in a greater percentage of red to blue. Whether this shift in blue at sunset has any biological or other significance remains to be seen.

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Pollen Diagrams from Sub-Arctic Central Canada

Abstract. *Peat from Keewatin and Manitoba contained macrofossil and palynological evidence of former latitudinal movements of the forest-tundra boundary in response to the changing location of the mean summer position of the Arctic front. Radiocarbon dating demonstrates the synchroneity of these climatic changes with those registered in northwest Europe during the past 6000 years.*

The work of Bryson, Irving, and Larsen (*1*) on the stratigraphy of the forest-tundra ecotone in Canada demonstrated the northward extension of continuous forest beyond its present limit during postglacial time. These conclusions are now supported and amplified by palynological evidence from two peat bogs which contain records of vegetational and climatic change.

The two sites lie in the northern part of the Boreal forest and at the tundra edge, locations which should have recorded past movements of the forest limit in response to climatic change. Bryson (*2*) has demonstrated the coincidence of the northern limit of continuous forest in central Canada with the average summer position of the Arctic frontal zone. He suggests that past movements of the tree line in this area have been in response to changes in the climatic boundary between Arctic air in the north and air masses of Pacific or tropical origin in the south. I have attempted to estimate the position of the Arctic front from the forest history derived from the pollen diagrams, especially the Ennadai pollen diagram. Its ecotonal location and sphagnum peat constitution make it more sensitive to climatic changes than Lynn Lake, the latter being in a more "complacent" position in the middle of the Boreal forest. The Lynn Lake diagram provides confirmation of the major changes registered at Ennadai.

Peat monoliths were collected from Ennadai Lake, Keewatin, (61°10'N, 100°55'W) by J. A. Larsen, and from Lynn Lake in Manitoba (56°50'N, 101°03'W) by me. Both deposits lie within the Cockburn end-moraine system, which may represent a late-Wisconsin ice sheet that occupied the Hudson Bay area until at least 8000 years ago (*3*).

Ennadai Lake (Fig. 1) lies at the limit of continuous Boreal forest. Its northern end is in the tundra, while the southern end of the lake is surrounded by an open forest composed mainly of *Picea mariana,* occasional *Picea glauca, Larix laricina, Alnus crispa,* and *Salix spp.* (*4*). The transition from continuous forest to tundra is quite sharp in this area, taking place within about 20 km. Lynn Lake, about 450 km south of Ennadai, lies in an area of open subarctic woodland, where spruce forest dominated by *Picea mariana* constitutes the vegetational climax for the region.

The peat bank at Ennadai Lake is composed primarily of *Sphagnum* bog mosses in varying states of humification. The significance of atmospheric moisture to the growth of *Sphagnum* makes it possible to gain a rough idea of the precipitation-evaporation budget from the rate of *Sphagnum* growth and the degree of humification (or oxidation) of the peat. In northern Europe this concept has resulted in the recognition of wetter and drier episodes from the "recurrence surfaces" and "retardation layers" in the peat bogs (*5*). I suggest

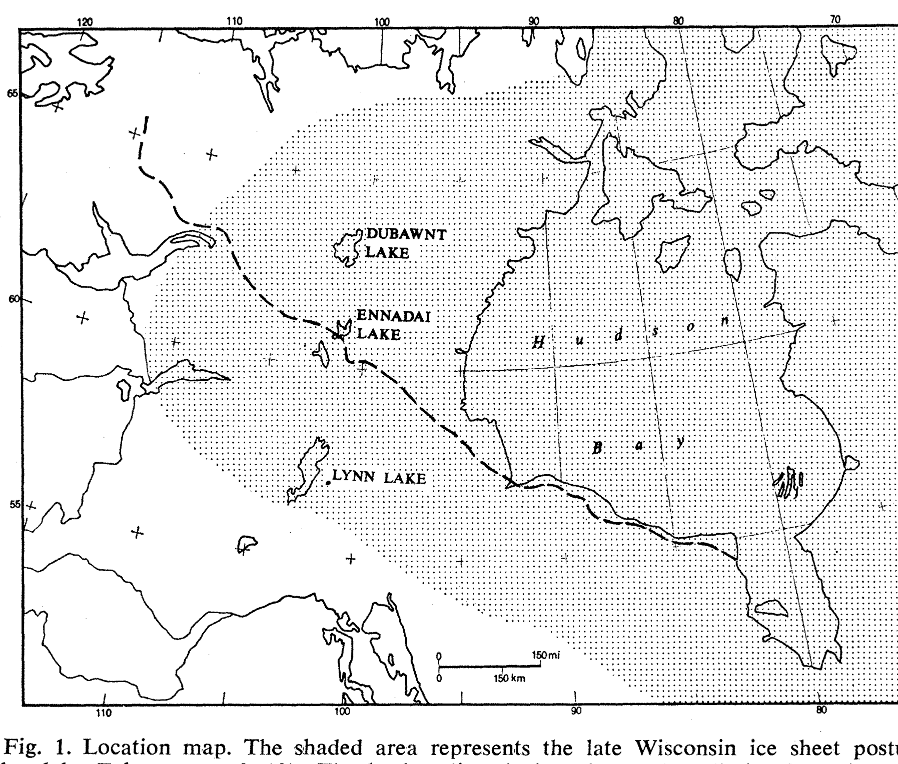

Fig. 1. Location map. The shaded area represents the late Wisconsin ice sheet postulated by Falconer *et al.* (*3*). The broken line depicts the modern limit of continuous forest as mapped by J. A. Larsen (*17*).

that at Ennadai the very fresh unhumified pale-brown *Sphagnum* peat (which often contains very high percentages of *Sphagnum* spores) accumulated under relatively warm, wet conditions, when the Arctic front lay farther north in summer. The dark-brown humified peat (with low *Sphagnum* spore counts) represents drier and colder periods, characterized by dominance of Arctic air at the site. A southward extension of the average summer position of the Arctic front means that the associated storm track affects more southerly latitudes than before. Ennadai, lying north of the frontal zone, experiences colder and drier conditions at the same time as sites to the south get colder and wetter. When the frontal zone is far to the north Ennadai enjoys warmer and wetter conditions, while more southern locations are drier since they are missed by the storm track.

The peaks of *Sphagnum* spore numbers recorded in the Ennadai diagram are often associated with changes in peat humification, some of them not very clearly marked. The growing season is short at Ennadai Lake and for most of the year the peat is frozen and is not subject to oxidation. At this site the production of *Sphagnum* spores seems to be a more sensitive indicator of climatic change than is peat humification (*6*). However, farther south in Canada there are clearer changes in peat humification which correlate very well with the numbers of *Sphagnum* spores [as in the pollen diagram of Clearwater Bog in southern Manitoba (*7*)]. Tyrrell (*8*) noted that *Sphagnum* bogs were found extensively in the lowland woods of northern Manitoba and that they reached to the northern limits of the forest; *Sphagnum* growth appears to be inhibited by the cold, dry Arctic air which occupies the tundra.

The late-Wisconsin ice sheet which covered this area at least as late as 8000 years ago seems to have melted very rapidly, for by 6500 years ago accumulation of organic mud had begun at Lynn Lake. A relatively warm climate (suggested by high percentages of *Alnus* and *Picea* pollen at the base of the pollen diagrams) seems to have characterized this period, and this probably explains the swift wasting of the ice. The pollen diagrams show that, shortly after the melting of the ice sheet, spruce and alder were quickly established in northern Manitoba and southern Keewatin. The low values for nonarboreal pollen at the base of both diagrams plus the presence of *Picea* needles in the peat at Ennadai suggests that any tundra which may have fronted the ice was of limited extent and was swiftly replaced by open spruce forest. This time of rapid climatic amelioration in central Canada (about 8000 to 6000 years ago) falls within the period of maximum postglacial warmth experienced by northwest Europe.

At Ennadai from about 5700 to 3600 years ago (radiocarbon laboratory sample numbers WIS 85, 80) (*9*), values obtained for *Sphagnum* are low and counts of *Alnus* and *Picea* pollen are high (Fig. 2). The first decline of *Picea* at Ennadai occurred 4800 ± 90 years ago (WIS 166), and there was a decrease in spruce at Lynn Lake 5130 ± 100 years ago (WIS 112) with an associated peak of *Sphagnum* spores. It seems likely that this was, on the whole, a warm period, but with a cooling episode about 5000 years ago. During this time the forest extended far north of Ennadai, as the Arctic front retreated toward the North Pole. Podsols were formed under spruce forest as far north as Dubawnt Lake (63°02′N, 100°48′W), 280 km beyond the present tree line, where there is

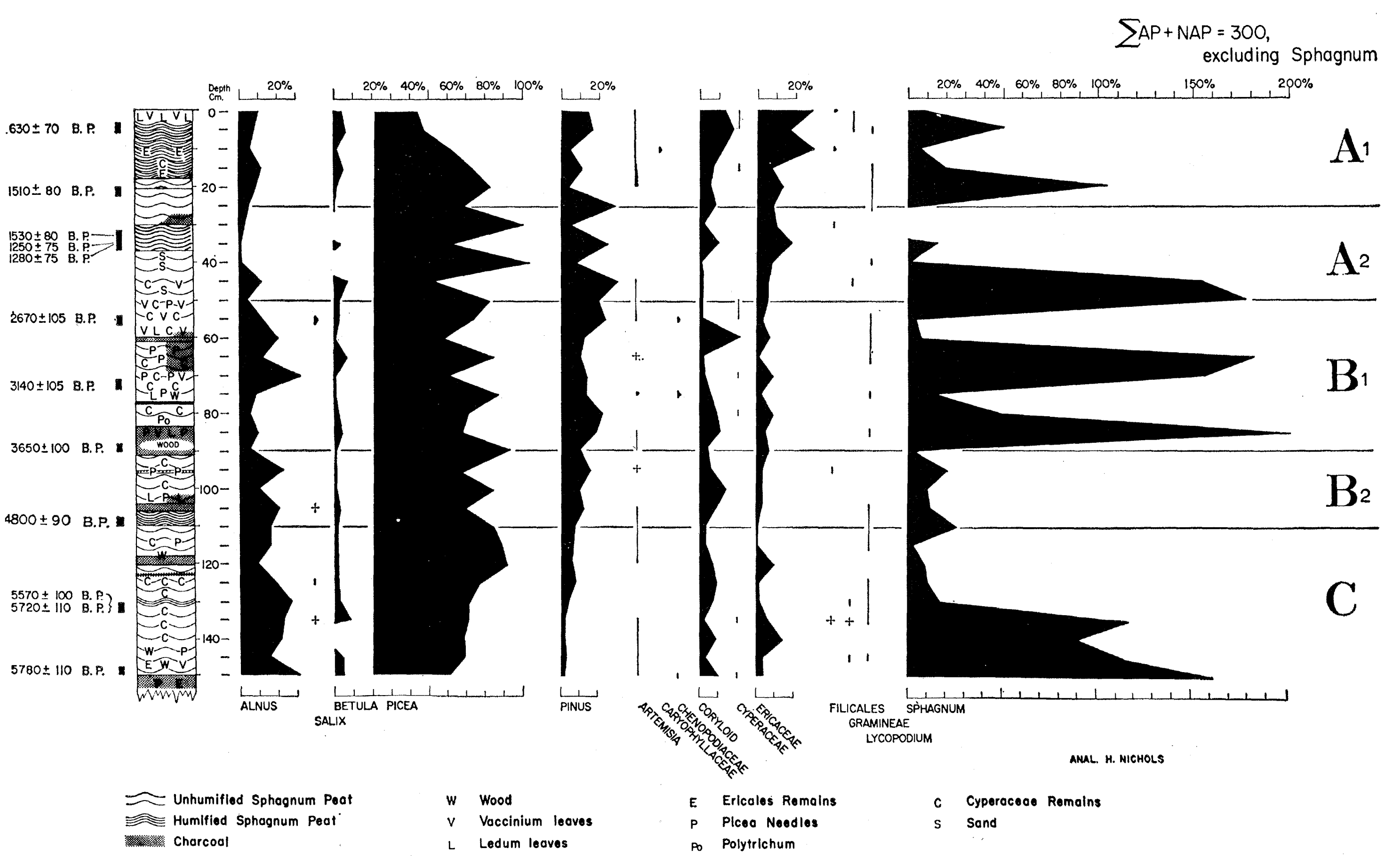

Fig. 2. Pollen diagram from the northern end of Ennadai Lake, Keewatin, Northwest Territories. The zonation employed is intended only for local use. *NAP*, nonarboreal pollen; *AP*, arboreal pollen.

a burned forest horizon about 3430 ± 110 years old (WIS 12) (*10*). The temporal equivalent in northwest Europe (about 6000 to 3500 years ago) saw the continued warmth of the "climatic optimum" in the late Atlantic zone, then the opening of the climatically variable and cooler sub-Boreal period about 5000 years ago.

From 3650 to about 2600 years ago (WIS 80, 93), percentages for *Sphagnum* and *Picea* at Ennadai Lake varied. At Lynn Lake *Alnus* declines as *Pinus* (and later *Betula*) rise (Fig. 3). This fluctuation indicates a cooler period, with the Arctic front located in the Ennadai area, and the position of the front probably shifted to north and south of that site, so that the tree line fluctuated about Ennadai Lake. The variation in *Sphagnum* counts at Ennadai may thus have reflected a variable storm track location.

This sporadic recurrence of *Sphagnum* growth at Ennadai is probably of more than local significance. The Canadian "muskeg" is similar to the "blanket peat" of northern Europe, and the few radiocarbon dates available for this type of accumulation indicate that in Canada much of it started to grow about 2400 years ago (*10*, *11*), the date of the original "Grenzhorizont" (Granlund's RY III) (*12*). There are peaks in *Sphagnum* percentages at Ennadai which may have registered accelerated peat growth under wetter conditions. There was a major rise in *Sphagnum* at Ennadai a little less than 3650 years ago (WIS 80). Material underlying the successive *Sphagnum* peaks has been assigned ages of 3140 ± 105, 2670 ± 105, 1510 ± 80, and 630 ± 70 years (WIS 139, 93, 88, and 133). At Lynn Lake a peak of *Sphagnum* spores occurred a little more than 2170 ± 80 years ago (WIS. 113). The *Sphagnum* spore peaks occurring 2670 ± 105 years ago at Ennadai and 2170 ± 80 years ago at Lynn Lake are very similar in age to the major recurrence surface which marked the beginning of the cold, wet sub-Atlantic period in northwestern Europe at approximately 500 B.C. (*5*). The significance of the dates of the other increases in *Sphagnum* requires special discussion (*13*).

At Ennadai, the period 2600 to 1500 years ago was characterized by low *Sphagnum* counts, humified peat, irregular *Picea* values, increased percentage of Ericaceae and the presence of sand grains in the peat at 40 cm. A drier, colder climate probably pre-

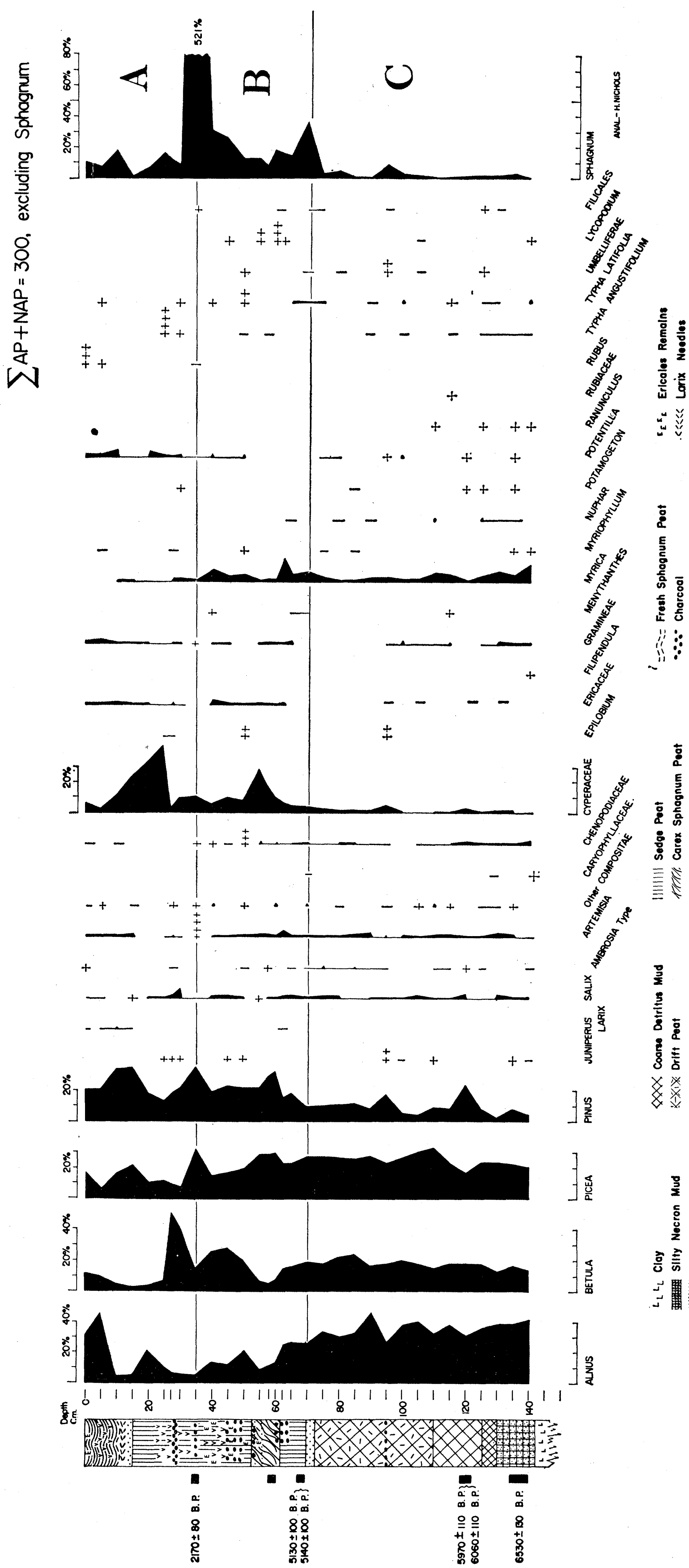

Fig. 3. Pollen diagram from Lynn Lake, Manitoba. Crosses mark grains f ound while scanning the slides, which were not included in the pollen sum.

vailed during the growing season at Ennadai (the Arctic air mass extended south), so that the spruce forest retreated or became patchy, the peat grew slowly and oxidized, and the tundra spread around Ennadai Lake. The sand grains probably represent breakdown of the local plant cover, which exposed the nearby sandy eskers to attack by wind.

At Ennadai about 1500 years ago there is a peak of *Picea* and *Sphagnum*. The forest limit probably moved north for a time after this date as the Arctic front retreated poleward. An age of 1140 years (WIS 17) for a burned forest horizon at Dimma Lake (61°33′N, 100°38′W) (*1*) provides evidence for the successful growth of spruce 40 km north of the Ennadai peat bank during this climatically favorable period.

The final peak in *Picea* representation is followed by a prolonged decline, and there is no increase of other arboreal pollen to take its place. Instead, numbers of nonarboreal pollen rise, particularly those of the Ericales, and macrofossils of *Ledum palustre* and *Vaccinium vitis-idaea* were recovered from the peat. Percentages of *Sphagnum* declined and the peat became very humified and stopped growing about 600 years ago. I suggest that this situation reflected a southward extension of the Arctic air mass in summer, which brought a colder, drier climate to Ennadai. The result was a retreat of the forest to the south of Ennadai peat bank, the establishment of tundra vegetation at the north end of Ennadai Lake, and the cessation of peat growth. This latest climatic deterioration recorded at Ennadai occurred at the same time as worsening climatic conditions in the North Atlantic inhibited the voyages of the Scandinavians between Vinland, Greenland, and Norway (*14*).

The vegetation changes registered in these pollen diagrams have dates which correspond to climatic changes experienced by northwestern Europe. This synchroneity and apparent climatic parallelism encourage the correlation of the late postglacial climatic histories of the two regions. It then becomes worthwhile to employ palynological evidence from central Canada (relatively undisturbed by human activity) to investigate climatic changes in northern Europe, where the fossil pollen record for the past 5000 years has been affected by anthropogenic factors.

The events described are not at variance with the generalized picture of climatic change in Canada (summarized by Terasmae, *15*) which resembles the familiar anathermal-hypsithermal-hypothermal sequence. However, no published Canadian pollen diagram has yet been as closely dated as that from Ennadai Lake. Radiocarbon determinations for the Canadian late Holocene period are particularly sparse. It is easier to compare the diagrams described here with the closely dated sequence of northern European climatic changes than with the imperfectly known history of neighboring parts of Canada (some of which are in different climatic zones). It is premature to correlate the changes in the Ennadai and Lynn Lake pollen diagrams with the palynological work of Ritchie (*16*) in adjoining southern Manitoba, since his diagrams have as yet no radiocarbon dates which relate to those of the above-mentioned pollen diagrams.

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Stereoscan Electron Microscopy of Soil Microorganisms

Abstract. *Details of the surface structure of microorganisms growing in soil and the complex topography of individual soil particles were observed with the Stereoscan electron microscope. Because it was not necessary to remove the microorganisms from the soil particles, it was possible to establish their occurrence in different microhabitats. This technique can provide useful ecological information about the soil microflora.*

Much is known about the microorganisms that can be isolated from soil and studied in pure culture. Confirmation of the importance of these organisms in soil can be obtained by direct observation of their natural environments. The value of such observations is limited by the comparative lack of good techniques for making them.

Microscope slides (*1*) or glass capillaries (*2*) were buried in the soil and recovered from time to time. The rate and nature of their colonization was then assessed. While much important information has been obtained from these techniques, we cannot be certain whether colonization of the glass surfaces is similar to colonization of the mixture of humus and mineral particles occurring in undisturbed soil. To avoid this problem, soil smears (*3*), individual soil particles (*4*), and sections of soil impregnated with resins (*5*) were examined with the light microscope. Evidence of the size, nature, and distribution of different microorganisms was obtained, but the resolution of the light microscope is such that details of microbial and environmental structure cannot be seen. The value of these techniques was increased by use of fluorescent dyes coupled with incident ultraviolet illumination (*6*); in this way, organisms on opaque organic soil particles may be seen.

With electron microscopes having great resolving power, detailed pictures of soil organisms were obtained (*7*). Unfortunately, the organisms had to be removed from the particles they were colonizing since it was not possible to examine thick specimens. Ultrathin sections of the root surface and its environment were prepared (*8*), and bacteria were seen clearly; but only in such regions of dense microbial colonization are sectioning techniques applicable. Elsewhere, ultrathin sections would rarely include microorganisms because only a very small percentage of the sur-