Quaternary Erosional and Stratigraphic Sequences in the Alaska-Canada Boundary Range

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ABSTRACT

Field studies in the Boundary Range provide a Quaternary history of the northern Cordilleran Ice Sheet. In the Alaskan coastal sector, dense forest cover and mass-wastage have rendered interpretations difficult, but stratigraphic evidence has been obtained from sites exposed by debris avalanches and construction work. An erosional chronology is established from cirque distributions, revealing a seven-fold pattern with a vertical spacing of 220 m. A sequence of glacial berms in trunk valleys is also correlated. Observations in the Alaska Panhandle are discussed from upper Lynn Canal to Taku Inlet and eastward to the border, with comparisons drawn from the less afforested Canadian sector between Tulsequah, B.C. and the northern end of Atlin Lake in the Yukon.

A number of Pleistocene glacial stages are identified, but the relationship is made complex by multiple provenances of ice. Two widespread occurrences of middle and late Wisconsinan till are noted, with evidence of a more extensive drift sheet from the early Wisconsinan. The only indications of pre-Wisconsinan glaciation is given by the presence of truncated high-level ice-scour features. Although the early Wisconsinan glaciation left erratics and well-weathered till sheets on upland surfaces above later glaciation limits, much of this evidence has been destroyed by the intensity of subsequent glacio-climatic events. The youngest tills are most commonly found in the lower valleys and fjord areas of the coast and in the basal sectors of broad valleys inland in the Atlin region. On the coast the uppermost till member is an indurated blue-gray boulder clay diamicton with course rounded clastics, situated at the top of the Gastineau Channel Formation. In places this unit is of marine origin, containing late Wisconsinan *Clinocardium* sp. shells. It rests on an older till with zones of mixed colluvium and glacio-fluvial facies. In the Panhandle, the lower till member has a mild weathering profile and is more compact and unsorted than the overlying unit. It too is a diamicton with included Leda-type shells. At higher levels it correlates with a weathered silty facies containing a few large boulders stratigraphically below but topographically above stained deltaic gravels of Holocene age at the mouth of distributary streams from the Coast Range icefields

Above the boulder silt, to elevations of 160 m, is a marine clay containing shells of *Clinocardium*, *Pectin* and *Macoma* calcarea gemlin species, many of which have been disrupted and broken by subaqueous flow. An apparent correlate of this drift is the surface till in a terrestrial sequence on the hum of interior valleys. The weathering reflects regional intraglacial conditions, designated as the Post-Atlin II Intraglacial in the interior and the Post-Gastineau-Sloko stage on the coast.

Counterparts of the sequence have been found in the Alexander Archipelago as well as in the inland Taku-Tulsequah and Boulder Creek-McKee Creek-Atlin sectors. In the latter a Pine Creek Intraglacial and a Boulder Creek Intraglacial have been extrapulated at some 20,000 and 21,000 years BP, based on weathering and C^{14} evidence. Radiocarbon dates on the lowest till found in a sequence of three distinctive tills near Atlin reveal that a warmer wetter condition persisted in the interior prior to 40,000 years BP. A genetic relationship of the lowest till to oxidized high-level ground moraines near timberline is suggested and further related to paleosol horizons on higher nunataks of the Boundary Range. The youngest till member along the coast also appears to correlate with a two-fold late-Pleistocene moraine and kame terrace complex in the Fourth of July Creek Valley northeast of Atlin. High elevation lacustrine terraces on the shores of Tagish, Atlin and Tesline Lakes and a series of four interior cirque levels spaced some 100 m apart on massifs of the continental flank of the Boundary Range provide further teleconnectional evidence of mid and late Wisconsinan glaciations.

Our palynological and periglacial research provides an interpretation of Holocene glacio-climatic events with the Holocene initiated between 9400 and 10,000 years BP. Evidence here includes an array of peat bogs and relict palsen and peat plateau above 300 feet (900 m) elevation in the interior areas, as well as relict stone rings and other structured ground at and above this level. Some new plasen are developing in the present cooling trend of the Cordilleran Little Ice Age and active permafrost features are found above 5000 feet (1500 m).

The Wisconsinan and Holocene chronology is tabulated with correlations suggested from other areas in North America. In terms of Pleistocene stratigraphy of the Alaska coast, the main morph-erosional and morphostratigraphic sequences, abetted by available time-stratigraphic evidence, are sub-divided into early, middle and late Wisconsinan stages. These form the early Wisconsinan Juneau/Atlin and the mid-Wisconsinan Gastineau/Sloko stages and the late Wisconsinan Douglas/Inklin and Salmon Creek/Zohini stages. Inland the northwestern B.C. counterparts are called the Pre-Atlin I (pre-classical) Wisconsinan stage; the Atlin I/Gladys I stage of middle Wisconsinan and the Atlin II/Gladys II stage of late middle Wisconsinan. On the basis of sequence, the latter two should be equivalents of the Port Huron and Valders glaciations of the mid-continent chronology.

INTRODUCTION

Field studies over the past 20 years of the Juneau Icefield Research Program in the Alaska-Canada Boundary Range provide a basis for outlining the Quaternary history of the northern end of the region affected by the Pleistocene Cordilleran Ice Sheet. Along the coast (Figure 1), dense forest cover and mass wastage make interpretations difficult. By extending the studies inland to the upper Taku River Valley and the Atlin Lake region on the continental flank of the Boundary Range (Figure 2), useful comparisons are drawn from less afforested areas in the Canadian sector. Recourse is also made to the evolution of erosional topography. Phases of glaciation are suggested by study of the nature and spacing of tandem cirques and rock-shouldered berms, as well as by investigation of the distribution of relict and active periglacial features found throughout the region. Discussion begins with consideration of surface deposits in the Taku District near Juneau.

TAKU DISTRICT

A fossil-rich drift sheet, partially of submarine origin, is well exposed as the Gastineau Channel Formation in the Juneau area (Figure 3). At the top are terrestrial sand and gravel deposits from tributary valleys that grade in places into massive slump areas. Recent work extends earlier mapping of these deposits (Miller, 1956, 1963) and reveals that continuing mass wastage has taken place in Neoglacial time. A radiometric date of peat overlying the uppermost member of this formation gives 7,812 $\pm$ 120 years BP, indicating that it is late Pleistocene and early Holocene in age (AU-108). Carbon isotope dating of an avalanche-sheared and colluvium-covered stump (ca 800 C^{14} years BP) on the Glacier Highway, one mile north of Juneau, reveals recent modification of the topmost layer, possibly by earthquake if not by climatic-induced debris avalanches in the 12th century.

In a geologic appraisal of the formation, as part of an earthquake hazard study of Alaskan coastal communities (Miller, 1973), these glacial tills are considered to be diamicton deposits contaminated throughout by berg-rafted boulders (Figure 3). I suggest that the Gastineau Formation be referred to as a slumped, glacio-marine diamicton with its submarine glacial origin emphasized. As such, only the upper surface zone would be affected by berg-rafting in the final phase of deglaciation in a subaqueous environment. It is recognized that the drift sheet has been subjected to varying degrees of flow deformation well after deglaciation. This process is presumed to be largely responsible for the fracturing and further dissemination of embedded fossil shells.

A two-phased nature of the glacio-marine facies is accentuated by differences in weathering on the two main units involved. The weathering is a function of both age and environment (reducing vs oxidizing conditions). Of special interest is that the upper blue-gray unit extends beneath Neoglacial moraines of the Mendenhall Valley up to an elevation of 150 feet (50 m) above mean sea level. The oxidized lower unit is found in fossil-rich zones at elevations of 300 to 500 feet (90-150 m) on the sides of gulleys and valley tributaries in the Gastineau Channel and Lynn Canal sector (Miller, 1956, 1972a). Thus, at least 500 feet (150 m) of sea-level change has taken place since the advent of the Holocene. This is corroborated by Twenhofel (1952) who, on epeirogenic evidence, suggested that at least half of the shoreline changes in this sector of Alaska have been

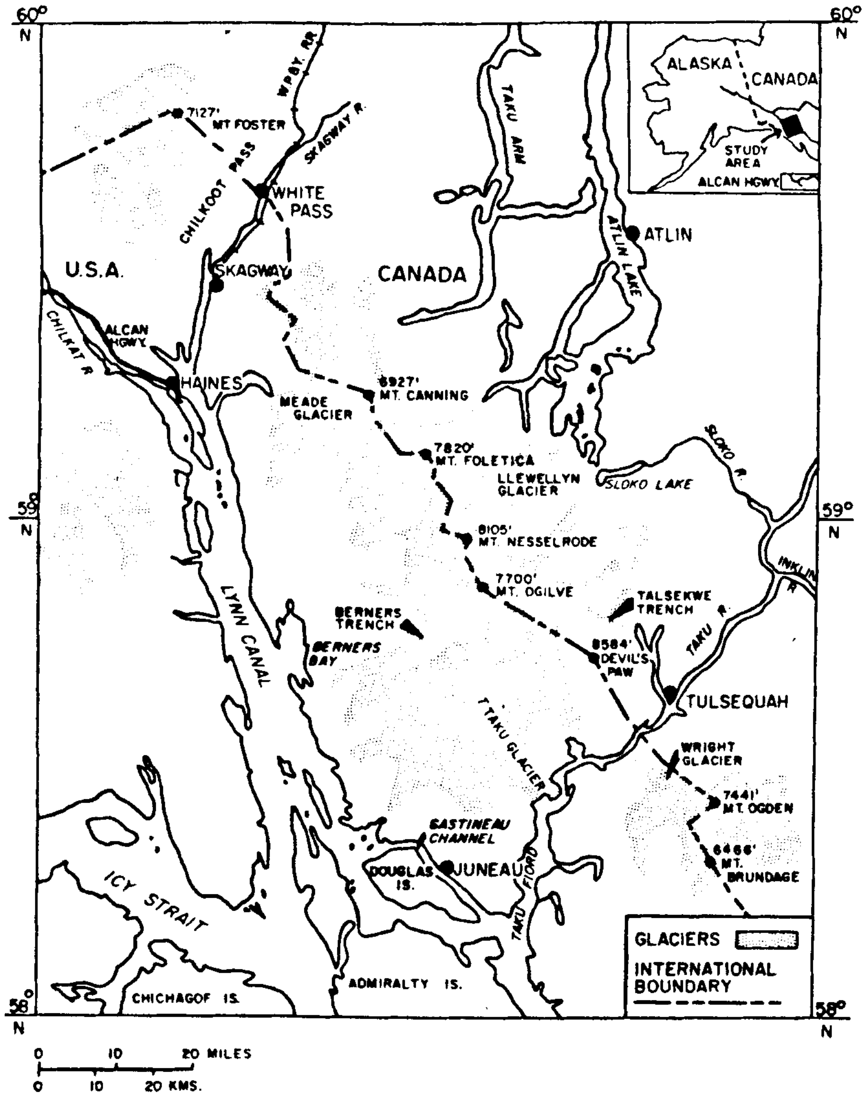

Figure 1 The Northern Boundary Range and the Juneau Icefield, Alaska-Canada. (From Miller and Anderson, in Mahaney, 1974).

due to postglacial rebound.

Counterparts of these two youngest tills are found in the lower parts of other valleys and on the coast in emerged fjord deposits (Miller, 1963). What is apparently a correlate of this two-phased sequence has been found in the Alexander Archipelago (Swanston, 1967, 1969; Miller and Swanston, 1968). Regionally, the top member commonly

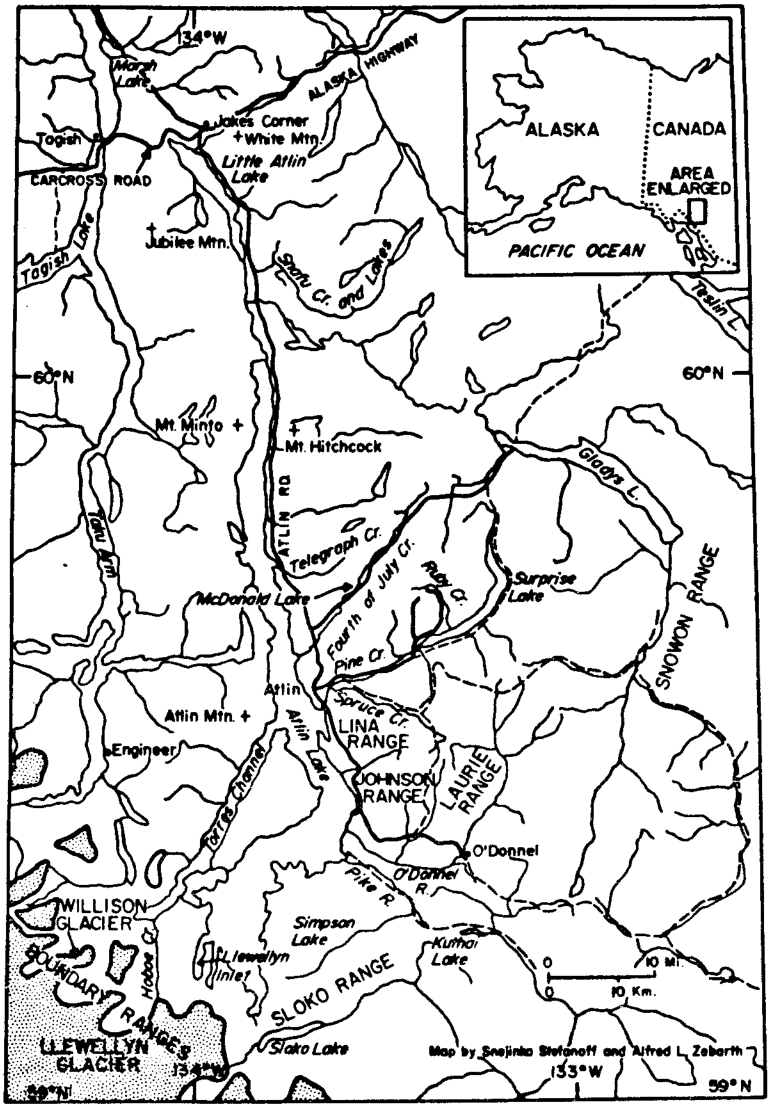

Figure 2 Map of the Atlin Region (modified from Miller and Anderson, in Mahaney, 1974); Copyright National Geographic Society.

occurs as an indurated blue-gray boulder clay diamicton, with coarse clastics. Because of its well distributed boulder and cobble content and much intercalated outwash material, it is essentially subaqueous glacial in origin. Our studies in the Gastineau Channel area reveal it to contain late-Wisconsinan *Clinocardium spp.* shells and to rest on an older till with zones of mixed colluvium and glacio-fluvial

Figure 3 A diamicton of glacio-marine origin in a section of the Gastineau Channel Formation near Juneau, Alaska. An unweathered younger member is above (top background) and an older, weathered unit below (bottom foreground).

facies. The lower segment is a more definite, compact and ill-sorted till with a mild weathering profile. In part 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 (Figure 4). 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 m), is a marine clay containing shells of *Clinocardium, Pectin* and *Macoma* calcarea gemlin species. Many have been disrupted and broken by subaqueous flow. The weathering profile on the basal unit in this drift, and an apparent correlate in the Atlin region (Figure 4), appear to reflect intraglacial conditions. This sequence, when taken as glacially-related and in conjunction with other evidences (such as the regional array of cirques and berms) helps to resolve the Wisconsinan chronology for the Taku District.

Tandem Cirques and Berms

One of the most striking geomorphic features of the coastal 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 (Figure 5). In the Alaskan sector, regardless of structural or lithologic character of the Bedrock, the cirques form a five-fold

Figure 4 A two-phased drift sequence at Boulder Creek in the Atlin Region. Top member is an unweathered, late-Wisconsinan till, with a till-outwash deposit of Middle Wisconsinan age below, overlying a buried peat horizon exhumed in an excavation pit at base. The peat is dated at >31,000 years BP.

sequence (C-1 to C-5) extending up to 5,000 feet in elevation and with a roughly 700-foot (212 m) spacing between elevation zones from 300 to 3,200 feet (about 100 to 1000 m) (Miller, 1961). Above the 3,200-foot (1000 m) level, there are four additional cirque systems (C-6 to C-9), but these are largely ice-filled and with less distinct spacing. They lie between the elevations of 4,000 and 6,200 feet (about 1200 and 1900 m).

On the continental flank of the range, five distinct cirque levels are identified between 4,000 and 6,600 feet (approx. 1210-2000 m). The upper four levels approximate the elevation distribution of the higher clearly identifiable cirque systems on the Juneau Icefield. Comparative distribution reflects a pronounced rise of Pleistocene snowlines inland (Miller and Tallman, 1976).

In Table 1, the mean elevations are given for each cirque system, designated C-1 to C-9. Comparison is also made with interpretations from the Alexander Archipelago in southeastern Alaska (Swanston, 1967)

Table 1. Mean cirque elevations in the boundary range showing correlation with respect to coastal and inland sectors

	Southeastern Alaska Flank of Range		Canadian Continental Flank of Range	
Cirque Level	Juneau Icefield and The Taku District[a] (Miller, 1956, 1961)	Prince of Wales Island (Swanston, 1967)	Fourth of July Creek Region (Tallman, 1975)	Cathedral Range (Jones, 1975) (Miller, 1975a,b)
C1	300 ft. (90m)	0.500 ft. (0-150m)	—	—
C2	1050 ft. (318m)	650-950 ft. (200-290m)	—	—
C3	1800 ft (550m) King Salmon-Port Huron?	1050-1350 ft. (320-410m)	4100 ft. (1249m)	—
C4	2500 ft. (760m) Tulsequah-Early Valders?	1450-1950 ft. (440-590m)	4900 ft. (1494m)	4500 ft. (1370m)
C5	3200 ft. (975m) Sittakanay-Late Valders?	2050-2650 ft. (625-805m)	5500 ft. (1676m)	5100 ft. (1550m)
C6	3900 ft. (1190m) Early Holocene and Neoglacial, including today		6000 ft. (1829m)	5800 ft. (1770m)
C7	4600 ft. (1400m) Thermal Maximum			6500 ft. (1980m)
C8	5500 ft. (1676m) Thermal Maximum and Sangamonian?			
C9	6200 ft. Thermal Maximum and Sangamonian			

[a]with postulated reference to those glacial stages most recently filling these cirques with ice

Figure 5 Abandoned cirques in tandem sequence on southern flank of the Juneau Icefield just west of the Lower Taku Glacier (Figure 1). Note elevation of selected cirques C1 to C5 in Table 1 of text. (U.S. Navy photo, July, 1948).

and in the Atlin, B.C. area on the Cathedral Massif (Jones, 1975) and the Fourth of July Creek Valley (Tallman, 1975). Allied with the cirque distribution is an equally remarkable sequence of valley-in-valley profiles produced by rock-spur benches on cleavers and rock-shouldered berms along the walls of main trunk valleys in the region (Miller, 1963). As shown in Figure 6, these lie at elevation intervals of 200-300 feet (60-90 m) and are reflections of former major phases of valley glaciation. They reveal a five-fold tandem pattern with cyclopean stairs similar to those in the sequences of abandoned cirques. In any attempt to correlate these berm levels with the cirque pattern, the upper berms, of course, integrate with the lower levels of cirques (v. Table 3).

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

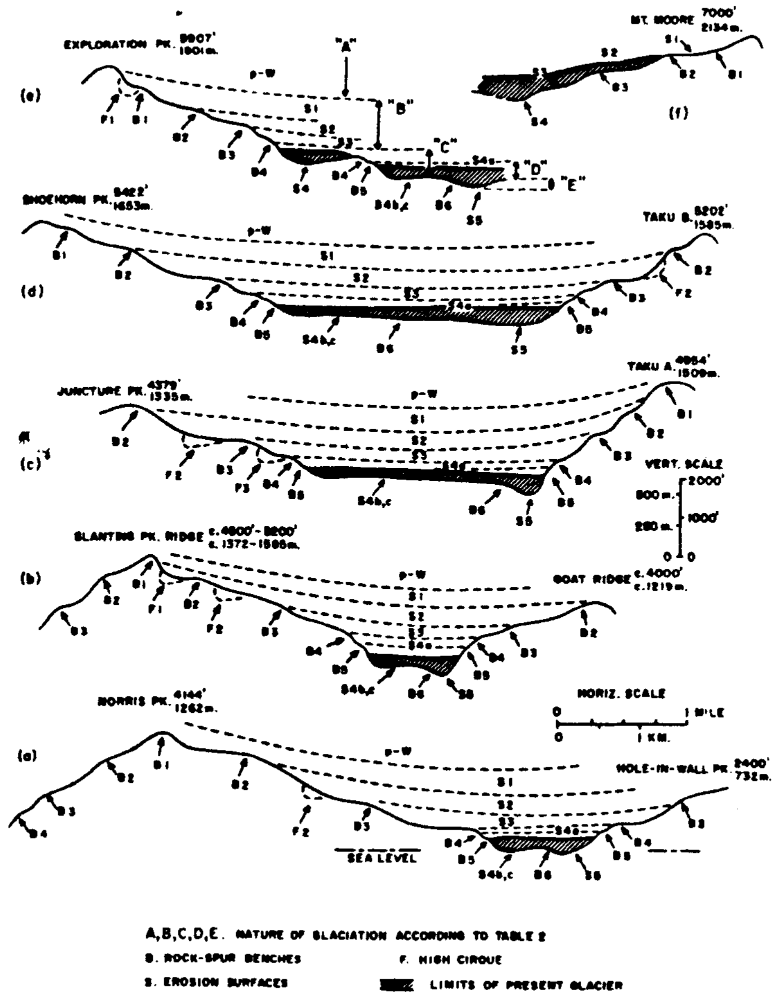

Figure 6 Sketch cross-profiles of valley-in-valley system of Taku Glacier, showing sequence of rock-shouldered erosional berms.

the Wisconsinan. The main development of cirques is attributed to waxing and waning phases, abetted by periglacial processes in intraglacial phases (Miller, 1961). The glacial stage most recently affecting each cirque and berm level is indicated in Table 2.

Periglacial Evidence

Relict stone circles of late Pleistocene and early Holocene age are found at 2,500 to 2,800 feet (760-850 m) elevation on benches

Table 2. Morphogenetic phases of glaciation in the boundary range Alaska - Canada

A. Intermontane "Icecap" Glaciation, with stages (Kerr's Continental Ice-sheet Stage; Davis and Mathews' Phase IV)	Maximum phase, attained only in pre-Wisconsinan. Sub-continental proportion. Generally covering all summits and overriding most, but with radial flow from local centers. Confluent with Laurentide ice-sheet, lobes of which were deflected north and south. Transfluent to west through passes and transrange river gorges.
B. Mountain Ice-sheet Glaciation, with stages. (Kerr's Mountain Ice-sheet Stage; Davis and Mathews' Phase III)	Corresponds to the Wisconsinan maxima. Regional proportion, with localized centers and nunataks protruding through ice-sheet. Confluent mass of mountain and lowland piedmont and valley-filling glaciers extending beyond topographic borders of range. Coalesced with Yukon and Stikine Plateau ice to east derived from centers in Cassiar Range. Distinct stages designated as Greater, Intermediate and Lesser Mountain Ice Sheets.
C. Extended Icefield Glaciation (Kerr's "Intense Alpine" Stage; Davis and Mathews' Phase I)	A stage of district proportion with local centers. Essentially a mountain glaciation with Greater and Lesser (Limited) variations of diffluent lobes: corresponds with maximal and minimal limits of latest Wisconsinan. Confined within fiords and valleys of Boundary Range.
D. Retracted Icefield Glaciation (Kerr's "Alpine" Stage; Davis and Mathews' Phase I)	A sub-stage or stade of local proportion with neve areas restricted to intermediate and high elevations. Corresponds to Neoglacial situation and has Greater and Lesser (Limited) variations. The Greater Retracted Icefield phase represents maximum Little Ice Age pulsations.
E. Limited Icefield Glaciation	Equates to lesser phase of Retracted Icefield condition, typified by intraglacial warm interval of mid-Neoglacial time.
F. Local Glacier Condition	End phase (or initial phase) just before complete disappearance or just after reappearance of ice. Disconnected glaciers or small icefield systems only at the highest elevations. Characterized interglacial periods including Thermal Maximum. Locally an adjunct phase, typified by minor glacierets and high-level cirque glaciers above or outside the main icefields during each of the other stages noted.

Table 3. Glaciation phases during the Wisconsinan according to elevation of cirques and berms with suggested chronologic relationships

Index Cirques (with elevation in feet)	Berm Levels in Main Valleys	Nature and Relative Magnitude of Regional Glaciation[a]	Suggested Chronology with Short Designations	Probable Time Range of Development
C6–3500[b]–3900 (1190m)	B1	Retracted Icefield	Neoglacial	
C5–3200(975m)	B2	Extended Icefield		GIVc C5
C4–2500(760m)	B3	Lesser Mountain Ice-sheet	Late Wisconsinan	GIVb C4
C3–1800	B4	Lesser Mountain Ice-sheet		GIVa C3
C2–1050(318m)	B5	Intermediate Mountain Ice-sheet	Upper Middle Wisconsinan	GIII C2
C1–(embayment stage)	B6	Greater Mountain Ice-sheet	Lower Middle Wisconsin	GII C1
C1–300 (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	

[a]As related to major excavation of cirques at reference level

[b]Level of present semi-permanent névé-line on western side of Juneau Icefield

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, with active patterned ground representing periglacial conditions today occurring only above 4,000 and 5,500 feet respectively in each sector (approx. 1210 and 1670 m). Several examples from Camp 17 near Juneau, from an upland tundra area at 4500 feet (1360 m) in the Atlin region and from the 3,000-foot level (910 m) in the 4th of July Creek Valley area are shown in Figure 7a, b, c, and d.

The existence of relict structures related to exposure of the ground surface in the final retrogressive phase of the Wisconsinan and probably also to early Holocene climatic conditions. This interpretation is based on C^{14} samples of basal organic horizons in bogs (Figures 8a and b) adjacent to areas where these features are found. As will be discussed later, the deglaciation was not much earlier than 9,800 C^{14} years BP.

The abundance of tanks (Figure 9) and tors on maritime ridges of the Coast Range at 3,000 to 4,000 feet (approx. 900-1200 m) and in the Atlin region at 4,500 to 5,200 feet (approx. 1360-1670 m) further testifies to the long-enduring intensity of frost climates in late-Glacial and early Holocene time (Fleisher, 1972; Tallman, 1975). At 4,200-4,400 feet (1270-1330 m) along Cairn Ridge near Lynn Canal (Figure 1), numerous small-sized stone rings (up to 0.5 meter) are found. Most are relict, but a few have reactivated centers relating to a current cooling trend. At higher elevations, especially on flat ridge tops above 7,000 feet (2120 m) on the crestal nunataks of the Juneau Icefield (Figure 7b) and on level surfaces greater than 5,500 feet (1515 m) in elevation in the Atlin sector (Figures 7a, c, and d), active stone circles, stone stripes and other evidences of presently developing patterned ground are found in abundance (Hamelin, 1964; Nelson, 1975). In interior areas at elevations as low as 3,000 feet (910 m) sporadic frozen ground phenomena, such as palsen and ice-cored peat plateaux (Figures 8a and b), also occur. The significance of this anomaly is considered later.

Late Holocene Moraines

In the intermediate-elevation hanging valley of Ptarmigan Glacier, 6 miles east of the Juneau Airport, a sequence of late-Glacial and Holocene moraines, kame and outwash features typifies the maritime sector. Of seven distinct moraines, only the first is pre-Holocene and characterized by stabilized felsenmeers between zones of thick heath matte at the valley entrance.

The four most recent terminal moraines are untruncated and lie in the lower Ptarmigan Valley (Table 4). Lichenometric measurements on these moraines give the most reliable time-stratigraphic information to supplement morphostratigraphic details. This involved statistical sampling of thalli diameters of hundreds of crustose lichens on each moraine using *Placopsis gelida* (growth rate 1 cm per 25 years) and *Rhizocarpon geographicum* (growth rate 1 cm per 800-1000 years) (See, 1974).

In this sequence, the time-span between moraines I, II and III

Figure 7a Relict stone circles on upland tundra plateau at about 4500 ft. (1360 m) in the Atlin Region.

Figure 7b Active felsenmeer surface at 7500 ft. (2270 m) on Mt. Bressler near center of Juneau Icefield, showing crude development of periglacial stripes and other patterned structures in abundant frost-heaved blocks of closely-jointed granodiorite.

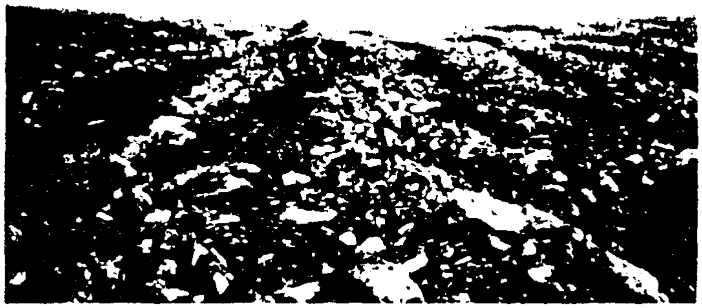

Figure 7c Typical stone stripes.

Figure 7d Active stone garlands at 5400 ft. elevation (1580 m) on the Cathedral Massive, Atlin region.

Figure 8a Palsa (hydrolaccolith) development at 3000 ft. elevation (910 m) in an esker complex in the intermediate 4th of July Creek Valley, Atlin region.

Figure 8b Ice-cored peat plateau at 3500 ft. elevation (1060 m) in palsa bog sector of the upper 4th of July Creek Valley, Atlin region.

Table 4. Neoglacial moraines in Ptarmigan Valley, Juneau Icefield, Alaskan coastal sector

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

Figure 9 Tanks on maritime ridges of the Boundary Range at elevations at and above 3000-4000 ft (900-1200 m). In the Interior Atlin Region, these are found at 4500-5200 ft (1360-1670 m).

appears to fit the 80-90 year cyclicity described for this region (Miller, 1956, 1971, 1972b, 1973). The time spacing between moraines III and IV appears to represent a 20-30 year pulsation. The present ice position is slowly downwasting at the first narrowing of the inner valley. This moraine sequence is prototypical as a base for further comparison with glacier regime changes in other valleys of the Boundary Range.

Erosional Landforms and Morphogenetic Phases of Glaciation

The character of Pleistocene erosional sequences given by berms and cirques has been further discussed in several recent studies (Egan, 1971; Jones, 1975; Miller 1961, 1963; and Tallman, 1975). A description of the morphological nature of the sequential phases of glaciation pertaining to the Cordilleran Pleistocene has been described by Miller (1964) from field evidences in the Boundary Range. The glacio-morphogenetic character and relative magnitudes of these regional phases are noted in Table 2.

Based on the cirque and berm sequence, in Table 3 the elevations of index cirques and the relative positions of main valley berms, both on the coast and in the interior, are related to the magnitude of glaciation phases. Because the cirques and berms are products of multiple erosive cycles during Wisconsinan time, this table further postulates a period of development through a number of glacial stages.

Relative lengths of the arrows do not suggest time magnitudes but represent probable chronologic ranges of activity.

Pleistocene Depositional Stages

A number of Pleistocene stages[1] have been identified in the Boundary Range, but relationships are made complex by the multiple provenances of ice. Both in the coastal Taku District and in the interior Atlin region, two widespread occurrences of middle to late-Wisconsinan tills are reported. These are not to be 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. The only evidences are high-level U-shaped cols and formerly rounded summits, today seen as severely serrated ridges due to the intensity of Wisconsinan degradational processes. 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 climate condition at high elevations that even during intraglacial intervals retarded soil development. The presence of deep and weathered soils on till post-dating the early Wisconsinan maximum, suggests that this glaciation was prior to 50,000 years BP. Recent radiocarbon evidence seems to corroborate this conclusion (v. below and Table 5).

ATLIN DISTRICT, B.C. - YUKON

An inland correlate of the upper member of the Gastineau Channel Formation is found in the Tulsequah and Atlin regions (Figures 1 and 5). Here two upper tills have been well exposed by sluice operations in gold placer streams in the vicinity of Atlin, especially in Spruce, Pine and Boulder Creeks (Miller, 1975a; Tallman, 1975). In McKee Creek, these, plus an underlying older till and associated outwash, are exposed. At the base of the intermediate section in an adit of the Vesnayer Mine, a peat horizon has been dated at $32{,}850 {+2750 \atop -2050}$ C^{14} years BP (GX 4053). On the Harvey claim, the lower till is underlain by gravel beds with an organic layer dated at much greater than 37,000 C^{14} years BP (GX 4054). Radiocarbon dates on intercalated peats in the Boulder Creek valley section also show that organic horizons developed 31,000 (AU-43) and 37,000 (GX 3932) C^{14} years BP. As the older sample from McKee Creek showed no C^{14} activity at all, the suggestion is that its actual age is closer to 50,000 years BP, inferring that in this region there were two periods of amelioration with warmer and wetter conditions persisting in the interior for some time at least prior to 40,000 years BP. More recent C^{14} dates from bogs near the Alaska and Atlin Highways and in the banks of other creeks reveal that final deglaciation in the Atlin region was well underway before 10,000 years BP (Anderson, 1970; Miller, 1975a; Tallman, 1975).

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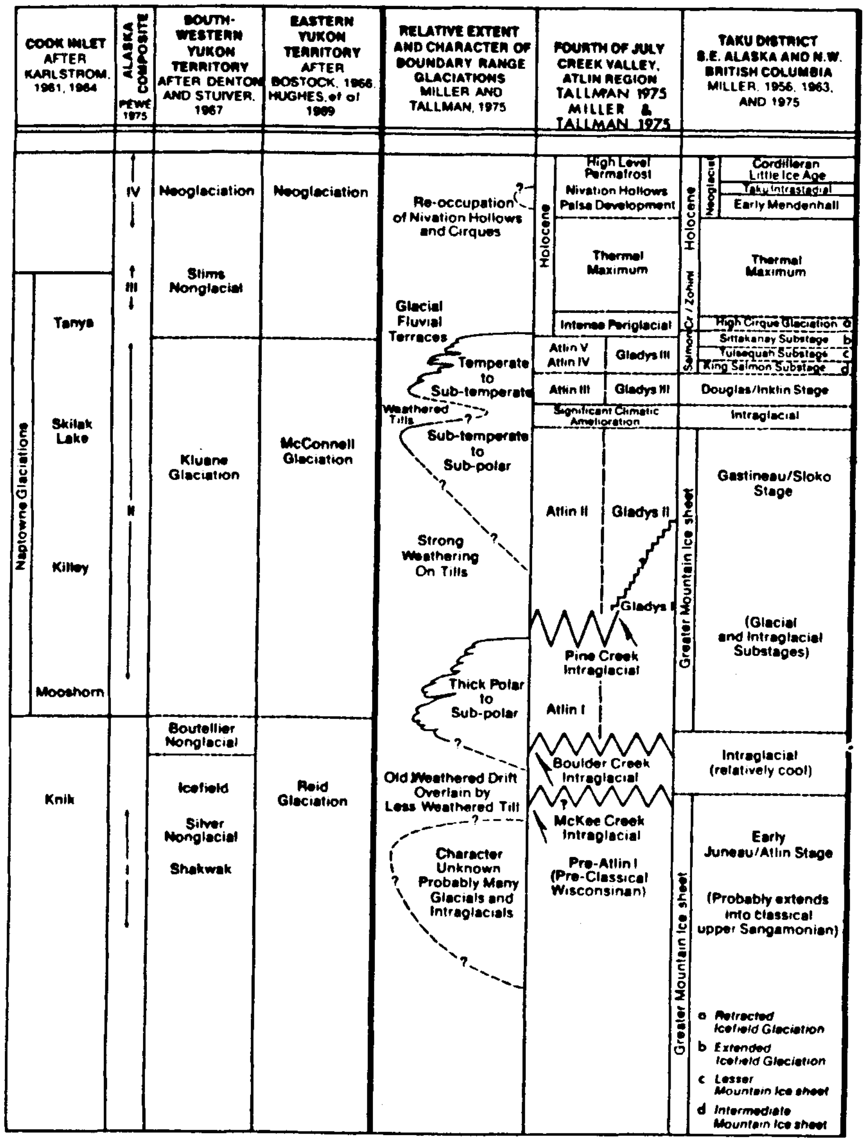
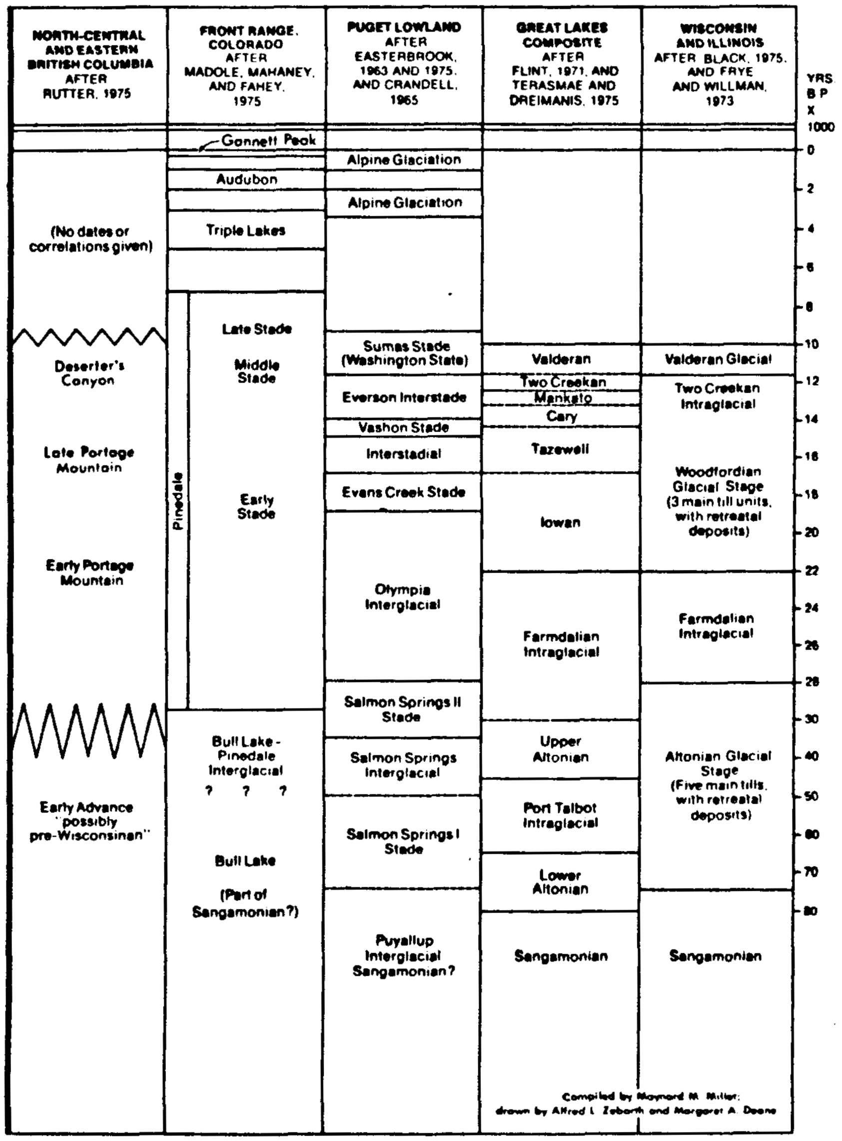
[1] Stages have time-stratigraphic meaning, whereas phases represent glaciation magnitudes. Therefore, a phase is a geometric concept with only morphostratigraphic significance. A glaciation phase may embrace repeated stages.

Table 5. Provisional Wisconsinan and Holocene stratigraphic sequences in the Northern Boundary Range (Alaska-Canada) with suggested correlations with other regions




NORTH-CENTRAL AND EASTERN BRITISH COLUMBIA AFTER RUTTER, 1975
FRONT RANGE, COLORADO 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
YRS. B P X 1000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
40
50
60
70
80
(No dates or correlations given)
Deserter's Canyon
Late Portage Mountain
Early Portage Mountain
Early Advance "possibly pre-Wisconsinan"
Gannett Peak
Audubon
Triple Lakes
Pinedale
Late Stade
Middle Stade
Early Stade
Bull Lake - Pinedale Interglacial
? ? ?
Bull Lake
(Part of Sangamonian?)
Alpine Glaciation
Alpine Glaciation
Sumas Stade (Washington State)
Everson Interstade
Vashon Stade
Interstadial
Evans Creek Stade
Olympia Interglacial
Salmon Springs II Stade
Salmon Springs Interglacial
Salmon Springs I Stade
Puyallup Interglacial Sangamonian?
Valderan
Two Creekan
Mankato
Cary
Tazewell
Iowan
Farmdalian Intraglacial
Upper Altonian
Port Talbot Intraglacial
Lower Altonian
Sangamonian
Valderan Glacial
Two Creekan Intraglacial
Woodfordian Glacial Stage (3 main till units, with retreatal deposits)
Farmdalian Intraglacial
Altonian Glacial Stage (Five main tills, with retreatal deposits)
Sangamonian
Compiled by Maynard M. Miller;
drawn by Alfred L. Zeborth and Margaret A. Deane

The second oldest till in the interior region, represented by a basal till at Boulder and Pine Creeks and by an intermediate till at McKee Creek, is much more altered by weathering than the lower member of the Gastineau Formation. As it is in a drier interior climate, this till is considered to be much older, leaving the lower Gastineau member to correlate with the upper McKee Creek unit (i.e., the youngest Atlin till). There appears to be a genetic relationship between the lower Pine Creek 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). This suggests intraglacial conditions, provisionally termed the Pine Creek Intraglacial in Table 5. Correlation has been found with a two-fold Wisconsina moraine and kame-moraine complex in the intermediate and upper 4th of July Creek Valley, northeast of Atlin (Tallman, 1975). Here northeasterly flowing ice lobes from the Tagish and Atlin Valleys flowed into an interlobate junction near the upper limit of northwesterly flowing ice from the Teslin and Gladys Lakes area. Local nourishment was alos provided via ice from the nearby highlands, as indicated in the sequence of interior cirques noted in Table 1.

In the Atlin Lake region, the diminishment and retreat of Wisconsinan ice was recorded by massive embankment moraines and proglacial valley-mouth deltas in the northern part of the main valley and by esker complexes in highland tributary valleys to the northeast. Following deglaciation was an interval of palsa development, presumably terminated by warmer climate in the Thermal Maximum as discussed below. Some palsen are redeveloping in the present cooling trend, with thick covers of insulating peat allowing bog derived ice cores to be retained at elevations some 2500 feet (760 m) lower than the regional permafrost level (Miller, 1973; Miller and Anderson, 1974; Tallman, 1973).

Key questions are when did the Holocene begin and did it actually end at the beginning of Neoglacial time? The palynological records reported in Miller and Anderson (1974) indicate that for the Neoglacial in the Boundary Range climatic cooling was well under way by about 2,500 years BP. This is corroborated by a C^{14} date of 3090 $\pm$ 170 years BP (AU-108) on the lowest elevation palsa (Figure 10) found at 3,000 feet (900 m) in the 4th of July Creek Valley. Further verification is given by C^{14} dates from postglacial bogs in the Surprise Lake area (Figure 2), where significant climatic change appears to have begun about 2,770 C^{14} years BP (Tallman, 1975). Radiocarbon ages of buried forest remains in the Mendenhall Glacier valley prove that 2,000-2,200 year BP ice was overriding forest beds in coastal valleys. If we assume a 500 to 800 year buildup of glaciers in the Coast Range after the Termal Maximu, a date of 3,000 years BP is reasonable as the effective beginning of Neoglacial time in this part of the North Pacific Cordillera.

As for the early Holocene, samples of basal peat from the higher elevation palsa bogs and peat plateaux in the upper 4th of July Creek Valley (Figures 8a and b) give several C^{14} dates from 9315 $\pm$ 540 to 8050 $\pm$ 430 C^{14} years BP (GX 2694, 2695). These peats represent the initiation of organic growth following deglaciation. The conclusion is corroborated by the 10,000 year BP minimum date of ice recession given by palynological evidence from the north end of Atlin Lake

(Anderson, 1970). In the regional context, we may add to this the C^{14} date of 7812 ± 120 years BP (AU-108) from the basal peat immediately above the younger diamicton till in the Gastineau Formation near Juneau (AU-108). As well, there is a range of 9,000 to 11,000 years BP on peat and logs from the base of muskeg in the Lemon Creek and Montana Creek valleys near Lynn Canal (Heusser, 1960; Miller and Tallman, 1975).

Further testifying to initiation of the Holocene right after final retreat of late-Wisconsinan glaciers from the Atlin region is the truncation of intermediate elevation lateral moraines produced by the latest Wisconsinan Atlin Valley ice along the 3,000-foot (900 m) contour of Atlin Mountain (Figure 2). Here rock glaciers from abandoned cirques at 5,000 to 6,000 feet (1500-1800 m) have flowed down to breach these moraines, revealing that these periglacial features are less than 8,000 years old. A similar situation pertains in a rock glacier valley southeast of Cathedral Glacier (Figure 2).

In view of all this, the Holocene climatic trends show a rather continuous warming from above 10,000 years BP to about 6,000 years BP. This preceded 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, active periglacial processes only affected higher elevation surfaces, while the much retracted Juneau and Stikine Icefields received a new input of accumulation on their crestal neves, as did cirques at elevation levels C-5 and C-6 (Table 1). Today these cirques are some 700 feet (212 m) higher than the lowermost cirques at present filled with ice in the Atlin region. They are also an equivalent elevation above today's permafrost level in these interior highlands.

Neoglaciation and the Cordilleran Little Ice Age

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

The Thermal Maximum was followed by a secular cooling trend as the Arctic Front again moved inland. This was coincident with decreased storminess and drier conditions as well as lowered temperatures on the continental flank of the Range. Concurrently on the coast, relatively cooler and wetter conditions dominated, leading to increased glaciation in maritime sectors of the Juneau and Stikine Icefields. These out-of-phase climatic trends have been documented and their nature explained by Miller and Anderson in recent publications (1974).

That the Neoglacial was two-phased is suggested by the warm interval that produced a retraction between about 1,100 and 700 years BP (Tallman, 1975). The best evidences are the C^{14} dates on overridden trees in the Davidson and Taku Glacier areas (Egan, 1971; Miller, 1973). The Cordilleran Little Ice Age began following this warm interval from A.D. 900 to 1300 and has continued into the present. This is also substantiated by dendrochronological dates obtained on ice-pushed trees on the Bucher Glacier moraines of the Juneau Icefield (Beschel and Egan, 1965).

The time interval from about 3,000 to 900 years BP, representing the early part of Neoglacial time, was as much as 4°F (3°C) cooler than today. This resulted in intensified glacial activity in the high center of the Boundary Range and also renewed periglacial activity in the area of palsas and sporadic permafrost at the 3,000-3,500-foot (900-1150 m) level in the Atlin region. Then came the short and warmer interstadial, persisting until about the end of the 13th century (Miller, *et al.*, 1968). Since the 14th century, the Boundary Range and its peripheral sectors have experienced markedly cooler and wetter conditions with minor fluctuations of an extended icefield condition characterizing the Cordilleran Little Ice Age (Table 2) righ down to the present.

CHRONOLOGY OF THE QUATERNARY

The interpretation of glacial landforms investigated in this region at the northern end of the Pleistocene Cordilleran Ice Sheet permits a provisional chronology for the Quaternary Period to be developed. It is hoped that this chronology, tabulated in Table 5 (Miller and Tallman, 1976), will spur further research, especially because in this region only the evidences for Wisconsinan glaciation are certain.

On the assumption that major glacial phases represent teleconnectional changes in global climate, this chronology of the Taku and Atlin regions is, in order of sequence, compared with chronologies suggested by others in 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, this volume). Comparison is also made with key sectors in the northern tier of states that were affected by similar rigors of climatic change and by major changes of glacier position during the Pleistocene Epoch (Madole *et al.*, this volume; Easterbrook, 1963, this volume; Crandell, 1965; Flint, 1971; Terasmae and Dreimanis, this volume; Black, this volume; Frye and Willman, 1973).

Wisconsinan Sequence

The evidences cited are mainly morpho-erosional and morphostratigraphic, but they are abetted by time-stratigraphic and soil-stratigraphic information. In the Taku District, the Wisconsinan Age subdivides into four glacio-climatic stages. These are an Early Juneau/Atlin Stage (representing a pre-classical Wisconsinan glaciation) characterized by a Greater Mountain Ice-sheet type of glaciation and followed by a distinctly cool intraglacial interval. Then the rebirth of glaciation reached the levels of a subsequent Greater Mountain Ice-sheet phase, culminating in the Gastineau/Sloko Stage, that lasted from at least 30,000 to 14,000 years BP. Following this was a short intraglacial and then the Douglas/Inklin and Salmon Creek/Zohini Glacial Stages. With respect to each event, place names are cited referencing diagnostic features and type stratigraphy (Miller, 1975a).

The latter two glacial stages were represented by Intermediate and Lesser Mountain Ice-sheet pahses and on the order of sequence should equate to the Port Huron and Valders glaciations of the mid-continent chronology. In the Boundary Range, the Salmon Creek/Zohini Stage has at least three distinguishable pulsations termed the King

Salmon, Tulsequah and Sittakanay sub-stages. After this was the high-cirque glaciation (C-4 and C-5 levels) at the beginning of the Holocene, with pulsations probably comparable to those of the Cordilleran Little Ice Age during the past few centuries.

In the Atlin region there are notable correlates of the Taku District chronology. Although a similar sequence pertains, some differences arise that require explanation. Here, too, a pre-classical Wisconsinan (early Wisconsinan) glacial stage is recognized, with evidence that its thermophysical character was initially quite Temperate and then more Polar (Miller, 1975b). Called a Pre-Atlin I Glaciation by Tallman (1975) and an Early Juneau/Atlin Glacial Stage by Miller, the fluctuational character is unknown. Presumably it had several intraglacial stages, one of which is recognized from a much greater than 40,000 years BP compressed peat matte (the date being inferred from the radiocarbon analysis described earlier), found at the Harvey claim at McKee Creek. This stage of uncertain age is indicated in Table 5 as the McKee Creek Intraglacial. Next, after the early Wisconsinan glaciation, the Boulder Creek Intraglacial is identified. This represents the significantly warmer interval recognized from the well-delineated peat horizon in Boulder Creek dated as "older than 31,000 years BP" (AU-59), and by the comparable organic horizon found in the Vesnaver Miner at McKee Creek, interpreted at its lower C^{14} limit as possibly 31,000 C^{14} years BP (GX 4053). Further support to this interpretation is given by the presence of thick mantles of deeply weathered till on tundra benches at high elevation in the Atlin region.

Following the Boulder Creek Intraglacial was the Atlin I Stage of glaciation, with a slightly out-of-phase Gladys I glaciation impinging from the south (Tallman, 1975). These involved thick Polar to sub-Polar ice masses which laid down bold lateral moraines at high level, with the lowest till member overlying the above cited Boulder Creek peat. Strong weathering on the surface of this till connotes a significant intraglacial, referred to as the Pine Creek Intraglacial because of good exposures found in the gold valleys, including Pine Creek near the 1898 discovery claim five miles east of Atlin. As shown in Table 5, there is a correlate of this middle Wisconsinan glaciation in the Teslin-Gladys Lake depression. This has been termed by Tallman the Gladys I Stage, having an uncertain upper limit with respect to dating of the Pine Creek Intraglacial.

After the Atlin I/Gladys I Glaciation there developed the Atlin II/Gladys II Glaciation of late-middle Wisconsinan age, again with separate lobes being somewhat out-of-phase. These are considered to have been of sub-Polar to sub-Temperate thermophysical character in recognition of more subdued lateral moraines in the terminal sectors of the intermediate and upper 4th of July Creek Valleys. This broad regional glaciation is interpreted as the confluent correlate of the Gastineau/Sloko Stage in the Taku District. The absence of an intraglacial in the Gastineau/Sloko Glaciation is explained by high elevation provenance of ice from the more maritime Alaskan sector than was involved in the Canadian Atlin/Gladys source areas...in other words, differential climatic conditions caused by rising freezing levels and increased glaciation in some of the higher areas in the coastal mountains.

Indicating a significant "climatic amelioration" (intraglacial?) is the mild surface weathering of tills produced after the Atlin II/ Gladys II Glaciation. This probably correlates with the same mild weathering interface on top of the lower till of the Gastineau Formation on the coast. Also 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. Correspondingly, the Douglas/Inklin correlate would be the Gladys III Substage and the Salmon Creek/Zohini correlate is suggested as the Gladys IV Substage. All are considered to be of late-Wisconsinan age (Table 5).

Holocene Sequence

In the chronology table, the final time interval is the Holocene. The Thermal Maximum is equally well documented on both the maritime and continental flanks of the Boundary Range (Heusser, 1960; Anderson, 1970). The Neoglacial Stage in the Taku District is two-phased, with the early phase (2500-1200 years BP), termed the Early Mendenhall Stade (or substage), well-delineated by C^{14} dates in the Mendenhall Glacier valley (Miller, 1975a). The latest period of intensive mountain and cirque glaciation representing the Cordilleran (Alaskan) Little Ice Age Stage (or substage) was from about 600 years BP to present. The short, warm interval of the Middle Ages (800 to 1300 A.D.) is so well-documented by organic C^{14} samples from modern tills of the Davidson Glacier and particularly by tree trunk samples from the soles of the Mendenhall and Taku Glaciers that it is termed the Taku Interstadial.

It is of glacio-climatological interest that the Taku Interstade of mid-Neoglacial time was characterized by the Limited Icefield Glaciation phase, noted in Table 2. In contrast, the latest Wisconsinan pulsation limits were represented by the Extended Icefield Glaciation. Following this, the maximum morphogenetic glacial phases at the beginning and also at the end of the Holocene were Greater Retracted Icefield Glaciations which involved significant enlargements of the low-level neves and of glacier lobes stemming from them during the Cordilleran Little Ice Age.

Lesser Retracted Icefield Glaciations pertained during shorter periods of negative mass balance, when down-wasting of the low neves was attended by a significant rise in freezing levels, leading to corresponding expansion of the high neves. In this circumstance, which is similar to conditions that have pertained over the past 30 years, low elevation glaciers produced advancing forms with associated terrain characteristics imprinting the out-of-phase patterns. During the Thermal Maximum, a Limited Icefield Glaciation affected the high central sectors of the Juneau and Stikine Icefields, with Local Glacier Conditions pertaining in much of the peripheral area that is buried by present-day ice.

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