Alaskan Glacier Commemorative Project, Phase V: Studies in Quaternary Chronology and Glaciology of the Alaska-Canada Boundary Range

By Maynard M. Miller

Reprinted from: National Geographic Society Research Reports, 1968 Projects, pages 255-304, 18 figures

Washington, D. C.
1976

Alaskan Glacier Commemorative Project, Phase V: Studies in Quaternary Chronology and Glaciology of the Alaska-Canada Boundary Range

Principal Investigator: Maynard M. Miller, Michigan State University, East Lansing, Michigan, and Foundation for Glacier and Environmental Research, Seattle, Washington.

Grant No. 719: In support of the fifth year (1968) of a continuing program to investigate changes in existing glaciers and the causes of glaciation along the southern Alaskan coast since the Society's Tarr and Martin investigations early in the century.

In the summer of 1968 the fifth annual field season of research was carried out on the Alaskan Glacier Commemorative Project (Miller, 1969). Additional studies were made of the glacial and periglacial geology of the Alaska–Canada Boundary Range (fig. 1), as well as of the glaciology of selected glaciers. Special emphasis was placed on the Pleistocene and Holocene chronology of the Taku and Atlin Districts (Miller, 1969, 1971, 1972a, 1975a; Tallman, 1975) and on the glaciology of the Juneau Icefield (Zenone, 1972; Miller, 1973; Waag, 1972, 1975).

In this report the glacial geological studies are considered first, followed by a brief account of the 1964-68 glaciological research conducted with National Geographic Society support on the Mendenhall, Lemon, Ptarmigan, Taku, Vaughan Lewis, Gilkey, and Llewellyn Glaciers. Previous concepts are considered and a new theory is introduced on the formation of ring-banded structures on glaciers characterized by wave-ogives (Freers, 1965; Kittredge, 1967; Miller, 1968; L. Miller, 1970). Notation is also made of axillary contributions in other glaciological research programs during the 1968 field season. Each project is taken up in order of its geographical location at pertinent research sites on a transect inland from Lynn Canal on the Alaskan coast to Atlin Lake on the British Columbia—Yukon border (fig. 2).

Alaskan Coastal Sector

The rationale of this program has been to work outward from the existing glacial positions on the Juneau Icefield into peripheral areas affected by Neoglacial, Holocene, and late Wisconsin glacial variations. The first work was done in the Lynn Canal, Gastineau Channel, and Berner's Trench sectors of the maritime flank of the Northern Boundary Range (fig. 1). This was followed by research in the Taku Valley, which transects this range inland to the Yukon and Stikine Plateaus and the sector north of the Juneau Icefield in the Atlin District. Special attention was paid to the retreating termini of six key glaciers in the area, starting with the Ptarmigan and Lemon Glaciers near Juneau.

In the past five decades all but one of these ice masses have been experiencing negative mass balances in contrast to the behavior of the Taku Glacier (and its distributary Hole-in-Wall Glacier) discussed in the Phase IV report (Miller and Anderson, 1974a). Significant aspects of Little Ice Age mass balance and also paleoclimatic characteristics of the early Holocene are considered as revealed by the presence of previously unreported glacial and periglacial features in distributary valleys of the icefield close to the Neoglacial limits. With respect to the glacier névés, pertinent aspects of mass-balance, heat-balance, and liquid-balance regimes are also noted.

Evidences of Neoglaciation

Interglacial Forest Beds in the Mendenhall Valley. In the proglacial sector of the Mendenhall Valley near Juneau unique buried-forest remains were investigated and organics sampled at four sites (fig. 3). All sites were once buried by Neoglacial ice and have recently been exhumed by ice downwasting and melt-water runoff. The forest beds at Sites 1 and 2 are stratigraphically equivalent, as are those at Sites 3 and 4. Stump samples collected from Sites 1 and 2 yield dates of 2,000 ± C-14 years B.P., thus delineating the early Neoglacial advance in the Alaska Panhandle, and representing the final forest growth of Thermal Maximum time (Lamont Carbon-14 dates, Columbia University, 1952). Radiocarbon dates of log samples from Sites 3 and 4 give dates of 1,100 years B.P. ± (University of Alaska Radiocarbon Lab., 1974).

Site 1 is at the northwest edge of the festoon of 18th-century moraines shown in the vertical air photo of figure 3. Here ice-sheared stumps *in situ* have been exhumed, and radiocarbon data indicate that the glacier covered a mature forest growing far up the Mendenhall Valley in pre-Neoglacial time. The existence of Little Ice Age moraines stratigraphically above these old forest zones suggests that the mid-18th-century maximum was close to that of the comparable earlier advance just before the beginning of the Christian Era. Site 2, on the southwestern shore of Mendenhall Lake (fig. 3), corroborates this as it represents an extension of the same forest litter, comprised of tree stumps imbedded in fibrous peat and sandy soil. This horizon is a half meter thick, with contained logs and tree trunks as large as 70

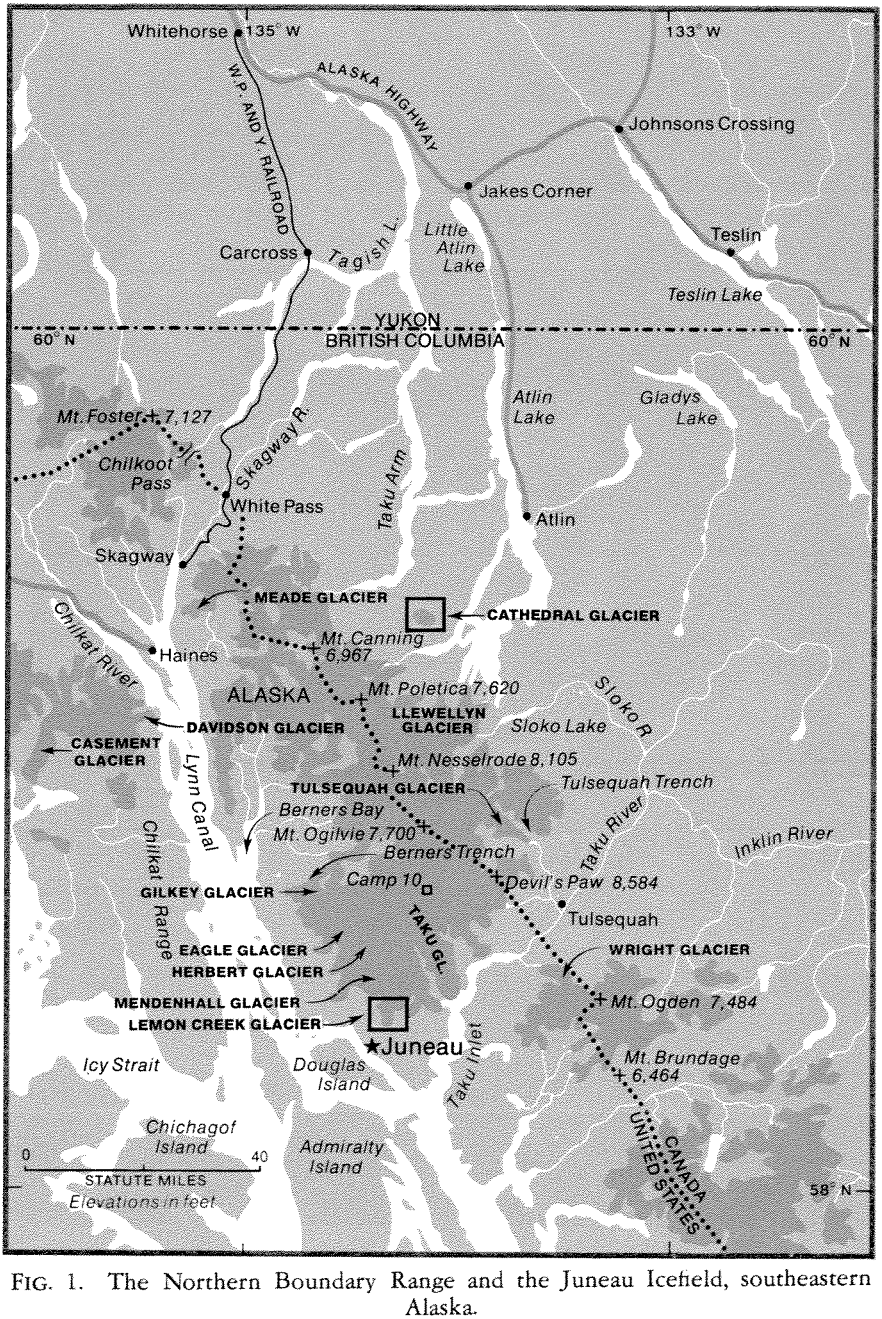

FIG. 1. The Northern Boundary Range and the Juneau Icefield, southeastern Alaska.

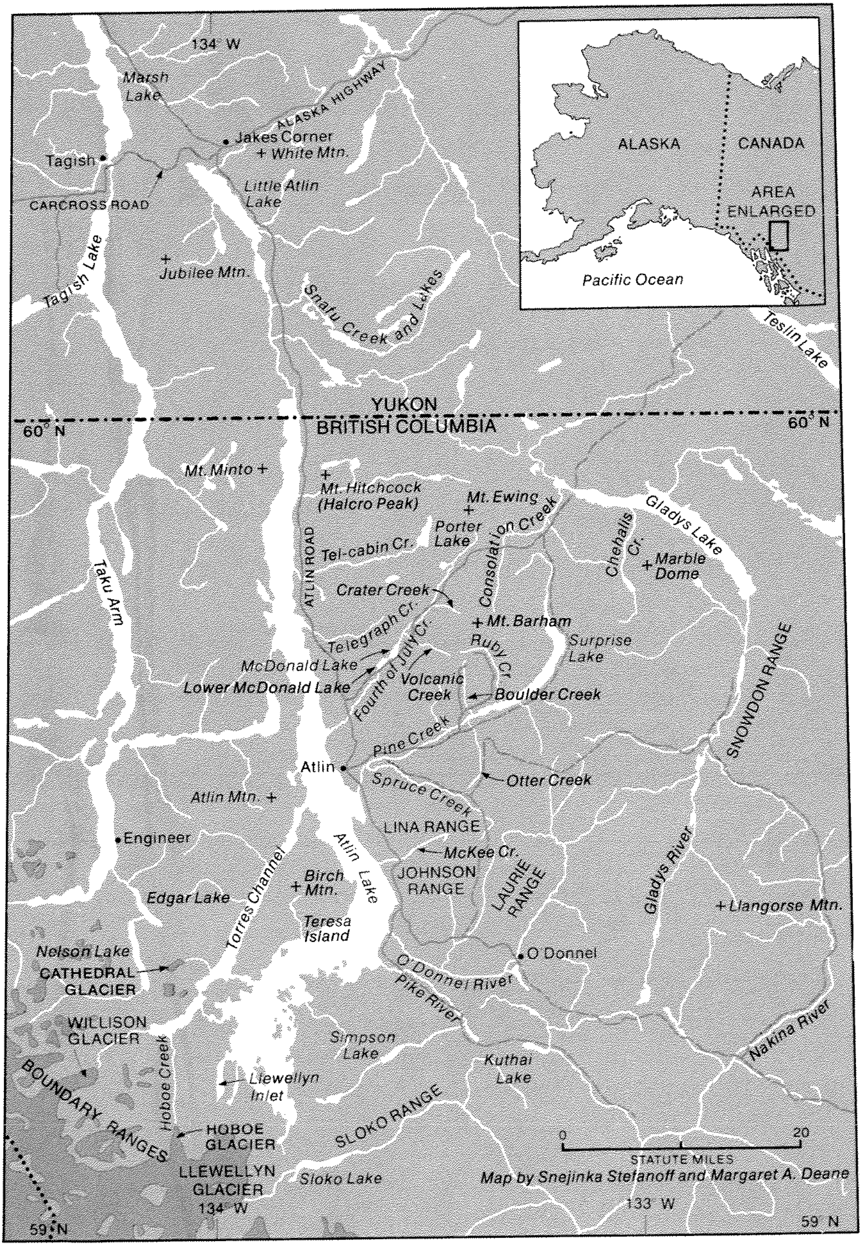

FIG. 2. The Atlin Lake District north of the Juneau Icefield, British Columbia–Yukon.

centimeters in diameter. This proves a substantial interval of uninterrupted growth in early Neoglacial time in a sector some 2 miles farther upvalley than Site 1.

The unique character of the Site 2 forest presents some difficulty in interpretation as many of the trees are in downed positions and buried by a deposit of glacial drift. The stratigraphically higher drift is comprised of unweathered boulder till. Trees that can be conclusively demonstrated to be *in situ,* with roots intact and extending through the underlying peat to the top of a basal sandy horizon, are all lying prone. The most enigmatic aspect is that their tops aim upvalley in directions between N. 25 and N. 45 E. This is difficult to square with the expected direction had the trees been sheared by overriding ice of the early Neoglacial advance.

Possible explanations of the anomalous orientation are: (1) Ice push from the west ... improbable because no other evidence for ice flow in an upvalley direction as recently as 2,000 years B.P.; (2) slumping of the forest bed by undercutting of a proglacial river ... largely discounted because of lack of geomorphic evidence of meander scars or fluvial terraces; (3) a tsunami effect or washdown by a giant wave from Lynn Canal ... a suggestion vitiated by elevation of the forest bed (ca. 30 meters above mean sea level) and the distance (10 kilometers) from Lynn Canal; as well, there are numerous islands and bedrock ridges along the coast to attenuate giant wave effects; (4) ice push from upvalley (northeast), which might have terminated near this zone producing a shearing rotation of the trees in an upvalley direction ... a concept too difficult to visualize in terms of glacier dynamics; (5) a mass wastage or soil-flow effect ... ruled out because again the mechanics are difficult to invoke; and (6) wind-racking or the result of a blowdown by storm winds.

Of these alternatives the blowdown theory is the most likely. On this basis the Site 2 forest would be an extension of that at Site 1, but in a sector where strong southwest winds could produce wind-racking during severe storm conditions prior to the period of advancing ice. This is in line with inland shifts of the Arctic Front, which delimited maritime pressure cells during early Neoglacial cooling, and hence also could relate to change in dominant storm winds from southeasterly to southwesterly flow along the periphery of the maritime cyclonic cell (Miller, 1973; Miller and Anderson, 1974a, 1974b).

Furthermore, logs in the Site 2 forest bed are not flattened or significantly damaged. Many still have bark and the root systems are intact. This allows us to conclude that the trees were buried by thin outwash preceding the advance of two millennia ago and that this outwash was later incorporated in overlying till. The interpretation is borne out by presence of a sandy horizon above the forest litter. It is further corroborated in muskeg bogs in

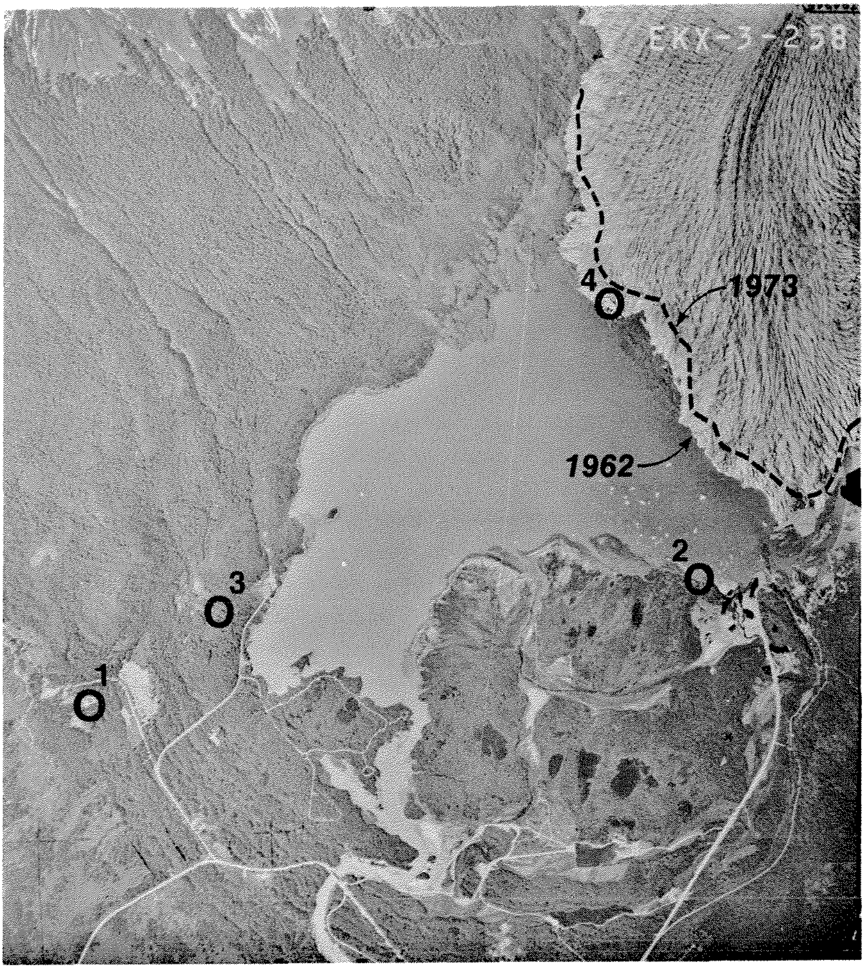

FIG. 3. Mendenhall Glacier showing proglacial lake and arcuate pattern of moraines since the mid-1700's. Circles denote carbon-14 sites of buried or ice-overridden forest remains. Approximate terminal limit in 1973 shown by dashed line. (U. S. Forest Service photo, July 4, 1962.)

the Montana Creek valley just north of Site 1 (Cross, 1968). The significance of Sites 3 and 4 lies in their location on the north edge of the proglacial lake nearer the present ice front. The younger dates represent the mid-Neoglacial warm interval occurring between the 7th and 13th centuries (discussed below). This also relates to trees overriden by the Taku Glacier described by Miller (1967, 1974).

FIG. 4. General view of the Davidson Glacier ice-sheared buried forest. Photo by C. P. Egan.

Davidson Glacier Buried Forest. In the course of the 1961-62 aerial survey of Alaskan Coastal Glaciers (Egan and Miller, 1968; Miller, 1969), our pilot, K. Loken, directed attention to a remarkable buried forest in the Chilkat Range west of Lynn Canal. The site was near sea level in proglacial delta material of Davidson Glacier just south of Haines, Alaska (fig. 1). In 1968 we continued a ground study of the forest bed that had begun in 1965-67 and mapped a large number of *in situ* stumps exhumed in the glacial outwash (fig. 4). Several wood samples from this organic zone were collected, with resulting radiocarbon dates showing that ice advanced to bury these stumps ca. A.D. 1210± 100 years (University of Michigan Radiocarbon Lab.). The next greatest advance occurred in the 1700's.

Of considerable value here is the finding of a large logged-off tree stump in the proglacial zone less than 1 meter from the outer edge of the mid-18th-century moraine. This tree had 425 annual growth rings when cut in 1961, proving that the Davidson Glacier's mid-18th-century advance (maximum for the Little Ice Age) was the greatest since at least 1530 (Egan, 1971).

Ice-tilted trees on the outermost moraine were also studied by dendrochronology, pinpointing that the maximum Little Ice Age advance occurred in 1752. Study of trees rooted in the proterminal zone also revealed a significant growth repression from 1742 to 1765, with a particularly notable repression about 1765-1779. Before and after this repression tree growth was normal and rapid. A weak repression was also noted for the interval 1626-1646, during a time when substantial cooling is known to have taken place in maritime regions of northwestern Europe and also when sunspots were reported at a minimum (Miller, 1956, 1972b).

The Davidson Glacier's late Neoglacial (Little Ice Age) fluctuations may be summed up as threefold in nature and taking place in A.D. 1210 ± 100, in 1410 ± 100, and in 1750-55. This is probably somewhat typical of the glaciers with intermediate elevation névés on the eastern flank of the Chilkat Range and western flank of the northern Boundary Range. This is all new information which delineates the earliest Little Ice Age advances described in this region to date. The situation has counterparts in the Bucher, Antler, and Gilkey Glacier fluctuations noted below.

Moraine Sequences on the Bucher, Antler, and Gilkey Glaciers. The largest tributary to the Gilkey Glacier (fig. 1) is the Bucher Glacier, which enters it about 7 miles (11.3 kilometers) upvalley from the Gilkey terminus. Its névé is contiguous to that of the Upper Gilkey Glacier and lies near Camp 25 on the Nesselrode Plateau at 4,000 to 7,000 feet (1,200-2,170 meters). Part of the Bucher Glacier flows across a low divide and is distributary to the Antler Glacier system. Another part is distributary to and terminates in a marginal glacial trough about 2 miles above the confluence with Gilkey Glacier. Ice formerly flowed through this trough, shortcutting the passage to the main Gilkey Valley (Berner's Trench). A sequence of well-preserved moraines on the gently sloping floor of this tributary valley has also provided new information.

The outermost moraine stands as an arc 7 or so meters high and in places has a plexal character suggesting at least two pulsations. The moraine's downvalley side is oversteepened, and on its uppervalley side an inner moraine arc is separated by a distance of 70 meters. Two lesser moraines lie between the two main moraines, and behind the larger moraine, between it and existing ice, are three more pulsational moraines. One of these is clearly defined and at least two lesser ones are discontinuous.

Scrubby mountain hemlocks growing on the outer moraine were studied and dendrochronological dates obtained by disc techniques (Beschel and Egan, 1965; Egan, 1971). A cross-section from the largest hemlock contained 330 growth rings, with another 30 or more having been rotted out of the decomposed core. From the growth-rate analysis of this tree and other discs obtained from living trees near the Antler Glacier terminus, the maximum recent advance on Bucher Glacier is shown to have occurred between 1590 and 1600. By adjusting the flow-lag (névé to terminus response time), this advance would be a correlate of the 15th-century advance of the Davidson Glacier.

Preliminary studies were also made of Little Ice Age advances of the termini of Antler and Gilkey Glaciers (fig. 4 in Miller, 1971), with a pre-1700's advance revealed on Antler Glacier and a 1780's maximum advance on Gilkey Glacier (Egan, 1971; Heusser and Marcus, 1964). The latter date correlates with mid- to late-18th-century advances on the Eagle, Herbert, Mendenhall, and Twin Glaciers, reported as regional prototypes by Lawrence (1950).

WISCONSINAN STRATIGRAPHY AND PERIGLACIAL EVIDENCES

Our field studies provide a basis for outlining the Quaternary history discussed at the end of this report concerning this key region at the northern end of the Pleistocene Cordilleran Ice Sheet. In the coastal sector dense forest cover and mass wastage make interpretations difficult, but by extending the studies inland to the upper Taku River Valley and the Atlin region (fig. 2) on the continental flank of the Boundary Range we can draw useful comparisons from less afforested areas in the Canadian sector. Recourse is made also to the evolution of erosional topography with the phases of glaciation suggested by study of the nature and spacing of tandem cirques and rock-shouldered berms, as well as relict periglacial features found in coastal and inland areas. The discussion begins with consideration of surface deposits in the Taku District near Juneau. During the course of this, reference may be made to the chronology chart, table 4.

Tills and Diamictons in the Taku District. Two fossil-rich drift sheets partially of submarine origin were investigated in the Juneau area (fig. 6, *upper*). These are overlain by terrestrial sand and gravel deposits from tributary valleys and grade in places into massive slump areas. This work extends earlier mapping of these deposits (Miller, 1956, 1963) and reveals that continuing mass wastage has taken place in Neoglacial time. Radiocarbon dating of peat overlying the uppermost member of this formation proves it to be late Pleistocene and early Holocene in age—ca. 8,500 years B.P. (University of Alaska, Radiocarbon Dating Lab., 1974). Carbon isotope dating of an avalanche-sheared and colluvium-covered stump (ca. 800 C-14 years B.P.) suggests quite recent effects in the topmost layer possibly by earthquake if not climatic-induced debris avalanches in the 12th century.

A geologic appraisal of the formation as part of an earthquake hazard study of Alaskan coastal communities (R. D. Miller, 1973) has considered these glacial tills as diamicton (slump) deposits. Although differences of opinion may rest on how this term is used, I suggest that the Gastineau Formation be referred to as a largely slumped, glaciomarine till-sheet and that its submarine glacial origin be emphasized. It is recognized, of course, that the drift sheet has been subjected to varying degrees of flow deformation after deglaciation, which process is presumed to be largely responsible for the fracturing and dissemination of embedded fossil shells.

The two-phased nature of the glaciomarine facies is accentuated by differences in weathering on the two tills involved. The weathering is a function of both age and environment (i.e., reducing vs. oxidizing conditions). Of special interest is that the lower blue-gray unit extends beneath the Neoglacial moraines of the Mendenhall Valley shown in figure 3 up to an elevation of 50 meters above mean sea level. Also the oxidized upper unit is found in fossil-rich zones at elevations of 300 to 500 feet (90-150 meters) on the sides of gulleys and valley tributaries in the Gastineau Channel and Lynn Canal sector (Miller, 1956). Thus at least 500 feet (150 meters) of sea-level change has taken place since advent of the Holocene. This is corroborated by Twenhofel (1952) who, on epierogenic evidence, suggested that at least half of the shoreline changes in this sector of Alaska have been due to postglacial rebound.

Glaciofluvial Deposits in Coastal Valleys. During this season a study was made of the valley-train deposits in several coastal valleys of the Taku District. Emphasis was on the lower Mendenhall Valley and the interaction between detrital clastics of differing resistances and degradational and aggradational processes in the glaciofluvial erosion, transportation, and deposition. Compositional gradients were detected in the valley train, for estimating provenance and directions of transport. The coarse fraction (granodiorite clasts) from the Coast Range batholith was mechanically and chemically more stable than the biotites and quartz-muscovite schists derived from bedrock suites on the margin of the range. A progressive alternation of the abundance of schists was also found over short distances from overridden outcrops. In both moraines and outwash the proportion of schistose builders was noticeably reduced downvalley, with a concomitant increase of schist clasts in the sand fraction. At greater distances a relative enrichment in the sand fraction was observed by the sedimentology team (Ehrlich and Davies, 1968). In a subsequent laboratory study (Ehrlich, 1970) analyses were made of relative abundances of sizes and compositions in standard volumes.

As the distance-source relationships are fairly constant this area has good potential for glaciosedimentological research with respect to differing intensities of degradational processes taking place in successive periods of glacial activity.

Cirque and Berm Sequences. One of the most striking geomorphic features of the ridge flanks of the Boundary Range is a magnificent array of well-developed and for the most part ice-abandoned cirques, many in tandem sequences. Regardless of structural or lithologic character of the bedrock, in the Alaskan sector the cirques form a fivefold sequence (C-1 to C-5) up to 4,000-feet elevation with a roughly 700-foot spacing in elevation zones from 300 to 3,200 feet (Miller, 1961). Above the 3,200-foot level there are four additional cirque systems (C-6 to C-9), but these are largely ice-filled and with less distinct spacing and lie between 4,000 to 6,200 feet.

On the continental flank of the range four distinct cirque levels are identified between 4,000 and 6,000 feet. The upper three levels are roughly

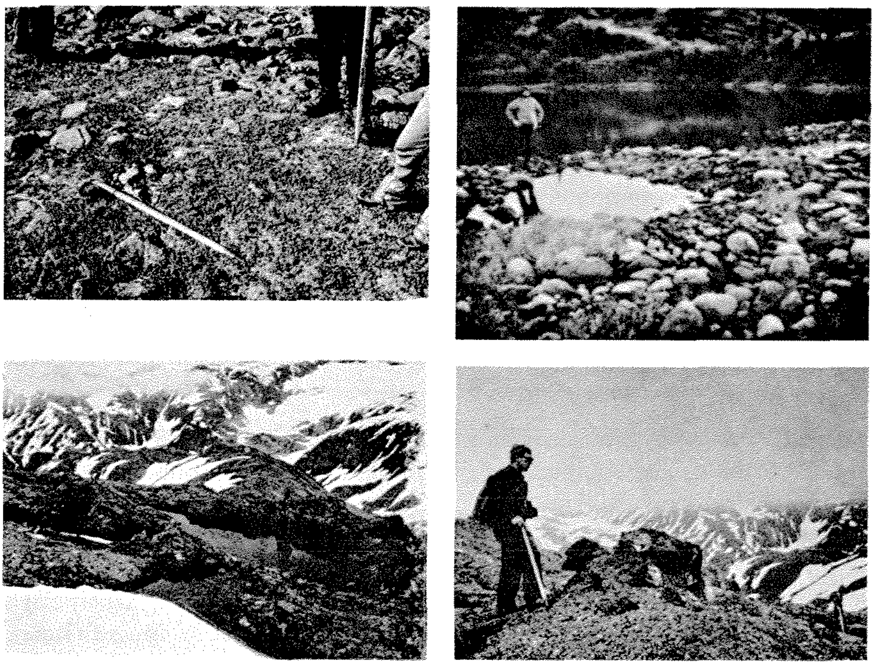

FIG. 5. *Upper left:* Relict stone circles on surface just outside of Neoglacial moraine sequence near Camp 17A, elevation 2,500 feet; center areas of circles thickly vegetated with heath matte (July 1973). *Upper right:* Relict stone circles in esker complex, upper Fourth of July Creek valley, elevation 3,200 feet, Atlin area (August 1970). *Lower left:* Tank topography at 3,300 feet elevation on Ptarmigan Ridge, near Ptarmigan Glacier (July 1973). *Lower right:* Small tor at 3,500 feet elevation on Ptarmigan Ridge in Camp 17 sector (July 1973). (Photos by M. M. Miller.)

TABLE 1—COMPARISON OF MEAN CIRQUE ELEVATIONS IN THE BOUNDARY RANGE SHOWING CORRELATION WITH RESPECT TO COASTAL AND INLAND SECTORS

	Southeastern Alaskan Flank of Range	Continental (Canadian Flank of Range)		
Cirque Level	*Juneau Icefield and The Taku District** (Miller, 1956, 1961)	*Prince of Wales Island* (Swanston, 1967)	*Fourth of July Creek Region* (Tallman, 1975)	*Cathedral Range* (Jones, 1975; Miller, 1975)
C1	300 feet (90 meters)	0-500 feet (0-150 meters)	–	–
C2	1,000 feet (305 meters)	650-950 feet (200-290 meters)	–	–
C3	1,800 feet (550 meters) King Salmon-Port Huron?	1,050-1,350 feet (320-410 meters)	4,100 feet (1,249 meters)	–
C4	2,500 feet (760 meters) Tulsequah-Early Valders?	1,450-1,950 feet (440-590 meters)	4,900 feet (1,494 meters)	4,500 feet (1,370 meters)
C5	3,200 feet (975 meters) Sittakany-Late Valders?	2,050-2,650 feet (625-805 meters)	5,500 feet (1,676 meters)	5,100 feet (1,550 meters)
C6	3,900 feet (1,190 meters) Early Holocene and Neoglacial, including today		6,000 feet (1,829 meters)	5,800 feet (1,770 meters)
C7	4,600 feet (1,400 meters) Thermal Maximum			6,500 feet (1,980 meters)
C8	5,500 feet (1,676 meters) Thermal Maximum and Sangamonian?			
C9	6,200 feet Thermal Maximum and Sangamonian?			

*With postulated reference to glacial stages most recently filling these cirques with ice.

parallel to the elevation distribution of the higher cirque systems on the Juneau Icefield. The comparative distribution reflects a pronounced rise of Pleistocene snowlines inland.

In table 1 mean elevations are given for each cirque system, designated C-1 to C-9. Comparison is also made with interpretations from our colleagues who have worked on this problem in the Alexander Archipelago in southeastern Alaska (Swanston, 1967), on the Cathedral Massif (Jones, 1975), and in the Fourth of July Creek Valley of the interior Atlin region (Tallman, 1975). Allied with the cirque distribution is an equally remarkable sequence of rock-shouldered berms along the walls of main trunk valleys in the region (Miller, 1963). These are reflections of major phases of valley glaciation and as such reveal a fivefold tandem pattern with cyclopean stairs similar to those in the tandem cirques. In any direct attempt to correlate these berm levels with the cirque sequence the upper 13 berms of course integrate with the lower levels of cirques.

Significance of the cirque and berm sequence lies in an apparently close relationship between cirque floor elevations and mean freezing levels (elevations of maximum snowfall) during sequential stages of the Wisconsinan. The main development of cirques is attributed to waxing and waning phases, abetted by periglacial processes in intraglacial phases (Miller, 1961).

Reference (table 1) is also made to the glacial stage most recently affecting each of the cirque and berm levels (i.e., filling or eroding them).

Late-Wisconsinan and Early Holocene Periglacial Conditions. Relict stone circles of early Holocene age are found at 2,500 to 2,800 feet elevation on benches and shoulders of the coastal valleys in southeastern Alaska as well as at slightly higher elevations in the interior Atlin region. These are decimated structures, as today true periglacial conditions occur only above 4,000 and 5,500 feet, respectively, in each sector. Two examples from the Camp 17 area near Juneau and the upper Fourth of July Creek valley in the Atlin region (fig. 2) are shown in figure 5.

Development of this patterned ground relates to exposure of the ground surface in the final retrogressive phase of the Wisconsinan and probably also to early Holocene climatic conditions. This is based on C-14 samples of basal organic horizons in bogs where some of these features are found, giving deglaciation at about 9,700 C-14 years B.P. (Geochron, 1973).

The abundance of tanks and tors on maritime ridges of the Coast Range at 3,000 to 4,000 feet and in the Atlin region at 4,500 to 5,500 feet is further testimony to the long-enduring intensity of frost climates in late Glacial and early Holocene time (Fleisher, 1972; Zwick et al., 1974; Tallman, 1975). Along Cairn Peak Ridge near Camp 17 (fig. 7) numerous small-sized stone rings (up to 0.5 meter) are found. Most of these are relict but a few have reactivated centers. At higher elevations on the central nunataks of the Juneau Icefield and at levels greater than 5,000 feet in the Atlin sector, stone circles, stone stripes, and other evidences of relict and presently developing patterned ground are found in abundance.

Late Holocene Moraines in the Ptarmigan Valley. Our investigation of the intermediate-elevation valley of the Ptarmigan Glacier 6 miles east of the Juneau Airport has revealed a sequence of late-Glacial and Holocene moraines and allied kame and outwash features that are typical of this maritime sector. There are seven distinct moraines, the first of which is pre-Holocene and characterized by stabilized felsenmeers between zones of thick heath cover west of Camp 17A.

The four most recent terminal moraines are untruncated and lie in the inner Ptarmigan Valley (table 2). Lichenometric measurements give the best time stratigraphic information to supplement the morphostratigraphic details. This was accomplished by statistical sampling of hundreds of thalli diameters of crustose lichen on each moraine using *Placopsis gelida* (growth rate of 1 centimeter per 25 years) and *Rhyzocarpon geographicum* (estimated growth rate of 1 centimeter per 80-100 years).

TABLE 2.—LITTLE ICE AGE MORAINES IN PTARMIGAN VALLEY

	Geomorphic Feature	*Lichenometric Characteristics*	*Estimated Dates of Formation*
M1.	Outermost Little Ice Age Moraine; a bold terminal arcuate in form; 5 meters high and 20 meters wide, with huge boulders in consolidated till. Many lichens.	Considerable heath, grass, and sedge matte. Large number of *Rhyzocarpon* thalli of 2 to 2.5 centimeters mean diameter	ca. 1715-1760
M2.	An arcuate, more subdued, and less vegetated moraine; low hummocks 3 meters in height; rooted willows of 2 centimeters diam. Large boulder fragments; Intermediate development of lichens.	Some sedge and grass, many *Rhizocarpon* of 1.5 centimeters mean diameter. A few *Placopsis* of 2-2.5 centimeters	ca. 1820-1830
M3.	Only slightly vegetated moraine, subdued in relief. Some slump zones, with coarser materials than older moraines. Few lichens.	Slight growth of grass and moss. No *Rhyzocarpon*. *Placopsis* up to 2.5 centimeters	ca. 1900-1905
M4.	Fresh-appearing unslumped hummocks, essentially nonvegetated ground moraine. Very few lichens.	Only a few *Placopsis*, mean diams. 1-2 centimeters	ca. 1925-1930
M5.	Ground moraine near present still-stand of Ptarmigan Glacier terminus. Relatively fresh fill with unslumped hummocks. No lichens.	Fresh-appearing material; no vegetation	ca. 1960-present

In this sequence, the time span between moraines I, II, and III appears to fit the 80-90-year cyclicity described for this region (Miller, 1969, 1971, 1974). The time spacing between Moraines III and IV appears to represent only a 20-30-year pulsation. The present ice position is slowly downwasting at the first narrowing of the inner valley. This moraine sequence is significant as a base for further comparison with glacier regime changes in other valleys of the Boundary Range.

FIG. 6. *Upper:* Sequential late Wisconsinan diamicton tills and subaqueous outwash in the Gastineau Formation, near Douglas, Alaska, Lynn Canal sector. *Lower:* Part of middle- and late-Wisconsinan till-outwash sequence on Atlin-Whitehorse Road, Atlin District, British Columbia–Yukon. (Photo by M. M. Miller.)

Glaciological Investigations on the Lemon-Ptarmigan Glacier System. As part of an on-going glaciohydrological program covering the International Hydrological Decade (1965-74) selected investigations were conducted on the liquid, mass, and heat balances of the Lemon Creek and Ptarmigan Glaciers (fig. 1). Some of the results are briefly reviewed.

Glaciohydrology and Stream-gauge Records. During the years 1966-1970 summer-period discharge data were obtained on the outflow streams of Lemon and Ptarmigan Creeks. These are correlated with daily synoptic meteorological records from Camp 17A, Camp 17, and the Juneau Airport. The locations of the stream-gauge sites and pertinent weather stations are shown in the map, figure 7. In figure 8 comparison is made between runoff and the ambient temperature, precipitation, and radiation (in langleys) at Camp 17 over representative parts of a 2-month period.

Significance of the trends and variations represented in these curves lies in the close similarity between fluctuations in Lemon and Ptarmigan Creeks, attesting to the dominance of regional climatic influences. Also noted is the clear-cut control of variations in insolation on diurnal temperature and in turn the direct influence reflected in snow and ice ablation, and therefore in runoff. The additional effects of heavy rainfall are revealed. Thus most peaks in the gauged flow can be related to either or both of these factors. On some days almost exact agreement is found between flow variations in the separate streams in spite of large differences in the volumes of water involved.

On a few occasions Lemon Creek experienced anomalous hydrological surges not recorded on the Ptarmigan Creek gauge. The nature and cause of this phenomenon are considered next.

Englacial Reservoirs and the Jokulhlaup Phenomenon. In this summer a unique glacier cave system was discovered in Lemon Glacier (figs. 9, 10), associated with the impounding and periodic self-discharge of glacier Lake Linda in the headwall sector (fig. 7). Part of the northeastern distributary tunnel of this cave system was explored in 1968 although not finally mapped until 1973 (Miller, 1975b). A larger distributary tunnel was mapped between 1969 and 1971 (Asher et al., 1974).

This unique network of glacier caves serves as an englacial reservoir for the storage of liquid water during the buildup of melt in late spring and summer. It serves also as the locus of periodic floods and probably explains anomalous pulsations in drainage noted on the stage record at the Lemon Creek gauging site. Certainly it represents a geological hazard to be encountered in many Alaskan valleys drained by glacier-fed streams. Hydrological surges have been well documented in Iceland, whence the old Gaelic

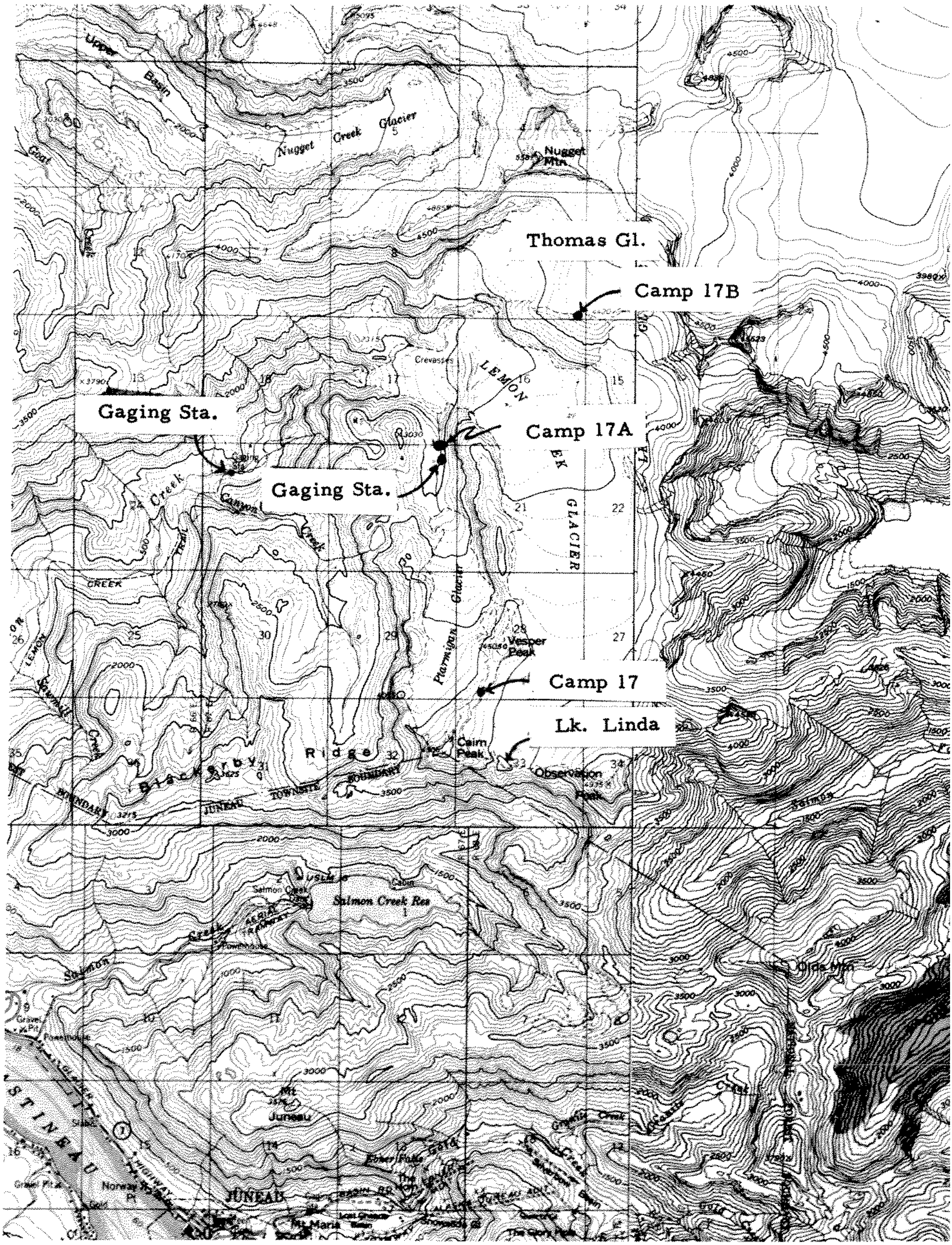

FIG. 7. Map of the Lemon-Ptarmigan Glacier System, showing camp and research sites.

term *jokulhlaup* comes. Because of the importance of this kind of catastrophic flow we are engaged in further investigations on this and other self-dumping ice-dammed water bodies in the Boundary Range (Zenone, 1972; Bugh, 1972; Jones, 1975).

Heat-balance Measurements and the Net Radiation Budget. In order to delineate various factors involved in ablation of a glacier's surface, heat-balance studies were carried out in 1967 and 1968 (Wendler and Streten, 1969; Dobar and Miller, 1972). A few results are presented here covering an observation period from August 5 to 20 on a nearly flat surface of the Lemon Glacier névé. The research site was at 4,100 feet elevation and some 600 feet east of Camp 17 (fig. 7).

Radiation measurements of incoming short-wave radiation were made by Wendler and Streten using a PD4 radiometer and a Belfort actinograph. Combined with this were continuous meteorological readings during the experimentation period. The heat balance is calculated for individual 24-hour periods. As the glacier was thermophysically temperate, there can be no heat flux across the glacier surface, and thus in the heat-balance equation only the following are considered: (1) net radiation balance; (2) possible and latent heat flux; (3) firn melt at the surface.

Albedo on this midsummer firn-pack was found to vary considerably with the sun elevation. This was shown also by Hubley (1957) and Dobar and Miller (1972) in previous seasons of the Juneau Icefield Research Program. In 1968 albedos ranged from 64 percent at a sun angle of 50° to 80 percent at about 80°. In figure 11 the heat balance for this particular firn surface is diagrammatically shown after calculations by Wendler and Streten (1969).

In terms of these summer-season results, the total energy needed to melt firn involved the following ratios in the net budget.

CONTRIBUTION BY	PERCENTAGE
(1) Net radiation (over all wavelengths)	49
(2) Latent heat	8
(3) Sensible heat	43

These calculations provide a basis for glaciometeorological interpretations in the heat-balance (energy) segment of the total mass/energy continuum, which is comprised of the sum of the glacier's mass balance, liquid balance, and heat balance. The results are considered representative of glaciers in the maritime sector of the Boundary Range.

Mass-balance Trends via Changes in the Névé-line and Firn Stratigraphy. As the five main glaciers on the southwest edge of the Juneau Icefield represent the maritime flank of the Boundary Range their regimes are being carefully monitored. Type situations are as follows:

On the Lemon Glacier during the summers of 1965 through 1970, ablation produced a distinct névé-line trending diagonally across glacier in a southeasterly direction. On the Ptarmigan Glacier, a more irregular line (actually a patchy zone) appeared in late summer with an estimated mean elevation usually about 250 feet higher than on the Lemon Glacier. On both glaciers, the seasonal névé-line is reached during the first week of September. The Taku Glacier névé-line averages some 600 feet lower than that on the Lemon Glacier. In contrast, on the Llewellyn Glacier on the continental flank of the range the seasonal névé-line is some 1,500 feet higher than on the Taku. On the Cathedral Glacier it averages 2,200 feet higher than on the Lemon Glacier. The mean névé-lines (10-year mean since 1965) are as follows:

1965-74 MEAN SEASONAL NÉVÉ-LINE ON SELECTED GLACIERS ON A SOUTH-NORTH TRANSECT ACROSS THE JUNEAU ICEFIELD

Ptarmigan Glacier	*Lemon Glacier*	*Taku Glacier*	*Llewellyn Glacier*	*Cathedral Glacier*
3,800 feet	3,650	2,900	4,800+	5,700

Since the mid-1960's, changes in the yearly névé-line positions indicate increasingly positive mass balance on the Lemon Glacier, with the Ptarmigan and Cathedral Glaciers approaching equilibrium but with their termini not yet reflecting a reversal in trend. In its total system the Llewellyn Glacier retains a negative mass balance.

In addition to the névé-lines, test-pit and crevasse-wall stratigraphy measurements on the 3,500-foot névé of the Taku Glacier reveal that in the past 15 years a strong increase in net accumulation has occurred. The increases since 1960 have been on the order of 8 centimeters of additional water equivalent (mean net gain) per year. This is commensurate with a pronounced downward trend in névé-line positions since the early 1950's (Miller, 1969, fig. 9). The relationship of these statistics to the over-all regime of these glaciers is discussed after brief consideration of the total ice volumes involved.

Glacier Depths and Subglacial Topography. From 1965 to 1968 we carried out seismic studies on the Juneau Icefield using a Geo-Space CT-2 Interval Timer. The energy sources were dynamite explosions and in some cases thumper technique (Prather et al., 1968). Adjunct to this have been gravity surveys from which ice depths have also been computed (Miller, 1956, 1963; Theil et al., 1957; Heffernan, 1973).

Cross-glacier profiles and longitudinal traverses of large parts of the upper Taku-Llewellyn Glacier system have been completed. Profiles also

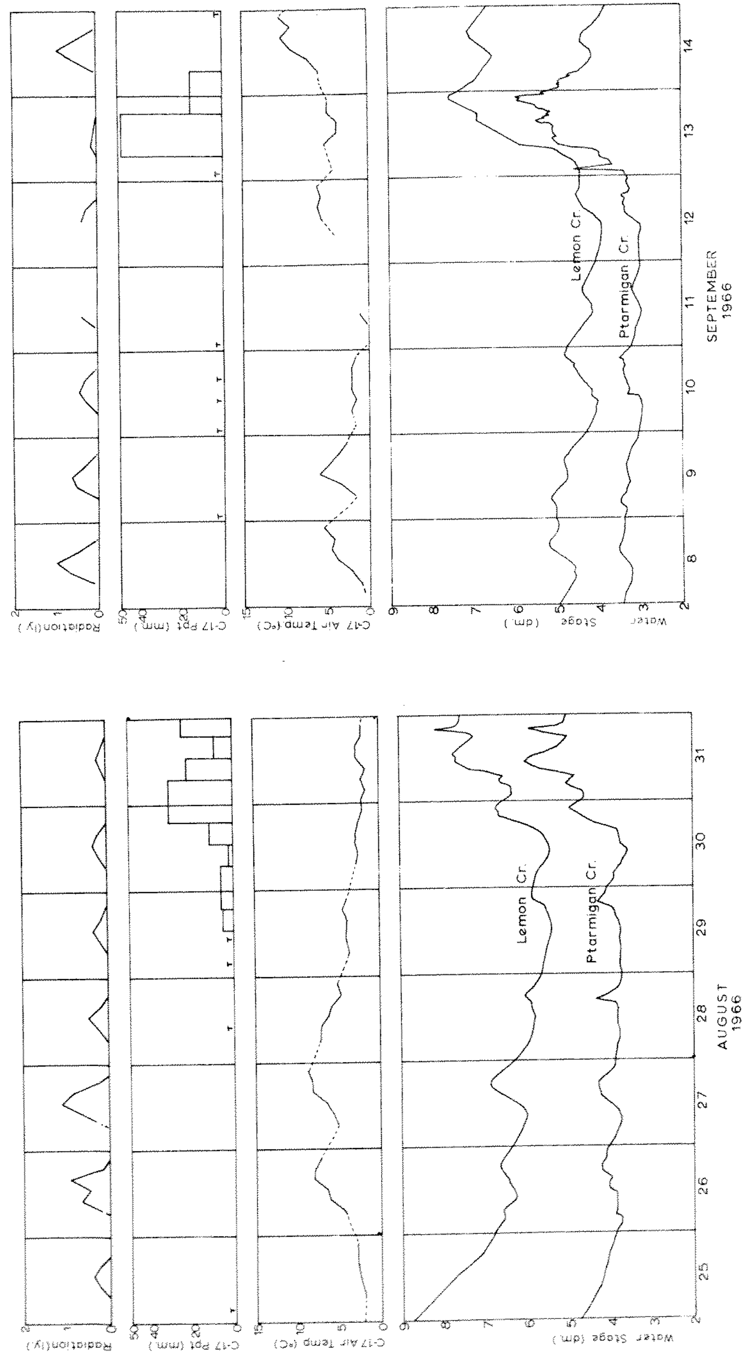

FIG. 8. Comparative hydrometric curves for Lemon and Ptarmigan Creeks, showing relation to summer ambient air temperatures and solar radiation.

were obtained on the névé and below the icefall of the Vaughan Lewis Glacier as shown in figure 16.

In 1968 an additional line supplemented previous profiles on the highest névé of the Lemon Glacier (Shaw et al., 1972). This permitted completion of an isopach map showing configuration of the glacier's bedrock floor, as well as ice thicknesses in various sectors. This map helps us to recognize the dominant control that bedrock structures exert on the slope and orientation of subglacial valley walls, and it abets other work in the area relating surface geomorphology to the bedrock geology (Egan, 1971; Seppala, 1975). Because of this basic control the Lemon and Ptarmigan subglacial profiles are essentially rectilinear, with a maximum depth of 720 feet (220 meters) on the Lemon Glacier.

Central Boundary Range Sector

THE TAKU-LLEWELLYN TRANSECTION GLACIER

Some of the main research effort in glaciology in 1968 was made on the Taku-Llewellyn Glacier system, which comprises a 65-mile-long ice mass extending from the crest of the Juneau Icefield south for 40 miles to Taku Inlet and north 25 miles to Atlin Lake (figs. 1, 2). Since the early 1890's the Taku Glacier has thickened drastically and advanced nearly 7 miles (Field and Miller, 1951; Miller, 1973), whereas since the 1920's the Llewellyn Glacier has extensively downwasted and receded laterally almost 2 miles.

Hypsometric Relationships. An area/elevation (hypsometric) graph of these glaciers (fig. 12) aids in clarifying the causal factors involved in their converse regimes. In this we can see that with respect to the Taku Glacier the elevation of maximum area lies at the 3,000-4,500-foot level, just above the mean névé-line discussed above. It also represents the zone where, since the 1940's, there has been increasing snowfall, a fact substantiated by our annual records of test-pit and crevasse-wall stratigraphy since 1948. And because this is the maximum area it also means optimum conditions for developing a strongly positive mass balance. Thus the Taku Glacier continues to be in a very healthy state. We can expect a further crowding forward of the terminus and that of its distributary tongue, the Hole-in-Wall Glacier, for at least another 20 years. The hypsometric graphs reveal also that the maximum area of the Llewellyn Glacier lies at elevations of 3,000 to 5,000 feet, which is well below the mean névé-line of recent decades on the continental flank. From this it is easy to see why this glacier and its distributary tongues, the Sloko and Hoboe Glaciers (fig. 2), have continued in states of negative regime, with high trimlines and wide scour zones in their terminal zones.

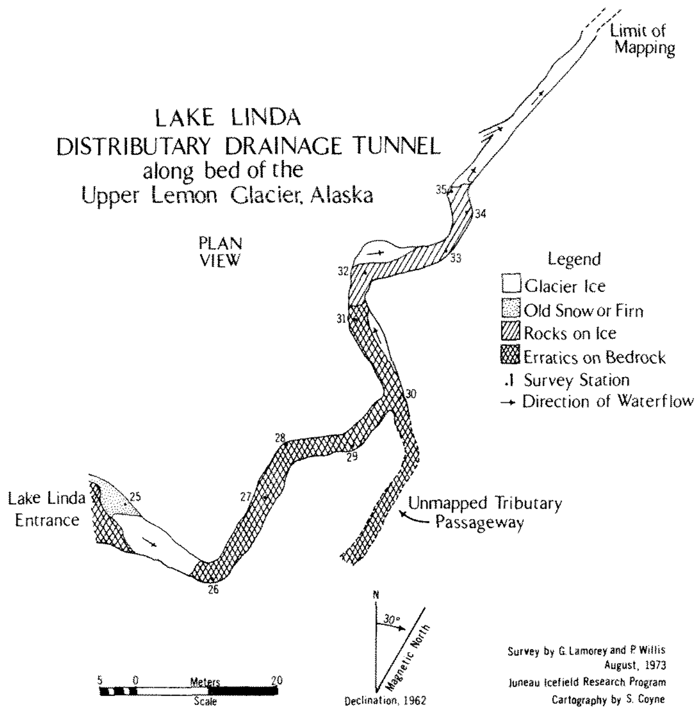

FIG. 9. Longitudinal plot of north reservoir glacier cave in the Lemon Glacier.

Supraglacial Lakes and Englacial Caves. A number of supraglacial lakes have been observed and monitored on the Juneau Icefield. Most of these on the ice itself are close to the mean névé-lines of the particular glaciers involved. Lakes impounded in marginal moats occur most commonly at elevations of less than 1,000 feet above the névé-line. They are also much more abundant on the maritime flank of the range.

The Taku Glacier is particularly characterized by supraglacial lakes, some of which, along with changes in transient snow-lines and névé-lines, are being carefully monitored by ERTS satellite imagery. Two of particular interest are the marginal moats in Icy Basin, at the foot of Taku B (Salla Lake) and a deep moat lake below Juncture Peak, at the confluence of the southwest and central branches of the Taku Glacier. Some controversy has arisen with respect to the origin of glacial moats. I suggest that they are mainly the result of intensified summer ablation in that those in question, as well as Lake Linda on the Lemon Glacier, are all located at the base of vertical rock cliffs from which there is considerable radiation of heat in the summer months, tending to keep them enlarged. They are believed also to be relicts from a time when the névé-line was higher, i.e., in the 1920's to 1940's. In contrast, Seppala (1973) has suggested that they are essentially wind-erosion features. The difficulty with this theory is that during several autumn and winter periods of observation at Camp 10 we have not observed wind patterns or velocities capable of generating such features, although large wind-scooped moats have indeed been observed at much higher elevations where there is more direct exposure to processes of aeolian erosion. Regardless of the causal factor(s) involved, the moats serve as remarkable loci for ponding of melt-water until around mid-July, when they "self-dump," producing hydrological surges within the glacier's internal drainage.

Associated with some of the moats are a number of glacier caves. Some of these have been explored (as noted in the Lemon Glacier discussion earlier). A well-articulated network of glacier caves occurs on the Llewellyn Glacier near its névé-line at about 5,000 feet elevation (in the vicinity of Camp 26). A preliminary study of aspects of the form and speleogenesis in one section of these caves, which has been measured to be no less than 2,100 feet in length, has been reported by Seppala (1972).

STRUCTURAL GLACIOLOGY OF THE VAUGHAN LEWIS GLACIER AND ITS MORPHOLOGICAL SECTORS

The Vaughan Lewis Glacier (fig. 14) is nourished by a high basin (C-8 cirque level) at 5,500-6,000 feet elevation on the southern flank of the Blizzard Range near Mount Ogilvie (fig. 1). The ice flows westerly out of this basin into the Berner's Trench, tumbling down in a spectacular ice cascade some 2,000 feet in a distance of only half a mile. From the base of this icefall where it is confluent with the Gilkey Glacier, it flows 10 miles down the Berner's Trench to an ice-calving terminus in an impounded glacial lake. Investigations have been under way on the full glacier system for a number of years (M. Miller, 1963, 1969, 1972, 1975; L. Miller et al., 1968; M. Miller et al., 1968; Freers, 1965, 1967; Kittredge, 1967; Havas, 1965; L. Miller, 1970; Pinchak, 1968, 1972, 1975; Waag, 1972, 1975).

The glacier is comprised of five glaciomorphic zones, noted as A through E in the cross-section and plan views of figure 13. These zones extend from elevations of 7,000 feet down to 2,500 feet. The prime nourishment zone (A), or plateau névé, is the highest. An icefall, or discharge zone B, lies between 5,000 and 3,600 feet. Below this is the expanded foot of the icefall, formed as an ice apron (C) and characterized by splaying radial crevasses. This is also the wave-band, wave-ogive, or wave-bulge zone. The next lower level is in the valley glacier section, or the zone of maximum wastage (D).

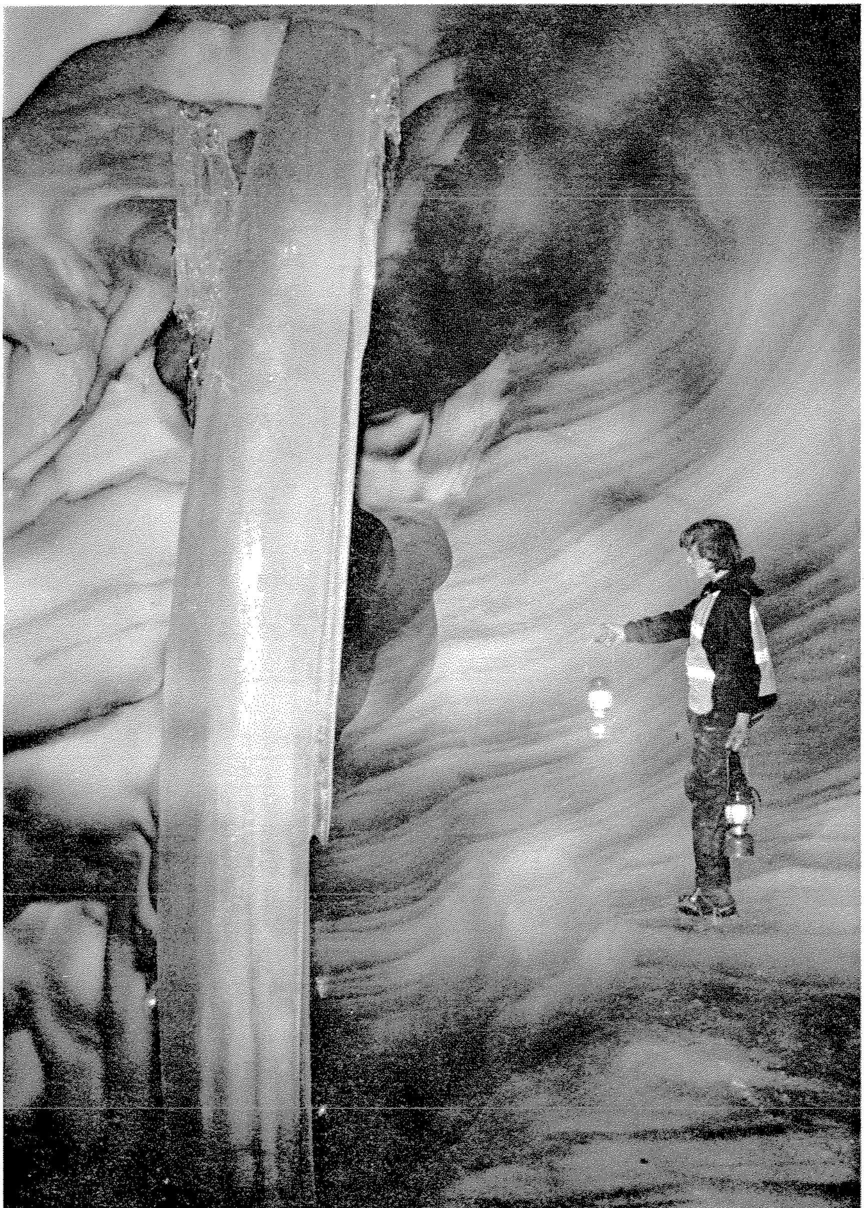

FIG. 10. Interior view of Lemon Glacier cave, showing giant ice stalactite and foliated basal glacier ice. (Photo by R. A. Asher.)

Finally we have the terminal zone (E), where the glacier calves into the ice-dammed lake in Avalanche Canyon.

The mean névé-line over the past 10 years has been at 3,800 feet near the base of the icefall, but high enough to reveal englacial structures for study late in the summer. These structures are manifest at the ice surface, on crevasse walls, and in marginal collapse zones. They include transverse tension crevasses (Zones A and B and fig. 14); oblique and splaying radial crevasses (fig. 15) plus low-angled thrust faults (Zone C); tectonic (flow) foliation beautifully exposed at the surface (in Zones C and D); normal and recumbent englacial folds plus surface wave-bulges with the foliated structures deforming into ogives (Zone C, fig. 15); and cross-cutting secondary ice veins and white-ice inlays exposed on the ice apron downglacier (Zones C and D). To understand and explain these each of the fractures must be related to the structural glaciology system in the glacier as a whole and cannot be considered as separate entities.

Wave Bulges and Ogives. The sequence of upbulged surface waves and relative thickening in the apron region is considered to be the result of annual variations in longitudinal stress produced by regime changes in the névé (L. Miller, 1970). This is abetted by the impinging of ice against a bedrock threshold shown by seismic depth soundings taken in the 1965 JIRP field season (Kittredge, 1967). The nature of the low-angled threshold is noted in long and cross-sections in figure 16. As the wave bulges pass over the threshold and the bedrock gradient increases, compressive stress is replaced by tension and the bulges rapidly attenuate.

The ogive pattern so well displayed downglacier is attributed to hyperbolic deformation of the folded tectonic foliation, further exposed by ablation. As the ogives pass downvalley in the two-dimensional expression they assume more parabolic form. Ogives are coincident with the bands in the wave-bulges, but in this upglacier area they have no surface amplitude and show no detectable outlining with respect to the bulges. But the attenuation of bulges downstream increases the delineation of the ogives because more and more debris becomes concentrated at the surface from ablation of the basal foliation, thus concentrating dirty zones along banded lines. Some of the intervening white ice inlays are of clean and bubbly ice, shown as thinly raised linears in figure 15. These are believed to represent compressed crevasse fillings from winter snow avalanches in Zone B at the base of the icefall. Corroboration of this idea seems to come from the disappearance of these inlays far downvalley (Freers, 1966).

Variable deformation of the ogive patterns from the pointed arch (projectile) form to more rounded and parabolic forms is ascribed to streaming (parabolic) flow, which results when the glacier is undergoing minimal basal slippage (see Phase III report). When such slippage increases in consequence of the rectilinear or plug-mode of flow, these arched bands even become rectangular in pattern, giving rise to the term rectilinear flow (Miller, 1974). Variations of this kind are found in the downvalley sector of the Vaughan Lewis Glacier. For this reason the term "ogive" may not be fully appropriate, except in cases where there are geometrically true "ogive" forms. For more general usage it was suggested some years ago that these features be called arch-bands (Miller, 1955). This suggestion was first made in 1951 when the Juneau Icefield Research Program addressed itself to this problem on similar structures of the East Twin Glacier on the Juneau Icefield (Leighton, 1951).

For our purposes the term *wave-bulges* (up-warped wave-ogives) is reserved for those large surface undulations that begin to form at the base of icefalls and that in this case in the ice apron sector have their fullest development with amplitudes up to 80 feet and wave lengths of 300 or more feet. The general term *ogive* is still used, however, but is reserved for reference to arch-banded structures exposed two-dimensionally on the surface in Zone D after the wave-bulge effect has attenuated.

For convenience, the term *wave-ogive* has value if specifically referring to the banded structures revealed in the bulge zone. These bands relate to a remarkable series of tectonic folia (figs. 15, 16). They are also well shown at the surface and margins of the apron below the icefall (fig. 14).

A Theory of Ogive Formation. Field studies between 1962 and 1968 have led to the development of a new theory of wave-ogive formation, first expressed at the Symposium on Surging Glaciers and their Geologic Effects, held at Banff, Alberta, Canada, in 1968 (Miller, 1968). The theory involves rapid downvalley movement of an icefall and its maximized longitudinal stress, which is responsible for development of recumbent isoclinal fold structures. Although rarely exposed at the surface, these have been found in deformed folia at the glacier's margin. The overturning is occasioned by a sudden change of declivity as ice moves over buried bedrock cliffs. The folds are subsequently righted into more normal positions as the glacier passes from a zone of tensile stress to a zone where the principal stress becomes compressive (see figs. 13 and 16). The character of such foliation "folds" is accentuated at lower elevations where truncation by ablation exposes remnants of them in a way similar to erosion of plunging sedimentary folds in bedrock of the Appalachians.

The manner in which these folds are produced from basal foliation parallel to the glacier bed in Zone A, to deformed and overturned folia in Zone B, and finally to re-orientated positions in Zone C, is depicted in figure

16. The relationship of alternating clean and dirty ice in the sector of maximum ogive exposure farther downglacier is discussed below.

The presence of low-angled thrust surfaces and of inlays of what have been suggested as compressed segments of young, bubbly glacier ice are diagnostic, as in the presence of splaying radial crevasses from extension effects in the ice as it emerges from the constriction of its bedrock defile (bottom of Zone B). These are all expressions of tectonic processes in the lower icefall region. The crux of the explanation lies in a plunge-pool effect due to existence of the bedrock threshold shown on the seismic profiles for Zones B and C (fig. 17). The bedrock topography provides just the right compression to upbulge the rapidly flowing ice before its surface is leveled by atmospheric ablation processes.

Supraglacial Streams. The in-ice structural features produced by shearing processes and the results of upbulging are important in evolution of the supraglacial ponds and surface streams below the apron. These ponds are concentrated in the depressions between wave bulges, and, as seen in figure 15, they cut through the bulges, following the trace of radial crevasses. Once ice passes beyond the bedrock threshold into Zone D, downvalley from the wave-ogive zone, water flowing in the streams finds egress into moulins and ceases to score the surface with the fluted canyons which characterize their channels in the undulation zone (Pinchak, 1972). Of special interest, however, is the tendency for the surface streams to produce sine-generated meanders within a very few weeks, in some of which the meander curves actually spiral downward, particularly in sections where the ice surface after leveling out steepens again. This is a dramatic revelation of the interrelated roles of structure, material, process, and time in evolution of surface morphology of glaciers.

Pleistocene Teleconnection and the Interior Sector

In connection with the regional objectives of the Alaskan Glacier Commemorative Project and long-term glacioclimatological studies of the Juneau Icefield Research Program (JIRP) research was initiated in the early 1960's on the Quaternary geology and geobotany of the Atlin region (fig. 2). This has resulted in a number of reports and publications (Anderson, 1970; Miller, 1972a, 1975a; Miller and Anderson, 1974a, 1974b; Miller and Tallman, 1975; Lietzke, 1972; Lietzke and Whiteside, 1972; Tallman, 1972, 1975; Jones, 1975). These researches are allied with earlier work since the 1940's on Pleistocene erosional and depositional sequences in the Taku

District and adjacent sectors of the Alaska Panhandle (Miller, 1956, 1961, 1963; Beschel and Egan, 1965; Miller and Swanston, 1968; Swanston, 1967, 1970, 1972; Egan and Miller, 1968; Egan, 1971; Østrom, 1972), including the Lynn Canal sector to the west and the Taku River Valley beyond Tulsequah to the east (fig. 1).

Pleistocene Erosional Landforms and Morphogenetic Phases of Glaciation

The character and significance of erosional sequences given by berms and cirques have been considered earlier in this report. As well, they have been discussed in other publications (Miller, 1961, 1963). Also a description of the morphological nature of the sequential phases of glaciation and their relative magnitudes pertaining to the Cordilleran Pleistocene has been previously described from field evidences in the Boundary Range (Miller, 1964).

TABLE 3—TYPES OF GLACIATION DURING THE WISCONSINAN ACCORDING TO ELEVATION OF OLD CIRQUES AND BERMS WITH SUGGESTED CHRONOLOGIC RELATIONSHIPS

Index cirques (with elevations in feet)	*Berm levels in main valleys*	*Nature and relative magnitude of regional glaciation**	*Suggested chronology with short designations*	*Probable time range of development*
C6-3,500**	B1	Retracted Ice-field	Neoglacial	
C5-3,200	B2	Extended Ice-field		GIVc C5
C4-2,500	B3	Lesser Mountain Ice-sheet	Late Wisconsinan	GIVb C4
C3-1,800	B4	Lesser Mountain Ice-sheet		GIVa C3
C2-1,100	B5	Intermediate Mountain Ice-sheet	Upper Middle Wisconsinan	GIII C2
C1-(embayment stage)	B6	Greater Mountain Ice-sheet	Lower Middle Wisconsinan	GII C1
C1-350 (initiation stage)				
Over-deepening of longitudinal valley into present U-form		Greater Mountain Ice-sheet	Early Wisconsinan	GI
Cross erosion of upper slopes and ridges deepening of main valleys		Intermontane Ice Cap	Pre-Wisconsinan	

*As related to major excavation of cirques at reference level.
**Level of present semipermanent névé-line on western side of icefield.

Based on the cirque and berm sequence, the elevations of index cirques and the relative position of main valley berms on the coast and in the interior are noted in table 3 as these are all related to the nature and magnitude of these regional phases of glaciation. Because the cirques and berms are the product of multiple erosive cycles during Wisconsinan time, this

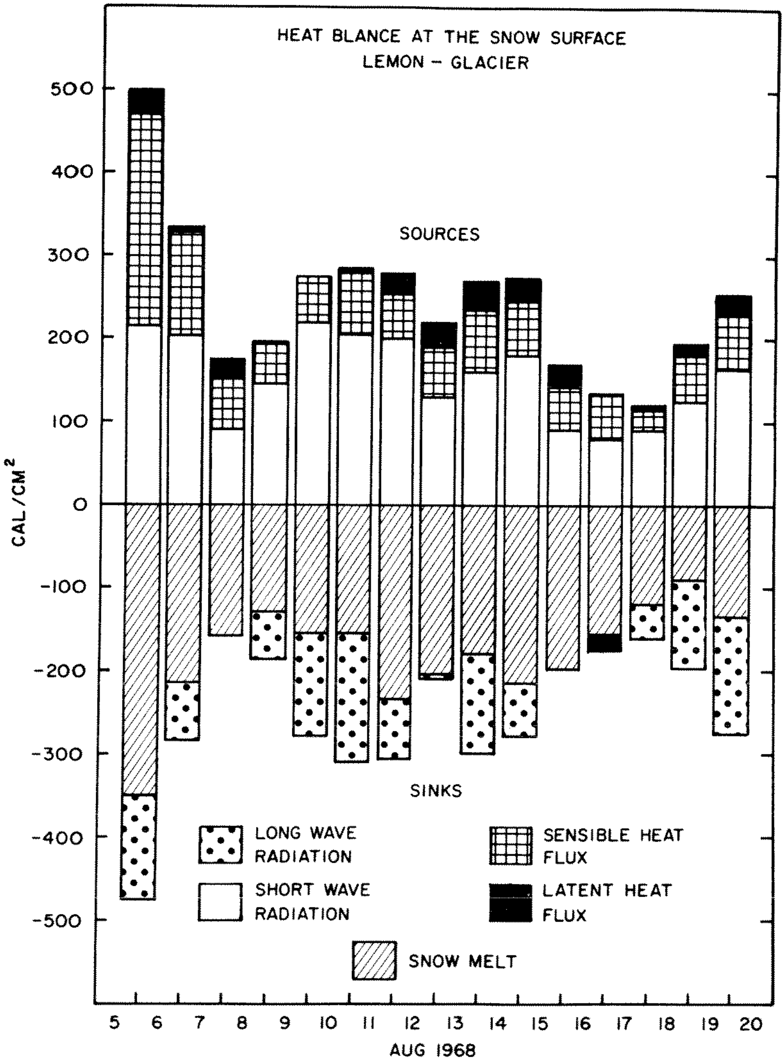

FIG. 11. Heat-balance diagram for the Lemon Glacier firn surface, midsummer 1968.

table postulates a reasonable period of development through a number of glacial stages. The relative lengths of the arrows do not represent time magnitudes but only suggested chronologic ranges.

Pleistocene Depositional Stages. The distinction between stages and phases is that stages have time-stratigraphic meaning, whereas phases represent glaciation magnitudes; i.e., it is a geometric concept and hence only has morphostratigraphic significance. A phase of glaciation, of course, may embrace repeated stages.

A sequence of Pleistocene stages has been identified in the over-all region of our concern, but the relationships are made complex by multiple provenances of ice. Both in the coastal Taku District and in the interior Atlin region, two widespread occurrences of middle to late-Wisconsinan till are reported, but these are not construed as contemporaneous. Regionally, however, there is evidence of a widespread drift sheet attributed to the early Wisconsinan. Pre-Wisconsinan glaciation too was all-inclusive, but the only evidence is high-level U-shaped cols and formerly rounded summits, today seen as serrated ridges due to the intensity of Wisconsinan erosional processes. Also, even though early Wisconsinan glaciation left extensive erratics on ridges above later glaciation limits, much of the evidence has been destroyed by the intensity of subsequent periglacial processes. A factor in this is the generally cold climatic condition at high elevations that even during intraglacial intervals retarded soil development. The presence of weathered and relatively deep till soils postdating the early Wisconsinan maximum suggests that this glaciation was prior to 50,000 years B.P.

Surface Stratigraphy on the Alaskan Coast. The two younger tills are found most commonly in the lower parts of valleys and on the coast in emerged fiord deposits (Miller, 1964; Swanston, 1967). In the Juneau area the top member is an indurated blue-gray boulder clay diamicton with coarse clastics, designated in this sector as the upper segment of the Gastineau Formation, termed the Gastineau Channel Formation by Robert Miller of the U. S. Geological Survey (1973). In places this formation is of glaciomarine origin, the final disposition being modified by berg-rafted debris. Because there is a well-distributed boulder and cobble content and much intercallated outwash material (fig. 6, *upper),* I consider it to be essentially subaqueous glacial in origin. Our studies reveal it to contain late-Wisconsinan *Clinocardium* sp. shells and to rest on an older till with zones of mixed colluvium and glaciofluvial facies. The lower segment is a more definite compact and ill-sorted till with a mild weathering profile. In part, however, it too is a diamicton with included *Leda*-type shells. At higher levels it appears to correlate with a weathered silty facies containing a few large boulders lying stratigraphically below but often topographically above stained deltaic gravels considered to be very late-Wisconsinan in age. A number of such deltas occur at the mouths of distributary streams from the Coast Range icefields.

Above the boulder silt, to elevations of 520 feet (160 meters), is a marine clay containing shells of *Clinocardium, Pectin,* and *Macoma* calcarea gemlin species. Many of these have been disrupted and broken by subaqueous flow. What is apparently a counterpart of this two-phased sequence has been found in the Alexander Archipelago (Swanston, 1970). The weathering profile on the basal unit in this drift and an apparent correlate in the Atlin region appear to reflect intra-glacial conditions. This sequence, though some uncertainty lies in its glacio- vs. glacio-marine origin, when taken as a glacially related feature in conjunction with other evidences, such as the regional array of cirques and berms, is aiding in the resolution of Wisconsinan chronology for the Taku District as noted in the chart, table 4.

Inland Counterparts in the B.C.-Yukon. A probable correlate of the upper member of the Gastineau Formation is found inland in the Tulsequah and Atlin Lake regions. In the latter, the two tills have been well exposed in road cuts (fig. 6, *lower)* and by sluice operations in the main gold placer streams in the vicinity of Atlin, i.e., McKee, Spruce, Pine, and Boulder Creeks (Miller, 1975a; Tallman, 1975). Radiocarbon dates on a section in Boulder Creek valley show that warmer and wetter conditions persisted in the interior prior to 40,000 years B.P. Other C-14 dates from bogs near the Alaska and Atlin Highways (Anderson, 1970) and in creek banks (Tallman,

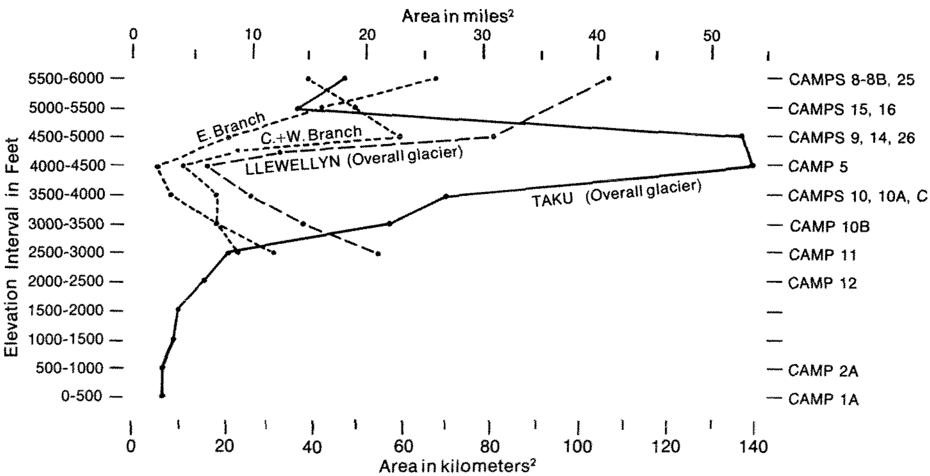

FIG. 12. Comparative area-elevation distribution of Taku and Lewellyn Glaciers.

1975; Miller, 1975a) reveal that deglaciation in the Atlin region was well under way before 10,000 years B.P.

The second oldest till in the interior region (e.g., at Boulder, Pine, and McKee Creeks) is much more altered by weathering (revealed by a yellow limonitic soil) than the lower till-like member of the Gastineau Formation. As it is in a much drier interior climate, this weathered till is believed to be considerably older, leaving the lower Gastineau member to correlate with the upper McKee Creek unit, i.e., the youngest Atlin till. There appears, however, to be a genetic relationship between the lower Pine and Boulder Creek deposits and oxidized high-level moraines near timberline, and possibly to a paleosol horizon on higher nunataks of the Boundary Range (Lietzke and Whiteside, 1972). Intraglacial conditions seem to be suggested (provisionally termed the Pine Creek Intraglacial in table 4). There is correlation, too, with a twofold Wisconsinan moraine and kame-moraine complex in the intermediate and upper Fourth of July Creek Valley northeast of Atlin (fig. 2, also Tallman, 1975). Here northeasterly flowing ice lobes from the Tagish and Atlin Valleys flowed into a junction (interlobate) zone not far from the upper limit of northwesterly flowing ice from the Teslin and Gladys Lake Depression and via these channels from the Yukon Plateau west of the Cassiar Mountains.

There is also evidence in McKee Creek and in the high-elevation tundra plateaus of the Atlin region that a more intensive glaciation deposited an extensive earlier till(s). Research is proceeding on this significant aspect of what we believe to represent an early Wisconsinan glaciation. The complex nature of the regional glaciation is also recorded in a series of glacial moraines and fluvial and lacustrine terraces at high elevation in the Tagish, Atlin, and Teslin Lakes area, as well as by the sequence of interior cirques noted in table 1.

In the Atlin Lake region the final diminishment and retreat of Wisconsinan ice are documented by massive embankment moraines and proglacial valley-mouth deltas in the northern part of the main valley, as well as by esker swarms in highland tributary valleys to the northeast. Here C-14 dates reveal that ice remained on high plateau areas probably as recently as 8,000 B.P. and that even the lower level ice did not melt away much prior to 10,000 years B.P.

Character and Features of the Holocene

Our palynological and periglacial research provides an interpretation of Holocene glacioclimatic events in the Boundary Range. Aspects of the past

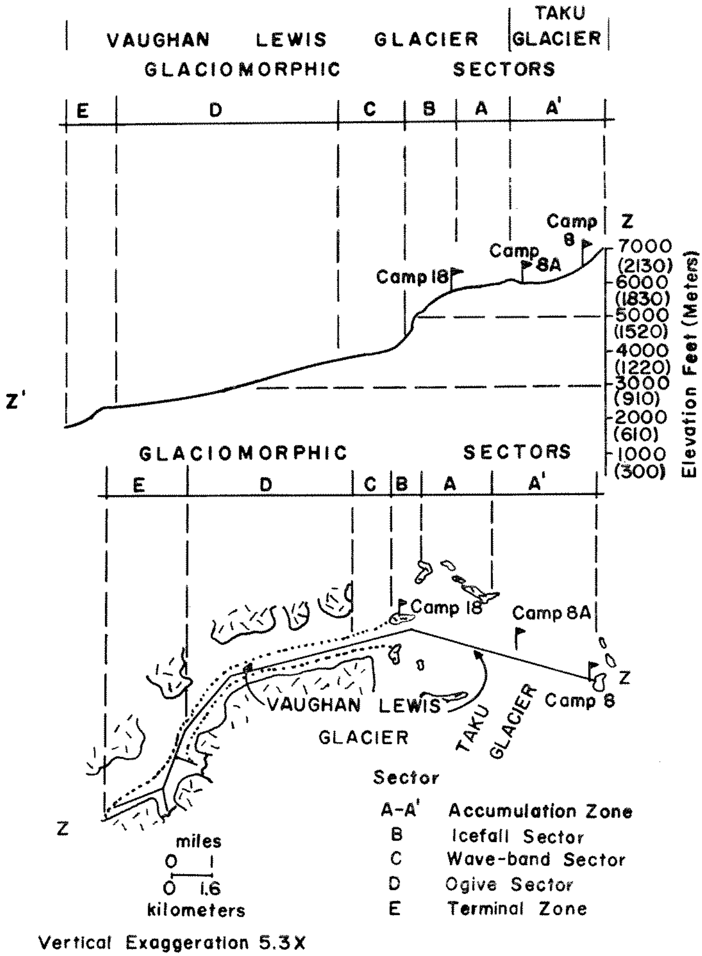

FIG. 13. Longitude profile and plan view of Vaughan Lewis Glacier, showing glaciomorphic sectors.

FIG. 14. Aerial oblique view of Vaughan Lewis Glacier. (Photo by M. M. Miller.)

10,000 years have been discussed with respect to the Alaskan coast. In the interior, an array of relict palsas (hydrolaccoliths) in the Fourth of July Creek Valley (fig. 2) provide especially useful information (Phase IV report). Some of these are redeveloping in the present cooling trend (Miller, 1973; Tallman, 1975).

When Was the Holocene Initiated?[1] Key questions to ask are: When did the Holocene begin? And did it actually end at the beginning of Neoglacial time? The palynological records reported in the Phase IV report (Miller and Anderson, 1974a) indicate that for the Neoglacial in the Boundary Range climatic cooling was well under way by about 2,500 years B.P. This is suggested also by a C-14 date from post-Glacial bogs in the Surprise Lake area (Geochron, 1974; Tallman, 1975), where significant climatic change appears to have begun about 2,770 C-14 years B.P. Evidence from the Mendenhall Glacier area described at the beginning of this report suggests that 2,000-2,200 years B.P. ice was overriding forest beds in coastal valleys. If we assume a 200- to 500-year buildup of glaciers in the Coast Range following the Thermal Maximum, a date of about 3,000 B.P. is reasonable as the effective start of Neoglacial time in this sector of the North Pacific Cordillera.

A two-phased nature of the Neoglacial is suggested by the warm interval that produced a retraction about 1,100 to 700 years B.P. or from A.D. 900 to 1300 (Tallman, 1975; Egan, 1971). The best evidences are the C-14 dates on overridden trees in the Taku Glacier and Davidson Glacier areas, previously discussed (Miller, 1973, p. 160 and fig. 2). Thus, the Alaskan Little Ice Age is assumed to have begun following this warming interval—i.e., approximately—in the 1300's, a suggestion corroborated by the dendrochronology dates obtained on the Bucher Glacier moraines.

As for the early Holocene, samples of basal peat from palsa bogs in the Upper Fourth of July Creek Valley give several C-14 dates around 9,700 ± 100 years B.P. (Geochron, 1972; Tallman, 1975). These peats, of course, represent the initiation of organic growth following deglaciation. This conclusion is further corroborated by the 10,000 years B.P. date of ice recession from the lower end of Atlin Lake (near Jake's Corner, see fig. 2; also see Anderson, 1970). Added to this is a C-14 date of 8,000 years B.P. for the basal peat horizon immediately above the younger diamicton till in the Gastineau Formation near Juneau (University of Alaska, Radio Carbon Lab., 1975); as well as a range of 9,000 to 11,000 years B.P. on peat and logs from

[1] Defining the *Holocene* as the interval since the last major glacial or large-magnitude climatic event. For this definition the Holocene can represent quite different time spans in different regions of the globe.

FIG. 15. Wave-bulge, foliation, and radial crevasse structures in ice apron sector below Vaughan Lewis Icefall.

the base of muskeg in the Lemon Creek and Montana Creek valleys near Gastineau Channel (Miller, 1975; Heusser, 1960).

Further testifying to the initiation of the Holocene right after the final retreat of late-Wisconsinan glaciers from the Atlin region is the truncation of intermediate elevation lateral moraines produced by Atlin Valley ice along the 3,000-foot contour of Atlin Mountain. Here rock glaciers from abandoned cirques at 5,000 to 6,000 feet have flowed down to truncate these moraines, proving that these periglacial features are less than 8,000 years old.

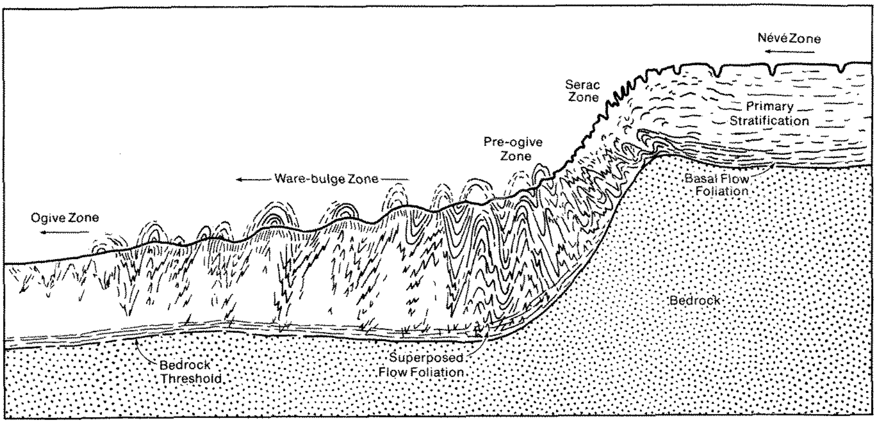

FIG. 16. Schematic long-section, showing evolution of folded tectonic foliation on Vaughan Lewis Glacier and relationship to changing dip of folia in wave-bulge and ogive zones.

In view of all this, the Holocene climatic trends show a rather continuous warming from about 9,500 years B.P. to about 6,000 B.P. This led up to the Thermal Maximum interval when mean annual temperatures in the interior region reached some 2° F. (3° C.) warmer than present. During this warm interval the most intensive of periglacial processes also migrated to higher elevations and the much-retracted Juneau and Stikine Icefields received a new input of accumulation on their crestal névés, as did the cirques at the elevation of levels 5 and 6. Today these cirques are some 700 feet higher than the lowermost cirque at present filled with ice in the interior Atlin region. They are also an equivalent elevation above today's permafrost seep level in these interior mountains.

The Alaskan Little Ice Age. Near the end of the Thermal Maximum, the Arctic Front (defined in Miller, 1956, 1973) held a mean position some distance west of the inner reaches of the Inside Passage in the Alaskan Panhandle. Then wetter conditions and increased storminess prevailed on the continental flank of the Boundary Range.

The Thermal Maximum was followed by a significant cooling trend as the Arctic Front again moved well inland. This was coincident with decreased storminess and drier conditions with general cooling on the continental flank of the Range. Concurrently on the coast, relatively cooler and wetter conditions dominated and led to increased glaciation in maritime sectors of the icefield highland. The nature of these out-of-phase climatic trends has been documented and explained by Miller and Anderson in recent publications (1974a, 1974b).

TABLE 4.—PROVISIONAL CHART OF WISCONSINAN AN
ERN BOUNDARY RANGE, ALASKA–CANADA, WIT

COOK INLET AFTER KARLSTROM, 1961, 1964	ALASKA COMPOSITE PÉWÉ 1975	SOUTH-WESTERN YUKON TERRITORY AFTER DENTON AND STUIVER, 1967	EASTERN YUKON TERRITORY AFTER BOSTOCK, 1966, HUGHES, ET AL., 1969	RELATIVE EXTENT AND CHARACTER OF BOUNDARY RANGE GLACIATIONS MILLER AND TALLMAN, 1975	FOURTH OF JULY CREEK VALLEY, ATLIN REGION TALLMAN, 1975	TAKU DISTRICT S.E. ALASKA AND N.W BRITISH COLUMBIA MILLER, 1956, 1963, AND 1975
	IV	Neoglaciation	Neoglaciation	? Re-occupation of Nivation Hollows and Cirques	Holocene: High Level Permafrost Nivation Hollows Palsa Development	Holocene — Neoglacial: Alaska Little Ice Age Taku Intrastadial Early Mendenhal
	III	Slims Nonglacial			Thermal Maximum	Thermal Maximum
Naptowne Glaciations: Tanya				Glacial Fluvial Terraces	Intense Periglacial	Salmon Cr./Zohini: High Cirque Glaciatior Sittakanay Substage* Tulsequah Substage** King Salmon Substage***
	II	Kluane Glaciation	McConnell Glaciation	Temperate to Sub-temperate	Atlin V Atlin IV / Gladys III	
					Atlin III / Gladys III	Douglas/Inklin Stage
Skilak Lake				Weathered Tills ?	Significant Climatic Amelioration	Intraglacial
				Sub-temperate to Sub-polar ?	Atlin II / Gladys II	Greater Mountain Ice sheet: Gastineau/Sloko Stage
Killey				Strong Weathering On Tills ?	? Gladys I	(Glacial and Intraglacial Substages)
Mooshorn				Thick Polar to Sub-polar	Pine Creek Intraglacial Atlin I	
Knik		Boutellier Nonglacial		?	Boulder Creek Intraglacial	Intraglacial (relatively cool)
	I	Icefield Silver Nonglacial Shakwak	Reid Glaciation	Old Weathered Drift Overlain by Less Weathered Till ?		
				? Character Unknown Probably Many Glacials and Intraglacials ?	Pre-Atlin I (Pre-Classical Wisconsinan)	Greater Mountain Ice sheet: Early Juneau/Atlin Stag (Probably extend into classical upper Sangamonia

*Retracted Icefield Glaciatior
**Extended Icefield Glaciatior
***Lesser Mountain Ice shee
****Intermediate Mountain Ice shee

HOLOCENE STRATIGRAPHIC SEQUENCES IN THE NORTH-
SUGGESTED COMPARISONS WITH OTHER REGIONS.

NORTH-CENTRAL AND EASTERN BRITISH COLUMBIA AFTER RUTTER, 1975	**COLORADO FRONT RANGE** AFTER MADOLE, MAHANEY, AND FAHEY, 1975	**PUGET LOWLAND** AFTER EASTERBROOK, 1963 AND 1975, AND CRANDELL, 1965	**GREAT LAKES COMPOSITE** AFTER FLINT, 1971, AND TERASMAE AND DREIMANIS, 1975	**WISCONSIN AND ILLINOIS** AFTER BLACK, 1975, AND FRYE AND WILLMAN, 1973
	Gannet Peak			
		Alpine Glaciation		
	Audubon			
		Alpine Glaciation		
(No dates or correlations given)	Triple Lakes			
	Pinedale: Late Stade			
	Pinedale: Middle Stade	Sumas Stade (Washington State)	Valderan	Valderan Glacial
Deserts Canyon		Everson Interstade	Two Creekan	Two Creekan Intraglacial
			Mankato	
			Cary	
		Vashon Stade		
Lake Portage Canyon		Interstadial	Tazewell	
	Pinedale: Early Stade	Evans Creek Stade	Iowan	Woodfordian Glacial Stage (3 main till units, with retreatal deposits)
Early Portage Mountain		Olympia Interglacial	Farmdalian Intraglacial	Farmdalian Intraglacial
		Salmon Springs II Stade		
	Bull Lake - Pinedale Interglacial ? ? ?	Salmon Springs Interglacial	Upper Altonian	Altonian Glacial Stage (Five main tills, with retreatal deposits)
Early Advance "possibly pre-Wisconsinan"		Salmon Springs I Stade	Port Talbot Intraglacial	
	Bull Lake (Part of Sangamonian?)		Lower Altonian	
		Puyallup Interglacial Sangamonian?	Sangamonian	Sangamonian

Chart compiled by Maynard M. Miller;
drawn by Alfred L. Zebarth and Margaret A. Deane

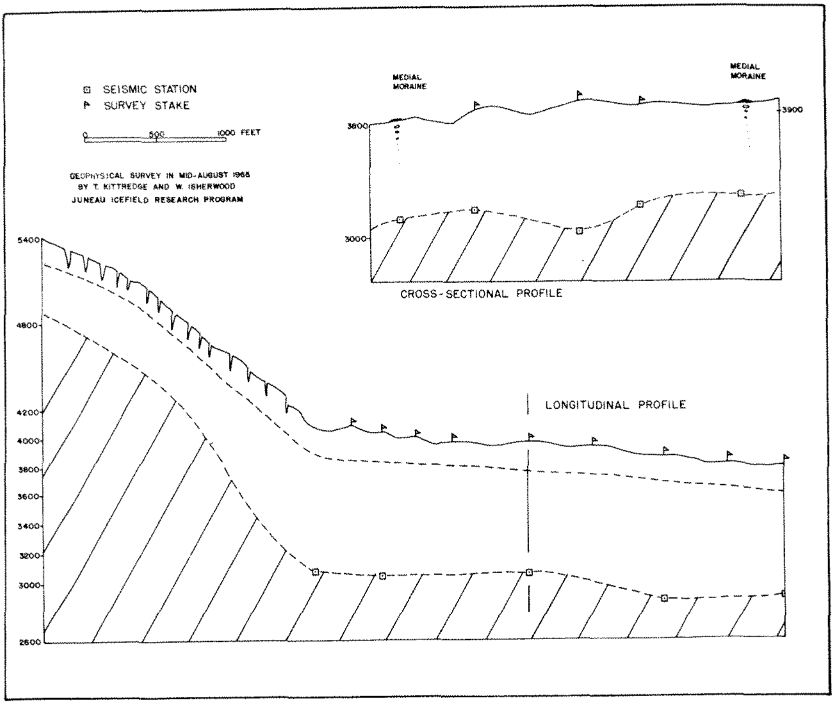

FIG. 17. Seismic profiles showing low bedrock threshold at base of Vaughan Lewis Icefall.

It is now apparent that the time interval from about 3,000 to 900 years B.P. was as much as 4° F. (2° C.) cooler than today. This was an interval of intense glacial activity in the high center of the Boundary Range, and also it represented intense periglacial activity in the area of palsas and sporadic permafrost at the 3,000-3,500-foot level in the Atlin region. Then came a short and warmer interstadial persisting until about the end of the 13th century (Miller, Egan, and Beschel, 1968). Since the 14th century the Boundary Range and its peripheral sectors have experienced relatively cooler and wetter conditions compared to the short preceding warm interval in the Middle Ages.

A Composite Chronology for the Quaternary

The array of glacial and glaciofluvial landforms investigated in this large region at the northern end of the Pleistocene Cordilleran Ice Sheet

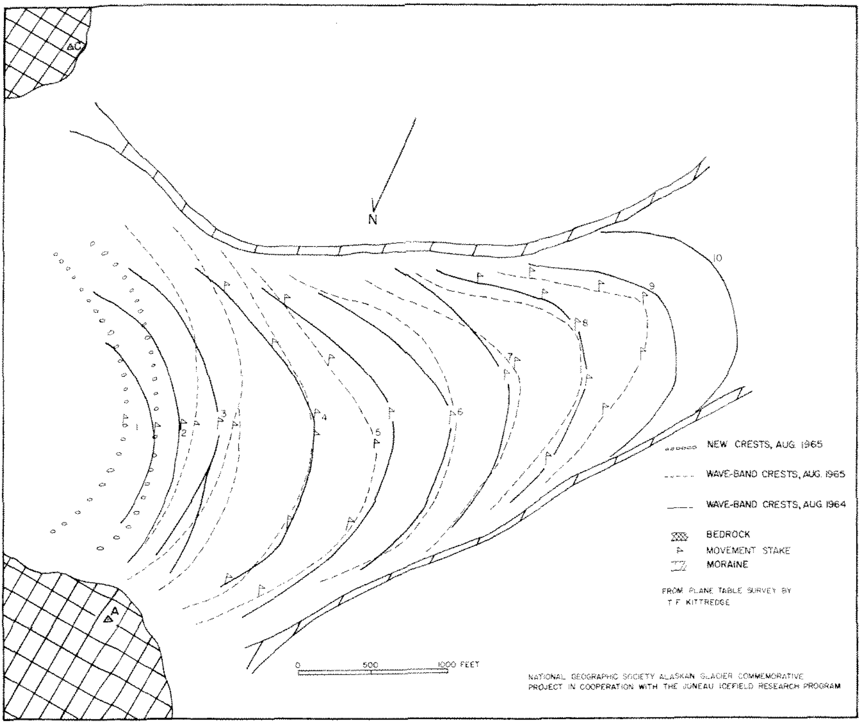

FIG. 18. Superimposed wave-band crests on the Vaughan Lewis Glacier as revealed by successive plane table surveys.

permits a composite chronology for the Quaternary Period to be developed. Although some interpretations are provisional, the chronology worked up in cooperation with Tallman (1975; Miller and Tallman, 1975) is tabulated in table 4. It should be considered as a basis for ready reference and to spur further field work out of which refinements will come.

On the teleconnectional assumption that major glacial phases represent major changes in global climate, the chronologies and terminologies developed for the Taku and Atlin regions are, in order of sequence, compared with chronologies suggested by other workers in the adjoining regions of Alaska, the Yukon, and British Columbia (Karlstrom, 1964; Péwé et al., 1965; Péwé, 1975; Denton and Stuiver, 1967; Bostock, 1966; Hughes et al., 1969; Rutter, 1975). Comparison is also made with other key sectors of the northern tier of states which have been affected by similar rigors of climatic change and by major changes of glacier position during the Pleistocene

Epoch (Madole, Mahaney, and Fahey, 1975; Easterbrook, 1963; Crandell, 1965; Flint, 1971; Terasmae and Dreimanis, 1975; Black, 1975; Frye and Willman, 1973).

Although the evidences cited are mainly morpho-erosional and morpho-stratigraphic, they are abetted by critical time-stratigraphic and soil-stratigraphic information. In the Taku District, the Wisconsinan Age is subdivided into four glacioclimatic stages (substages). These are an *Early Juneau/Atlin Stage* (early or preclassical Wisconsinan), represented by a Greater Mountain Ice-sheet type of glaciation, followed by a distinct and relatively cool intraglacial interval. Then the rebirth of glaciation reached the levels of a subsequent Greater Mountain Ice-sheet phase, finally culminating in the *Gastineau/Sloko Stage,* lasting from perhaps 40,000 to 14,000 years B.P. Following this was a short intraglacial and then the *Douglas/Inklin* and *Salmon Creek/Zohini Stages.* In each of these, place names are cited where diagnostic features and type stratigraphic units have been found.

The latter two are represented by Intermediate and Lesser Mountain Ice-sheet phases of glaciation and on the basis of sequence should be equivalents of the Port Huron and Valders glaciations of the midcontinent chronology. In the Boundary Range, the Salmon Creek/Zohini Stage has at least three distinguishable pulsations termed the King Salmon, Tulsequah, and Sittakanay substages. After this came the high-cirque glaciation (C-4 to C-5 levels) at beginning of the Holocene, with pulsations probably comparable to those of the past few centuries.

In the Atlin Region there are strong correlates of this chronology. Although a similar sequence pertains there are some differences that demand explanation. Here, too, a preclassical Wisconsinan (early Wisconsinan) stage is recognized, with evidence that its thermophysical character was probably quite Polar (Miller, 1975b). Called a *Pre-Atlin I Glaciation* by Tallman (1975) and an *Early Juneau/Atlin* stage by Miller (1972a) its fluctuational character is unknown, though presumably it had many glacial and intraglacial stages. Following this the *Boulder Creek Intraglacial* is identified. This is based on the well-delineated peat horizon in Boulder Creek dated as "older than 40,000 years B.P." (University of Alaska, 1973) by two other samples at greater than 36,000 and 37,000 years B.P. (University of Alaska, 1975; Geochron, 1975), as well as corroborated by a third basal organic till at McKee Creek, also older than 37,000 years B.P. (Geochron, 1975), and by the presence of old weathered surface till at high elevations.

Following this was the *Atlin I Stage,* involving thick Polar to sub-Polar ice, laying down bold lateral moraines at high level and with the lowest till overlying the Boulder Creek peat. Strong weathering on this till connotes a significant intraglacial, termed the *Pine Creek Intraglacial,* because of good exposures found in the gold creeks, such as Pine Creek near the discovery claim at Atlin. As shown in table 4, in the Teslin-Gladys Lake depression there is a correlate of this named by Tallman the *Gladys I Stage.*

Following the *Atlin I/Gladys I Glaciation* was the *Atlin II/Gladys II Glaciation,* considered to be of sub-Polar to sub-Temperate thermo-physical character, on the basis of less steep lateral moraines in the terminal sector of Fourth of July Creek Valley (again see Tallman, 1975). This glaciation is probably a correlate of the Gastineau/Sloko Stage in the Taku District. The absence of an intraglacial in the Gastineau/Sloko Glaciation is explained by the high elevation and provenance of ice in a more maritime region where climatic conditions caused rising freezing levels and hence more likely increased glaciation in some sectors.

A significant "climatic amelioration" (? intraglacial) is indicated by a mild surface weathering of tills following the Atlin II/Gladys II Glaciation. This is believed to be the same mild weathering interface found on top of the lower till of the Gastineau Formation on the coast.

Correlates of the Douglas/Inklin and Salmon Creek/Zohini Stages in the Taku District are suggested to be respectively the *Atlin III Substage* and the combined *Atlin IV and V Substages* . . . or correspondingly the Douglas/Inklin correlate would be the *Gladys III Substage* and the Salmon Creek/Zohini correlate is suggested as the *Gladys IV Substage.*

The final time interval is the Holocene, depicted on the chronology chart (table 4). Here the *Thermal Maximum* is equally well documented on both the maritime and continental flanks of the Boundary Range. The *Neoglacial Stage* in the Taku District is two-phased, with the early phase (2500-1000 B.P.) termed the *Early Mendenhall Stade* (or substage?) and the latest period of intensive mountain and cirque glaciation representing the *Alaskan Little Ice Age Stade* (or substage), ca. 600 B.P. to present. The short, warm interval of the Middle Ages (900 to 1300 A.D.) so well documented by C-14 samples from modern tills of the Davidson Glacier and from the sole of the advancing Taku Glacier, is termed the *Taku Interstadial.*

It is of glacioclimatological significance that the maximum morphogenetic phase of glaciation represented at the beginning of the Holocene and throughout the Little Ice Age was an Extended Icefield type of glaciation. Retracted Icefield Glaciations pertained during intervals of negative mass balance when low and intermediate elevation glaciers of the Stikine and Juneau Icefield took on the forms that we see in these regions today.

REFERENCES

ANDERSON, JAMES H.

1970. A geobotanical study in the Atlin region in northwestern British Columbia and south-central Yukon Territory, 380 pp., *illus*. Ph.D. *thesis*, Michigan State University.

ASHER, ROBERT A.; MILLER, MAYNARD M.; MCCRACKEN, JOHN; and PETRIE, CLARK

1974. An unusual cave in the Lemon Glacier, Alaska. Smithsonian Inst. Center for Short-lived Phenomena Spec. Rpt., 16 pp., illus.

BESCHEL, ROLAND E., and EGAN, CHRISTOPHER P.

1965. Geobotanical investigations of a 16th-century moraine on the Bucher Glacier, Juneau Icefield, Alaska. Proc. 16th Alaska Sci. Conf. AAAS, pp. 114-115.

[1975.] Glacial geology of Wisconsin and upper Michigan. Paper delivered at Quaternary Stratigraphy Conference, York University, Toronto. (In press; Benchmark Papers.)

BOSTOCK, H. S.

1966. Physiography of the Canadian Cordillera, with special reference to the area north of the 55th parallel. Geol. Surv. Canada Mem. 247, 160 pp., illus.

BUGH, JAMES I.

[1972.] Ephemeral supraglacial lakes on the Juneau Icefield, Alaska. *In* "Arctic and Mountain Environments." Proceedings of a symposium at Michigan State University, April 1972. (In press.)

CRANDELL, DWIGHT R.

1965. The glacial history of western Washington and Oregon. *In* "The Quaternary of the United States." Review volume, VII INQUA Congress, pp. 341-353. Princeton University Press.

CROSS, AUREAL T.

1968. Mendenhall Glacier buried forest, Juneau Icefield, Alaska. *In* "Science and the North," Proc. Alaska Sci. Congr. AAAS, Whitehorse, Yukon.

DENTON, GEORGE, and MINZE, STUIVER

1967. Late Pleistocene glacial stratigraphy and chronology, northeastern St. Elias Mountains, Yukon Territory, Canada. Bull. Geol. Soc. Amer., vol. 78, no. 4, pp. 485-510.

DOBAR, WALTER, and MILLER, MAYNARD M.

1972. Heat balance measurements and photometric tests on the Juneau Icefield, 1965. Pt. 9, Tech. Rpt. no. 33, Inst. Water Res., Michigan State Univ., pp. 35-40.

EASTERBROOK, DONALD T.

1963. Late Pleistocene glacial events and relative sea-level changes in northern Puget lowland, Washington. Bull. Geol. Soc. Amer., vol. 74, pp. 1465-1484.

[1975.] Quaternary geology of the Pacific Northwest. Paper delivered at 1975 Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.)

EGAN, CHRISTOPHER P.
1971. Contribution to the Late Neoglacial history of the Lynn Canal and Taku Valley sectors of the Alaska Boundary Range. Ph.D. thesis, Michigan State University, 200 pp., illus.

EGAN, CHRISTOPHER P., and MILLER, MAYNARD M.
1968. The Davidson Glacier buried forest, Chilkat Range, Alaska. Proc. 19th Alaska Sci. Conf. AAAS, Whitehorse, Yukon.

EHRLICH, ROBERT
1970. An exact method for characterization of grain shape. Journ. Sed. Petrol., vol. 40, no. 1, pp. 205-212.

EHRLICH, ROBERT, and DAVIES, DAVID K.
1968. Glacio-fluvial mineralogic gradients in the Mendenhall Glacier valley train. *In* "Science and the North," Proc. 19th Alaska Sci. Conf. AAAS, Whitehorse, Yukon.

FIELD, WILLIAM O., and MILLER, MAYNARD M.
1951. Studies of the Taku Glacier, Alaska. Journ. Geol., vol. 59, no. 6, pp. 622-623.

FLEISHER, JAY
1972. Periglacial features above the névé-line on the Ptarmigan Glacier, Alaska. *In* chap. 19 (pp. 79-81), Tech. Rpt. no. 33, Inst. Water Res., Michigan State Univ., on the hydrological balance of the Lemon Glacier system, Alaska.

FLINT, RICHARD F.
1971. Glacial and Quaternary geology, 500 pp. John Wiley & Sons, New York.

FREERS, THEODORE F.
1965. A structural and morphogenetic investigation of the Vaughan Lewis Glacier and adjacent sectors of the Juneau Icefield, Alaska., 1961-64. M.S. thesis, Michigan State University, 132 pp., illus.

FRYE, JOHN, and WILLMAN, H. B.
1973. Wisconsinan climatic history interpreted from Lake Michigan lake deposits and soils. *In* "The Wisconsinan Stage," Geol. Soc. Amer. Mem. 136, pp. 135-152.

GEOCHRON LABORATORIES (Kruger Enterprises), Cambridge, Massachusetts
1966-1975 radiocarbon dates.

HAVAS, THEODORE
1965. Surface velocity and strain rate measurements in certain Alaskan glaciers. M.S. thesis, Michigan State University, 72 pp., illus.

HEFFERNAN, RICHARD
[1973.] Preliminary gravity survey of the lower Vaughan Lewis-Gilkey glacier system, Juneau Icefield. Unpublished report, JIRP 1973. Foundation for Glacier and Environmental Research, Seattle.

HEUSSER, CALVIN J.
1960. Late-Pleistocene environments of North Pacific North America. Amer. Geogr. Soc. Spec. Publ. 35, 308 pp., illus.

HEUSSER, CALVIN J., and MARCUS, MELVIN G.
1964. Historical variations of Lemon Creek Glacier, Alaska. Journ. Glaciol., vol. 5, no. 37, pp. 71-86.

HUBLEY, RICHARD C.

1957. An analysis of surface energy during the ablation season on Lemon Creek Glacier, Alaska. Trans. Amer. Geophys. Union, vol. 38, no. 1, pp. 68-85.

HUGHES, O. L.; CAMPBELL, R. B.; MULLER, J. E.; and WHEELER, J. O.

1969. Glacial limits and flow patterns, Yukon Territory, south of 65°N. lat. Geol. Surv. Canada Pap. 6834 (rpt. and map).

JONES, VERNON K.

1975. Contributions to the geomorphology and Neoglacial chronology of the Cathedral Glacier system, Atlin Wilderness Park, British Columbia. M.S. thesis, Michigan State University, 180 pp., illus.

KARLSTROM, THOR N. V.

1961. The glacial history of Alaska: Its bearing in paleoclimatic theory. Ann. New York Acad. Sci., vol. 95, art. 1, pp. 290-340.

1964. Quaternary geology of the Kenai Lowland and glacial history of the Cook Inlet region, Alaska. U. S. Geol. Surv. Prof. Pap. 443, 69 pp.

KITTREDGE, THEODORE F.

1967. Formation of wave-ogives below the icefall on the Vaughan Lewis Glacier, Alaska. M.S. thesis, University of Colorado, 53 pp., illus.

LAMONT RADIOCARBON LABORATORY

1952 dates. Columbia University.

LAWRENCE, DONALD B.

1950. Glacier fluctuation for six centuries in southeastern Alaska and its relation to solar activity. Geogr. Rev., vol. 40, no. 2, pp. 191-223, illus.

LEIGHTON, R. BEACH

1951. Ogives of the East Twin Glacier, Alaska—their nature and origin. Journ. Geol., vol. 59, no. 6, pp. 567-589.

LIETZKE, DAVID A.

1972. Soils and soils-vegetation relationships in Pleistocene deposits of the cordillera ice sheets in the Alaska–Canada border region. Abstr. vol., "Arctic and Mountain Environments," Symposium, Michigan State University and Foundation for Glacier and Environmental Research, Seattle.

LIETZKE, DAVID A., and WHITESIDE, EUGENE P.

[1972.] Comparison of spodosols in nunatak soils of the Juneau Icefield and the glacial soils of Michigan. *In* "Arctic and Mountain Environments," Michigan State University in cooperation with Foundation for Glacier and Environmental Research, Seattle. (In press.)

MADOLE, R. F.; MAHANEY, W. C.; and FAHEY, B. D.

[1975.] Glacial geology and late Quaternary soil stratigraphy of the Colorado Front Range. Paper delivered at 1975 Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.)

MILLER, LOUIS R.

1970. Englacial structures of the Vaughan Lewis Icefall and related observations on the Juneau Icefields, Alaska, 1967-69. M.S. thesis, Michigan State University, 72 pp., illus.

MILLER, LOUIS R.; PINCHAK, ALFRED C.; TRABANT, DENNIS; and TRENT, D.
1968. Some 1967 and 1968 measurements on the surface bulges, movement and englacial structures of the Vaughan Lewis Glacier, Alaska. Abstr. Proc. 19th Alaska Sci. Conf., Whitehorse, Yukon.

MILLER, MAYNARD M.
1955. A nomenclature for certain englacial structures. Acta Geographica, vol. 14, pp. 291-299.
1956. Glacial geology and glaciology of the Juneau Icefield, S. E. Alaska, 800 pp., illus. U. S. Office of Naval Research Report, Project ONR-83001.
1961. A distribution study of abandoned cirques in the Alaska–Canada Boundary Range. *In* "Geology of the Arctic," 2 vols., pp. 831-847. University of Toronto Press.
1963. Taku Glacier evaluation study (engineering appraisal of road building plans in a glacier-threatened valley), 245 pp., illus. State of Alaska Department of Highways and U. S. Bureau of Public Roads.
1964. Morphogenetic classification of Pleistocene glaciations in the Alaska–Canada Boundary Range. Proc. Amer. Philos. Soc., vol. 108, no. 3, pp. 247-256.
1967. Alaska's mighty rivers of ice. Nat. Geogr. Mag., vol. 131, no. 2, pp. 194-217, illus.
1968. Theory of wave-ogive formation on the Vaughan Lewis Glacier, Northern Boundary Range, Alaska—B. C. Banff Symposium on Surging Glaciers and Their Geological Effects. National Research Council of Canada.
1969. The Alaskan Glacier Commemorative Project, Phase I. Nat. Geogr. Soc. Res. Rpts., 1964 Projects, pp. 135-152, illus.
1971. The Alaskan Glacier Commemorative Project, Phase II. Nat. Geogr. Soc. Res. Rpts., 1965 Projects, pp. 181-194, illus.
1972a. Pleistocene stratigraphy and the glacio-climatic chronology of the Taku-Atlin region, Alaska–Canada. Proc. 76th Ann. Meet. Michigan Acad. Sci., Arts and Letters (abstr.).
1972b. A principles study of factors affecting the hydrological balance of the Lemon Glacier system and adjacent sectors of the Juneau Icefield, S.E. Alaska, 1965-69. Inst. Water Res. Michigan State Univ. (in cooperation with Foundation for Glacier and Environmental Research). Techn. Rpt. 33, 210 pp., illus.
1973. Alaskan Glacier Commemorative Project, Phase III, 1966: A total systems study of climate-glacier relationships and the stress instability of ice. Nat. Geogr. Soc. Res. Rpts., 1966 Projects, pp. 157-196, illus.
1974. Entropy and self regulation of glaciers in arctic and alpine regions. *In* "Research in Polar and Alpine Geomorphology." Proc. 3d Guelph Univ. Symposium on Geomorphology, 1973, Ontario, Canada, pp. 136-158. Geoscience Abstracts, University of East Anglia, U. K.
[1975a.] Pleistocene erosional and stratigraphic sequences in the Alaska–Canada Boundary Range. Paper presented at 1975 Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.)

[1975b.] Thermo-physical characteristics of glaciers—toward a rational classification. Proc. 1975 International Symposium on Thermal Regime of Glaciers and Ice Sheets, National Research Council of Canada and Simon Fraser University, Vancouver. (In press, Journ. Glaciol.).

MILLER, MAYNARD M., and ANDERSON, JAMES H.

1974a. Alaskan Glacier Commemorative Project, Phase IV: Pleistocene-Holocene sequences in the Alaska–Canada Boundary Range. Nat. Geogr. Soc. Res. Rpts., 1967 Projects, pp. 197-223, illus.

1974b. Out-of-phase Holocene climatic trends in the maritime and continental sectors of the Alaska–Canada Boundary Range. *In* "Quaternary Environments," Proc. Symposium at York University, Geogr. Monogr. no. 5.

MILLER, MAYNARD M.; EGAN, CHRISTOPHER P.; and BESCHEL, ROLAND

1968. Neoglacial climatic chronology from recent radiocarbon and dendrochronological dates in the Alaskan Panhandle. Proc. 19th Alaska Sci. Conf., AAAS, Whitehorse, Yukon.

MILLER, MAYNARD M.; FREERS, THEODORE F.; KITTREDGE, TYLOR F.; and HAVAS, THEODORE

1968. Wave-ogive formation and associated phenomena on the Vaughan Lewis and Gilkey Glaciers, Juneau Icefield, Alaska–B. C. *In* "Science and the North," Proc. 19th Alaska Sci. Conf., AAAS, Whitehorse, Yukon.

MILLER, MAYNARD M., and SWANSTON, DOUGLAS N.

1968. Some comparative glacial geological interpretations in the Alexander Archipelago and the Alaska–Canada Boundary Range. Proc. 19th Alaska Sci. Conf., AAAS, Whitehorse, Yukon.

MILLER, MAYNARD M., and TALLMAN, ANN M.

[1975.] Pleistocene geology of the Atlin Valley and Atlin Provincial Park, British Columbia. *In* "Arctic and Mountain Environments," Michigan State University in cooperation with Foundation for Glacier and Environmental Research, Seattle. (In press.)

MILLER, ROBERT D.

1973. Gastineau Channel formation, a composite glaciomarine deposit near Juneau, Alaska. U. S. Geol. Surv. Bull. 1394-C, 20 pp.

ØSTROM, GUNNAR

[1972.] Height of the glaciation level in northwestern Canada and part of Alaska. *In* "Arctic and Mountain Environments," Michigan State University in cooperation with Foundation for Glacier and Environmental Research, Seattle. (In press.)

PÉWÉ, TROY

[1975.] Quaternary stratigraphy of Alaska. Paper delivered at 1975 Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.) (See also Téwé, T., Quaternary geology of Alaska, U. S. Geol. Surv. Prof. Pap. 835, 145 pp., illus., 1975.)

PÉWÉ, TROY; HOPKINS, DAVID M.; and GIDDINGS, J. L.

1965. The Quaternary geology and archaeology of Alaska. *In* "The Quaternary of the United States," review vol., VII INQUA Congress, pp. 355-373. Princeton University Press.

PINCHAK, ALFRED C.
1968. Avalanche activity on the Vaughan Lewis Icefall, Alaska. Journ. Glaciol., vol. 7, no. 51, pp. 441-448.
1972. Diurnal flow and thermal erosion in supra-glacial streams. Pt. 12, Techn. Rpt. 33, Inst. Water Res. Michigan State Univ., on the hydrological balance of the Lemon Glacier system, pp. 51-56.
1975. The evolution and morphology of supra-glacial streams. *In* "Mountain and Glacier Terrain Study in the Juneau Icefield region, Alaska—Canada." Final Rpt., U. S. Army Res. Office, Foundation for Glacier and Environmental Research monogr. ser., 137 pp., illus.

RUTTER, N. W.
[1975.] Multiple glaciation in the Canadian Rocky Mountains with special emphasis on northwestern British Columbia. Paper delivered at Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.)

SEPPALA, MATTI
1972. Glacier cave observations on Llewellyn Glacier, British Columbia. Acta Geographica, vol. 27, pp. 4-15.
1973. On the formation of small marginal lakes on the Juneau Icefield, S. E. Alaska, USA. Journ. Glaciol., vol. 12, no. 65, pp. 267-273.
1975. Influence of rock jointing on the assymetric form of the Ptarmigan Glacier valley, S. E. Alaska. Bull. Geol. Soc. Finland, vol. 47, 15 pp., illus.

SHAW, RICHARD M; HINZE, WILLIAM J.; and ASHER, ROBERT A.
[1972.] Gravity surveys on the Lemon and Ptarmigan Glaciers. *In* "Arctic and Mountain Environments," Michigan State University Symposium. (In press.)

SWANSTON, DOUGLAS N.
1967. Geology and slope failure in the Maybeso Valley, Prince of Wales Island, S. E. Alaska. Ph.D. thesis, Michigan State University, 206 pp., illus.
1969. A late Pleistocene glacial sequence from Prince of Wales Island, Alaska. Arctic, vol. 32, no. 1, pp. 25-33.
[1972.] Practical analyses of landslide potential in glaciated valleys of southeastern Alaska and similar sub-arctic or alpine regions. *In* "Arctic and Mountain Environments," Michigan State University Symposium. (In press.)

TALLMAN, ANN M.
[1972.] Frost mound and palsa investigations using electrical resistivity. *In* "Arctic and Mountain Environments," Michigan State University Symposium. (In press.)
1975. Glacial and periglacial geomorphology of the Fourth of July Creek Valley, Atlin region, Cassiar District, northwestern British Columbia. Ph.D. thesis, Michigan State University, 150 pp., illus.

TERASMAE, J., and DREIMANIS, A.
[1975.] Quaternary stratigraphy of southern Ontario. Paper presented at Quaternary Stratigraphy Symposium, York University, Toronto. (In press; Benchmark Papers.)

THIEL, EDWARD; LACHAPELLE, EDWARD; and BEHRENDT, J.
1957. Thickness of Lemon Creek Glacier, Alaska, as determined by gravity measurements. Trans. Amer. Geophys. Union, vol. 38, no. 5, pp. 745-749.

TWENHOFEL, WILLIAM S.
1952. Recent shore-line changes along the Pacific coast of Alaska. Amer. Journ. Sci., vol. 250, pp. 503-548.

UNIVERSITY OF ALASKA
1976. 1974 and 1975 dates from Radio Dating Laboratory. Radiocarbon, vol. 18, no. 1.

UNIVERSITY OF MICHIGAN
1967-1970 dates. Radiocarbon Laboratory.

WAAG, CHARLES
1972. Glaciers as models in structural geology. Abstr. with programs, 68th Ann. Meeting Cordilleran section, Geol. Soc. Amer., vol. 4, no. 3, p. 254.
1974. Firn folds—a model for cover rock deformation attendant to basement shortening. Abstr. with programs, 23d Ann. Meeting S. E. section, Geol. Soc. Amer., vol. 6, no. 4, p. 409.
1975. Rhombus and rhomboid parallelogram patterns on glaciers as natural strain indicators. Abstr. with programs, 71st Ann. Meeting Cordilleran section, Geol. Soc. Amer., vol. 7, no. 3, p. 383.

WENDLER, GERD, and STRETEN, NEIL
1969. A short-term heat balance study on a coast range glacier (the Lemon Glacier, Juneau Icefield). Pure and Applied Geophys., vol. 77, no. 6, pp. 68-77.

ZEZONE, CHESTER
1972. Glacio-meteorological parameters affecting the mass balance of the Lemon Glacier, Alaska. M.S. thesis, Michigan State University, 125 pp., illus.

ZWICK, TOM; CADWELL, DONALD; MILLER, MAYNARD M.; and FLEISHER, JAY
1974. Tank and tor topography on peripheral arêtes of the Juneau Icefield, Alaska. Abstract vol., 1974 Quaternary Environments Symposium, York, Toronto, University and Canadian Association of Geographers.

MAYNARD M. MILLER