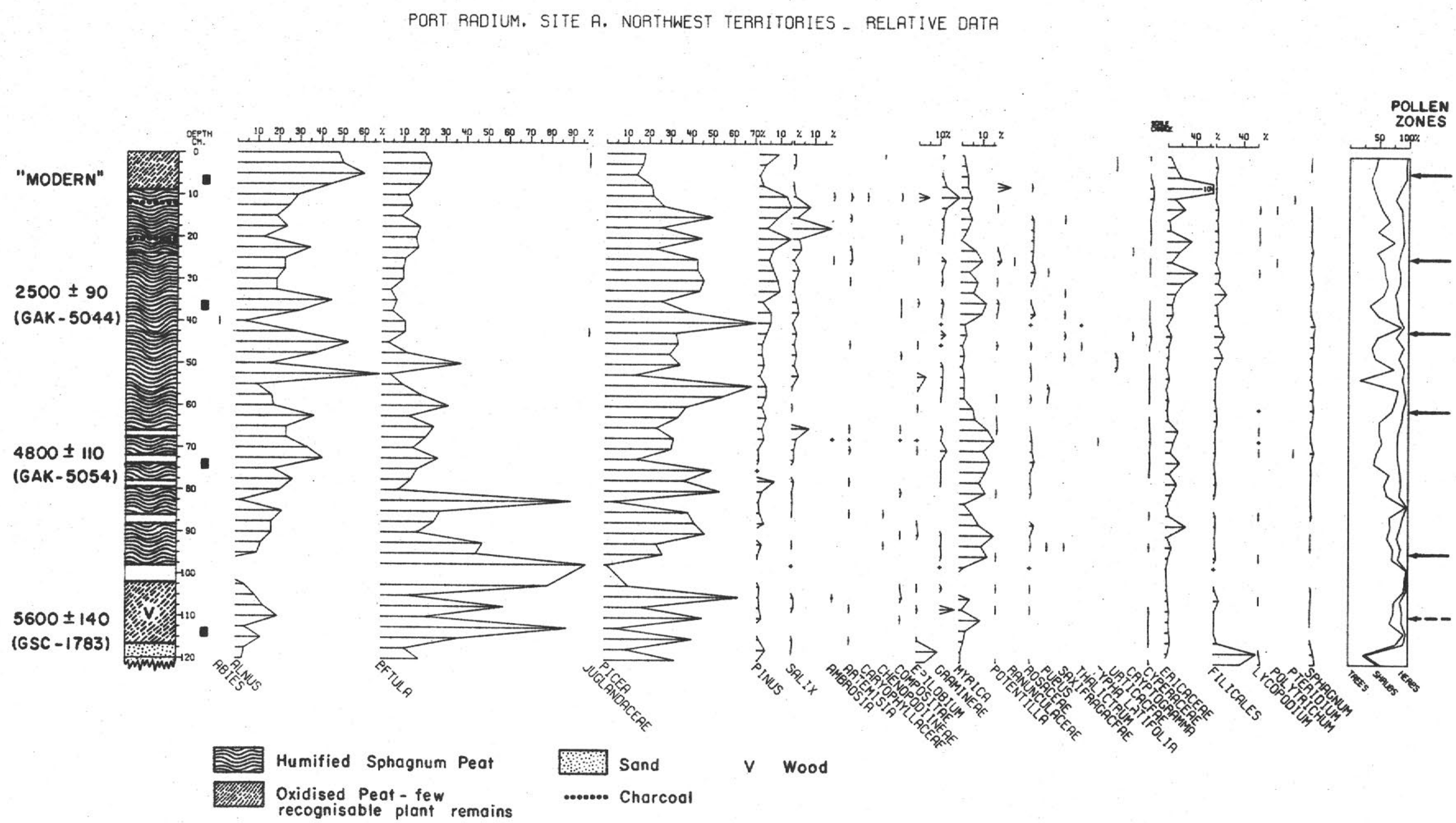


Figure 3: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

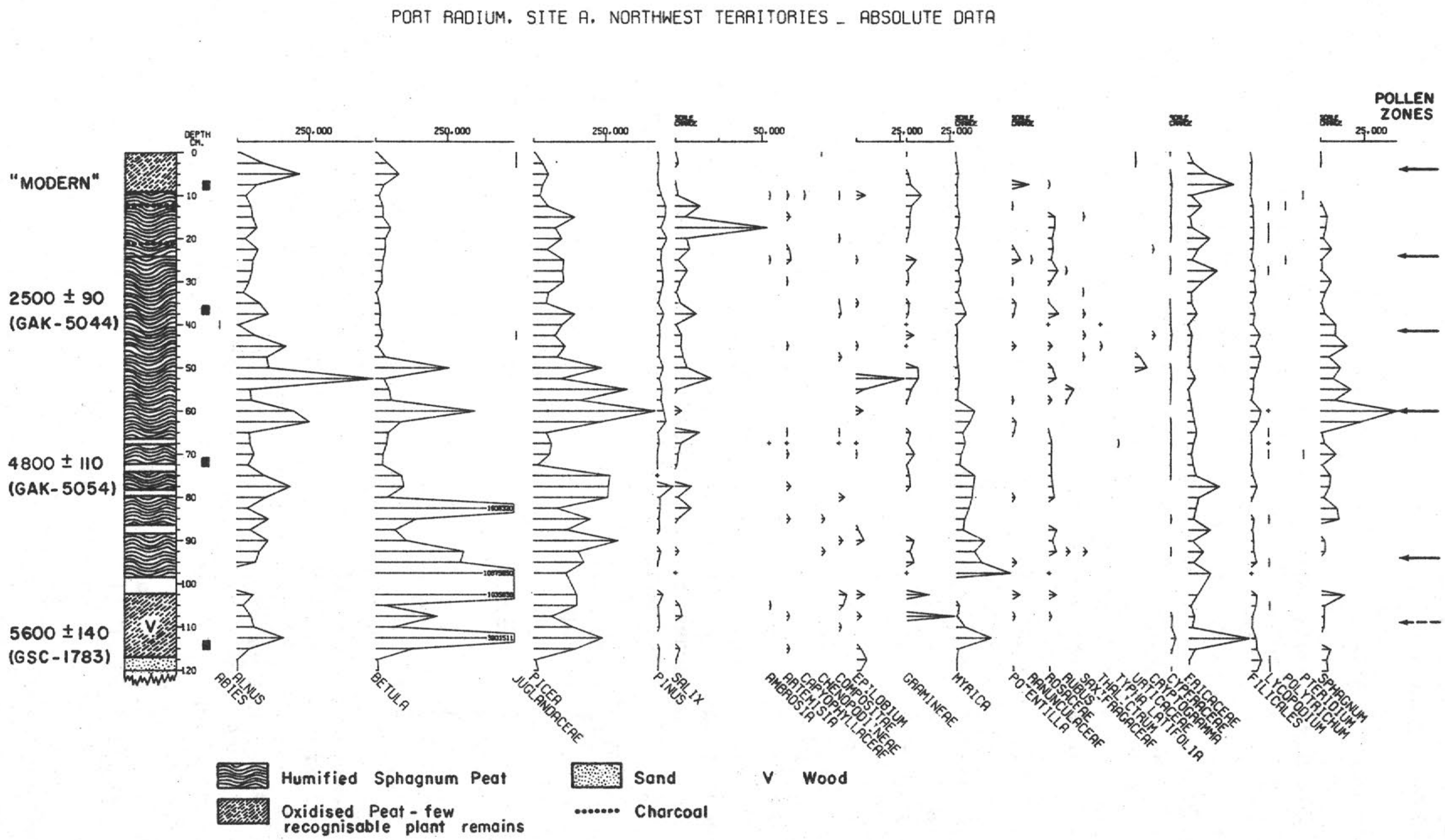


Figure 4: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines; the broken arrows indicate less significant sub-zones.

	Sphagnum peat 78 - 79½ cm, 86 - 88, and 95 - 97 cm. Wood at 95 cm.
98 -102	Destroyed by U.S. Customs examination.
102 -117	Black fibrous peat with wood fragments and sand.
117 -120	Sand to unknown depth.

Palynological data

The basal peat, dated 5600 ± 140 BP (GSC-1783) had low "absolute" counts. Soon afterwards, Betula had high values (almost 4 million pollen/g at 112.5 cm and almost 11 million/g at 97.5 cm) which formed short-lived peaks separated by lower numbers during the period 5600 to 5000 BP. Picea numbers were about 200,000 per g throughout this episode, and Pinus had low numbers, often less than 10,000/g or with no representation. Alnus often numbered about 70,000/g while Salix was low or absent. Epilobium was present at the base, and Ericaceae peaked shortly afterwards.

Just before 4800 ± 100 BP (GK-5045) at an estimated date of 5000 BP, Picea maintained high values (over 250,000 pollen/g) and Pinus rose to a short-lived peak (> 50,000 pollen/g), while Betula counts were much reduced. At 4850 BP, Pinus almost disappeared from the record; at 4800 ± 100 BP (GK-5045) Picea fell from 250,000 to about 20,000 pollen/g, and Alnus was reduced. This episode lasted for about 500-600 years, until ca. 4250 BP, when Picea, Pinus, and Alnus made rapid recoveries, and Sphagnum began a rise to maximum numbers.

Maximum values for Picea followed (430,000 pollen/g) with a subsequent sawtooth pattern of spruce decline. Pinus had a more regular but somewhat parallel decline. There was charcoal in the peat at 55 and 57.5 cm and there were increasingly large numbers of Epilobium pollen with a maximum for the diagram at 52.5 cm (27,000 pollen/g). The first Picea fall was at 3750 BP, the recovery at 3600 BP, and the next decrease at 3400 BP (with the Epilobium maximum and Alnus peak) with a final minor recovery of Picea and Pinus at 3200 BP, where Betula peaked. Sphagnum counts showed some parallelism with the Picea changes.

By 3000 BP Picea and Pinus were down to about 75,000 and 6000 pollen/g, respectively, and Betula was very low. These values continued through 2500 ± 90 BP (GK-5044) when Sphagnum and Alnus fell and Ericaceae rose. At 2200 BP Picea (45,000), Pinus (3000), and Sphagnum (600) decreased still further, to their minimum counts in this section of the diagram. Picea and Pinus made some modest recovery by ca. 1900 BP, but Picea never rose again above 140,000 pollen/g, or Pinus above 30,000. This Picea recovery lasted from 1900 to 1600 BP, after which Picea varied somewhat, and Pinus increased. At 15 cm, at ca. 950 BP, Picea had a small peak (140,000 pollen/g) and Pinus had sustained values of ca. 30,000 pollen/g. Picea then fell at 750 BP and Pinus at 600 BP (12.5 and 10 cm), and both stayed low up to the surface, while Sphagnum disappeared from the record. Ericaceae rose at ca. 200 BP, and Alnus peaked at a sample level dated "modern" (5 cm, GK-5046).

Data Interpretation

The basal peat date of 5600 ± 140 BP (GSC-1783) is much later than the suggested deglaciation date for the area of 8000 to 9000 BP (Bryson et al. 1969; Prest, 1970). Deltaic deposits above the level of this peat section (estimated 244 m a.s.l., 800 ft) show that Great Bear Lake was substantially higher than now after deglaciation and before 5600 ± 140 BP (GSC-1783). The basal organic material accumulated in a shallow swampy eutrophic pool (M. Kuc, pers. comm. 1973) apparently conformably over lake sand, though this last point was difficult to check because the deposit was permafrozen. The basal date thus represents a minimum age for the fall of lake level below 244 m (est.) and may even reflect the timing of beach emergence.

The low "absolute" pollen counts from 120 to 115 cm may reflect some minerogenic inclusions, but there clearly was also a fire at the base, as evidenced by charcoal fragments and the Epilobium pollen, which best explains the low tree and shrub numbers. Tree birches then colonized the burnt ground and a fairly open birch-spruce forest quickly developed with few or no pines. Frequent fires left charcoal in the peat in the lowest 40 cm, and this presumably explains the short-lived episodes of grass and heath growth, with the frequent dominance of birches between 5600 ± 140 (GSC-1783) and 5000 BP. The Picea counts indicate that the forest limit lay farther north than now, and thus summers were warmer; the low numbers for wet ground indicators (Cyperaceae, Myrica, Sphagnum) and the very humified crumbly nature of the dark brown peat (with few identifiable plant remains) suggests a fairly dry (fire-prone) summer climate. How far the reduction of lake level was related to this climatic condition is unknown.

At about 5000 BP the Picea forest became denser, possibly closed-crown, with a minor pine element and the elimination of most of the birch trees and open habitat herbs. This may have reflected a warmer summer climate from 5000 to 4800 BP, which from the paucity of wet ground indicators and extremely humified peat was probably dry.

A sharp change occurred at 4800 ± 110 (GK-5045) when fresh unhumified Sphagnum peat covered the lower humified deposit, and the closed spruce forest was opened up (or ceased pollinating). Local pines were eliminated entirely, and the small quantities of their pollen remaining at that level are attributable to long distance transport. Picea values were similar to those in the modern northern forest edge or southern tundra. This episode of deforestation apparently resulted from a prolonged period of cold wet summers similar to those of the present forest-tundra ecotone, where summer cyclogenesis results from interaction of the Arctic and Pacific air masses. The summer position of the Arctic Front was displaced southwards following 4800 ± 110 BP (GK-5045).

Following 4250 BP the spruce forest regenerated rapidly until by 3900 BP the open scattered woodland was replaced by closed-crown forest in response to warmer summers and northward displacement of the Arctic Front; this was the episode of maximum Picea pollen production. The forest was no sooner established than it began to be affected by frequent forest fires. A fire at 3750 BP was followed by spruce forest growth at 3600 BP. A major fire at 3400 BP caused replacement of much of the spruce with alders, fireweed, grasses, and later birch trees. It was followed by much weaker spruce regeneration so that by 3000 BP the area was covered by an open spruce woodland with alder shrubs, a few birch trees and willows, and members of the Rosaceae and grass families. The peat stratigraphy indicates this was a dry episode, which became colder and drier at 2500 ± 90 BP (GK-5044) when heaths spread and Sphagnum spore numbers diminished; the BMD program (p. 54) distinguished a major break at this point. The period of cold dry summers probably reflected more frequent incursions of Arctic air masses over Great Bear Lake, and the most markedly adverse conditions for spruce growth occurred at 2200 to 2000 BP when the site was largely tundra.

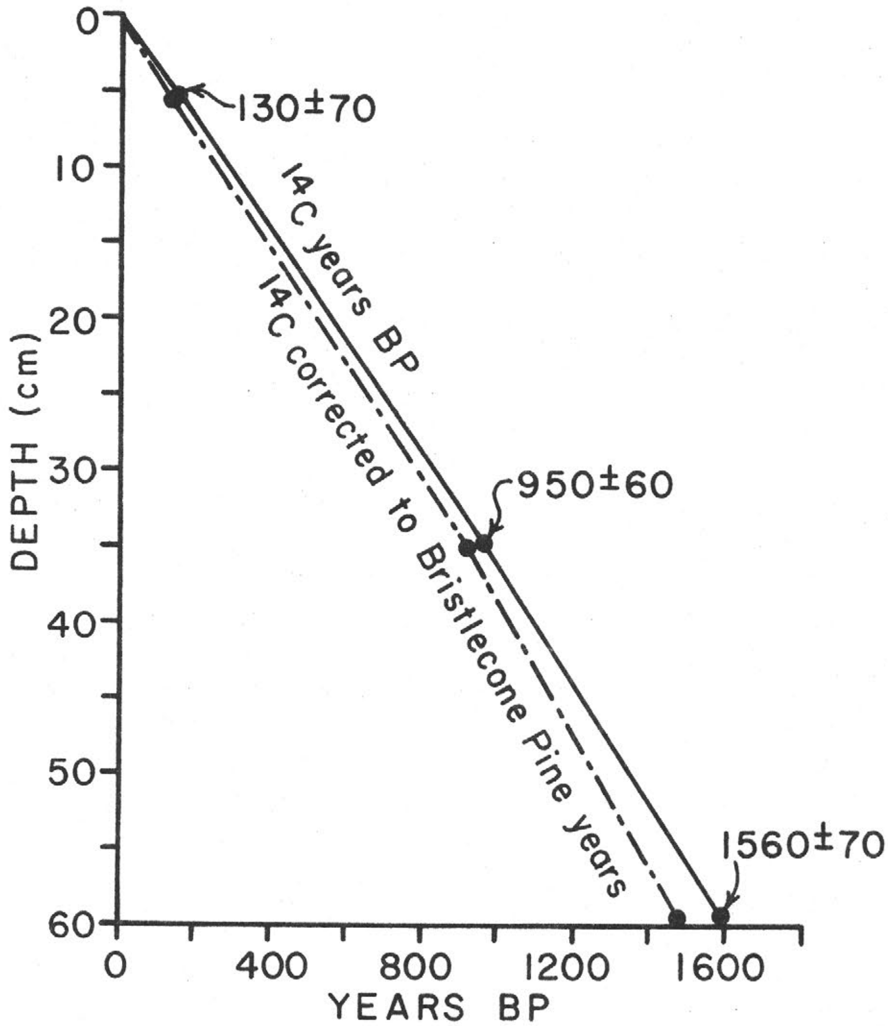
Some spruce woodland regeneration occurred from 1900 BP until ca. 1600 BP as the Arctic Front lay more consistently north of the site and summers warmed. Spruce cover then seemed to decrease and became variable, while heath communities expanded, perhaps responding to dry cool summers. By 950 BP the spruces were growing more successfully as an open forest in response to a short-lived warm episode, which ended at ca. 750 BP when the spruce cover thinned or largely ceased pollinating. This clear onset of cold dry summers spread tundra plants (especially heaths) more than hitherto, and Sphagnum mosses were adversely affected. The reduction in Pinus at 600 BP probably marks the elimination of any local pines and the reduction of long-distance airborne influx of pine pollen from the south due to an increase in dominant northerly winds in summer. This episode of dry cold summers with frequent incursions of Arctic air masses lasted until the present, and it suggests that the present dry, very open spruce woodland set amongst heath communities, rose thickets, and alder scrub might not achieve much spruce regeneration after a large-scale fire.

Port Radium, Site C (Figures 5-7)

Peat Stratigraphy: an abbreviated summary

Depth cm	
0 - 6	Dark brown oxidized peat, many cf. Ericaceae roots.
6 -12.5	Light brown unhumified Sphagnum peat.
12.5-17	Dark brown oxidized peat.
17 -21	As above, with some mixture of lighter Sphagnum peat.
21 -33.5	Light brown unhumified Sphagnum peat, with some very unhumified peat.
33.5-36	Mostly pale brown very unhumified Sphagnum peat, with several small (10 mm) angular pebbles. Some dense dark brown very humified peat containing unidentifiable wood fragments and flakes.
36 -55	Light brown unhumified Sphagnum peat.
55 -56.5	Dark brown humified litter.
56.5-	Mineral base, sloping deposit of sand and rounded pebbles, with angular rock fragments from talus slope.

Figure 5



Sedimentation chronology for Port Radium, Site "C", with correction to calendar years by bristlecone pine chronology (Suess, 1970).

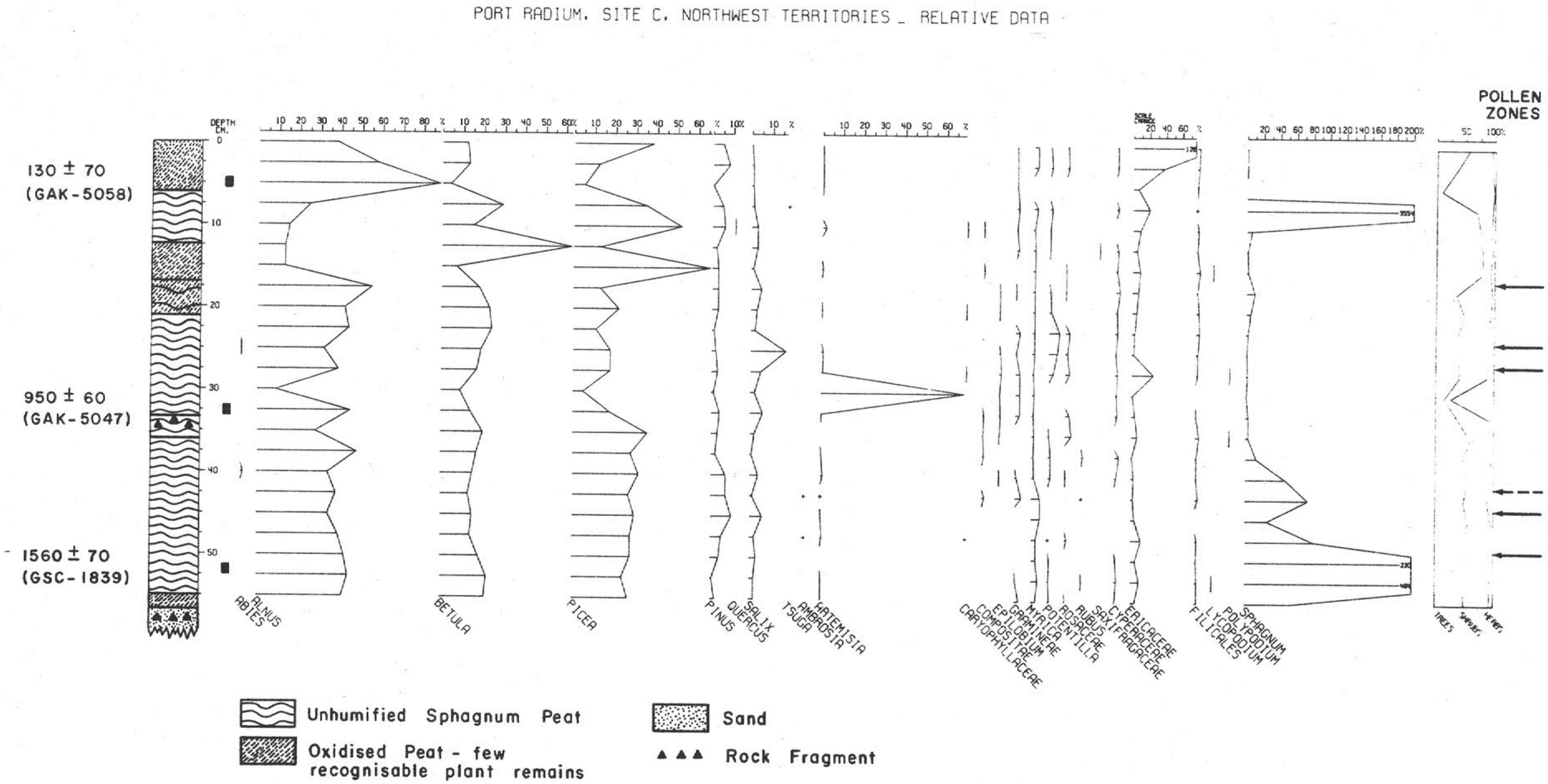


Figure 6: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

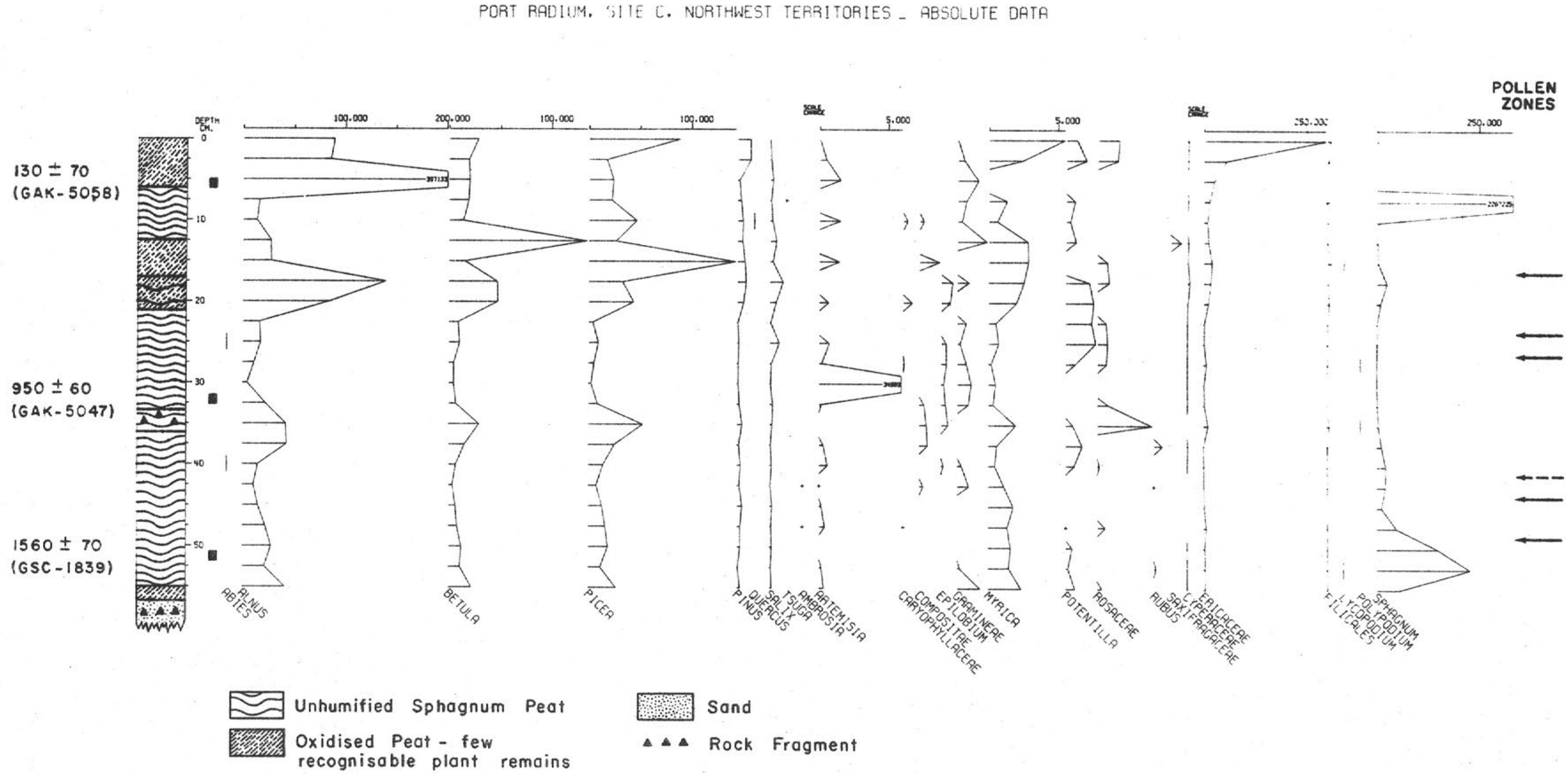


Figure 7: "Absolute"pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines; the broken arrows indicate less significant sub-zones.

Palynological data

The basal peat was dated 1560 ± 70 BP (GSC-1839), and was an unhumified Sphagnum peat overlying rounded boulders and sand and angular rocks from the cliff behind.

The primary features of this short diagram are the basal low to moderate Picea values (< 30,000 pollen/g), the basal high Sphagnum counts, the modest peak in Picea (59,000 pollen/g) at 950 ± 60 BP (GK-5047) followed by an immediate fall to prolonged low values (< 10,000 pollen/g), the increases of Artemisia and many heliophytes during the low Picea episode, the recovery of Picea values at ca. 400 BP, and the dominance of Alnus and high Ericaceae numbers at and following 130 ± 70 BP (GK-5058).

Data Interpretation

The late growth of unhumified Sphagnum peat over a coarse, well drained substrate on a sloping hillside, 4000 ^{14}C years after organic accumulation nearby (at Port Radium A), is tentatively referable to an environmental/climatic change towards greater available moisture. The high basal Sphagnum counts may support this suggestion (Fredskild, 1967; Bartley and Matthews, 1969).

From 1560 ± 70 BP (GSC-1839) to 950 ± 60 BP (GK-5047) there was a very open or infertile Picea forest near to its northern limit of sexual reproduction, with no pines present, some birch trees and numbers of alders, with patches of grasses, Artemisia, Potentilla, and lesser numbers of open-habitat taxa. The Arctic Front may have lain just north of the site in summer during this episode; a short cooler spell occurred at ca. 1100 BP.

High Picea counts which are thought to be indicative of warmer summers rose moderately from ca. 1000 BP to a peak at 950 ± 60 BP (GK-5047), suggesting a fairly short episode of warmer summer climate with fewer incursions of Arctic air masses. This episode ended at ca. 900 BP for Picea, with a total tree pollen minimum at 800 BP, and was followed by a tundra period of cold dry summers dominated by Arctic air masses lasting until ca. 500 BP.

At 20 cm, at ca. 500 BP, there was an episode of alder colonization when spruce values began to recover to a modest degree indicating open spruce woodland. The single sample of maximum Picea values at 15 cm (ca. 400 BP), which reached ca. 150,000 pollen/g, may be an artefact since the sudden flourishing of fairly dense spruce forest for such a short period is unlikely. Birch trees flourished during this episode of somewhat milder climate. At 7.5 cm (ca. 200 BP) the Sphagnum spore peak registered a possibly wetter event, while by 130 ± 70 BP (GK-5058) alders dominated the site and within the last century expansion of heaths and wild roses occurred within a dry open spruce woodland landscape comparable to the modern environment.

Here at Port Radium C there is more detail of the recent health of the dry open spruce woodland, and it supports the conjecture from the Port Radium A diagram that the Picea trees have not been very fertile within recent centuries, that the landscape has been dry and has seen frequent incursions of dry cold Arctic air masses in summer, so that the Picea woodland is not fully in equilibrium with the modern climate and there is possibly an historical inertial element in the location of the present forest-tundra ecotone to the north of the site. If forest fire occurred there, it would seem unlikely that spruce woodland would regenerate quickly (if at all) under the present summer climatic regime.

CHAPTER II

THE LATE HOLOCENE HISTORY OF VEGETATION AND CLIMATE AT COPPERMINE, DISTRICT OF MACKENZIE, N.W.T.

Location

Two peat deposits were located near the mouth of Coppermine River at Coronation Gulf in the Arctic Ocean. These tundra sites lie about 160 km north of the boreal forest limit on the north side of Great Bear Lake (Rowe, 1972), but a finger of open woodland and stunted relict trees juts from the forest edge almost to the Coppermine Eskimo settlement. It is suggested below that this may represent the maximum northward extension of the tree line during the postglacial thermal maximum.

Topography and Vegetation

The low arctic tundra area around the Coppermine Eskimo settlement and the mouth and lower reaches of the Coppermine River is topographically fairly uniform, and the relief of the coastal plain adjacent to Coronation Gulf is quite monotonous. Grasses and sedges are widespread on level lower ground of the coastal plain, and give the area a greener, lusher appearance than many drier areas of the Arctic. Emergent sea beaches and dry valleys cut into low sandy cliffs along the incised lower Coppermine River providing habitats for communities of low *Salix* spp. bushes which appear to benefit from sheltered snowbanks. The bases of the few low hills and the larger cracks in rock outcrops are similarly occupied by willows apparently related to long lying snow. The luxuriant willow communities colonizing the sandy shores of the Coppermine River and Coronation Gulf often have an understory of *Betula glandulosa* (dwarf birches), perhaps related to snow catchment. Heath communities occur on drier soils of the hilltops and the sands of the sea beaches. Weeds are abundant around the Coppermine village and are especially rank around the Eskimo huts where the summer presence of tethered husky dogs and the accumulation of refuse has encouraged nitrophilous plants.

In this area of low relief, topographic variety has been actively developing during the Holocene due to the relative movement of land and sea, involving plant colonization of emerging beaches and the creation of new protected environments due to down-cutting of rivers in response to isostatic uplift. Another variable has been the degree and duration of summer sea ice in the Coronation Gulf which affects coastal precipitation during the growing season and thus the plant cover. Increased sea ice during cold climatic episodes would probably reduce rain and snowfall amounts.

The timespan of Eskimo occupation at Coppermine is unknown; however, an archaeological site at the fishing station of Bloody Falls about 20 km up the Coppermine River was dated back to 3300 ± 90 BP (S-463) (McGhee, 1970) and has been occupied at least at intervals since (McGhee, 1972).

Climatic Data (see tables, pages 16 and 17)

Coppermine has a short arctic summer, but the ameliorating influence of the Arctic Ocean and Coronation Gulf leads to a longer, moister growing season than in the more southerly interior (e.g., the mid-Keewatin Barren Grounds). In summer winds are mostly from the north and east and have passed over the Arctic Ocean and over the tundra of the nearby coast and High Arctic islands. Summer days are often cloudy with light rain and occasional fog. These meteorological factors are significant in the transport of tree pollen from the boreal forest to Coppermine.

Coppermine Beach (Figures 8-10)

The shallow peat (62.5 cm deep) lay on the south side of the road from the Coppermine settlement to the Department of Transport airstrip constructed in 1969, at latitude 67°50'N, longitude 115°19'W, elevation 65' (19.8 m). The elevation was derived from a nearby Department of Transport benchmark at 72.16 ft. a.s.l., using a survey level and staff. The surface peat was fairly dry and very humified in 1969 and was covered by grasses. The date 230 ± 50 BP (GaK-5063) at 4-6 cm suggests that organic accumulation occurred until quite recently, though rather slowly.

Peat Stratigraphy: an abbreviated summary

Depth cm	
0 -62.5	Dark brown very humified fibrous peat, with sedge and grass fragments, Ericaceae roots, and numerous sand grains. Peat lacked almost any visible changes in humification or plant composition, except for slightly reduced humification and a few cf. Sphagnum mosses near the base.
62.5-	Frozen sea-beach sand.

Fossil Record of exotic pollen

The changes in "absolute" values of Picea (spruce), Pinus (pine), and Alnus (alder) pollen, windblown from the boreal forest onto the tundra around Coppermine, are thought to be indicative of the distance from tree line and perhaps of altered summer wind strengths and directions (cf. Nichols, 1970). The "absolute" counts of spruce and pine are compatible with exotic origins for these pollen taxa, and for the forest being considerably south of Coppermine throughout most of this record (Nichols, 1970).

A local factor influencing this long-distance transport may be the nearby presence of the Arctic Ocean. Tauber pollen trap samples from seaside locations along the west shore of Hudson Bay have collected fewer modern exotic pollen than their interior continental counterparts, suggesting that onshore winds and coastal rain and fog have diminished the numbers of transported long-distance pollen (Nichols, unpub.). These findings may be applicable to other coastal

Climatological Table for COPPERMINE

Month	Pressure	Air Temperature							Relative Humidity	Precipitation			Number of Days with		
			Mean of Daily		Mean of Monthly		Absolute Extremes								
	MSL	Daily Mean	Max.	Min.	Max.	Min.	Highest Recorded	Lowest Recorded	Mean	Mean Total	Max. Fall in 24 Hrs.	Mean Snowfall	Rain > .01 inch	Snow Depth > .1 inch	Frost
	MB	°F	°F	°F	°F	°F	°F	°F	%	inches					
January	1020	-19.4	-12.3	-26.5	9	-46	27	-54	M	0.49	0.90	4.9	0	9	31
February	1022	-22.1	-14.8	-29.3	8	-46	34	-58	M	0.31	0.80	3.1	0	7	28
March	1022	-14.5	- 6.8	-22.1	17	-41	29	-56	71	0.52	0.87	5.2	0	9	31
April	1021	1.0	9.8	- 7.9	32	-32	46	-47	77	0.41	0.55	4.0	*	7	30
May	1020	21.9	28.9	14.9	48	- 8	74	-24	82	0.46	0.61	3.9	1	6	30
June	1016	38.1	44.6	31.6	69	20	82	5	85	0.80	2.50	1.4	6	3	16
July	1012	48.7	56.0	41.3	78	34	90	31	80	1.34	1.35	0.2	10	*	*
August	1012	47.1	53.7	40.5	72	31	8.5	27	83	1.72	1.89	0.1	12	*	2
September	1014	36.6	41.5	31.6	60	18	79	7	83	1.10	0.72	2.6	8	3	17
October	1012	19.5	24.8	14.2	41	- 7	57	-28	86	1.02	0.70	8.4	2	11	*31
November	1017	- 3.9	3.0	-10.8	24	-30	36	-42	79	0.60	0.60	6.0	*	12	30
December	1018	-15.3	- 8.3	-22.2	12	-39	31	-49	78	0.45	1.01	4.5	0	9	31
Mean	1017	11.5	18.3	4.6											
Extreme or Total							90	-58		9.22	2.50	44.3	39	76	277
Period of Observations	1941 to 1960	1931 to 1960			1933 to 1967		1930 to 1966		1957 to 1966	1931 to 1960	1931 to 1966	1931 to 1960			1955 to 1967

* Average less than 0.5

Source: Climate of the Canadian Arctic
Meteorological Branch, Department of Transport, Canada.
Department of Mines, Energy and Resources, Ottawa, 1970.

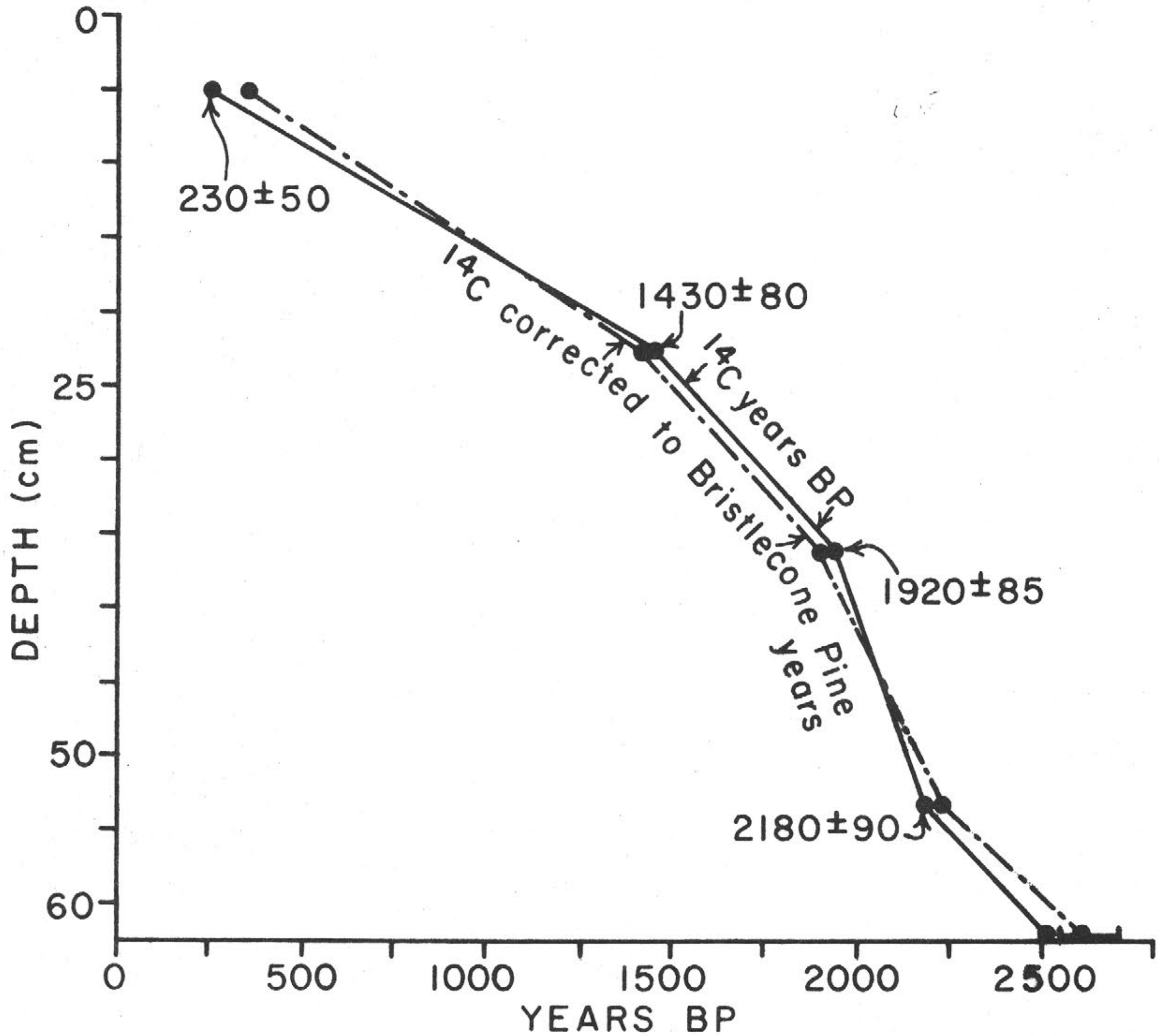
Coppermine climatology

Latitude 67°49'N **Longitude** 115°05'W **Altitude above MSL** 28 feet

Number of Days with			% of Time		Cloud Amount Tenths of Sky Covered				Wind Direction Percentage Frequencies								
Fog (vis. < 5/8)	Gale 34 kts.	Thunder	Clear Sky (< 2/10)	Overcast (> 8/10)	0600 GMT	1200 GMT	1800 GMT	0000 GMT	N	NE	E	SE	S	SW	W	NW	Calm
1	*	0	38	47	4.7	4.7	6.3	5.7	8	3	5	1	6	33	30	12	2
*	0	0	45	39	3.7	4.2	5.7	5.1	5	5	3	1	5	33	36	8	4
*	0	0	41	43	4.4	4.6	5.7	5.5	9	7	6	1	4	30	32	7	4
2	*	0	36	47	4.9	5.8	5.7	5.5	14	9	7	2	4	21	31	8	4
3	0	0	24	62	6.8	7.0	6.9	6.8	17	14	15	3	5	11	21	12	2
3	0	*	24	56	6.7	6.9	6.7	6.1	22	29	17	3	3	4	10	11	1
2	0	1	20	57	6.6	6.7	6.8	6.5	20	24	19	3	4	8	9	13	*
2	*	*	15	66	7.1	7.4	7.7	7.4	14	20	16	5	5	14	11	14	1
2	0	0	10	77	7.5	8.3	8.5	8.3	13	13	16	7	8	14	14	15	*
1	*	0	13	75	7.6	7.7	8.5	8.4	9	7	11	9	13	25	16	10	*
*	0	0	27	56	6.1	5.8	7.1	6.7	8	5	7	4	5	33	26	10	2
1	*	0	38	47	5.0	4.6	6.1	5.7	9	5	6	2	5	35	27	8	3
			28	56	5.9	6.1	6.8	6.5	12	12	11	3	5	22	22	11	2
17	*	1															
1955 to 1967		1941 to 1960	1941 to 1960						1955 to 1966								

* Average less than 0.5

Figure 8



Sedimentation chronology for Coppermine Beach with correction to calendar years by bristlecone pine chronology (Suess, 1970).

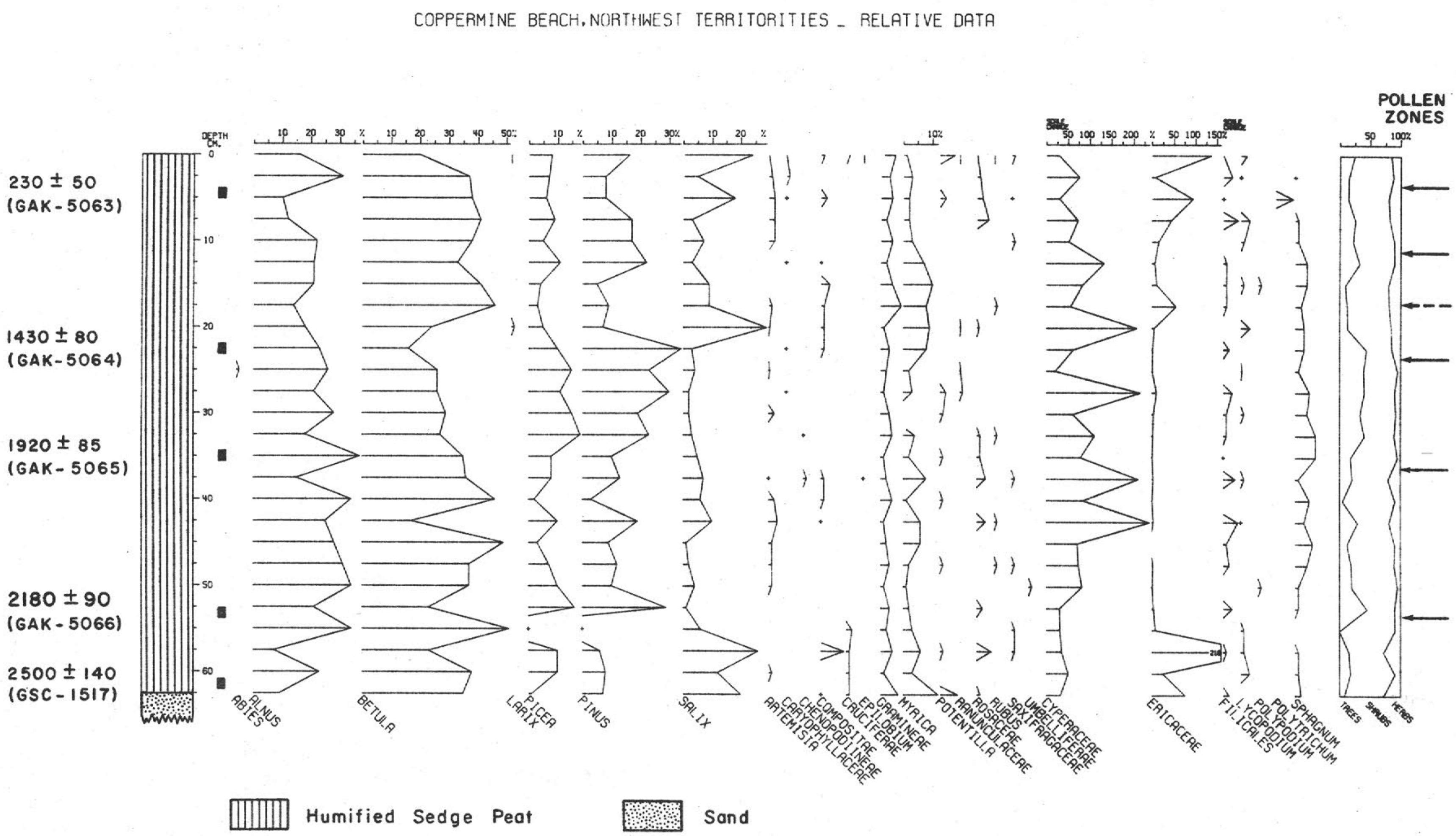


Figure 9: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

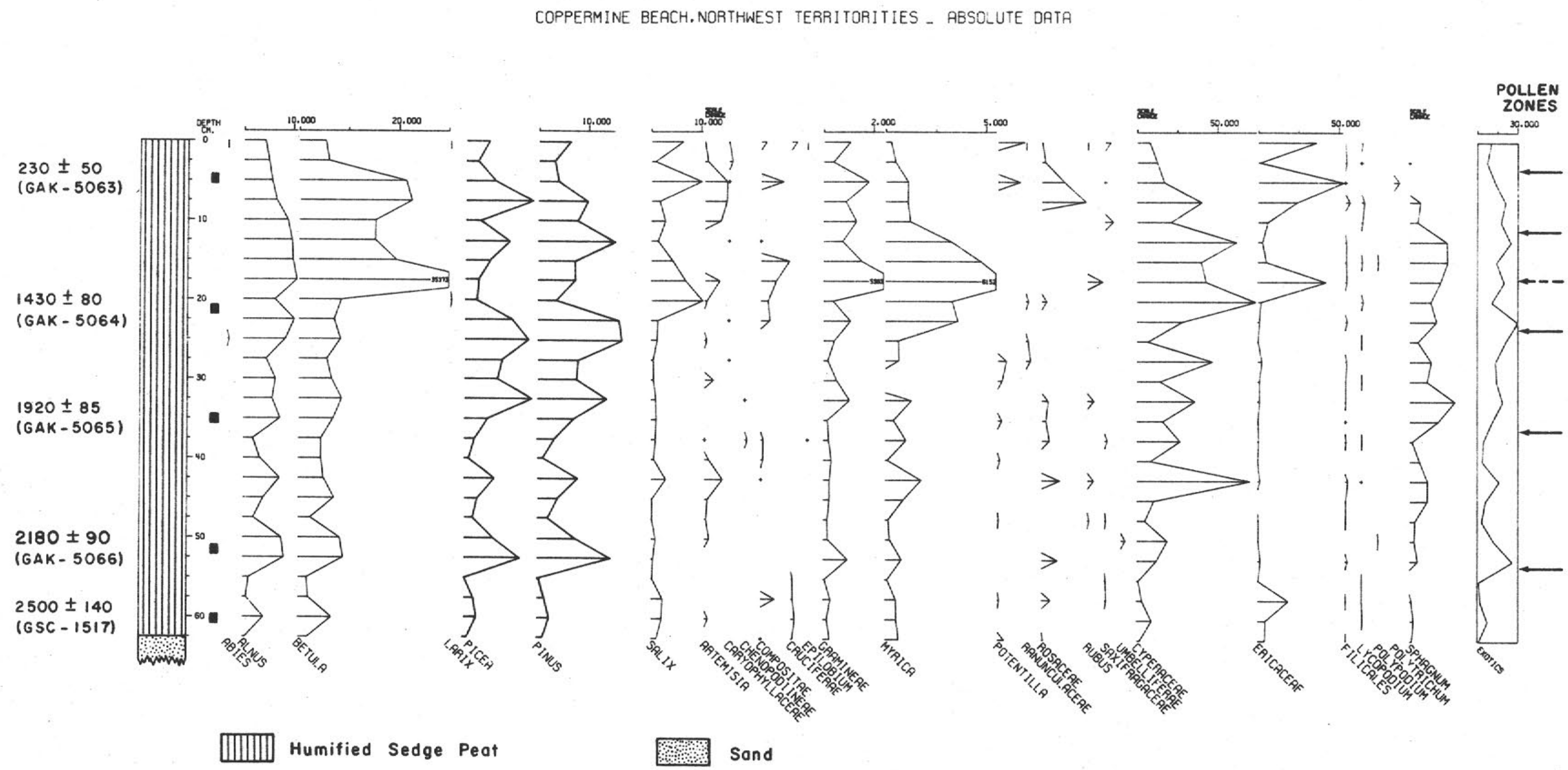


Figure 10: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines; the broken arrows indicate less significant sub-zones.

locations, and may explain the apparently reduced numbers of fossil exotic pollen in the Coppermine peats compared to other interior tundra sites (cf. Pelly Lake, Nichols, 1970). Thus, the presence of coastal rain, fogs, and onshore winds along the Coppermine coast during episodes of milder climate and ice-free conditions in Coronation Gulf may have acted to reduce the exotic pollen influx, despite more southerly/westerly winds. Conversely, colder summers with more sea ice might allow greater numbers of forest pollen to reach these sites.

The importance of exotic pollen of pine and spruce in these profiles as possible indicators of paleowind strength and direction led to modification of conventional pollen counting methods to increase the totals of these exotics to a statistically more reliable base. This was achieved by scanning at low power (200x) the total area of at least one and usually several slides (40 x 22 mm) from each level to recognize these relatively large and distinctive pollen and to relate their numbers to the sediment weight represented. These "absolute" totals are shown in Figures 10 and 13, labelled "Scan Picea and Pinus," and have been used in preference to the lower counts achieved by the normal means (Σ 300 pollen) as the basis for exotic pollen interpretation.

Palynological Data: exotic pollen

At the base of the Coppermine Beach diagram (2500 ± 140 BP, GSC-1517) the "absolute" numbers of Alnus, Picea, and Pinus were low (a few hundred pollen grains per gram). The joint lowest values of Picea and Pinus (14 and 5 pollen/g, respectively) occurred just before 2180 ± 90 BP (GaK-5066) at 2225 BP. Alnus also recorded very low values. This episode was followed by a substantial temporary recovery of alder, spruce, and pine values by 2150 BP. At 1920 ± 85 BP (GaK-5065) the exotic taxa began a more prolonged increase to a peak at 1800 BP. Reduced exotic values occurred from 1700 to 1600 BP followed by maximum Pinus and near maximum Picea and Alnus numbers registered at 1500 BP, just before the sample dated 1430 ± 80 BP (GaK-5064). Exotic pollen were reduced at 1275 BP but recovered by 770 BP. There were low exotic values around 230 ± 50 BP (GaK-5063). Single grain occurrences of Abies (fir) and Larix (larch/tamarack) occurred just before and just after the sample dated 1430 ± 80 BP (GaK-5064).

Local Pollen Influx

The birch pollen is attributable to dwarf arctic birch (Betula glandulosa). It had low values after 2500 ± 140 BP, moderate numbers after approximately 2000 BP, sustained high values after 1430 ± 80 BP (GaK-5064), and a decrease from 230 ± 50 BP (GaK-5063) onwards.

The arctic willows (Salix spp.) had modest pollen numbers at the 2500 BP base, followed by low values from 2400 to 1000 BP, when there was a modest peak and reduced values after 800 BP with generally lower irregular numbers leading to the surface.

The grasses (Gramineae) were represented by low values from 2400 BP to about 1000 BP, when a maximum occurred, followed by moderate values lasting until the modern surface.

"Absolute" numbers of sedge (Cyperaceae) pollen were generally low and variable from 2500 to about 2000 BP, after which very large numbers (often 40,000 grains/g) were counted; the values were moderate after 500 BP.

Sphagnum (bog moss) spore counts were low throughout the profile (below 2000 spores/g). None was recorded at about 2300 to 2400 BP, but low maxima followed 1920 ± 85 BP (GaK-5065) and from 1000 to 800 BP, but there was no record after 500 BP.

Interpretation

The basal organic material overlying the sea beach sand at 16.0 m (52.5 ft.a.s.l.) was dated 2500 ± 140 BP (GSC-1517), approximately 1500 years after this beach site emerged from the nearby Arctic Ocean (Andrews, et al., 1971). This suggests a probable deposition hiatus between shoreline emergence and organic accumulation. Spruce driftwood found nearby at the same altitude in permafrozen marine sand dated 3700 ± 80 BP (GSC-1820) supports this suggestion. The fact that basal aquatic mosses (Calliergon spp. and Scorpidium scorpioides) accumulated over sand after this long episode may have been due to a possible environmental/climatic change, perhaps marked by higher precipitation to evaporation ratios and/or higher permafrost levels, which would encourage waterlogging of the site (cf. Fredskild, 1967).

Interpretation of the Local Pollen Influx

Dwarf birch scrub (Betula glandulosa) was absent from the site from 2500 ± 140 BP (GSC-1517) to 1920 ± 85 BP (GaK-5065); and this, along with low values for willows, sedges, and Myrica and, possibly, the absence of Sphagnum at 2400 to 2300 BP, suggests cold dry summers for this episode.

Some regeneration of Betula glandulosa scrub, widespread growth of sedges, and some recovery of limited Sphagnum sporogenesis occurred following 1920 ± 85 BP (GaK-5065), pointing to somewhat warmer, wetter, though still cool, summer conditions (like the present). The birch scrub community flourished after 1430 ± 80 BP (GaK-5064) in association with sedges, bog myrtle (Myrica), and minor amounts of Sphagnum during moist, mild summers; the warming trend encouraged the growth of willows from about 1000 to 800 BP when grasses became locally important. Sedges were much reduced after 500 BP, Sphagnum produced no spores after that date, and birch scrub decreased by 230 ± 50 BP (GaK-5063), all suggesting colder, drier summers. It is notable that changes in Sphagnum "absolute" values paralleled the changing numbers of total exotics. About 500 BP, Ericaceae (heaths) joined grasses in dominating the site up to the present.

Exotic Pollen Influx

The deposition of Pinus, Picea, and Alnus pollen at Coppermine is considered to be primarily due to winds from the south and/or west which currently pass over the boreal forest and transport these alien pollen taxa a minimum distance of about 160 km (100 miles) from the forest limit on the northeast side of Great Bear Lake. In the Coppermine diagrams, the changes in "absolute" values of spruce, pine, and alder pollen are thought to reflect past alterations in wind strengths and directions, as well as actual shifts in tundra-forest ecotone locations and in pollen productivity due to climatic changes. There is evidence from macrofossils in the Coppermine Saddleback peat that spruce grew along this sea coast from 3700 to 2500 BP, but was reproducing vegetatively and not producing pollen.

I found spruce timbers (Picea sp.) in the permafrozen sea-beach sand at Coppermine which were assayed at 3700 ± 80 BP (GSC-1820); the surveyed elevation was 16.00 m a.s.l. (52.5 ft). These may have derived from the upper wooded reaches of the Coppermine River or from clonal tree growth along the Coppermine coast.

At the start of this investigation, it was realized that the trees must have come very close to reaching the Coppermine coast some time during the Holocene since dwarfed prostrate spruce clones grow on the Nipartoktuak River nearby, and Rowe's (1972) map shows some trees extending to within about 15 km of Coppermine. The northernmost trees growing in a vegetative state in the Arctic may represent the maximum northward expansion of the sexually-reproducing trees during the optimum warmth of the postglacial (Nichols, 1975).

Interpretation of Exotic Pollen Influx

The low "absolute" values of Alnus, Picea, and Pinus at 2500 ± 140 BP (GSC-1517) and the minima at about 2300 BP are thought to be indicative of reduced summer influx of southerly/westerly air originating over the boreal forest, and/or a southward retreat of the forest-tundra ecotone, marking colder summer climate. The recovery of all three taxa by 1920 ± 85 BP (GaK-5065) indicates the reduced dominance of northerly winds and/or the northward expansion of the trees expressing the end of the cold episode. The most substantial increase in the three primary exotic pollen taxa due to warmer summers, forest expansion, and/or more southerly/westerly winds began at 1430 ± 80 BP (GaK-5064), with a maximum of warmth beginning at 1100 to 1000 BP. Analogs from modern polster suggest that the pollinating trees did not reach Coppermine (Nichols, unpub.). The progressive decline of the exotics from 500 to 350 BP onwards marked colder summers, increasing dominance of northerly winds, and an expansion of tundra at the expense of the woodland to the south. The surface increases of pine and spruce pollen may be due to the continued slow influx of small quantities of these exotic taxa onto a dry peat surface which is currently accumulating very slowly, if at all. An alternative explanation is that this effect may be due to the climatic amelioration of the last century.

Coppermine, Saddleback Hill (Figures 11-13)

Peat was located on the gently sloping west side of Saddleback Hill at approximately 43 m a.s.l., about 1 km south of the Eskimo settlement of Coppermine. The organic material was almost entirely permafrozen, and the chainsaw was used to excavate a pit into the peat, from the side of which a continuous vertical series of monolithic sediment blocks was recovered. Total peat depth was 116 cm, below which lay 21 cm of clear ice overlying the bedrock base.

Peat Stratigraphy: an abbreviated summary

Depth cm	
0- 11	Slightly humified surface moss peat with Polytrichum, Drepanocladus, and Ericaceae stems, underlain by moderately humified fibrous peat with many Ericaceae roots.
11- 20	Mid-brown moderately humified peat with few Ericaceae roots and sand grains.
20- 35	Dark brown very humified peat with many angiosperm twigs (cf. Betula glandulosa), some grasses, a few rounded gravel and angular rock fragments. Rock fragment 33-35 cm.
35- 37	Fragments of Picea sp. wood with some possible charcoal, contained in nearly black oxidized peat.
37- 57	Dark brown humified peat with Picea wood fragments.
57- 85	Mid-brown humified peat, with fewer Picea wood fragments.
85-103	Gradual transition to darker brown, more humified peat with few plant remains, a few gymnosperm twigs (e.g. 82 cm), sedges, and sand grains.
103-116	Peat as above, becoming muddy, with few recognizable plant remains except for Picea wood down to base.
116-137	Ice.
137-	Bedrock base.

Exotic Pollen Influx

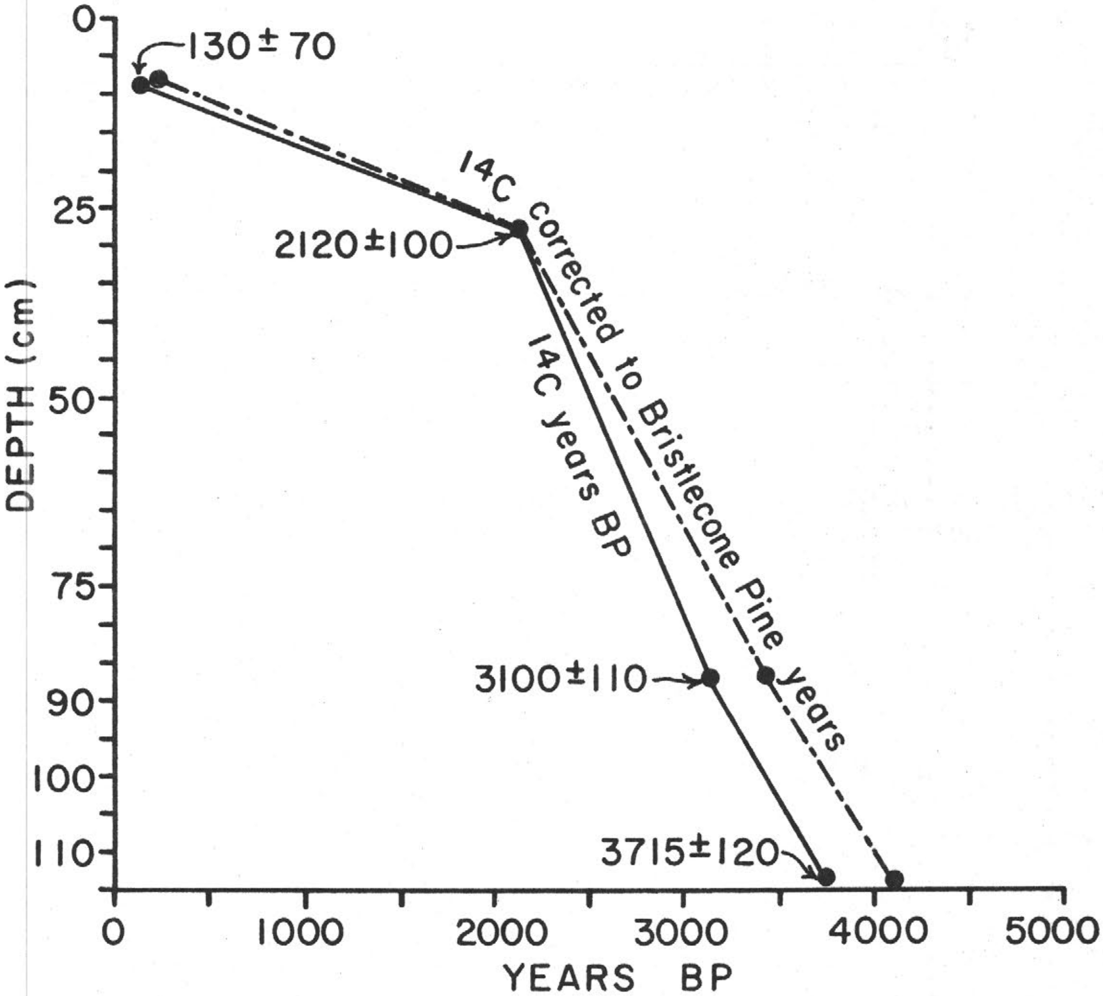
Pollen of Picea, Pinus, and Alnus were low in numbers from the organic base at 3715 ± 120 BP (GX-1813) to 3250 BP. These exotic taxa recovered at 3250 BP and then declined from 3100 to 2800 BP. Variable Picea values followed from 2800 BP to 2120 ± 100 BP (GaK-5054) when Picea and Pinus increased. Pinus numbers then maintained a plateau of about 1000 pollen/g while Picea sank to lower numbers from 1300 to 600 BP, but both taxa increased at 200 BP.

Abies occurred as single grains at times of other exotic peaks, at about 1000 BP and just before present (estimated 1920 A.D.). Ambrosia had single grain representation at 3100 ± 110 BP (GaK-5053), at about 1000 BP and at the modern surface. Eleagnus had a substantial influx at 2300 BP.

Local Pollen Influx

Pollen referable to dwarf birch (Betula glandulosa) dominates the diagram from the base at 3715 ± 120 BP (GX-1813) to 2120 ± 100 BP (GaK-5054), ranging between 100,000 and 200,000 pollen/g, with a major reduction from 3550 to 3400 BP, and a lesser reduction between 2400 and 2150 BP. Betula numbers were low from 1800 BP to the surface. Salix maintained fairly stable numbers throughout, with a reduction

Figure 11



Sedimentation chronology for Coppermine, Saddleback Hill, with correction to calendar years by bristlecone pine chronology (Suess, 1970).

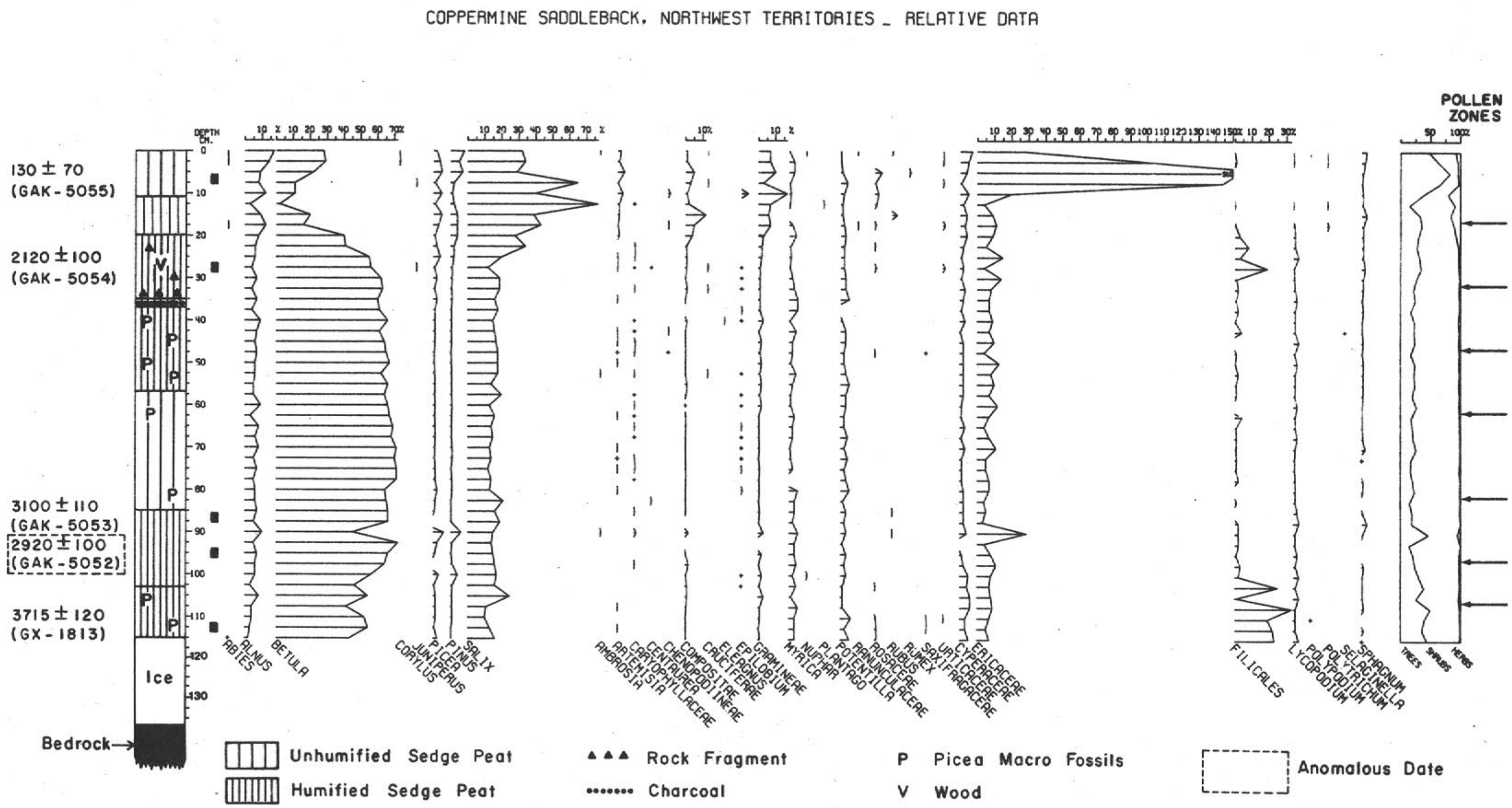


Figure 12: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

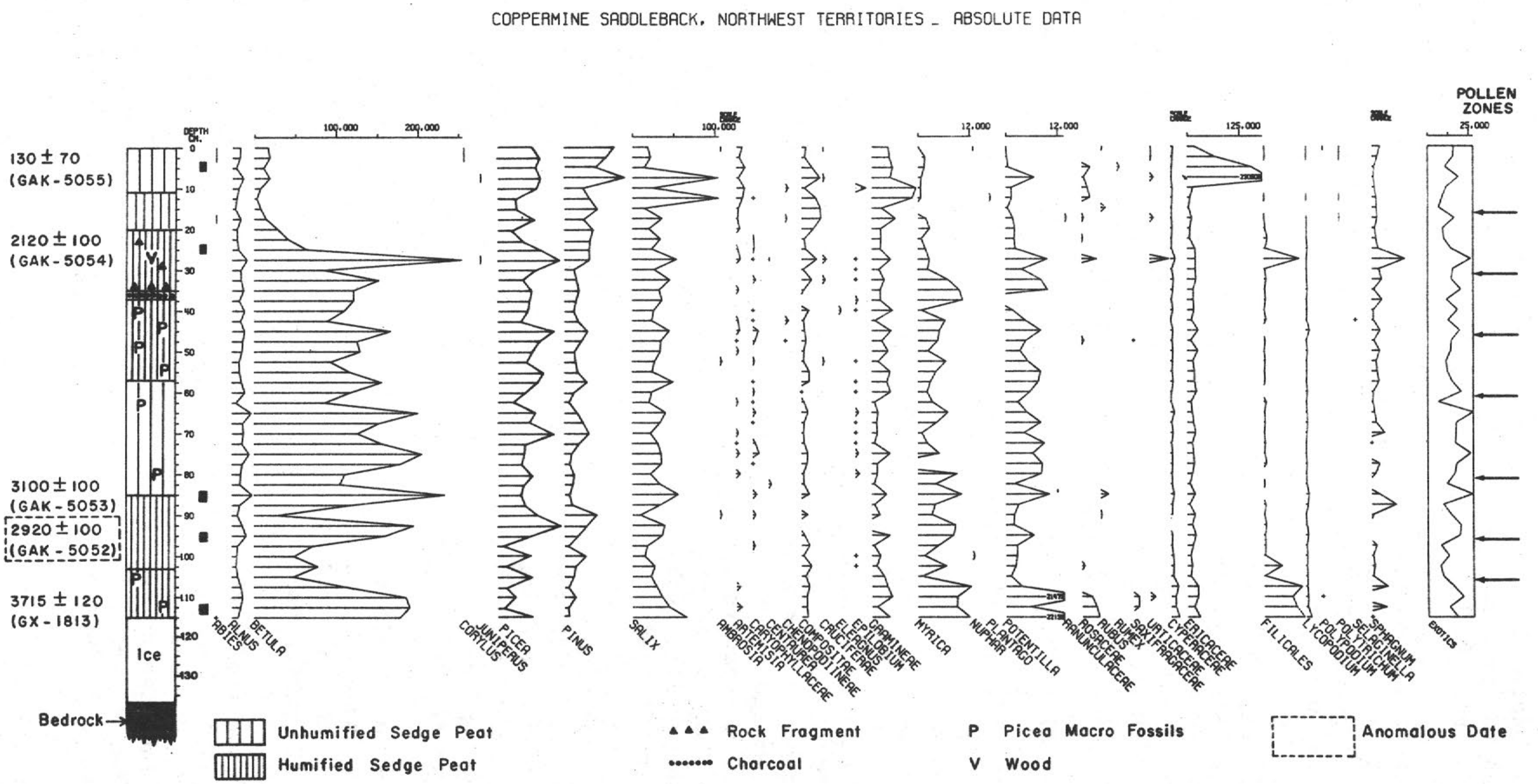


Figure 13: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines.

at 3400 BP and peaks at 600 BP and 130 ± 70 BP (GaK-5055). Artemisia had low values throughout but had continuous representation from 1350 BP to modern times. Low Compositae numbers increased between 1350 BP and the present. Gramineae increased after 1100 BP and peaked between 500 and 200 BP.

Myrica values were substantial from 3715 ± 120 BP (GX-1813) to 3600 BP. They then declined to more modest levels until an increase at 2300 to 2200 BP; from 2120 ± 100 BP (GaK-5054) onwards their numbers were low.

Potentilla numbers were high at 3715 ± 120 BP (GX-1813), while they were particularly low after 2120 ± 100 BP (GaK-5054). Cyperaceae counts were consistently low and stable. Ericaceae numbers were abundant and stable from the base to 130 ± 70 BP (GaK-5055) when there was high representation. Filicales spores were substantial only at the base of the profile. Sphagnum values were low throughout.

Nuphar appeared once at 3400 BP, Plantago was recognized just below 130 ± 70 BP (GaK-5055), and Rumex occurred just after that. Pollen referable to Urticaceae appeared in the basal and the topmost peat.

Interpretation

The basal frozen peat on the side of Saddleback Hill was dated 3715 ± 120 (GX-1813). This material lies at about 43 m a.s.l. and the ^{14}C assay is approximately 3000 radiocarbon years after the estimated emergence of the site from the sea (Andrews, 1970b, 1971). Like the beach peat (see above), there seems to have been a long hiatus before organic accumulation occurred on the sloping bedrock of Saddleback Hill, probably generated by some environmental/climatic change which favored peat growth (Nichols, 1969). This would usually (but not always) be associated with a cooler climate and more precipitation, and/or with a rise in permafrost levels which would lead to soil waterlogging (Fredskild, 1967; Nichols, 1969). This latter factor may be irrelevant here because of the impermeable bedrock base. Alternatively, under arctic conditions an increase in climatic warmth may apparently trigger the growth of peat (Bartley and Matthews, 1969; Nichols, 1970) due to snowbank melting or increased precipitation.

The date of 3715 ± 120 BP (GX-1813) falls at the end of a warm climatic episode in northern Canada, followed at about 3600 or 3500 BP by cooling (Bryson, Irving, and Larsen, 1965; Nichols, 1972). Saddleback basal exotic pollen values (especially alder, spruce, and pine) were low from 3715 ± 120 BP (GX-1813) to 3250 BP. There were many spruce wood macrofossils in the Coppermine Saddleback peat, but so few Picea pollen that it is clear that relict spruces were surviving on Saddleback Hill from 3700 to 2500 BP by vegetative means, and were not producing pollen. The highest exotic counts are, however, compatible with pollinating spruces fairly near to Coppermine, possibly in the Nipartoktuak valley where modern relict spruce clones exist.

The variable numbers for the exotic pollen from about 3300 to 2700 BP may not be confidently explained in the light of present knowledge, but the statistical validity of these changes at Coppermine Saddleback is supported by the BMD program which distinguished breaks at about 3250 BP (95 cm), 2960 BP (80 cm), and 2640 BP (60 cm). These short-lived alternations may conceivably have reflected latitudinal movements of the forest-tundra ecotone which lay to the south and/or shifts in dominance of southerly/westerly airflow over northerly winds. This interpretation was also applied to variations in pollen and stratigraphy at Ennadai Lake (Keewatin) between 3200 and 2600 BP (Nichols, 1967b).

The especially low exotic pollen values from 55 to 45 cm (five sample levels counted) occurred at about 2500 to 2250 BP. This is interpreted as being due to a southward movement of the forest-tundra ecotone and/or an increased summer dominance of northerly winds over southerly/westerly airflow. After 2500 BP spruce wood macrofossils disappeared from the Saddleback peat. This may have reflected the elimination of the spruce clones by climatic cooling or by Eskimo use (McGhee, 1972). This latter may have merely coincided with climatic change but if the cooling involved forest retreat to the south of Coppermine, this might intensify local Eskimo use of clonal spruces at a time when climatic alteration was increasing the difficulties of spruce clone regeneration.

For exotic spruce and pine pollen this episode lasted until 2120 ± 100 BP (GaK-5054). This cold interval needs further ^{14}C dating to confirm its timing, but it appears to match the chronology of the widely recognized cold interval, marked in Keewatin by forest retreat and noted elsewhere in Canada (Terasmae, 1961; Bartley and Matthews, 1969; Nichols, 1969; Ritchie, 1969). The recovery from this episode was distinguished by the BMD program, and the timing appears to be similar, though somewhat earlier, to that recorded elsewhere (at about 2000 BP) (Nichols, 1967b, 1970, 1972). It is worth reiterating here a point made earlier (Terasmae, 1967; Nichols, 1970): changes in exotic pollen values may register the climatic alterations more quickly than those reflected in local pollen productivity because the exotics are transported by dominant airflows, which can respond more rapidly to climatic perturbations than do plant communities.

After 2120 ± 100 BP (GaK-5054) the rate of peat accumulation was five times less than in the period 3715 ± 120 BP (GX-1813) to 2120 ± 100 BP (GaK-5054). The apparent timing of this change is derived from a part of the diagram which is not closely dated, so the start of this episode of very slow growth may, in fact, have been earlier. The reduction in peat accumulation may mean that less precipitation was available for plant growth, conceivably because generally cooler conditions led to more ice cover on Coronation Gulf. There is some supporting evidence of reduced open water in the Arctic Ocean during the last several thousand ^{14}C years, from dates on driftwood found in raised beaches (Knuth, 1967; Fredskild, 1969; Blake, 1972) generally attributed to increased sea ice cover. In Northern Greenland the ice increase was marked following 3300 BP and especially from about 2500 BP onwards, while in the Queen

Elizabeth Islands the driftwood was especially sparse from 4500 to 500 BP. Alternatively, the drier climate may have been associated with warmer summers.

The recovery of exotic pollen numbers after 2120 ± 100 BP (GaK-5054) may have been due to increased southerly/westerly wind strength resulting from a period of summer warming followed by a short cold episode at about 1400 BP. Warmer summers returned to produce the peaks in alder and spruce values at about 1000 BP. This period is known for forest advance in southern Keewatin at 1200 to 1000 BP (Bryson, Irving, and Larsen, 1965) and for peaks in exotic tree pollen in northern Keewatin at and just before 900 ± 75 BP (WIS-245) as a reflection of the same warm episode (Nichols, 1970).

Exotic pollen values at Saddleback Hill then declined at about 700 BP, due possibly to colder summers, stronger northerly winds, and a retreat of the northern forest edge. This coincides with the southern Keewatin forest retreat (Bryson, Irving, and Larsen, 1965) and the clearly evidenced tundra expansion there and in northern Quebec (Nichols, 1967a;Bartley and Matthews, 1969) at 630 ± 70 BP (WIS-133) and 670 ± 120 BP (NPL-125). There was a reduction in exotic pollen influx in the Keewatin Barren Grounds (Nichols, 1970) at the same time. Exotic pollen increases occurred within the last 130 ± 70 C14 years (GaK-5055) which may reflect the late 19th and early 20th century warming, since this date is essentially indistinguishable from "modern" in ^{14}C terms.

Local Palynological History

From 3715 ± 120 BP (GX-1813) to 2120 ± 100 BP (GaK-5054) the Saddleback Hill site was dominated by a community of dwarf arctic birches (Betula glandulosa), with subsidiary numbers of willows (Salix spp.), cinquefoil (Potentilla), bog myrtle (Myrica), and clonal infertile spruce (Picea glauca or P. mariana). This low arctic tundra assemblage represented mesic or possibly somewhat moist local conditions, which is also indicated by the inception of peat growth and its continued relatively rapid accumulation during that time (0.44 mm per year). The accumulation of 21 cm of ice between the peat and the bedrock points to a prior time of greater precipitation and reduced permafrost, probably associated with this general period, 3700 to 2100 BP. The willow pollen may reflect primarily the Salix communities along the nearby Coppermine River, which were well represented and fairly stable throughout this period. Between 3600 and 3350 BP the reduction in Betula, Myrica, Salix, Filicales (ferns), and possibly some species of Potentilla, along with reduced numbers of exotic pollen, suggests a drier and colder summer climate associated with a greater proportion of northerly winds relative to southerly and westerly airflows. The birch scrub community was also associated with stable heath (Ericaceae) communities nearby on the drier soils, and with grasses. Sedges were not locally abundant, though there were more at the base. The infertile spruces were eliminated after 2500 BP (see above).

After 2120 ± 100 BP (GaK-5054) the dwarf birch community no longer dominated the area, and Myrica and Potentilla were also much reduced, suggesting drier and colder summer climates. This agrees with the reduced exotic pollen counts. The later rise of the Compositae, grasses, and later heaths suggests continued dry summers through to the present. This may have resulted from increased summer sea ice cover on Coronation Gulf, such as was noted elsewhere in the Arctic after 2500 or 2200 BP by Knuth (1967), Fredskild (1969), and McGhee (1972) (and cf. Blake, 1972).

The increases in Compositae, Gramineae, and Artemisia which began to be substantial after 1300 BP are difficult to interpret paleoclimatically, since these taxa include such diversity of autecological response to change. A heath community developed locally at 130 ± 70 BP (GaK-5055). The occurrence of small quantities of plantain (Plantago), dock (Rumex), and nettle (Urticaceae) pollen in the topmost peat of Saddleback Hill probably reflects the soil disturbance and manuring around the nearby Coppermine Eskimo settlement about 1 km north of the peat site. Recent consolidation and enlargement of the village plus the increased White contact presumably explain these introductions of nitrophilous and alien weeds.

Comparison of the Coppermine Beach and Saddleback Records

The parts of the two records which overlap for the last 2500 ^{14}C years show a close resemblance in timing and direction of change in the pine and spruce "absolute" counts, as indeed they should if the hypothesis of an exotic origin is well founded. The recovery of exotic pollen values was dated 1920 ± 85 BP (GaK-5065) at the beach site and 2120 ± 100 BP (GaK-5054) at Saddleback; these dates overlap when two standard deviations are employed. The Saddleback peat was growing very slowly then, so that the vertical extent of the ^{14}C sample may be responsible for the difference in the date of recovery of exotic pollen values.

Some difference in sensitivity or emphasis is noticeable in the exotic pollen registration of a brief, possibly cold episode at about 1400 BP at Saddleback Hill which is not apparent at the beach site.

As expected, the two records of local plant ecology have fewer points in common, since there is great variation in tundra pollen deposition related to very local sources (Bartley, 1967; Ritchie and Lichti-Federovich, 1967; Terasmae, 1967; Nichols, 1970 and unpub.).

The major local change in birch scrub disappearance occurred at Coppermine Beach prior to or by 2500 ± 140 BP (GSC-1817), while at Saddleback Hill that event is dated 2120 ± 100 BP (GaK-5053). Doubling the standard deviation to give a 95% confidence limit brings the dates close together, but even allowing for sampling differences there does seem to be a metachrony here. This may, however, be more apparent than real. Prior to 2500 ± 140 BP (GSC-1517) the beach site was bare sand unoccupied by plants. The site may, therefore, have been unfavorable to Betula glandulosa colonization, especially at the time of a climatic change which eliminated the locally-established communities of that species. Differences in site microclimatology may also have been involved. Clearly, the date for decline of the established dwarf birch community (with a prior record) at Saddleback Hill (2120 ± 100 BP, GaK-5054) is more likely to be correct than that obtained for Coppermine Beach.

Other evidence for the differences between the two sites during this dry cold episode includes the sedge numbers which were low and almost unchanged throughout at Saddleback Hill, whereas sedges grew well at the beach site and had significant palynological trends. *Sphagnum* also produced more spores at Coppermine Beach. These differences may be due to the much wetter and more productive nature of the level beach, which accumulated peat more than twice as fast as did Saddleback Hill. The drier hill site has substantially more composite and grass pollen than the beach, possibly for the same reason. The *Betula* increase at the beach between about 1100 BP and 500 BP contrasts with the birch recovery at Saddleback between 130 ± 70 BP (GaK-5055) and the present, though both sites shared an increased heath cover in recent times.

CHAPTER III

THE MID-HOLOCENE HISTORY OF VEGETATION AND CLIMATE

NEAR THOMPSON LANDING, GREAT SLAVE LAKE, DISTRICT OF MACKENZIE, N.W.T.

Introduction

I visited the northeast arm of Great Slave Lake (McLeod Bay) in July 1971 primarily because Larsen (1971) had noted the very sharp forest-tundra ecotonal boundary in the area between Pikes Portage and Artillery Lake. Searches for peat profiles were based at the meteorological station at Fort Reliance just south of the ecotone (at 63° 43' N, 109° 08' W), but no profile of sufficient depth was found within walking distance of that location. A single-engine float plane was therefore chartered to fly along the north shore of Great Slave Lake. North of the abandoned settlement of Thompson Landing a profile in a peat cliff, eroded by a small unnamed lake at 63° 04' N, 110° 47' 30" W, was sighted and sampled by chain-sawing a monolithic series of blocks. Due to a variety of difficulties it was not advisable to stay long at this site, so that peat was only sampled down to 160 cm and no mineral base reached. Permafrozen peat was sampled to below the nearby lake level, but flooding of the excavation made further sample recovery impracticable.

Fires in the area and bad lighting conditions made any vegetational survey impossible. The peat profile was located just north of the forest-tundra ecotone, mostly in tundra but with small patches of dwarfed relict spruces. The site was about 16 km (10 miles) north of Great Slave Lake, just on the transition from open subarctic woodland (B.27) to mixed forest-tundra according to Rowe (1972), with the northernmost limit of tree-species about 96 km (60 miles) to the north (Rowe, 1972).

The woodland and tundra fires were interesting as a possible analog for past fires at times of climatic desiccation associated with overall cooling (Bryson, Irving and Larsen, 1965; Nichols, 1967a). The Arctic Front lay well south of the ecotone in July 1971, but because of prolonged sunshine, almost around the clock, the ambient air temperatures were reaching the 80°s F. at Fort Reliance. There were patches of forest fire from Reliance to Yellowknife (at least) along the forest edge, a flying distance of 320 km (200 miles). If this is a valid analog for past events, it suggests that at times of overall climatic cooling, due to southward displacement of the Arctic Front in summer, the ecotone itself might have experienced locally higher temperatures resulting in increased fire hazard.

Climatic Data (see following table, page 34)

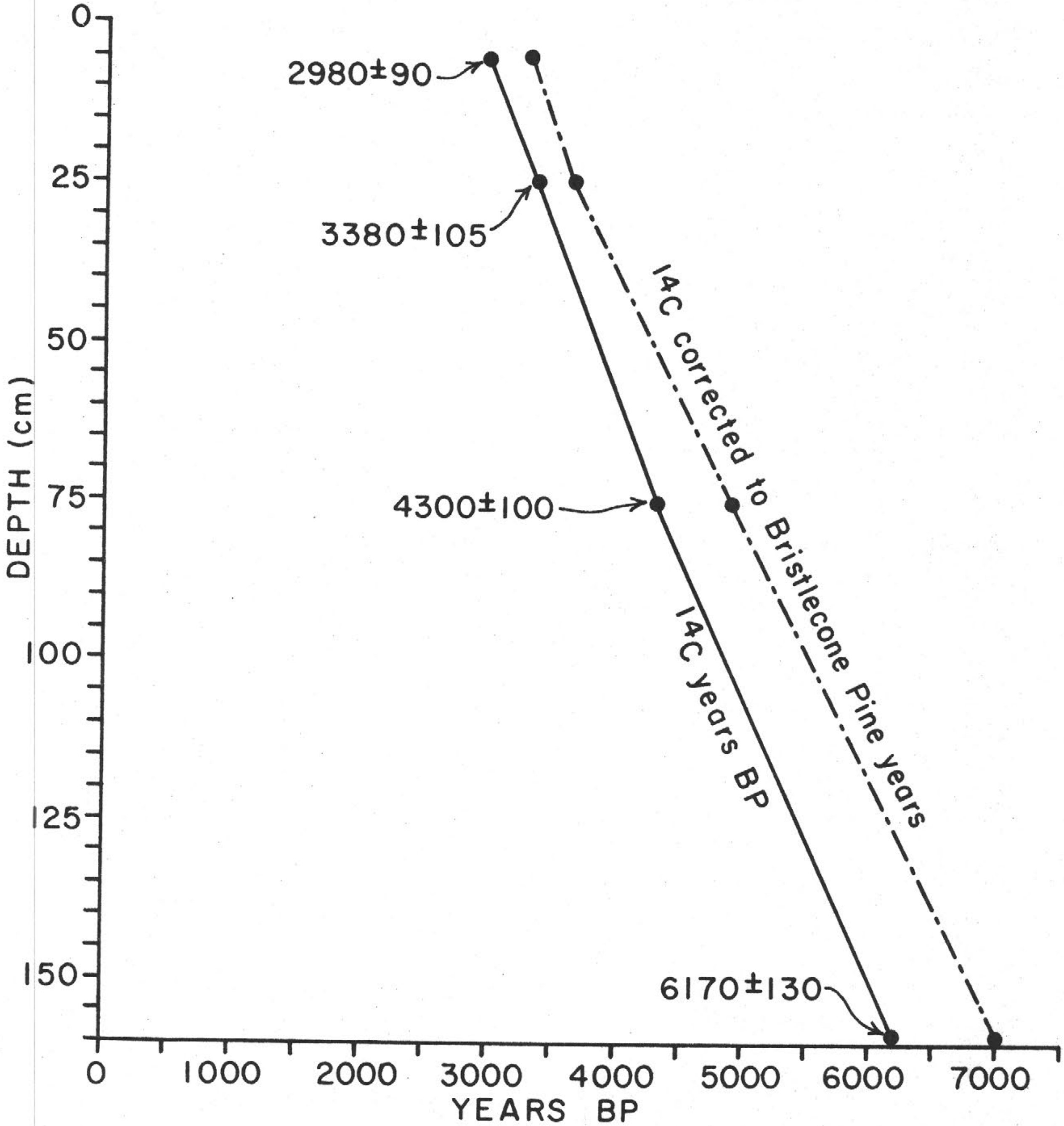
Fort Reliance provides the nearest comparable meteorological record:

FORT RELIANCE — LATITUDE 62 43 N LONGITUDE 109 06 W ELEVATION 539 FT ASL

	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR	
MEAN DAILY TEMPERATURE (DEG F)	-21.4	-17.6	- 4.5	14.3	33.8	46.6	55.2	55.3	43.7	27.0	7.0	-11.6	19.0	6
MEAN DAILY MAXIMUM TEMPERATURE	-13.9	- 8.6	6.3	25.0	42.3	56.3	64.0	62.5	49.2	32.0	13.6	- 4.0	27.1	6
MEAN DAILY MINIMUM TEMPERATURE	-28.9	-26.6	-15.2	3.6	25.2	36.8	46.3	48.0	38.2	22.0	0.3	-19.1	10.9	6
MAXIMUM TEMPERATURE	31	43	43	59	74	85	90	86	81	64	44	33	90	1
MINIMUM TEMPERATURE	-60	-57	-58	-35	-24	21	30	34	19	-10	-45	-50	-60	1
MEAN RAINFALL (INCHES)	0.00	0.00	0.00	0.02	0.21	0.74	1.10	1.08	0.89	0.28	0.01	T	4.33	4
MEAN SNOWFALL	4.0	4.1	4.0	3.6	2.2	0.2	0.0	0.0	1.3	7.9	9.4	7.4	44.1	4
MEAN TOTAL PRECIPITATION	0.40	0.41	0.40	0.38	0.43	0.76	1.10	1.08	1.02	1.07	0.95	0.74	8.74	4
NO.OF DAYS WITH MEASURABLE RAIN	0	0	0	1	4	5	8	9	8	3	*	*	38	2
NO.OF DAYS WITH MEASURABLE SNOW	9	8	8	7	4	1			2	9	13	12	73	2
NO.OF DAYS WITH MEAS PRECIPITATION	9	8	8	7	7	6	8	9	9	11	13	12	107	2
MAXIMUM PRECIPITATION IN 24 HRS	0.31	0.25	0.30	0.66	0.38	1.50	1.57	1.35	0.85	0.66	0.45	0.78	1.57	6

Source: Temperature and precipitation tables for the North - Y.T. and N.W.T. Canada, Department of Transport, Meteorological Branch, Toronto, 1967.

Figure 14



Sedimentation chronology for Thompson Landing, Great Slave Lake, with correction to calendar years by bristlecone pine chronology (Suess, 1970).

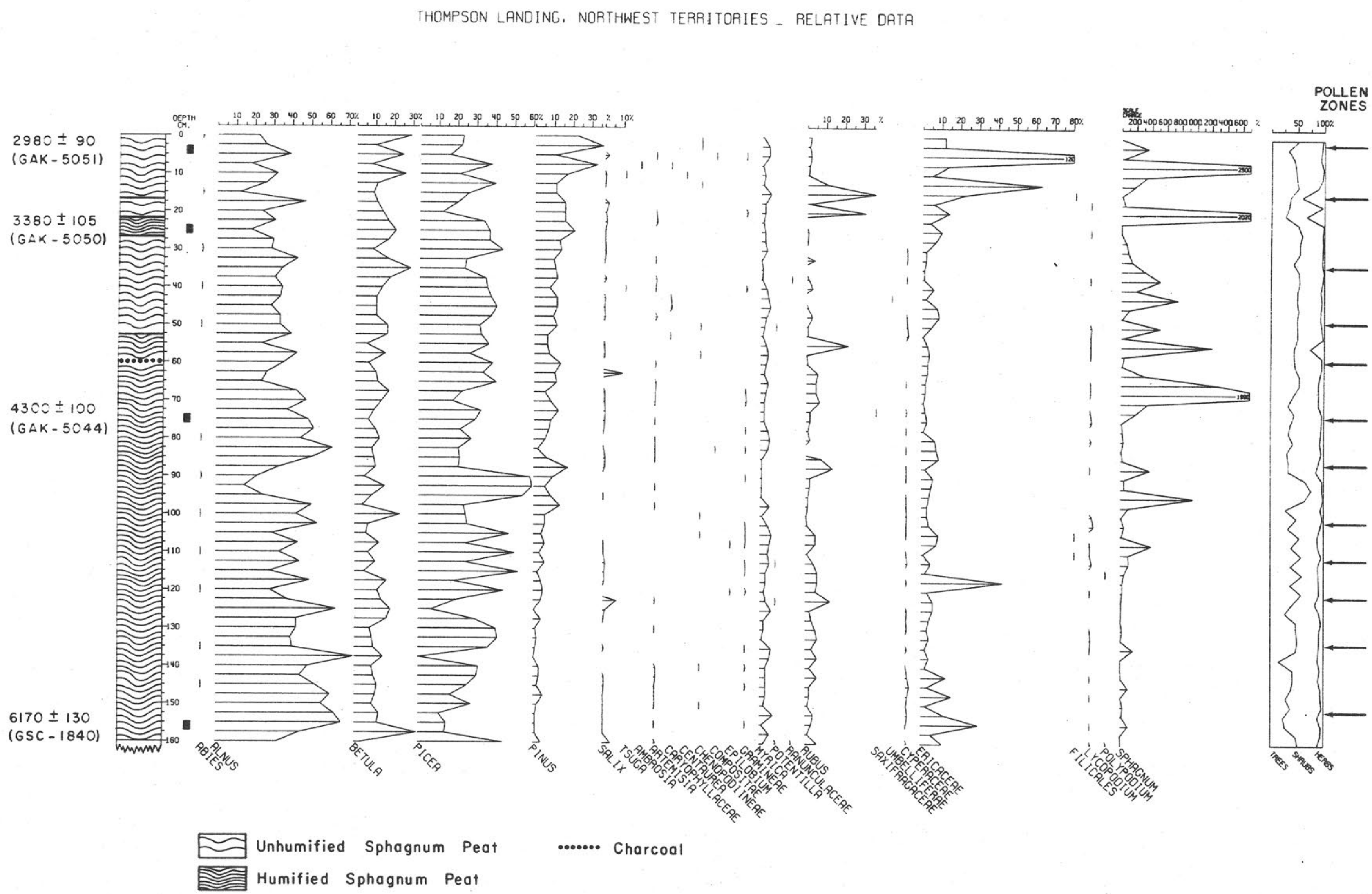


Figure 15: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

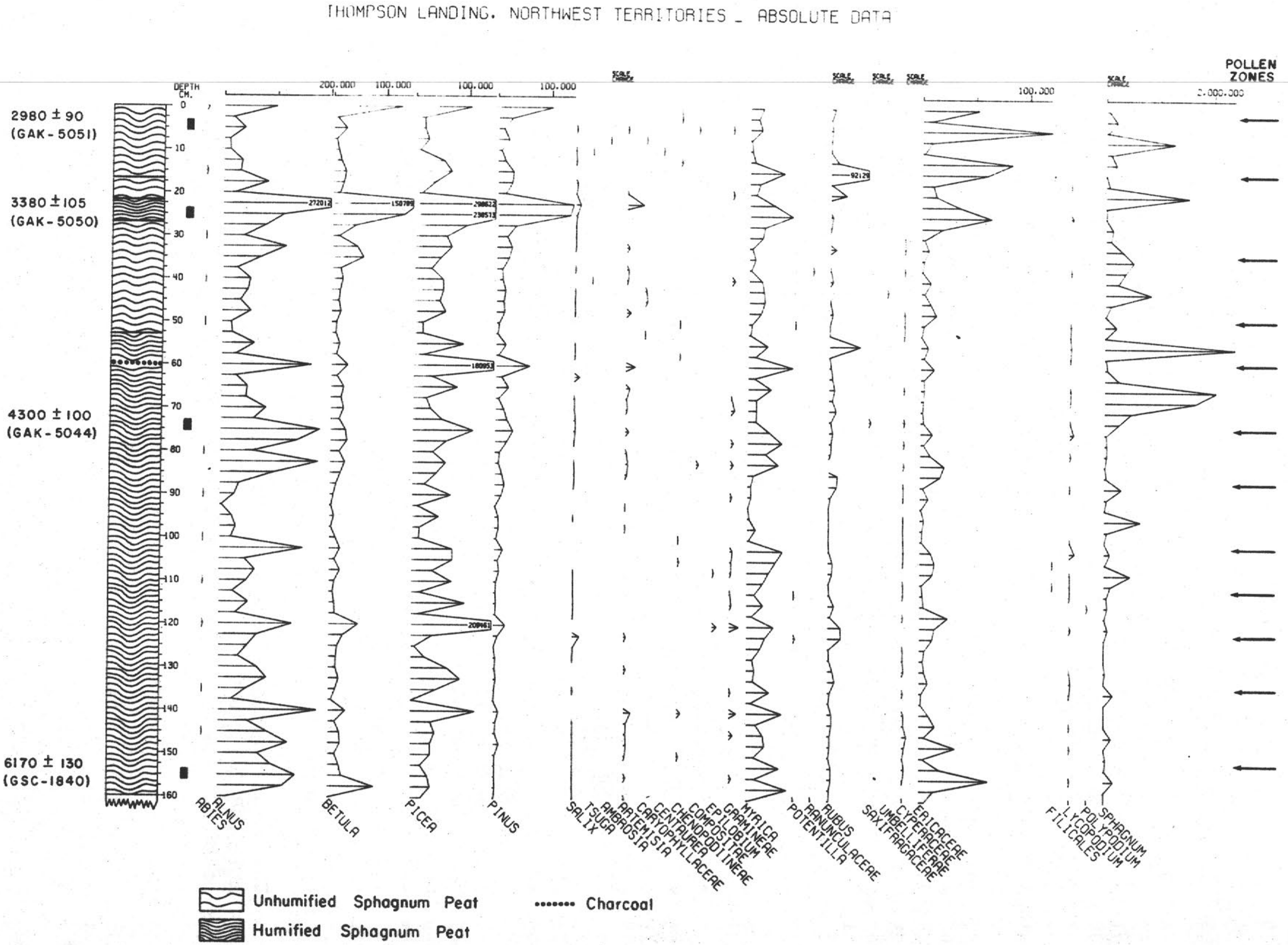


Figure 16: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines.

Peat Stratigraphy: an abbreviated summary

Depth cm	Modern surface unvegetated.
0 - 17	Light brown unhumified *Sphagnum* peat, grading into slightly darker peat 11-17 cm.
17 - 22	Light brown fresh *Sphagnum* peat.
22 - 27	Dark brown humified *Sphagnum* peat.
27 - 53	Light brown unhumified *Sphagnum* peat.
53 -160	Somewhat more humified *Sphagnum* peat but still fairly fresh. At 60 cm a band of charcoal 7 mm thick.
160 -	Samples not recovered beyond this depth (see text); no inorganic base reached.

Palynological Data (Figures 14-16)

The lowermost 60 cm (6170 ± 130 BP (GSC-1840) to 4900 BP) of this 160 cm sequence had moderate variable *Picea* and *Alnus* numbers, frequently between 50,000 and 100,000 pollen/g. Apart from smaller numbers of *Betula* and *Myrica*, the other taxa had low "absolute" values. *Alnus* was greatly reduced from 100 to 87.5 cm (4900-4500 BP) and *Picea* values also fell at 4900 BP; the BMD program distinguished major breaks at 4900 and 4500 BP. *Myrica* and Ericaceae were low during this period.

After 4500 BP there was a very marked *Alnus* recovery, a more gradual rise of *Picea* to variable, intermediate values (50,000-100,000 pollen/g) and increased *Myrica* after 4450 BP. *Picea* continued this pattern, with short-lived reductions followed by large peaks; these episodes often lasted as little as 50 years. Above 47.5 cm (3800 BP) *Picea* values were more stable at 50,000 pollen/g, and this taxon, along with *Pinus*, *Alnus*, and *Betula*, increased to maximum values up to 3500 to 3350 BP. *Sphagnum* peaks occur for the first time in the diagram from 4250 BP onwards at 3950 BP, 3700 BP, and 3300 BP.

At 3350 BP the peaks of *Picea*, *Pinus*, *Alnus*, and *Betula* collapsed, and for the rest of the diagram had only modest or low values. Ericaceae became an important element for the first time since ca. 6000 BP. *Rubus* peaked at 3200 BP, where *Picea* had a minor recovery and then fell again. *Sphagnum* alternated between high and low values. The topmost sample from the present-day dead peat surface had high values of *Alnus*, *Betula*, *Picea*, and *Pinus*. Peat growth was not recorded after 2980 ± 90 BP (GK-5051).

Interpretation

The lowest section of the diagram, from the organic base of 6170 ± 130 BP (GSC-1840) to 4900 BP, has "absolute" pollen values consistent with an open spruce forest with alder shrubs and *Myrica* (bog myrtle) (Nichols, unpub.). The peat was a fast growing unhumified *Sphagnum* spp. (bog moss) type. The forest border was north of the site and the summer climate was warmer and moister than now. Spruce and alder both suffered at times of fire, the effects of which were short-lived (pollen recovery within about 50 years). Fire was responsible for some of the spruce pollen variability, but perhaps here (as in other ecotonal diagrams) there is also evidence of a genuine short-term environmental variability due either to climatic changeability in the northernmost forest, or to cycles of spruce maturation, senescence, and decay. The somewhat more humified peat may have represented warmer, drier summers until 4900 BP.

At 4900 BP the BMD program recognized a change marked by reduced representation of spruce, alder, and bog myrtle; the Sphagnum peat was very unhumified, and Sphagnum sporogenesis increased. The forest became more open and patchy, and/or the forest-tundra ecotone moved south (until it reached or was very near Thompson Landing) due to colder wetter summers dominated by increased southward excursions of the Arctic Front with associated cyclogenesis. The absence of tundra plant macrofossils and the fresh unoxidized nature of the peat suggests that full tundra conditions were not established at that time and that the summer climate was not as cold and dry as now.

The recovery from this cold episode at 4500 BP was recognized by the BMD program. It was marked by an immediate establishment of alders which dominated the site from 4500 to 4300 BP, while the spruces reestablished themselves more gradually until there were "absolute" values indicative of open spruce woodland by 4300 ± 100 BP (GK-5049). Another cold summer episode began immediately after 4300 ± 100 BP, at 4250 BP, and lasted until 4150 BP; during this time there was more open spruce woodland, fewer alders, and very prolific Sphagnum sporogenesis (maximum values for the diagram, 2,652,000 spores/g). This reflected a southward shift in the mean position of the Arctic Front to a location close to the site. Short-lived regeneration of spruce woodland occurred, but its subsequent variations and the vacillations of Sphagnum counts may very tentatively be ascribed to frequent location of the summer Arctic Front near to the site.

At 3800 BP Picea values stabilized and an equilibrium of open spruce woodland with alder shrubs was established, with the Arctic Front consistently well to the north of Thompson Landing. From 3500 to 3380 ± 105 BP (GK-5050) the spruce forest apparently became denser. This appears from the "absolute" counts (Picea, 2-3,000,000 pollen/g) to be the episode of maximum spruce forest density at this site and possibly the time of greatest northward extension of the forest-tundra limit. Pine also appears to have invaded the area. This episode is, however, probably deceptive. The coincident peaks of pollen of alder, tree birches, and Ericaceae argue against the suggestion of closed spruce and pine forest; a more likely explanation is derived from the stratigraphy. At about 27 cm depth the Sphagnum peat was charred by fire, and from there to 23 cm the peat was extremely humified. This upper level consisted of unconsolidated powdered organic material, apparently the remains of peat weathered in situ, with numerous leaves of Ledum cf. palustre and Vaccinium cf. vitis-idaea, indicative of a cold dry tundra environment. The preferred explanation of events now is that the spruce forest did become denser between 3800 and 3700 BP, but this warm episode ended in a forest fire at 3500 BP, followed by prolonged domination of the site by the cold dry Arctic air masses. The maximum values of alder, birch, spruce, and pine after this event (at 3380 ± 105 BP, GK-5050) were thus due to reduced influx of these pollen types continuing to accumulate on a dead Sphagnum peat surface.

This effect is often seen at the top of subarctic or arctic pollen diagrams when peat growth has ceased centuries ago (Nichols, 1972). The Ericaceae domination of the rest of the diagram probably results from the occupation of the site by heath-tundra communities, represented by the leaves of Ledum cf. palustre and Vaccinium cf. vitis-idaea, under continued generally cold dry summers with Arctic air masses.

Some regeneration of spruce occurred at 3250 BP and open spruce woodland (with Rubus chaemamorus, cloudberry) reoccupied the area from about 3200 to 3100 BP during a short episode of milder summers as the Arctic Front's mean position shifted just north of the site. Tree seedling regeneration ceased at 3100 or 3050 BP due to renewed domination of the area by arctic air masses in summer, and this was true for the remainder of the record which was truncated shortly after 2980 ± 90 BP (GK-5051) (at about 2900 BP) probably due to continued cold dry summers which inhibited peat growth. The topmost material was an unhumified Sphagnum peat, and it seems likely that later, even drier climates (especially severe at 2500 and 2200 BP, Nichols, 1972) would have led first to extremely slow accumulation of very humified, powdery weathered peat (as at around 25 cm, 3400 BP) which would have eventually been blown away in the absence of later peat-growth due to continued generally cold dry summers during the last two to three millennia. The peat produced during this same dry cold episode (2500-1600 BP and 3200-1800 BP, respectively) at Ennadai Lake and Colville Lake (Nichols, 1967, 1972) was exceptionally humified, weathered, and extremely slow to accumulate.

The exposure of the unhumified peat surface at Thompson Landing to presumably several thousand years of weathering suggests that secondary post-depositional humification of Sphagnum peat is not important in the Arctic, and that peat humification is a product of processes contemporary with the accumulation of sediments.

CHAPTER IV

THE MID- AND LATE HOLOCENE HISTORY OF VEGETATION AND CLIMATE AT ENNADAI LAKE, DISTRICT OF KEEWATIN, N.W.T.

Introduction

Pollen and peat stratigraphic analyses of a peat monolith previously collected from Ennadai Lake have been published (Nichols, 1967a). These analyses expanded the findings of Bryson, Irving, and Larsen (1965) on tree line advance into the tundra, and indicated that there had been numerous Holocene advances and retreats of the forest-tundra boundary in southern Keewatin. In 1972 a peat column was collected in the same area at 61°14'40"N, 100°57'5"W, 10 km (6 miles) north of the first. Three additional sites were sampled farther south on Nueltin Lake but these have not been analyzed for lack of money.

Topography and Vegetation

Ennadai Lake is at an elevation of 325 m a.s.l. (1065 ft) in fairly level to gently rolling country interrupted by eskers and other morainic deposits. The forest-tundra ecotone crosses the southern edge of Ennadai Lake and, despite the fairly level ground and apparent absence of major geological and soil discontinuities in the area, the ecotone is particularly distinct. Larsen (1965) noted the abrupt transition and estimated the north-south distance from forest to tundra as less than 20 km. This was confirmed when my chartered float-plane made the transition from full open tundra to lichen woodland in the same area in 4½ minutes flying at 90 m.p.h., i.e. about 11 km (7 miles). The ecotonal position is thought to be controlled by the mean summer position of the Arctic Front, with which it broadly coincides (Bryson, 1966; Barry, 1967).

The open lichen woodland of the boreal forest reaches the southern end of Ennadai Lake and ends about 40 km (25 miles) south of the 1972 peat bank. The spruce woodland is composed of *Picea mariana* and *P. glauca*, with some shrubs of *Alnus crispa* (alder), and *Salix* spp. (willows), and frequently dominant Ericaceae (heath) communities between the trees. *Pinus banksiana* (jackpine) does not reach the ecotone.

Climatic Data (see following table, page 42)

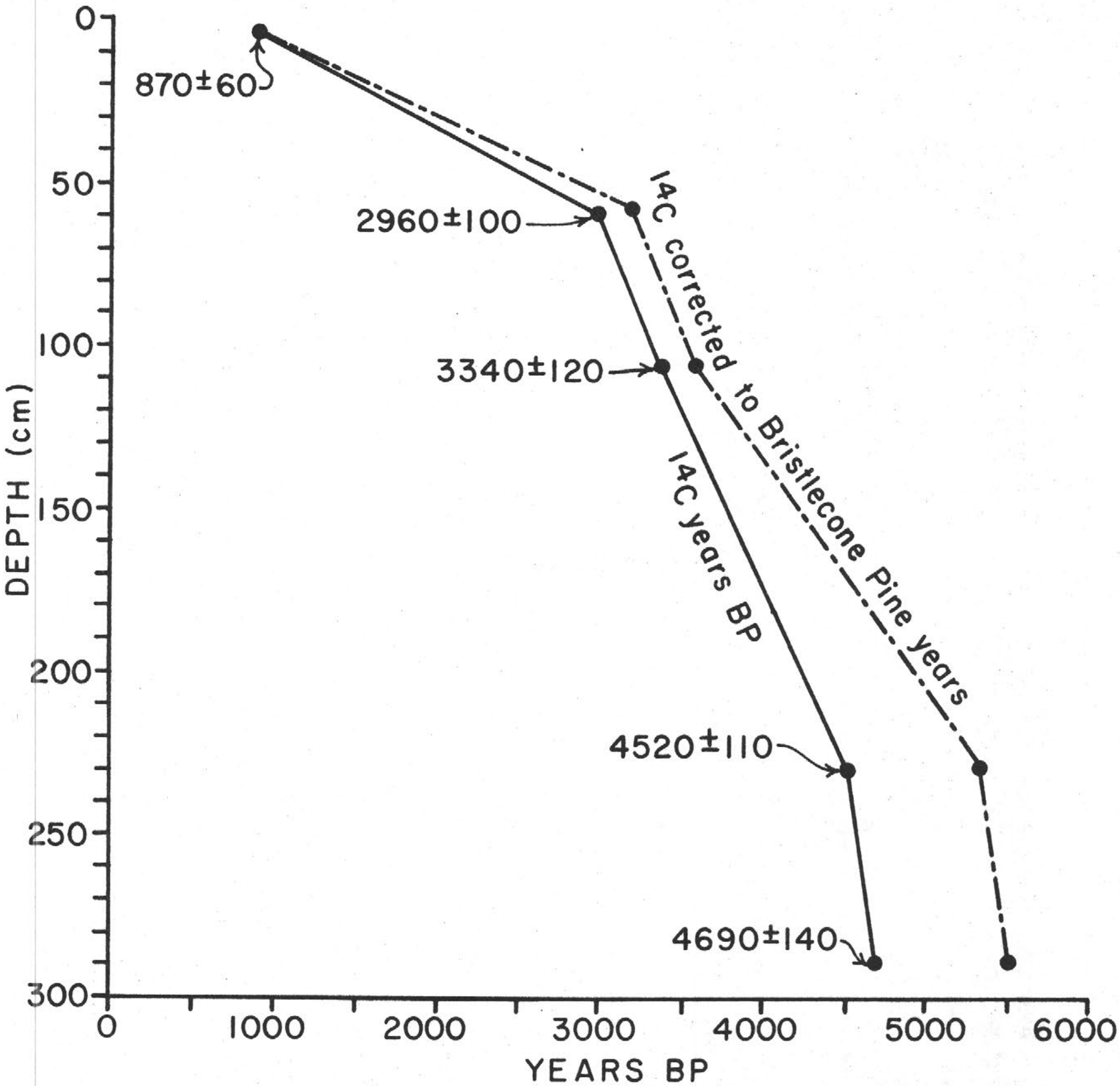
Peat Stratigraphy: an abbreviated summary

Depth cm	
0- 7	Very dark brown extremely humified peat.
7- 43	Light brown unhumified *Sphagnum* peat, slightly more humified below 23 cm.
43-126	Light brown slightly to moderately humified *Sphagnum* peat with some charcoal; charcoal layers at 60-63 cm,

ELEMENT and STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	YEAR	Type of Normal
ENNADAI LAKE	LATITUDE 61 08 N LONGITUDE 100 55 W ELEVATION 1065 FT ASL													
MEAN DAILY TEMPERATURE (DEG F)	-24.8	-20.0	- 9.1	8.4	25.8	43.1	54.3	53.1	39.5	22.2	1.6	-13.9	15.0	6
MEAN DAILY MAXIMUM TEMPERATURE	-18.3	-12.7	- 1.0	17.2	32.5	51.3	62.5	60.4	44.6	27.6	8.3	- 7.1	22.1	6
MEAN DAILY MINIMUM TEMPERATURE	-31.2	-27.2	-17.2	- 0.5	19.1	34.9	46.1	45.7	34.4	16.7	- 5.1	-20.6	7.9	6
MAXIMUM TEMPERATURE	27	33	38	51	62	84	89	81	76	62	38	34	89	1
MINIMUM TEMPERATURE	-55	-55	-50	-37	-20	17	31	30	13	-23	-41	-49	-55	1
MEAN RAINFALL (INCHES)	0.00	0.00	0.00	T	0.36	0.88	1.70	1.55	0.99	0.25	T	0.00	5.73	4
MEAN SNOWFALL	3.5	2.8	2.6	4.4	2.8	0.9	T	T	3.4	6.9	5.0	4.2	36.5	4
MEAN TOTAL PRECIPITATION	0.35	0.28	0.26	0.44	0.64	0.97	1.70	1.55	1.33	0.94	0.50	0.42	9.38	4
NO.OF DAYS WITH MEASURABLE RAIN	0	0	0	*	3	6	11	10	9	2	*	0	41	2
NO.OF DAYS WITH MEASURABLE SNOW	9	7	8	10	6	2		*	4	12	13	10	81	2
NO.OF DAYS WITH MEAS PRECIPITATION	9	7	8	10	9	8	11	10	12	14	13	10	121	2
MAXIMUM PRECIPITATION IN 24 HRS	0.18	0.18	0.22	0.37	1.20	1.37	1.60	1.71	1.14	0.59	0.25	0.52	1.71	6

Source: Temperature and precipitation tables for the North - Y.T. and N.W.T., Canada Department of Transport, Meteorological Branch, Toronto, 1967.

Figure 17



Sedimentation chronology for Ennadai Lake, 1972,
with correction to calendar years by bristlecone pine chronology
(Suess, 1970).

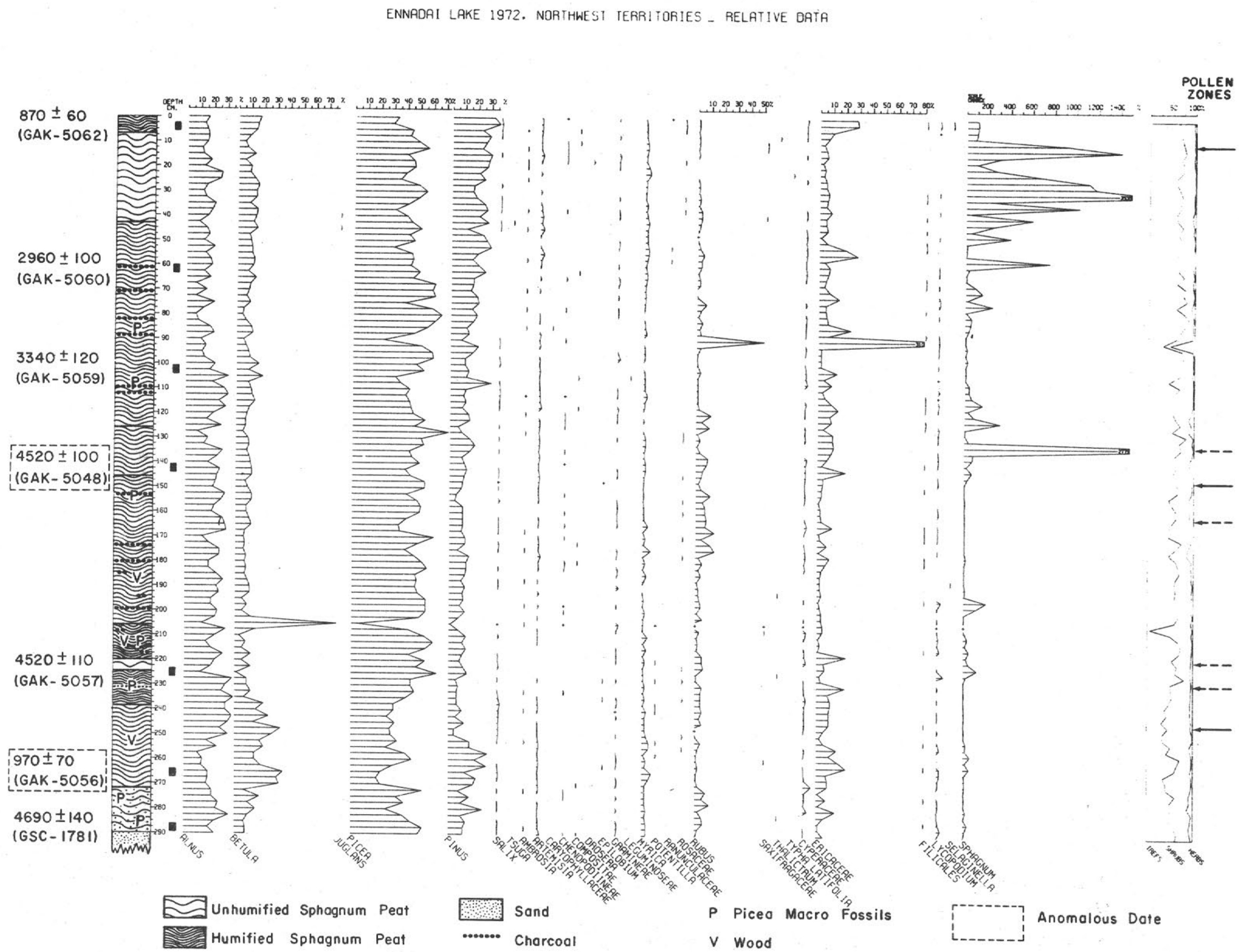


Figure 18: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

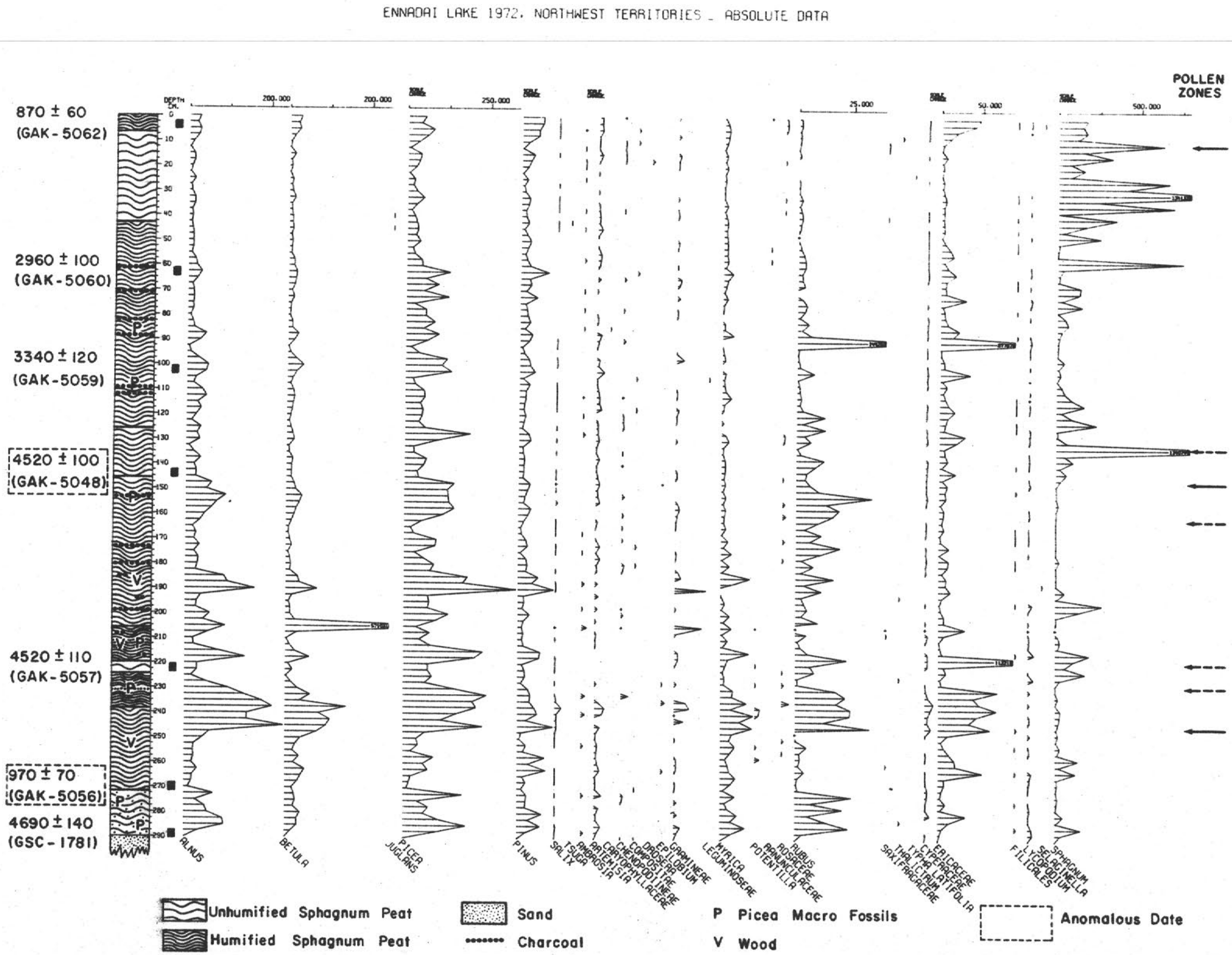


Figure 19: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines; the broken arrows indicate less significant sub-zones.

	70.5-72.5 cm, 82.5-86 cm, 88-91 cm. *Picea* wood at 87.5 cm. Horizon of humified peat and wood charcoal at 109-110 cm, with *Picea* and fragments. Less humified 102-126; thin layer of humified peat and/or charring at 112 cm.
126-146	Moderately humified light to mid-brown *Sphagnum* peat.
146-206	Mid-brown moderately humified *Sphagnum* peat, charred at 152-156 cm, and 174-176 cm. *Picea* wood 152.5-156 cm. Charring between 180 and 200 cm. *Alnus* wood at 187 cm.
206-220	Mid- to dark brown humified peat with wood fragments (including *Picea*) and charcoal.
220-224	Light brown unhumified *Sphagnum* peat.
224-238	Dark brown humified peat with *Picea* wood. Silt band 231-232 cm.
238-272	Moderately to lightly humified peat with high silt content, with band of mosses and *Betula* wood at 255 cm.
272-290	Light brown unhumified *Sphagnum* peat with some silt throughout, humified below. Many *Picea* needles.
290-	Coarse sand beach of Ennadai Lake.

Palynological Data (Figures 17-19)

The basal organic material which overlays lacustrine sand was dated 4690 ± 140 BP (GSC-1781). This level and most of the lowest meter of the diagram shows high values of *Picea* pollen, generally in excess of 50,000 pollen/g and often reaching over 100,000, from 4690 ± 140 BP (GSC-1781) to 4000 BP. *Sphagnum* peat accumulation was very rapid, 100 cm in 500 ^{14}C years, so the 2.5-cm sampling interval sometimes represented as little as 12.5 ^{14}C years in this lowest meter, and possibly only 7 ^{14}C years in the lowest 60 cm, if the date 4520 ± 110 BP (GaK-5057) is correct. Even at decadal intervals the spruce pollen production in this peat did not assume a smooth profile, but exhibited wide variations lasting several decades.

In the lowest meter of peat, high *Alnus* numbers varied roughly parallel to those of *Picea*. *Betula* tree pollen was less significant though still very substantial and varied. *Pinus* was generally much lower in numbers than *Picea*, often reaching only about 10,000-15,000 pollen/g, but at times of *Picea* peaks the *Pinus* numbers reached 50,000 pollen/g. Other pollen types were poorly represented, except for *Rubus*, basal Ericaceae, and *Myrica*. From 180 to 60 cm (4000 to 2960 ± 100 BP, GaK-5060) *Picea* numbers were somewhat reduced and more variable, and *Alnus*, *Pinus*, and especially *Betula* counts were lower. *Rubus* values were reduced, and *Sphagnum* rose at times to peaks of over 100,000 spores/g. The upper 60 cm (2960 ± 100 BP, GaK-5060, to 870 ± 60 BP, GaK-5062) saw low numbers of *Picea*, *Pinus*, *Alnus*, and *Betula* with large counts for *Sphagnum* (over 500,000 spores/g) and an Ericaceae increase in the topmost peats. Peat growth was very slow (35 ^{14}C years/cm) during this episode, and ceased just after 870 ± 60 BP (GaK-5062).

Interpretation

The growth of peat on the beach of Ennadai Lake at 4690 ± 140 BP (GSC-1781) occurred several thousand years after deglaciation (probably 8000-7000 BP; Falconer et al., 1965) and later than the basal peat at Ennadai Lake, 1967, 5780 ± 110 BP (WIS-67). The peat growth was probably related to some local or regional environmental and/or climatic change (Nichols, 1969). Current knowledge (Nichols, 1974, and this paper) suggests that after a cold dry episode at about 4800 BP, which pushed the tree line south, there was a recovery to milder moister summer climate about 4500-4400 BP. This is provisionally suggested as the causal mechanism of peat genesis at this site, consistent with the very rapid accumulation of the basal peat.

The basal pollen assemblage at 4690 ± 140 BP (GSC-1781) represented an open spruce forest with alders, with either local scattered pines (*Pinus banksiana*) or pines in larger numbers fairly close to the site. Pines are essentially absent from the northern 100 km of the modern forest. Substantial amounts of *Rubus chaemamorus* (cloudberry) pollen is probably indicative of moist peaty substrates. This assemblage is consistent with cool moist northern boreal forest summers dominated by Pacific air masses (Bryson, 1966) and warmer than present.

The close interval sampling during this episode of rapid peat growth (the 2.5-cm sampling interval is equivalent to about 7 years) clearly shows that in ecotonal forest situations the variations in pollen productivity can be very marked over short time intervals--probably even on an annual basis. The rate of peat growth was so fast that tests of year-by-year pollen productivity could be performed on this material.

This lowest episode from 4690 ± 140 BP (GSC-1781) to 4050 BP was ended by a subtle transition to greater *Picea* variability involving intermittent, quite low spruce counts which indicate very open woodland or partial deforestation due mostly to fire. Charcoal horizons were found at frequent intervals in the peat corresponding to these spruce pollen reductions. The forest fires seem to have occurred at approximately regular intervals of 150 ^{14}C years. However, using the corrected radiocarbon time scale of Suess (1970) on the basis of eight fires between 4650 and 3570 BP, the fire intervals are seen to be quite irregular, often occurring at 200 to 300-year intervals. The longest unburned forest episode was 350 (bristlecone) calendar years.

The peat throughout this profile was composed primarily of *Sphagnum* (bog moss) species, and at times of forest fire (e.g. 4500, 4200, 3600 BP) peaks of *Sphagnum* spores occurred. These peaks may have been a response to the incursion of cold Arctic air across the site in summer, thought to be the mechanism behind the recurrent forest fires (Nichols, 1967b). In this environment of fire-scarred open spruce woodland, the treeless episodes became lengthier as more major summer incursions of the Arctic air mass desiccated the forest. As fires spread farther south and covered more extensive woodland areas which became dried and damaged, spruce recolonization was even less rapid. Heath cover expanded during these open habitat episodes. The most prolonged fire episode began at 3570 BP and lasted until 3340 ± 120 BP (GaK-5048), after which there was some partial spruce woodland regeneration until 2960 ± 100 BP (GaK-5060). The reduction of *Rubus chaemamorus* (cloudberry) after 3500 BP is consistent with drier (and colder) summers.

After 2960 ± 100 BP (GaK-5060) the site was occupied by tundra and the forest border moved south as Arctic air occupied the site throughout the summers. This colder episode apparently stimulated *Sphagnum* sporogenesis, especially after 2500 BP, while the rate of peat accumulation was greatly reduced after 2960 ± 100 BP (GaK-5060) to an average of about 40 years/cm. It should be borne in mind that the topmost section of the diagram is the most hazardous for chronological extrapolation because of the very slow peat growth.

Some minor local regeneration of spruce or a small northward readvance of the woodland margin seems to have been registered beginning at 1500 BP, interrupted briefly at 1200 BP and revived at 1100 BP until shortly after 870 ± 60 BP (GaK-5062). *Sphagnum* spores were fewer after 1600 BP, then peaked from 1100-1000 BP and were low after 1000 BP. Ericaceae (heaths) spread after 1000 BP and increased up to the modern surface. This sequence is tentatively interpreted as minor summer climatic amelioration after 1600-1500 BP, with an interruption at 1200 BP. There were warmer summers from 1000 BP to shortly after 870 ± 60 BP (GaK-5062). Then, due to colder drier summers as the Arctic air mass moved south to cover the site throughout the summers of the last several centuries, tundra spread over the site and peat growth ended.

CHAPTER V

LATE HOLOCENE PALYNOLOGICAL DATA FROM THE MAKTAK FIORD SECTION, BAFFIN ISLAND, DISTRICT OF FRANKLIN, N.W.T.*

Introduction

In collaboration with Dr. J. T. Andrews' extensive research program on Baffin Island, short fossil peat sections were examined to learn to what extent paleowind shifts and displacements of the forest-tundra ecotone might be revealed in the deposition of exotic forest pollen in the high Arctic tundra.

Climatic Data (see table, page 50)

Peat Stratigraphy: an abbreviated description from comments by Dr. J. Dickson

Depth cm	
0 - 5.5	Decayed *Sphagnum* peat, with fragments of wood and bark and fresh herbaceous remains.
5.5- 10	As above, without wood or bark.
10 - 15	Well preserved *Sphagnum* peat and herbaceous material, wood fragments.
15 - 25	Partly decomposed homalthecii peat and herbaceous material, wood fragments.
25 - 65	Unhumified moss peat with decayed herbaceous material. Clay particles 30-35 cm.
65 -100	Well to moderately preserved *Polytrichum* moss, herbaceous material, wood and bark, sandy below 80 cm.

Methods

Pollen diagrams were prepared from samples taken at 2.5 cm intervals throughout the stratigraphic column. The chemical treatment of the samples prepared for palynology was conventional (Faegri and Iversen, 1964) and employed Erdtman's acetolysis technique, and prolonged boiling in hydrofluoric acid to remove the sand in the deposit; the reaction times were increased to allow for the reduced boiling point (90°C) at the altitude of Boulder, Colorado (5,500 feet) and the intractability of arctic peats.

Two types of pollen diagram were prepared: the conventional relative percentage diagram, excluding Cyperaceae, Ericaceae, and *Sphagnum* (because of their potential over-representation as peat formers at the sampling site), and an "absolute" diagram, based on dry weight of samples. The chosen pollen sum counted at each level was a minimum of 100 and ranged up to 300, excluding the three taxa

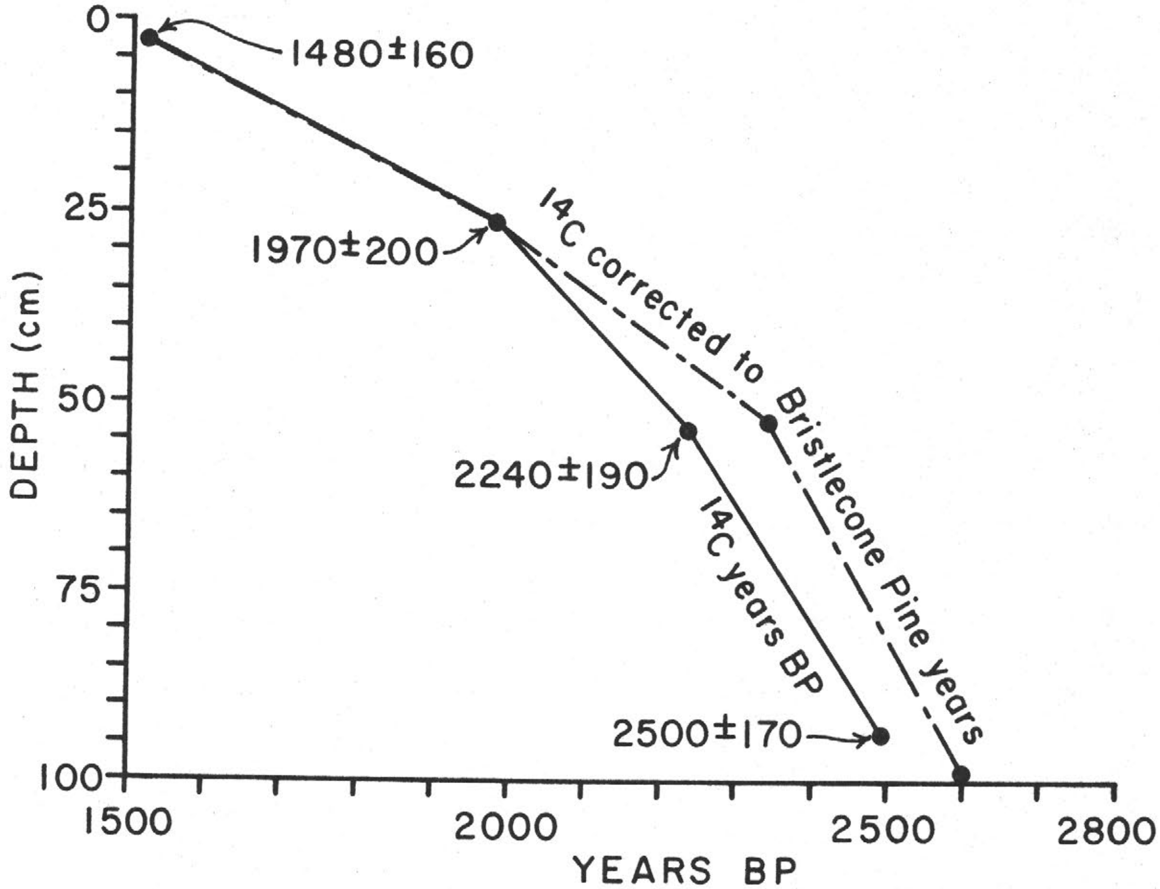
*Grant GB-25591 provided only partial support for this study.

Broughton Island, lat. 67^{o} 33' N, long. 64^{o} 03' W, Elev. 1905'

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
Mean daily temp. (°C)	-27.2	-28.0	-20.1	-18.7	-8.1	-0.7	5.6	4.1	-2.2	-8.7	-17.1	-24.0	-12.6
Mean daily max. temp. (°C)	0	1.3	- 1.9	6.3	7.5	16.9	20.6	20.6	16.3	7.5	3.8	5.6	20.6
Mean daily min. temp. (°C)	-46.9	-45.0	-44.4	-37.5	-29.4	-13.8	-6.9	-6.9	-13.1	-23.1	-35.0	-41.9	-45.0
No. of days with frost	31	28	31	30	31	27	12	16	27	31	30	31	325
Mean total precipitation (mm)	13	12	6	17	30	31	12	22	44	59	42	18	306

Data are derived from approximately 12 years of records, between 1941 and 1970. (Source: Dept. of Environment, Downsview, Ontario.)

Figure 20



Sedimentation chronology for Maktak Fiord, Baffin Island, with correction to calendar years by bristlecone pine chronology (Suess, 1970).

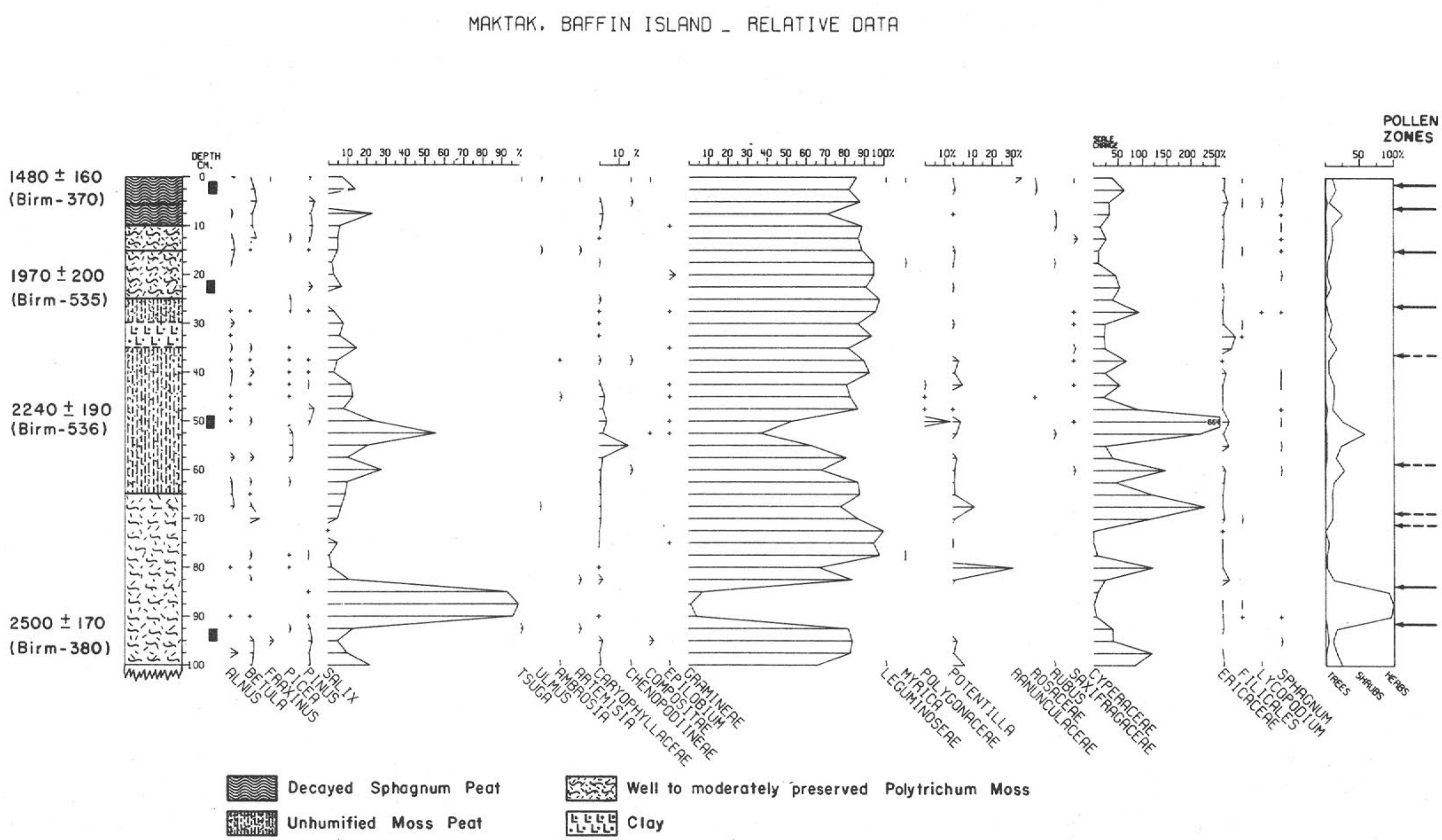


Figure 21: Percentage pollen diagram based on a total count of 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm.

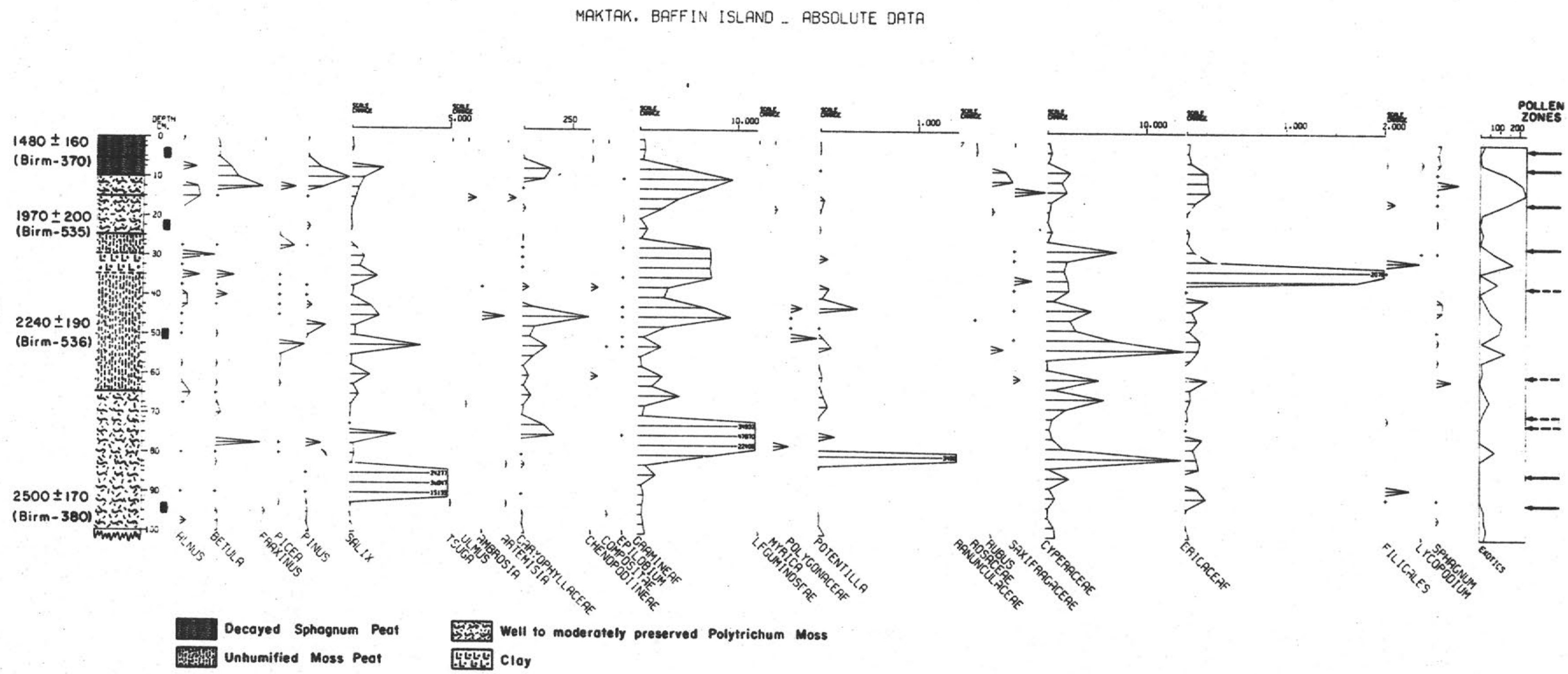


Figure 22: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines; the broken arrows indicate less significant sub-zones.

mentioned above. This total was sometimes smaller than the usual standard for this laboratory (300 excluding Cyperaceae, Ericaceae and Sphagnum) because of the sparseness of the pollen and spores, the difficulty of further refining the pollen extract from the intractable matrix, and particularly because the local pollen production derived from few plant taxa which were relatively uninformative about past environmental changes. However, numerous test counts of materials from a variety of sources have shown that small pollen totals (e.g. 100) from sparsely populated slides which have been carefully mixed to give approximately random pollen distribution are as meaningful statistically as substantially larger totals, where additional scanning for rare local pollen and for exotic pollen (related to "absolute" values) is performed (Nichols, unpub.).

Modification of Standard Technique for Counting Exotics

The Maktak results frequently involved the counting of one or more entire slides at each level. During the routine counting, small numbers of exotic pollen were identified (e.g. Alnus, Ambrosia, Fraxinus, Picea, Pinus, Tsuga, Ulmus), and a modified "absolute" counting method was employed to count some of these trace amounts to higher, more statistically reliable numbers. To do this, the pollen slides were scanned at lower than normal magnifications (200x rather than the routine 500x) and the large distinctive pollen of Picea and Pinus were identified from complete scanning coverage of one or more microscope slides (40 x 22 mm cover slip). These numbers were related to slide area counted and thus to weight of original sediment sample, like the other "absolute" counts. The possible significance of this approach will be examined later. Oil immersion objectives and Nomarski differential interference optics were available during the study.

The scale changes in the "absolute" diagram should be noted.

Pollen Diagram Component Analysis

Dr. J. T. Andrews suggested that the following steps be taken in attempting to derive an "objective" stratigraphy of the variations in "absolute" pollen in the Maktak diagram:

1) Punch cards of the Maktak data consisted of 41 levels and 28 taxa. For the purpose of this study, 4 numerically insignificant pollen types were removed, leaving 24 taxa which were run through a Principal Components program (BMD01M). This initial run indicated that 45% of the total variance was explained by the first five principal components. Factor scores were examined for the first five principal components which reduced the number of significant taxa to 12.

2) The program was then rerun using a modified version of BMD01M developed by J. Clark (INSTAAR, 1973) that outputs a punched deck of levels ranked against each principal component.

3) Because the original 28 taxa had been reduced to 12, the

variance explained increased for each principal component, 94% of the variance was explained by the first 6 principal components and accordingly these factor scores for this number of principal components was used in the next step.

4) J. Clark and N. Caine (INSTAAR, unpubl. ms and program, 1973) have developed a clustering routine based on the factor scores. From their output, a dendrograph can be constructed with the Y axis being the log of the F ratio for variance within the cluster/variance between clusters.

5) A dendrograph from the Maktak data indicated that there are six clusters, labeled I, IA, IB, II, III, and IV. Individual cluster names were then plotted in their stratigraphic order and this suggested the broad pollen zonations illustrated in Figures 21 and 22.

This approach is more complex than that adopted by Yarranton and Ritchie (1972) and parallels the methods employed by Gordon and Birks (1972).

Palynological Data (Figures 20-22)

The lowest 10 cm of organic sediment (90-100 cm) overlying the mineral base was dated 2500 ± 170 BP (BIRM-380). This episode in the percentage pollen diagram had high values of Gramineae and Cyperaceae pollen, while the "absolute" values of these taxa were not high (less than 1000 pollen/g each). Other local taxa, such as *Salix* and Ericaceae, were lower still. Of the exotic pollen, only *Pinus* had sustained values ($\sim$10 pollen/g).

A change in pollen representation occurred in the relative and "absolute" diagrams at 90 cm, where *Salix* dominated the Gramineae and Cyperaceae values. This is the highest *Salix* peak in the "absolute" diagram, reaching 36,000 pollen/g and lasting for three consecutive samples (90-85 cm). Gramineae and Cyperaceae were almost unchanged, but "absolute" numbers reached a low peak at 85 cm. Exotic pollen were low or absent.

The clustering routine distinguished a change in values at 95 cm.

After 85 cm, the high *Salix* numbers fell sharply, giving way to the highest Gramineae values in the diagram (up to 47,000 pollen/g). This change at 85 cm was distinguished by the percentage and the "absolute" diagrams and the clustering routine. The initial Gramineae rise at 80 cm was matched by single Cyperaceae and *Potentilla* peaks, which were not maintained. Exotic pollen values (*Picea*, *Pinus*, and *Alnus*) were low and sporadic or absent.

At 70 cm, the Gramineae numbers were greatly reduced, Cyperaceae began to rise to a sustained peak, followed by moderate maintained values of Caryophyllaceae and a Gramineae peak. *Salix* numbers were low. This episode had maximum *Alnus* and *Picea* values (50 pollen/g).

At 52.5 cm, Cyperaceae rose sharply to maximum values (13,000 pollen/g), and there followed sustained high Cyperaceae values, matched by high and later dominant Gramineae numbers. The later part of this episode also saw maximum Ericaceae values (1130 pollen/g). Salix numbers increased and were variable. Among exotic pollen, Alnus counts were substantial and maintained, while Picea and Pinus were variable.

The change at 52.5 cm at 2240 ± 190 BP (BIRM-536) was distinguished from the "absolute" diagram and the clustering routine, but was not discernible from the percentage diagram, where Gramineae values were almost unchanged from 82.5 cm to the surface, although the Cyperaceae peak following 52.5 cm was obvious.

Above 27.5 cm, Gramineae and Cyperaceae were sharply reduced at 1970 ± 200 BP (BIRM-535), with some later temporary recovery for Gramineae. Salix and Ericaceae were low and exotic pollen low, irregular or absent. This division was distinguished by the "absolute" counts and the clustering routine.

At 15 cm, Gramineae fell again, and all other pollen taxa were low except for Pinus which had a maintained rise to maximum values, followed by a reduction after 7.5 cm. Ulmus appeared in the 15 cm sample (4 pollen/g).

The topmost 5 cm were dated 1480 ± 160 BP (BIRM-370).

Interpretation

The initiation of continuous organic sedimentation at this site at 2500 ± 170 BP (BIRM-380) may indicate some shift in local or regional environmental parameters. The crossing of this threshold, which allowed organic buildup faster than decomposition, has previously been linked elsewhere to local or regional changes in moisture budget (atmospheric or surface water), and/or to altered levels of permafrost or snowbank buildup (Tallis, 1964; Fredskild, 1967; Nichols, 1969). The transgression of threshold values which promote such accumulations would no doubt reflect very local site values, including mineral soil permeability and species composition of the plant community involved, but where basal dates are synchronous with organic accumulations elsewhere it becomes legitimate to think in terms of regional environmental/climatic change. Several late Holocene basal peat accumulation dates in Canada group around 2500 BP (Nichols, 1969), and the same episode (2570 ± 110 BP, K-809, Fredskild, 1967) in coastal West Greenland saw development of Salix glauca scrub due presumably to moister conditions, followed by a very wet stage of Sphagnum squarrosum blanket bog with Carex spp. at 2350 ± 110 BP (K-811).

The initial palynological episode (100-90 cm) at Maktak was a sedge-grass community, while locally there were some willows and heaths, with fewer numbers of Caryophyllaceae (pinks), Potentilla (cinquefoils), and dwarf birch (Betula nana or B. glandulosa, Terasmae et al., 1966).

Shortly afterward, at 90 cm (2450 BP), there was a rapid change to a dwarf willow community at or close to the site, presumably due to a moister episode (cf. Fredskild, 1967). The "absolute" diagram shows that the status of grasses and sedges remained apparently unchanged.

The values of exotic pine, spruce and alder pollen were very low and this may be due to shifts in prevailing winds related to the above climatic change involving fewer incursions of southerly or westerly air, though the possibility exists that these low values were caused by the shielding effect of the dwarf willow scrub. As a possible analogue, a study of the long-distance aerial transport of boreal forest pollen into the Canadian tundra (Nichols, unpub.) has shown that at Ennadai Lake ($61^{o}10$'N, $100^{o}55$'W) two Tauber traps placed on the open tundra collected small numbers of exotic pine, spruce, and alder pollen, while a trap placed about 100 m away in a dense dwarf birch community collected no exotic pollen.

After 85 cm (2420 BP), the short-lived willow scrub episode gave way to a community of grasses, reflecting possibly somewhat drier (and colder?) conditions than before. Short-lived growth of sedges and cinquefoils occurred. The low numbers or absence of the exotic pollen (pine, spruce, and alder) may be related to reduced summer winds from the south and west, conceivably indicative of colder summer climate. However, the aerobiology of the High Arctic is poorly understood, and Fredskild (1973, p. 198) suggests that the total exotic pollen reaching Greenland is more or less constant, or that any small changes registered in pollen diagrams may plausibly reflect alterations in rate of pollen sedimentation. It is hard in the light of current knowledge of arctic climatology to see why this should be the case. Many of Fredskild's (1973) Greenland sediments are lacustrine, and it is not clear to what degree the factors of arctic lake sedimentation (and homogenization) bear on this problem. The peaks of exotic pollen in the peat profiles from Sermermuit did occur primarily at times of climatic change (Fredskild, 1967).

By 70 cm (2330 BP), the grass dominance was ended, but lower irregular grass values show that this was still an important element in the local plant cover. Sedges and heaths were minor elements, willows were few, there was very little dwarf birch locally, and among exotic pollen there was little pine but peaks of alder and spruce.

This episode ended at 52.5 cm, 2240 ± 190 BP (BIRM-536), when sedges and willows flourished near the site (corroborated by willow twigs at 54 and 51 cm), perhaps reflecting moister conditions. There followed a brief spell of increased heath cover from 35 to 25 cm, 2050 BP to 1970 ± 200 BP (BIRM-535), with increased grass cover and variable growth of willows. Of the exotic pollen, there was sustained alder representation, while pine and spruce numbers were variable.

After 25 cm (1970 ± 200 BP, BIRM-535), all "absolute" values for local pollen production were low, up to the surface at 1480 ± 160 BP (BIRM-370). The percentage diagram indicates that this was a grass community, with sporadic development of heaths. The reduced pollen numbers per gram dry weight may have been due to an increase in rate of organic accumulation, or increased amounts of sand in the sediment, or a reduction in pollen productivity. If it is not clear at present which of these factors was paramount, the first two seem likely in view of the burial of the deposit by fluvial-glacial sediments, possibly shortly after 1480 ± 160 BP (BIRM-370). Bryophyte evidence from Maktak (by J. Dickson, unpub.) suggests moisture increase towards the top of the profile. It is notable that at Sermermuit, across Davis Strait, Fredskild (1967) found that his peat profile recorded a moist Sphagnum peat episode (resembling a recurrence-surface) at 1540 ± 100 BP (K-913), shortly after which sedimentation stopped or the younger peat was removed by Eskimos.

Elsewhere in Baffin Island (Miller, 1973) and Canada (Bartley and Matthews, 1969; Nichols, 1967b, 1969) there is evidence of climatic change at about 1500 BP, though the direction of change seems sometimes equivocal or improperly understood.

Notes on Other Pollen and Spore Types

Sphagnum spore numbers were low (or absent) throughout the profile. The near-absence of this useful indicator of the moisture budget is probably due to Sphagnum's inability to produce large numbers of spores in the characteristically dry cold arctic summers; its low productivity probably points to such summer climatic conditions in general throughout the time span studied at Maktak.

At Sermermuit, approximately 560 km east-northeast, Sphagnum spore numbers rose to very high values at times of climatic cooling such as 2350 BP and 1530 BP, which also saw Cyperaceae (sedge) peaks (Fredskild, 1967).

The Use of Prolonged Scanning Procedures in Counting Exotic Pollen

The simple modification of routine microscope scanning at low power to relate slide area traversed to sample weight and thus to "absolute" values (see above) may help in refining High Arctic palynology. Arctic pollen diagrams usually contain some small numbers of exotic long-distance windblown pollen which normally appear to be statistically insignificant, and are usually ignored for this reason in the author's interpretation of data (e.g. Terasmae et al., 1966). High Arctic pollen diagrams may be composed almost entirely of local pollen from a few local plant taxa which are so adapted to the harsh and variable summer climates that their pollen productivity changes may not yet be clearly interpreted in paleoclimatic terms (Hegg, 1963). The modified scanning technique may then be used to bring the larger distinctive (easily visible) exotic pollen type numbers (e.g. pine and spruce) up to numerical levels where their changes may be usefully compared to paleowind alterations and shifts in ecotones, with the prospect of fuller interpretation of the latent data.

Exotic Pollen Representation

The pine, spruce, and alder pollen are the primary exotic taxa, and their representation has been described above.

The single occurrence of Tsuga is most likely Tsuga canadensis (hemlock) which grows in southeast Canada, approximately 2240 km (1400 miles) distant. Ulmus (elm) has the greatest representation among the exotic nonboreal forest trees, but occurs at only three levels, mostly as single pollen grains in each count. The nearest occurrence of *Ulmus americana* is about 2240 km (1400 miles) away in south-central or southeastern Canada.

Other occasional exotic pollen included *Fraxinus* (ash), *Ambrosia* (ragweed), and possibly *Artemisia* (wormwood, cf. Fredskild, 1973, though this grows elsewhere on Baffin Island). This wide range of long-distance windblown pollen taxa, some of which derive from south of the boreal forest, resembles the exotic taxa found by Fredskild (1973) in Greenland (p. 191). However, *Quercus* (oak) pollen was not found in the Maktak samples, though it was relatively common in Greenland.

CHAPTER VI

LATE HOLOCENE PALYNOLOGICAL DATA FROM WINDY LAKE, BAFFIN ISLAND, DISTRICT OF FRANKLIN, N.W.T.

Introduction

The Windy Lake organic profile was collected as monolithic blocks by Dr. G. H. Miller (INSTAAR and Carnegie Institute) in 1973. The streamside section was taken from a gully just south of the Windy Glacier on the west side of Weasel River, Pangnirtung Pass, at 66° 31' N, 65° 29' W. The sediment grades upstream into organic-rich fan deposits, while on the opposite bank it thins out into a shallow organic loam. The deposit thus seems to represent phenomena associated with aeolian infilling of a small depression.

Climatic Data (see Chapter V)

Lithology of the Sediments

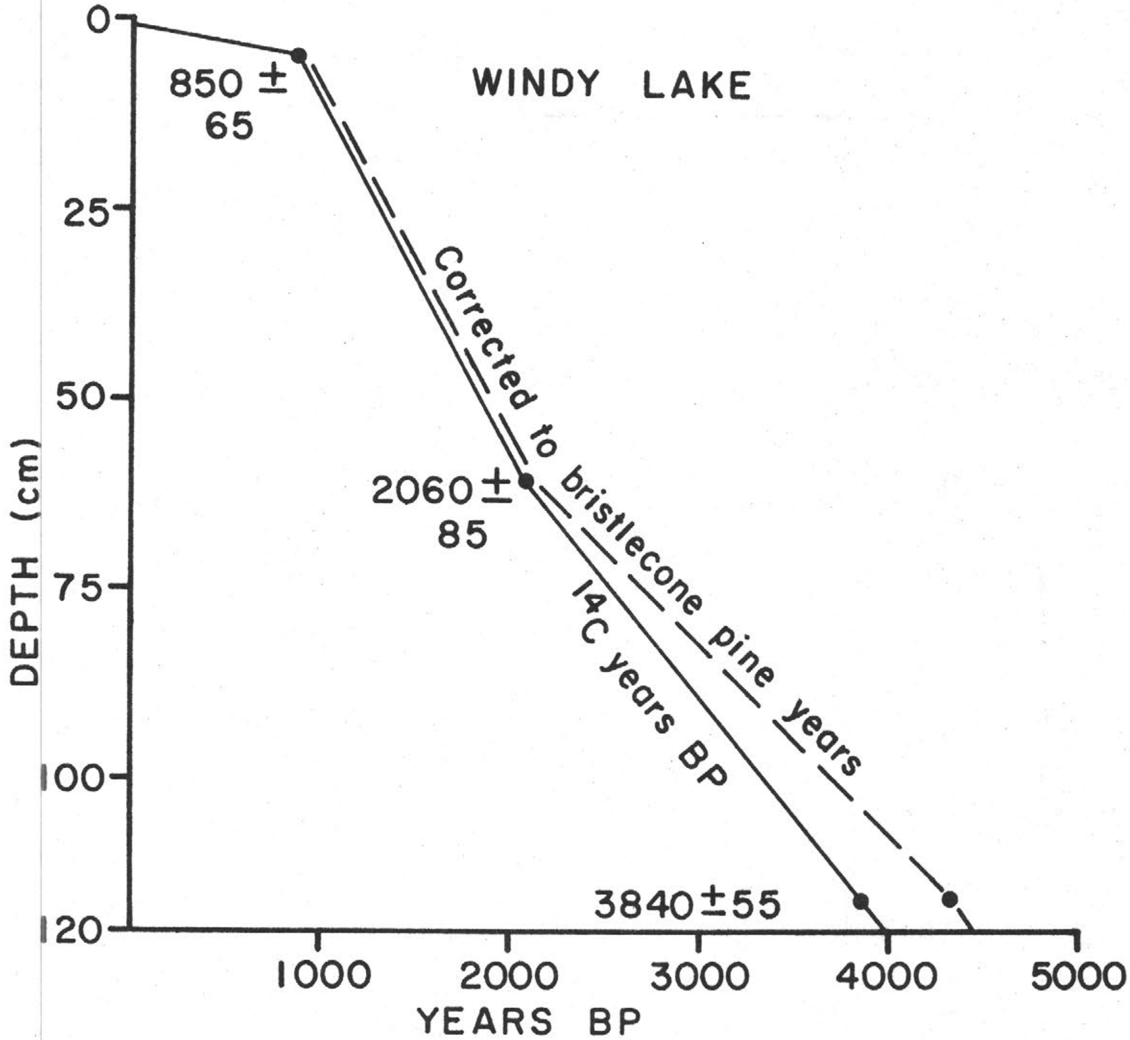
The Windy Lake sediment section is composed primarily of inorganic materials. Analysis indicates that the organic material is only 5 to 25% by weight of the sedimentary column. Microscopic examination of the sand size fraction indicates that over 90% of the material is subangular to angular quartz grains. Grain size curves show that the inorganic matrix of the peat can be classified as a sand to sandy silt. The material is not well sorted and the sediments cannot be called loess in the normal sense. They are undoubtedly of windblown origin, probably derived from the adjacent sandur in the early fall when the sandur surface was dry.

Pangnirtung Pass experiences high winds and blowing sand in winter, so that much of the sandy matrix resulted from poorly sorted sediment deposited by summer snow melt. Insufficient organic material remained after lithological analyses for the customary stratigraphic description.

Palynological data

The "absolute" diagram began with high *Gramineae* values, associated with many *Ericaceae* and (briefly) numerous *Caryophyllaceae*, at about 3840 ± 55 BP (DIC-328). *Gramineae* numbers continued to be high and variable throughout the lower half of the profile, until after 2060 ± 85 BP (GAK-5412). A *Salix* peak followed from 3250 to 3100 BP. There was a thin sand horizon at 2700 BP. A brief episode of *Sphagnum* sporogenesis occurred at 60 cm (254,702 spores/gm), dated 2060 ± 85 BP (GAK-5412), immediately followed by a 10 cm sand horizon. The upper half of the diagram above the major sand horizon was again dominated by reduced numbers of *Gramineae*. Small numbers of *Alnus* pollen were found throughout, as were lesser quantities of *Picea* and *Pinus*. *Sphagnum* spores were almost absent except for the peak at 60 cm.

Figure 23



Sedimentation chronology for Windy Lake, Baffin Island, with correction to calendar years by bristlecone pine chronology (Suess, 1970).

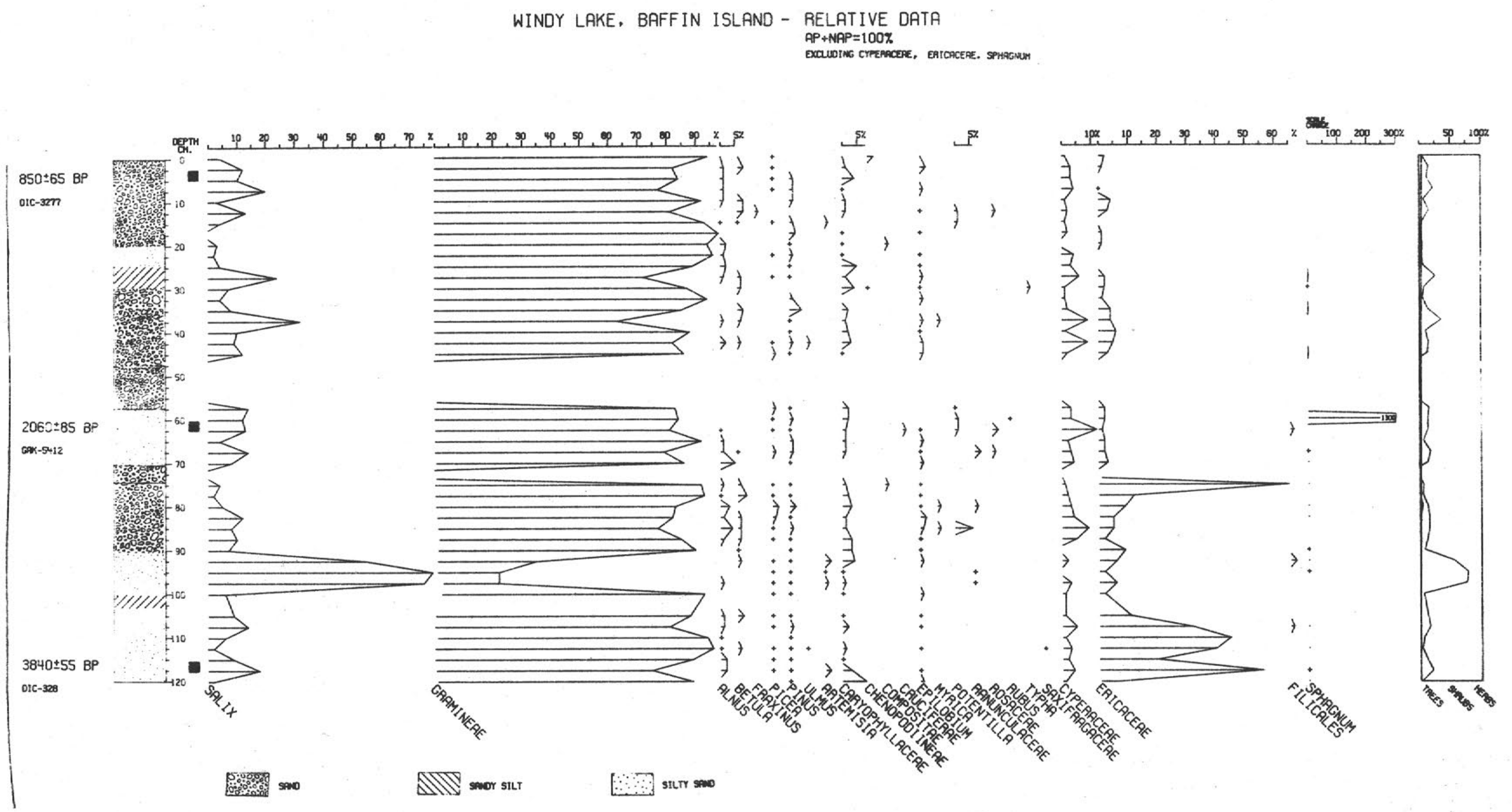


Figure 24: Percentage pollen diagram based on a total count of up to 300 pollen and spores, excluding Cyperaceae, Ericaceae, and Sphagnum. Sampling interval 2.5 cm. The blank units (48-57 and 70-74 cm) were sand and were not collected.

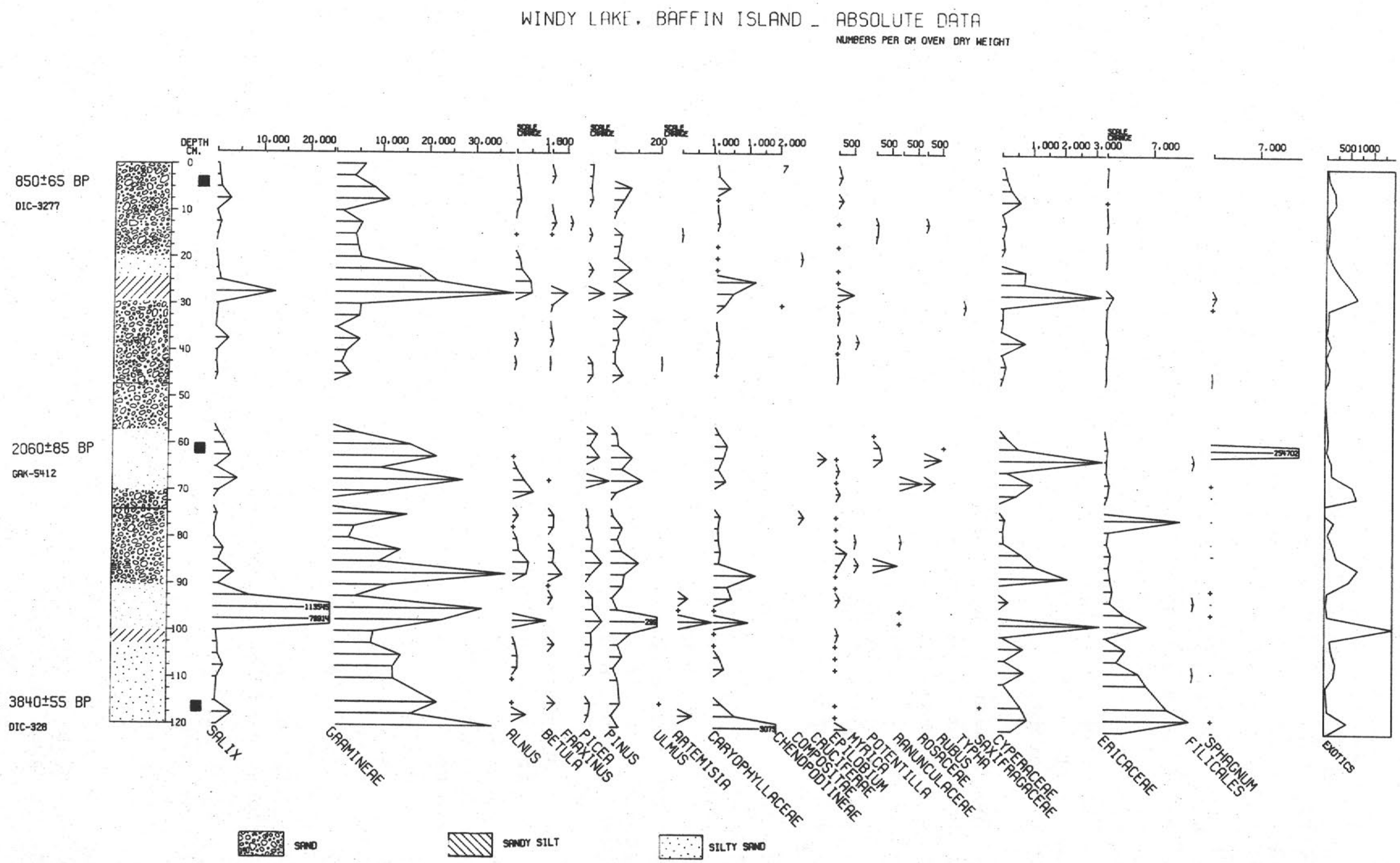


Figure 25: "Absolute" pollen diagram based on pollen and spores numbers per gram, oven-dry weight. The pollen zones marked by arrows were determined from the clustering routines. The blank units (48-57 and 70-74 cm) were sand, and were not collected.

Provisional interpretation

The earliest vegetational association represented in the profile consisted of grasses and heaths, with an initial short-lived component of Caryophyllaceae (pink family). Small numbers of dwarf willows and sedges grew locally, but almost no dwarf birches. These taxa grew in a dry-to-mesic environment with colonisation of locally bare sandy soils. However, the start of organic accumulation here may have represented some sort of local environmental shift. The basal date of 3840 ± 55 BP (DIC-328) was close in time to the shift towards cooler climate recorded after 3600 BP elsewhere in the arctic (Nichols, 1974, this work), which may have involved a rise in permafrost level along with some regional climatic change of currently unclear direction and magnitude in this area. Whether this may have promoted the organic build-up around Windy Lake is presently unknown.

The decline of heath pollen from 120 to 100 cm may have represented the increasing stabilization of the sandy ground, to be followed above 100 cm by a dwarf willow episode at about 3250 BP, representing a continuation of stabilization or possibly wetter conditions (cf. Fredskild, 1967). While the overall climatic trend was cooling during this time, there was a milder interval between 3200 and 3000 (this work) which matches this willow episode.

After 3000 BP grasses resumed their dominance of the site, while sedges increased episodically. The sand content of the sediments increased. The burst of Sphagnum spore production at 2060 ± 85 BP (GAK-5412) is thought to have represented a short period of milder and/or wetter climate; high numbers of Sphagnum spores rarely appear in mid-to-high arctic sediments (p. 58) or in modern Sphagnum polsters from that region (Nichols, in prep.)

The sand and gravel horizon following 2060 ± 85 BP (GAK-5412) may have resulted from a period of increased wind transport of lighter materials from the nearby bare sand surface of the sandur. It was followed by an apparent overall reduction in "absolute" pollen productivity due to a reduction in local plant cover, or possibly due to large amounts of sand in the sediment. About 1300 BP plant cover increased as grasses spread in association with sedges, members of the pink family, and willows. Organic accumulation ceased at about 850 ± 65 BP (DIC-327). Elsewhere in northern Canada (Nichols, 1974, and this work) cessation of organic accumulations (such as peat) occurred at approximately this time due to colder drier summers; whether this widespread climatic change was implicated in the ending of the Windy Lake record is unknown.

Exotic pollen

Pollen from plants not now growing on Baffin Island were recognized throughout the profile, totalled as "exotics" in the far right column. These taxa included Alnus, Picea, Ulmus (elm), and Typha (cattail). The boreal forest pollen (alder, spruce, and pine) which composed most of the exotics travelled a minimum distance of over 1600 km (1,000 miles) while the elm pollen originated at least 2100 km (1,300 miles) away. Alnus crispa was the main constituent; this shrub grows somewhat farther north than spruce in northern Labrador. Alder pollen numbers did not exceed 8000 pollen/gm, but frequently reached about 4000/gm periodically, which is a relatively substantial amount of exotic pollen, especially in light of the inorganic nature of these sediments. Further proof of the substantial airborne influx of alien pollen from the south and/or west is the lesser numbers of pine (up to 2000/gm) and spruce pollen (up to 1000/gm). Occasional pollen grains of *Ulmus* (elm) and *Fraxinus* (ash) derived from south of the Boreal Forest at least 1800 km distant. The influx of total exotic pollen shown on the "absolute" diagram was larger from 2060 ± 85 BP (GAK-5412) to 850 ± 65 BP (DIC-327) than from 3840 ± 55 BP (DIC-328) to 2060 ± 85 BP (GAK-5412).

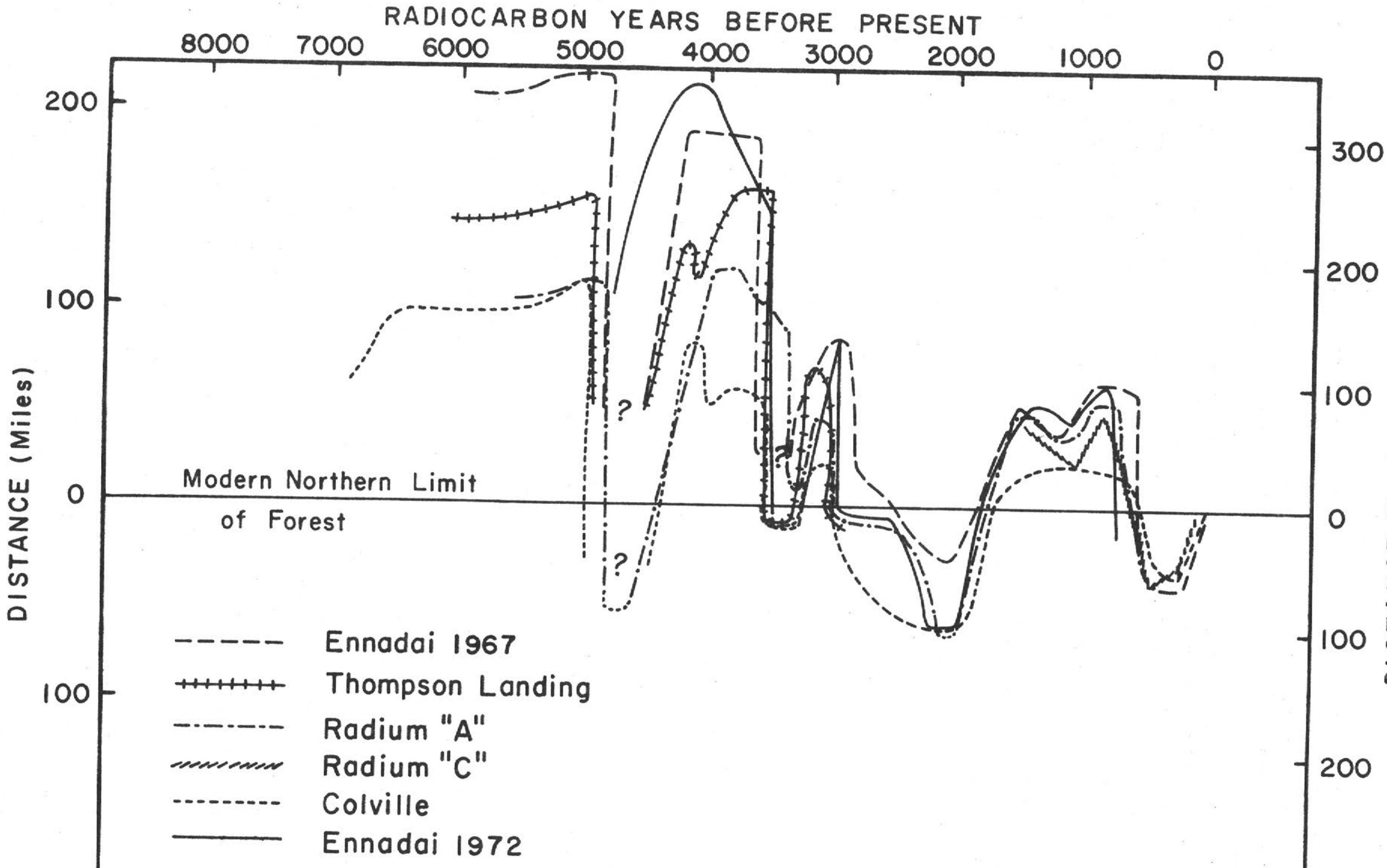


Figure 26: Tentative reconstruction of the location of the forest-tundra ecotone at several sites in northern Canada, based on palynology and macro-fossil evidence.

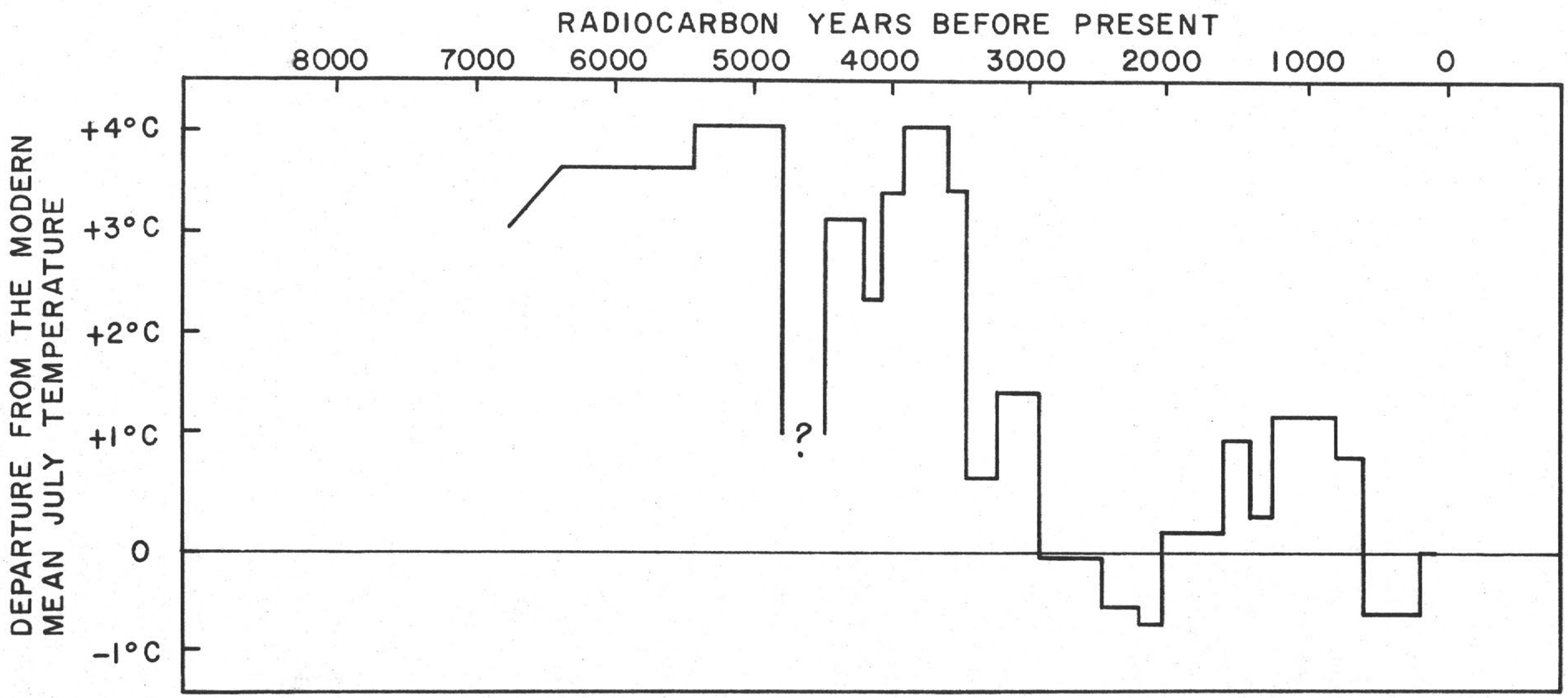


Figure 27: Tentative composite reconstruction of summer paleotemperatures at the palynological sites in Keewatin and Mackenzie, derived from Figure 26.

CHAPTER VII

GENERAL CONCLUSIONS, COMPARISONS, AND POSSIBLE CORRELATIONS

The oldest basal dates from Thompson Landing (6130 ± 170 BP, GSC-1840) and Port Radium A (5600 ± 140 BP, GSC-1783) which record spruce forest represented warmer than modern summers and fell within the well established hypsithermal episode.

A minor cooling episode was registered at Thompson Landing at 5500 BP, which may have influenced the growth of basal peat at Port Radium A at 5600 ± 140 BP (GSC-1783). There was an identical date for basal peat of 5600 ± 70 BP (BGS-146) in northwest Canada (Zoltai and Tarnocai, 1975). These events may have reflected a hitherto unnoticed minor summer cooling in the subarctic.

A maximum of summer warmth between 5300/5200 and 4800 BP was registered most clearly at Port Radium A and at Thompson Landing. It is clearly detectable (though it went unremarked) at Ennadai Lake in 1967 and at Colville Lake (Nichols, 1974). This was synchronous with the range extension of <u>Pinus strobus</u> in Quebec (49°N, 75°W) at 5030 ± 130 BP (GSC-585, Terasmae, 1970) due to warmer summers, and the range extension of the moss <u>Ceratophyllum demersum</u> in the northwest Canadian tundra at 5400 BP (L-428) (Terasmae and Craig, 1958). This particularly warm episode has not been identified before in the Canadian north as a distinct though apparently brief climatic event.

The subsequent cooling was dated 4800 ± 110 (GaK-5045) at Port Radium A and at 4900 BP at Thompson Landing. It was clearly expressed as a southward retreat of forest until the ecotone almost reached its modern limit, implying summer temperature reductions almost down to present-day values. This event was also dated 4800 ± 90 BP (WIS-166) at Ennadai Lake in 1967 (Nichols, 1967b) and interpolated as 5000 BP at Colville Lake (Nichols, 1974). The above-mentioned Quebec <u>Pinus strobus</u> macrofossils (Terasmae, 1970) were buried and preserved by peat growth which I suggest might have represented cooler moister summers after 5030 ± 130 BP (GSC-585). Thus, the cooling after 4900 BP is a strongly-marked event which has not previously been clearly recognized by palynology in northern Canada, but its initial identification at Ennadai (Nichols, 1967b) is now strongly supported. Other evidence elsewhere suggests climatic cooling at this time (Andrews, 1970a, 1970b, 1974; Mercer, 1967; Frenzel, 1966).

While the dates for the beginning of this cold episode were closely grouped, the vegetational recoveries which registered its end were spread over several centuries, as one would expect from plant migrational lag. They occurred at Thompson Landing at 4500 BP and at Port Radium A at 4250 BP. Other recoveries were 4500 BP at Ennadai Lake (1967) and 4400 BP at Colville Lake (Nichols, 1967b, 1974). Peat genesis at Ennadai Lake (1972) at 4690 ± 140 BP (GSC-1781) occurred under mild moist conditions and may perhaps have registered the true time of recovery from the cool dry summers, prior to other types of plant response.

This recovery to warmer than modern summers was briefly interrupted at 4250 to 4150 BP at several sites. At Port Radium A, Thompson Landing, and Ennadai (1972), the primary index of this cooling was synchronous Sphagnum sporogenesis, with less clearly detectable opening of the spruce woodland. This brief cooling was also marked by a Sphagnum peak at Colville Lake at 4130 ± 55 BP (WIS-294). It should be stressed at this point, though, that the relationship between climate and sporogenesis of the Sphagnum species is far from being understood.

The renewed summer warming after 4150 BP resulted in the closing of the spruce forest registering a time of peak warmth at about 4000 to 3900 BP at Port Radium A and less clearly at about 4200 to 4100 BP at Ennadai (1972). Thus, some of the most dense spruce forest recorded in the profiles occurred fairly briefly around 4000 BP, though this overall episode of summer warmth lasted until about 3500 BP. However, fires occurred at frequent intervals from about 4000 BP onward, so that the forest stability and density was subtly reduced after 4000 BP at Ennadai. The climate was still warmer than present and allowed forest regeneration after the fires.

A major and very devastating forest fire followed by tundra expansion due to summer cooling was recorded at all the sites at a range of times from 3600 to 3400 BP: at Ennadai (1972) at 3570 to 3340 ± 120 BP (GaK-5048), at Thompson Landing at 3500 to 3380 ± 105 BP (GaK-5050), and at Port Radium A at around 3400 BP to 3200 BP. This episode was dated 3500 to 3180 ± 65 BP (WIS-295) at Colville Lake. Fire alone was dated at 3650 ± 100 BP (WIS-80) at Ennadai Lake (1967) (Nichols, 1967b) and at 3550 ± 120 BP, 3540 ± 110 BP, and 3430 ± 110 BP (WIS-18, 52, and 12) at sites north of Ennadai (Bryson, Irving, and Larsen, 1965). Bryson et al. suggested that the fire related to colder drier summers as the Arctic Front moved south over the forest margin, so that fire in the desiccated forest was followed by a prolonged tundra period. Nichols (1967b) predicted that, if this event was due to regional climatic change, fires should be recorded at other locations along the ecotone; this is now very clearly demonstrated. The uncertainty as to whether this was a continuous synchronous forest fire or a series of events (Nichols, 1967b) is now answered; the fires ranged over 200 years. This fits the evidence from West Greenland of Canadian windblown charcoal being detected there from 3510 ± 120 BP to 3360 ± 120 BP (Fredskild, 1967). This event may prove to be synchronous throughout the entire Canadian forest-tundra ecotone, and possibly also in Russia.

There was some forest regeneration after 3300 BP, occurring at 3200 BP at Port Radium A, after 3340 ± 120 BP (GaK-5048) at Ennadai (1972), at 3250 BP at Thompson Landing and Coppermine Saddleback (detected by exotic pollen), and at Colville Lake at 3180 ± 65 BP (WIS-314). This woodland readvance was not very substantial or long-lived. By 3000 BP a prolonged episode of colder summers had opened up the forest and caused ecotonal retreat at Port Radium A, Ennadai (1972), and at Thompson Landing, where cold dry summers stopped all peat growth from 2980 ± 90 BP (GaK-5051). In northwest Canada near-surface peat dates demonstrate peat growth cessation after 3150 ± 90 BP (BGS-216), 2710 ± 60 BP (BGS-147), and 2650 ± 80 BP (BGS-218) (Zoltai and Tarnocai, 1975) due presumably to the same effect. Tundra extended over the formerly forested site of Colville Lake shortly after 3180 ± 65 BP (WIS-314) at about 3000 BP (Nichols, 1972). Thus, at widely spaced ecotonal sites the first really prolonged tundra expansion after the hypsithermal occurred at about 3000 BP.

Cooling progressed through 2500 BP when there was a further southward summer advance of the Arctic Front and tundra expansion. Drier colder summers reduced peat growth and spread heaths at 2500 ± 90 BP (GaK-5044) at Port Radium A, reduced the influx of exotic forest pollen at Coppermine Saddleback at 2500 BP, and stimulated basal peat growth at Coppermine Beach at 2500 ± 140 BP (GSC-1517) and Sphagnum sporogenesis at Ennadai (1972) following 2500 BP. This episode had spread tundra and slowed peat growth (after a burst of Sphagnum sporogenesis) after 2670 ± 105 BP (WIS-93, Nichols, 1967b) at Ennadai (1967). The coldest summers were registered about 2200 to 2100 BP at Coppermine and at Port Radium A.

Recovery to warmer summers was recorded at a range of dates from 2000 to 1500 BP, presumably as plant growth thresholds were crossed by gradually increasing temperatures and as plant migrational lag was overcome. Woodland regeneration occurred at 1900 BP at Port Radium A and 1500 BP at Ennadai (1972), while the recovery of the exotic pollen influx (more quickly responsive to climatic change) at the Coppermine sites occurred at 2120 ± 100 BP and 1920 ± 85 BP (GaK-5054, 5065). This warming was recorded by exotic pollen at 1900 BP at Pelly Lake (Nichols, 1970), at 1810 ± 60 BP (WIS-297) at Colville Lake, and not until 1500 BP at Ennadai (1967).

This northward movement of the woodland margin was interrupted briefly by cooler summers dated between 1600 and 1400 BP at Port Radium A and Coppermine Saddleback and estimated later at 1200 BP at Ennadai (1972). This cooling may have influenced basal peat growth at Port Radium C at 1560 ± 70 BP (GSC-1839).

Warmer summers followed this short interval and woodlands advanced beyond their modern limits again by 1100 BP at Ennadai (1972), by 1000 BP at Port Radium A and C (to peak at 950 ± 60 BP, GaK-5047) and were recorded by exotic pollen increases at 1100 to 1000 BP at the Coppermine sites. These data agree with the forest advances found by Bryson, Irving, and Larsen (1965) and evidence from Ennadai (1967) and Pelly Lake (Nichols, 1967b, 1970).

Strong evidence for tundra expansion due to colder drier summers following 800 to 600 BP is universal in arctic pollen diagrams and for many desiccated peat profiles it spelled the end of their record. The Port Radium woodlands became more open and drier, while exotic pollen influxes at Coppermine were low from 700 and 500 BP onwards.

A recent slight warming was seen at Coppermine Saddleback in the exotic counts at 130 ± 70 BP (GaK-5055) and possibly in some changes at Port Radium C following 200 BP and 130 ± 70 BP (GaK-5058) which may have reflected the instrumentally recorded 19th and 20th century warming.

For sake of clarity, the correlations with Bartley and Matthews (1969) work in arctic Quebec and that of Fredskild (1967, 1969, 1973) in Greenland have been omitted from this summary, but the evidence from these distant areas is clearly synchronous and parallel with the above data (see Nichols (1974) for further comparisons). The implications of apparent differences in site sensitivity between the Mackenzie delta (Ritchie and Hare, 1971) and the rest of northern Canada will be examined elsewhere.

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APPENDIX 1

Radiocarbon Assays

Code No.	Sample	Age BP Date[a]	Remarks
Radiocarbon dates purchased from Gakushuin University ^{14}C laboratory from NSF grant GB-25591			
GaK-5044	Peat, Radium A, 37-41 cm	2500 ± 90 550 B.C.	
GaK-5045	Peat, Radium A, 71.5-73.5 cm	4800 ± 110 2850 B.C.	
GaK-5046	Peat, Radium A, 6-9 cm	Modern $\delta^{14}C$ = +2.2 ± 1.1%	
GaK-5047	Peat, Radium C, 33.5-36.5 cm	950 ± 60 A.D. 1000	
GaK-5048	Peat, Radium C, 4-6.5 cm	130 ± 70 A.D. 1820	
GaK-5049	Peat, Thompson Landing 74-76 cm	4300 ± 100 2350 B.C.	
GaK-5050	Peat, Thompson Landing 23-25 cm	3380 ± 105 1430 B.C.	
GaK-5051	Peat, Thompson Landing 4-6 cm	2980 ± 90 1030 B.C.	
GaK-5052	Peat, Coppermine Saddleback 97-99.5 cm	2920 ± 100 970 B.C.	Anomalous date
GaK-5053	Peat, Coppermine Saddleback 85-89 cm	3100 ± 110 1150 B.C.	
GaK-5054	Peat, Coppermine Saddleback 27-29 cm	2120 ± 100 170 B.C.	
GaK-5055	Peat, Coppermine Saddleback 8-10 cm	130 ± 70 A.D. 1820	
GaK-5056	Peat, Ennadai 270-271 cm	970 ± 70 A.D. 980	Anomalous, redated 1350 ± 150

GaK-5057	Peat, Ennadai 228-230 cm	4520 ± 110 2570 B.C.	
GaK-5058	Peat, Ennadai 146.5-148.5 cm	4520 ± 100 2570 B.C.	Anomalous date
GaK-5059	Peat, Ennadai 103-105 cm	3340 ± 120 1390 B.C.	
GaK-5060	Peat, Ennadai 60-62 cm	2960 ± 100 1010 B.C.	
GaK-5061	Peat, Ennadai 46.5-48.5 cm	2790 ± 100 840 B.C.	
GaK-5062	Peat, Ennadai 3-6 cm	870 ± 60 A.D. 1080	
GaK-5063	Peat, Coppermine Beach 4-6 cm	230 ± 50 A.D. 1720	
GaK-5064	Peat, Coppermine Beach 21.5-24 cm	1430 ± 80 A.D. 520	
GaK-5065	Peat, Coppermine Beach 35-37.5 cm	1920 ± 85 A.D. 30	
GaK-5066	Peat, Coppermine Beach 52.54.5 cm	1570 ± 85 A.D. 380	Anomalous, redated 2180 ± 90

^{14}C dates on the palynological sediments made without charge

GSC-1783	Basal peat, Radium A 113-117 cm	5600 ± 140
GSC-1839	Basal peat, Radium C 52-56 cm	1560 ± 70
GSC-1840	Basal peat, Thompson Landing 157-159 cm (N.B. no mineral base reached)	6170 ± 130
GX-1813	Basal peat, Coppermine Saddleback, 112-115 cm	3715 ± 120
GSC-1517	Basal peat, Coppermine Beach 60-63 cm	2500 ± 140
GSC-1781	Basal peat, Ennadai 288-290 cm	4690 ± 140

Birm-380	Basal peat, Maktak 88-100 cm	2500 ± 170	
Birm-536	Peat, Maktak 51-53 cm	2240 ± 190	
Birm-535	Peat, Maktak 24-26 cm	1970 ± 200	
Birm-370	Peat, Maktak 0-5 cm	1480 ± 160	
Dates derived from other projects			
GaK-5282	Basal peat, Windy Lake 130-132 cm	650 ± 230	Anomalous date
GaK-5412	Peat, Windy Lake 68-70 cm	2060 ± 85	

[a] BP = Years before 1950.

APPENDIX 2

ANALYTICAL METHODS

Chemical treatment of the sediments followed the conventional scheme of Faegri and Iversen (1964), with increased reaction times to allow for the altitude of Boulder. The "absolute" method of pollen preparation and counting was based on oven-dry weight of the pre-treatment sample (cf. Jørgensen, 1967) and careful weighing of the amount of post-treatment sample counted. Samples were analysed at vertical intervals of 2.5 cm, using a total pollen and spore count of 300, exclusive of the possibly over-represented Cyperaceae, Ericaceae and *Sphagnum*, the usual peat-formers. Some of the tundra peats (eg. Coppermine and Baffin Island) were abnormally difficult to break down chemically, and low in pollen content, so that entire sets of samples were re-prepared and counted several times to assure sample consistency and statistical validity of the counts. Intermediate pollen counts (at 100 and 200 totals) were routinely recorded for each level as a check on the internal consistency of the final 300 pollen count. This confirmed that with consistent preparation the pollen counts were statisically reliable before the 300 total was reached: usually at between 100 and 150 pollen. Any inconsistencies were re-sampled and re-counted.

The numbers of exotic tree pollen reaching the tundra sites were small, so that to increase the counts to reveal significant trends we modified the routine counting at 500 x. To do this, the pollen slides were scanned at 125 x or 200 x, and the large distinctive pollen of *Picea* and *Pinus* were identified from complete scanning coverage of several microscope slides (40 x 22 mm coverslip). These numbers were related to slide area counted and thus to weight of original sediment sample, like the other "absolute" counts.

From these experiments we realized the supreme importance of extremely careful mixing of the chemically-treated pollen residue to achieve random spreading of the pollen sample over the slide. It also crystallized our understanding of the need to count only the central area of the slide to avoid the bias of the "edge effect" on pollen distribution. Experiment confirmed the importance of counting the y-axis traverses of microscope slides to limit this bias.

After the receipt of adequate ^{14}C dating control, we have begun a comparison of volumetric sampling with the dry sediment weights from each of these cores, so that there will be a presentation of pollen influx per cm^{-2} per year, in addition to the dry weight "absolute" approach. Exotic microspores of *Lycopodium* and *Eucalyptus* pollen as prepared in Stockmarr (1971) tablets were added to some of the later pollen diagrams, to ensure that there were no unacceptable levels of pollen loss during prolonged chemical preparations.

The Pollen Diagrams

The palynological data were transferred to punched cards and computer programs were developed by M. F. Nichols to produce publication-ready diagrams by machine plotter (CALCOMP, see Appendix 3).

Numerical Methods

An approach involving a more "objective" recognition of significant episodes of palynological change in the "absolute" pollen data was employed by means of principal components analysis. A clustering routine used on the factor scores allowed the construction of a dendrograph which indicated the pollen zonations (see p. 54).

APPENDIX 3

COMPUTER TECHNIQUES FOR THE PRESENTATION OF PALYNOLOGICAL AND PALEOENVIRONMENTAL DATA

by

Margaret Nichols

Margaret Eccles

and

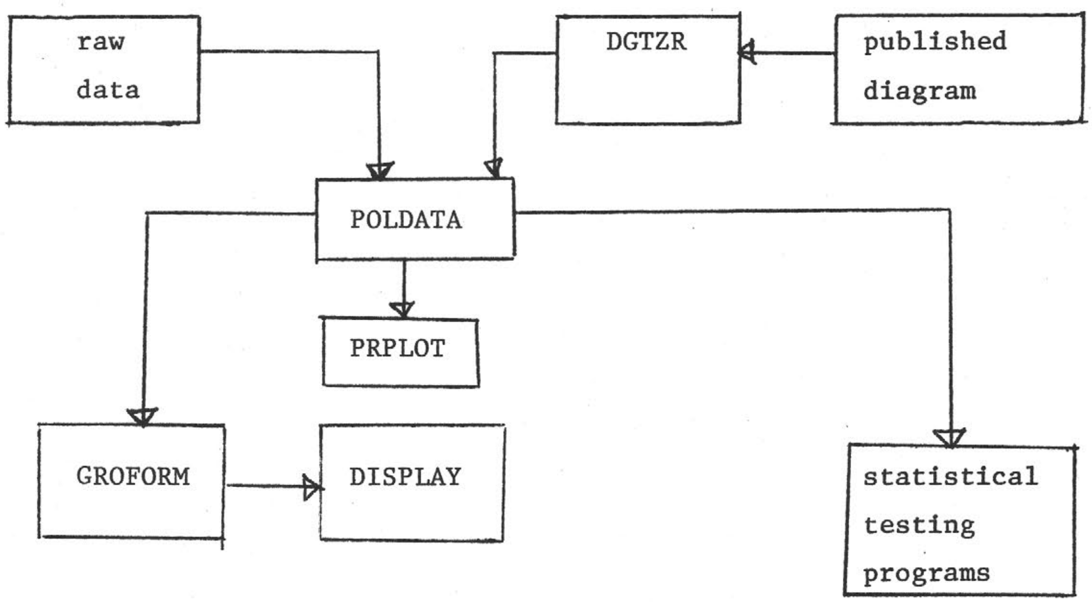
Harvey Nichols

PREFACE

The following is taken from Institute of Arctic and Alpine Research Occasional Paper #16 of the same title.

The programs described in this report have been developed to assist in the handling, storage and manipulation of large volumes of paleoecological data and in the semi-automatic production of diagrams suitable for journal publication.

This flow chart demonstrates the procedural order in which the programs are used.



INTRODUCTION

The funding of NSF contract GB-25591 allowed the production of paleoenvironmental data in large volumes, and problems were duly encountered in handling this information. The situation became more acute with the funding of GB-25889 and even more so as grant GB-33497 produced its aerobiological data. Fortunately, this latter contract had budgetary support for computerization so that, with financial assistance from the University of Colorado Computer Center, programs were prepared to handle both the GB-33497 and the GB-25591 data.

The only available relevant programs known to us at that time were from Canberra, Australia (Dodson, 1971) and Durham, England (Squires, 1970). For our own use we developed an information storage and retrieval system that would be easily transferred to other computers, with minor modifications due to compiler differences. We believe this system achieves a wide degree of flexibility and applicability within the palynological field and potentially elsewhere in the paleoenvironmental sciences; for example in studies concerning fossil seed analyses, beetle remains, grain size analyses, and also in stratigraphic paleoentology.

Much impetus for the development of our methods came from the progressive use of "absolute" pollen techniques in this laboratory, which produce more "objective" data than the relative percentage methods used hitherto. In relative percentage pollen diagrams, the final count total is divided into each individual taxon sum and then plotted as a percentage, and mistakes frequently occur. These problems are manifold in the production of the "absolute" diagram, being drawn from the calculated values of the real total number of grains for each individual taxon.

In determining these "absolute" values, we follow the method as described by Jørgenson (1967) in which the number of grains per gram dry weight of material is derived from the relative data. The pollen on a slide is determined by

(i) counting the entire slide; or

(ii) recording the number of microscope traverses (t) necessary to obtain a certain grain total (n) such that the number of grains on the slide is

$$N = \frac{nT}{t}$$

where T is the total number of traverses it is possible to make on that particular size coverslip on that particular microscope, at that particular power of magnification.

Then the total number of grains (N') in the treated sample may be determined by dividing the slide weight (a) into the sample weight (A), so that

$$N' = \frac{AN}{a}$$

and the total number of grains in the original sample per gram dry weight is therefore

$$N'' = \frac{A}{a}\frac{N}{G}$$

where G is the pre-treatment dry weight of the sample.

To hand calculate these "absolute" values devised according to the above method is tedious and leads to numerous errors, and so the simple repetitive nature of obtaining the "absolute" value for each taxon lent itself very well to computerization.

All of this assumes that there is no loss of pollen during preparation of the material. By adding a known amount (L) of an exotic tracer such as Lycopodium clavatum grains or Eucalyptus grains embedded in a matrix of calcium, it is possible to calculate the percentage loss during chemical reduction (Stockmarr, 1971). Therefore, the true "absolute" number of grains per gram is

$$\underline{N} = N'' \frac{L}{l}$$

where l is the number of exotic tracer grains recovered in the prepared sample.

It is also useful to determine this recovery factor as a percentage, as the efficiency of the sample recovery has significant bearing on later considerations placed on the data, including repreparation of the sample. Preparation losses do vary substantially depending on the type of sediment being treated, and data is being collected so that previously determined "absolute" values on different types of sediment may be intercompared.

The program POLDATA is the first stage necessary for examination of the data after counts have been obtained. It produces a computer printout, listing the count totals and other information concerning that particular analysis. Then the calculated values of the relative percentages and the "absolute" values, as determined from equation (1), are printed. For further manipulation of the data, a separate punched card output of these values is generated.

A preliminary diagrammatic presentation of the relative percentage pollen diagram and the "absolute" value pollen diagram can be produced economically and quickly, for inspection of the profile by means of the program PRPLOT. This is achieved by having fixed scale parameters and using a line printer giving a histogram representation of the relative and "absolute" values. The input values that the diagram is plotted from are obtained from the punched card outputs from the POLDATA program.

When the data are judged complete the line printer diagram is used to calculate the scales and truncation points to be used in drawing a diagram of the required size for publication on the CALCOMP Plotter using the program called DISPLAY.

Also, it was thought that the Arctic fossil pollen diagrams being produced contained much more paleoenvironmental information than had previously been demonstrated by temperature latitude approaches to these sediments. For example, changes in exotic pollen influx, due to transport of boreal forest pine and Spruce pollen hundreds of miles into the tundra cannot be fully observed from a normal count total since the percentage occurrence of these pollen types is so low compared to the local vegetation. It was decided to scan count entire slides just for the exotic pine and spruce, at a lower magnification than normal (200X). One or more slides are counted depending on whether higher totals are desired. For ease of data presentation a punched card output of these scan values is also produced by the POLDATA program.

In our paleoenvironmental investigations the statistical significance of relatively small scale vegetational changes in plants adapted to variable arctic summers can most easily be judged by the machine approach rather than the normal palynological approach of visual appraisal. Using the card outputs of the "absolute" values, a principal components analysis is performed. Factor scores are examined to reduce the number of significant taxa being considered. Then a clustering routine is used based on these factor scores and a dendrograph drawn from this output. The pollen zonations are then determined from the replot of the clusters in stratigraphic order. This of course gives the major environmental divisions in the diagram, which may then be sampled for radiocarbon dating.

It was also required that various palynomorph assemblages be presented from the same data set. From the initial POLDATA "absolute" punched card output, an additional reclassification of the taxa is made, into wet, mesic, dry and exotic as an Ecology diagram and also a Life Form diagram giving a tree/shrub/herb/graminoid/moss/fern breakdown. These are calculated as "absolute" numbers and also as percentage ratios to the total pollen numbers by the program GROFORM. Concurrently, the Simpson's diversity ratio and the Shannon's Diversity ratio are also calculated. All of these produce punched deck outputs of the numbers, which are then used as input to the DISPLAY program.

A literature search was conducted in order that the programs could be written from the outset such that the data of other workers both present and past could be tabulated or digitized (depending upon whether working from original data counts or from published diagrams). Options have been included such that the "absolute" number of grains per sample is calculated for any given unit of measurement. If a volumetric determination is made, the total number is divided by the volume of the original sample. Similarly, to obtain the number of grains per unit area of sample the calculated value is divided by the cross-sectional area.

Additional flexibility is provided by the reordering option. Thus it is possible to have the final output (both cards and printout) in alphabetical order, or in taxonomic groupings, regardless of the order of the input. It is also possible to omit taxa entirely. This assists in the inter-laboratory exchange and interrogation of data and could form the basis of a national or international archival system and aid secondary analysis of the data by any interested party. This may be used in the correlation of environmental studies of different regions.

This prospect is enhanced by the program DCTZR, which was developed to derive numerical data from our own or other people's published or unpublished pollen diagrams, using a digitizer. Then the other programs are used to statistically manipulate, rearrange and compare the data and generate new diagrams by automatic plotter. This is being used on our own pollen diagrams which were counted prior to the development of the programs, and we intend to use it on other workers' published diagrams to aid comparison with our findings. We intend to seek further funding from the National Science Foundation for experimental work with this technique to answer the question "To what extent can previously published palynological work be digitized to allow 'objective' pollen zone analysis by statistical methods to check the author's zonation decisions, normally based only on visual inspection, so as to facilitate comparison and correlation and to produce more uniform diagrams?"

SUMMARY

In producing the pollen diagrams drawn on the CALCOMP plotter and the punched card outputs, the following steps are taken:

1) Coding of original data counts or the digitization of diagrams.
2) Keypunching and listing the cards to check for mispunches.
3) Making preliminary runs of POLDATA until it has been thoroughly checked out with the counting sheets.
4) Producing final POLDATA listing, reordering if necessary. Also producing the card output decks, interpreting and sorting card decks according to type: relative R, "absolute" A, and scan values S.
5) Producing a line printer diagram using card output decks (R and A) as input to PRPLOT.
6) Using the "absolute" compressed deck as input to the GROFORM program to obtain numerical values and card decks ecology E & Life form L, used in Ecology and Life form diagrams.
7) Interpreting and sorting these punched deck outputs.
8) Using DISPLAY program to produce CALCOMP plots of <u>R</u>elative, <u>A</u>bsolute, <u>E</u>cology and <u>L</u>ife form diagrams.
9) Using card output deck A as input to statistical routine, for the selection of radiocarbon dating horizons.
10) Drawing labels and legend of the diagram, as well as radiocarbon assays, on the CALCOMP plotter and adding them to the diagram prior to photography.

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