the Devonian age of the metamorphic rocks in the northern part of the Bokan Mountain area. The metamorphic rocks must be Ordovician or older, but their relationship to other Ordovician or pre-Ordovician rocks in southeastern Alaska, such as the Wales Group (*2*), is not known. Our results also require a revision of the ages previously assigned by MacKevett (*1*) to the intrusive rocks of the area. The Bokan Mountain Granite has been considered to be possibly Cretaceous or Tertiary in age, and the other granitic rocks possibly Cretaceous. Our data indicate a Late Triassic or Early Jurassic age for the Bokan Mountain Granite and an early Paleozoic, probably Ordovician, age for the other granitic rocks in the area.

The presence of granitic detritus in Silurian and Devonian conglomerate units in southeastern Alaska has been known since the early 1900's (*2*). The detritus indicates a pre-Silurian plutonic source, but no source had been documented until this study. The older intrusive rocks of the Bokan Mountain area may have been one source of the detritus. Work presently in progress indicates that early Paleozoic granitic rocks occur on Chichagof Island (Fig. 1); probably other areas of early Paleozoic intrusive rocks will be found in southeastern Alaska.

Potassium-argon ages of approximately 350 million years in two areas of western Canada (*5, 9*) are the only additional direct evidence for a Paleozoic granitic event in the North American Cordillera. But both of these areas are more than 800 km east of the Pacific Ocean. Thus, the Bokan Mountain data provide the first direct evidence for the emplacement of early Paleozoic granitic intrusive rocks along the Pacific margin of North America.

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11. Publication authorized by the director, U.S. Geological Survey.

27 April 1964

Origin of Ice Ages: Pollen Evidence from Arctic Alaska

Abstract. *Pollen analysis of radiocarbon-dated samples from the arctic coastal plain of Alaska shows that vegetation of 14,000 years ago reflected a climate colder than the present, and that there has been a progressive warming, culminating in the present cold arctic climate. The record indicates that the Arctic Ocean has been covered with ice since the time of the Wisconsin glacial maximum, suggesting that the essential condition of the Ewing and Donn hypothesis for the origin of ice ages, that the Arctic Ocean be ice-free up to 11,000 years ago, cannot be met.*

A theory for the origin of ice ages put forward by Ewing and Donn (*1, 2*) requires that the Arctic Ocean be unfrozen as a condition for glacial advance. Livingstone has pointed out (*3*) that, if polar climatic changes were out of step with those of the rest of the world as required by the theory, the vegetation changes in circumarctic lands would be out of step with those to the south of the ice sheets. Livingstone put forward evidence from pollen that vegetation changes in Northern Alaska during the last 8000 years were not out of step with those of temperate regions, but the objection was raised (*4*) that this record did not penetrate the glacial period and thus could not be used to test the hypothesis. A series of samples from the Northern Alaskan coastal plain has now been obtained, which enables the pollen record to be extended to include the glacial period. This record can be used to test the proposition that the Arctic Ocean was ice-free during glacial times.

The samples used in this study were collected (*5*) from Point Barrow and Ikpikpuk on the northern coastal plain of Alaska, and from Umiat and Killik in the arctic foothills (Fig. 1). The materials are from the organic horizons of buried soils, buried peat, or material thawed from ice-wedges. I have analyzed the pollen content of the samples, following procedures described elsewhere (*6*).

In Fig. 2, the samples are arranged according to age (*7*) so that the pollen spectra of successive time intervals can be compared. It is important to note, however, that Fig. 2 is not strictly comparable to a standard pollen diagram, since the ordinate does not represent a continuous section through sediments. The less abundant types of pollen are not included in Fig. 2.

The pollen spectra may be compared with pollen zones found to be applicable to fossil pollen sequences in various parts of Arctic Alaska (*6, 8–10*), and particularly with the pollen zones of a sediment core at Umiat (*11*). The top four samples in Fig. 2 can, on the basis of their alder content, be assigned to zone III. The pollen spectra of these four samples appear similar, if allowance is made for their geographic spread.

It appears that the vegetation and climate of the Arctic coastal region have been rather stable over the last 4000 years. There is a 5000-year gap in the record at this point, followed by a group of four samples (*e* to *h*) with radiocarbon ages of close to 9000 years. These four samples are all from organic soils which may have been buried at about the same time (*12*). The four pollen spectra differ mainly in the content of pollen types, willow (*Salix*) and heaths (*Ericaceae*), which may be expected to be influenced by local factors, and thus to reflect characteristics of the several sites rather than climatic regimens. Changes in the grass-sedge (Gramineae-Cyperaceae) ratio also seem to have little climatic significance in arctic pollen diagrams (*6, 8, 11*). On the basis of the modest birch con-

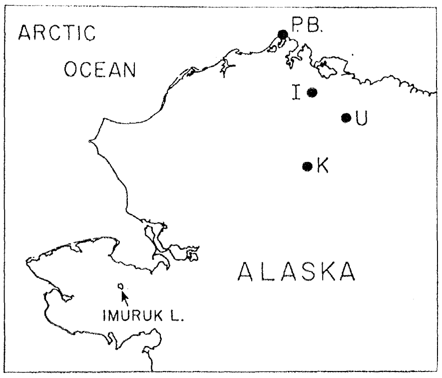

Fig. 1. Sketch map of Northern Alaska showing sample sites. (*P.B.*, Point Barrow; *I*, Ikpikpuk; *K*, Killik; *U*, Umiat.)

tent, and dominance by grass and sedge pollen, the four pollen spectra (*e* to *h*) can be assigned to zone I. They conform very well to zone I of the Umiat core (*11*), and may be taken to extend that record of cold climate in Northern Alaska to about 9000 years ago.

At the bottom of Fig. 2 are three samples (*i* to *k*) taken from different levels, in successive borings, from a single site at Point Barrow (*13*). Samples *i* and *j* are lenses of buried peat in ground disturbed by frost, at depths of 1.5 and 3.0 meters. Sample *k* was obtained by melting a bloek of ice buried below the other two samples, and collecting the residue of mineral and organic matter. The pollen spectrum of sample *i* can be assigned to zone I, along with those from the slightly younger buried peat samples (*e* to *h*), but it is noteworthy that the birch (*Betula*) content is rather low. The older samples *j* and *k* are remarkable for a virtual absence of birch pollen. Since absence of a pollen taxon is a rather dangerous criterion from which to draw conclusions, I carefully searched the entire pollen preparations of several thousands of grains each for birch pollen, finding a single grain on one and none on the other.

Dwarf birch is withdrawn from the tundra with increasing latitude (*8*), presumably as a reflection of increasing cold. The virtual absence of its pollen from zones *j* and *k* suggests even colder conditions than existed in zone I. A similar zone at Imuruk Lake (zone H in *6* and *10*) was described as a "type 0" zone and considered to represent an extremely frigid tundra. The two type 0 zones are not temporally correlated, because of the six degrees of latitude separating the sites (Fig. 1), but they can be taken to represent similar frigid conditions. Dwarf birches were not present in the surrounding vegetation; grasses and sedges grew amidst patches of bare, frost-scarred ground, and dwarf willows were able to maintain themselves on sites favored by shallow summer thawing. For such frigid conditions to exist on the Arctic coastal plain, there can be little doubt that the Arctic Ocean was frozen over for most of the year.

This record of the arctic coastal plain tundras of the last 14,000 years implies an uninterrupted succession of cold climates, in which the present inclement weather of the place must be regarded as comparatively mild. The trend over the whole period has been one of warming. The Arctic Ocean is ice-covered now; for the even colder climates recorded by these samples to have been possible, the ocean must have been ice-covered throughout the last 14,000 years. Since climatic changes must be allowed a reasonable amount of time to produce their effects on vegetation, there can be no doubt that conditions cold enough for the Arctic Ocean to have been ice-covered existed well before the 14,000-year date, through the period of the Wisconsin maximum 18,000 years ago. The theory of ice ages (*1*), which requires the Arctic Ocean to be open up to about 11,000 years ago, accordingly fails.

The theory of ice ages can be modified to suggest that an open Arctic Ocean existed earlier in Wisconsin time, but that it froze over at about the time of the glacial maximum, leading to the progressive retreat of the ice. A pollen sequence from Imuruk Lake (Fig. 1) is similar enough to that from the arctic coastal plain to suggest that zone 0 is the temporal equivalent of zone J (*6, 10*). Despite some difficulties with the earlier chronology of the long Imuruk Lake record, which I have discussed fully elsewhere (*6*), it is likely that a zone J tundra occupied Seward Peninsula from a remote period beyond the reach of radiocarbon dating to about 14,000 years ago. This suggests a similar antiquity for zone 0 at Point Barrow. An open Arctic Ocean was, therefore, probably not present during the period of the Wisconsin advance, suggesting that the conditions for such a modification of the theory cannot be met.

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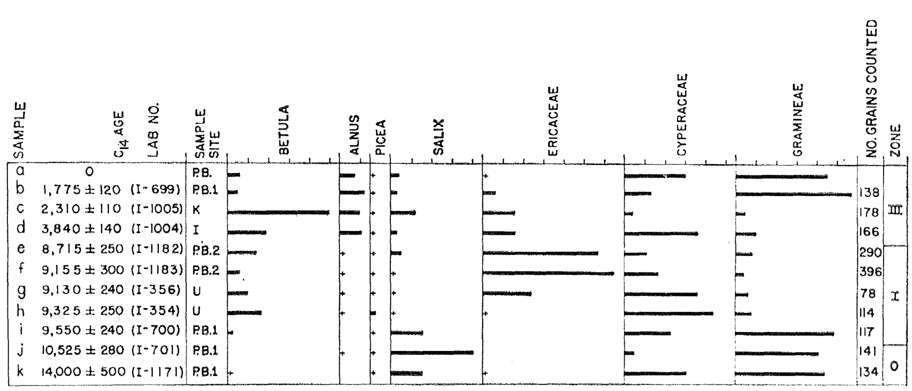

Fig. 2. Pollen spectra from Point Barrow (*P.B.*), Ikpikpuk (*I*), Killik (*K*), and Umiat (*U*) on the coastal plain of Northern Alaska. Each division represents 10 percent of the total pollen and spores; + represents 2 percent or less. The spectrum for a surface sample (*a*) from Point Barrow was constructed from Livingstone's data (*8*).

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