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Institute of Polar Studies
Report No. 18

Glacial Geology of Muir Inlet, Southeast Alaska

by
George M. Haselton
Institute of Polar Studies

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The Ohio State University
Research Foundation
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ABSTRACT

Muir Inlet is in the northeast part of Glacier Bay National Monument in Southeastern Alaska, about 135 kilometers northeast of Juneau. Muir Inlet is part of a large dendritic glacial valley system that has three tidal glaciers. It is flanked on the east, north and west by peaks of the St. Elias Mountains, with maximum elevations of about 2,200 meters. To the south, Muir Inlet is joined by Wachusett and Adams Inlets before it joins Glacier Bay. The region has a maritime climate with cool summers and mild winters. Glaciers in this part of Glacier Bay Monument are downwasting and retreating rapidly, and vegetation is re-establishing itself on the deglaciated areas.

The stratigraphy in Muir Inlet can be divided into six units. From oldest to youngest they are:

(1) The Forest Creek Formation, which is marine clay, silt and sand with abundant marine fossils. Radiocarbon dating of shell material indicates a minimum age of 10,000 ± 220 years B.P.

(2) The Muir Till is the lower, more weathered and indurated of two tills in the section. Wood at the interface between the Forest Creek Formation and Muir Till is 10,400 ± 260 years old. This gives a maximum age for Late Wisconsin ice advance in Muir Inlet.

(3) The Van Horn Formation is composed of three members: a lower gravel, a middle lacustrine member, and an upper gravel. The Van Horn Formation was deposited during the interval from Late Wisconsin ice retreat to the beginning of the Neoglacial advance. Interstadial time lasted about 5,000 years, as determined by the dates of trees in place in this formation. Lake sediments accumulated from about 4,500 years B.P. to about 2,500 years B.P. Late interstadial gravels cover most lake deposits.

(4) The Glacier Bay Till is the upper, relatively unweathered of the two tills in the section. Wood in place that is covered by this till has been used to date the Neoglacial ice advance in the Muir Inlet area. Ice moved westward down Wachusett Inlet and reached the base of the Curtis Hills 2,735 ± 160 years B.P., and ice had thickened and covered the lower two-thirds of White Thunder Ridge near the head of Muir Inlet, 2,120 ± 115 years B.P. Neoglacial ice may have started advancing as early as 3,000 years ago.

Ice may have started retreating from a terminal moraine at Bartlett Cove in the late 1600's or early 1700's. By 1794, it was retreating north of Bartlett Cove. Since then, it has retreated at least 70 km to its present terminus in Muir Inlet. The recession from Icy Strait up Glacier Bay, about 100 km, is the greatest observed anywhere in the world. Trees are re-establishing themselves on the deglaciated terrain and the arms of Muir Inlet are once more filling with outwash. Uplift from ice unloading is known to be in the order of 3.5 cm/yr. Ice movement directions that can be plotted from ground observations (such as striae and crag-and-tail features) and from the study of aerial photographs, show that ice advanced down Muir Inlet from north to south.

From old photographs, it has been determined that between 1890 and 1892 the McBride Remnant area was still covered by nearly 600 meters of ice. Ice continued to downwaste and retreat from 1892 to 1948. From 1948 to 1963 the rate of ice downwasting in the McBride Remnant region averaged 6.6 meters per year. Old photographs show a succession of old marginal drainage channels which can be traced across the McBride Remnant area. Smaller marginal drainage channels mark the former edges of dead ice that existed near the south end of the McBride Remnant region. Ice-cored kames and eskers are scattered throughout the McBride Remnant region. North of Nunatak Knob, crag-and-tail orientations suggest that, after separation from the Muir glacier, the McBride Remnant Glacier reversed its direction of flow. Streamlined glacial forms in the McBride Remnant area are composed of grooved till and gravel ridges and crag-and-tail features. Drumlin-like forms occur near the mouth of Wachusett Inlet.

Minor linear ridges crossing the McBride Remnant area were developed by filling of crevasses, till liberated from shear planes, and possible squeeze-ups into subglacial voids. A smaller network of closed or partly closed ice-disintegration ridges formed around the edges of detached, small ice blocks.

ACKNOWLEDGMENTS

This study of the glacial stratigraphy and ice-contact deposits in the McBride Remnant region of Upper Muir Inlet, carried on during the summers of 1963 and 1964, was supported by National Science Foundation grants GP-1058 and GP-2537, awarded to The Ohio State University Research Foundation (RF Projects 1639 and 1813).

This work is an outgrowth of a study started by Dr. Richard P. Goldthwait, of the Institute of Polar Studies and Chairman of the Geology Department. His work laid the foundation for this stratigraphic study in Muir Inlet. The writer is deeply indebted for his help in planning the project and for encouragement during the study.

The generous logistical support of the U. S. National Park Service aided this investigation in many ways, particularly in transportation to and from the field and in communications. Those whose unfailing support contributed markedly to the success of this field work are: Mr. L. J. Mitchell, Superintendent of Glacier Bay and Sitka National Monuments; Mr. John Fisher, Mr. David Butts, Mr. Kenneth Youmans and Mr. Charles Janda, all of the Park Service Staff at Bartlett Cove. To Captain James Saunders and the crew of the Park Service Motor Vessel "Nunatak" special thanks are given for their help with transportation.

Professor Fred Larsen of Norwich University and Robert Whitelaw of Colby College were of great help during the 1963 field season, as were Mr. Carl Weiman of Yale University and Mr. Kenneth Fitzpatrick of The Ohio State University during the summer of 1964. Mr. David Gordon drafted the line drawings, and Mr. Herbert Merhling assisted the writer in logistical preparation prior to the field work.

The manuscript was reviewed by Dr. R. P. Goldthwait, Dr. Arthur Mirsky, Dr. Richard L. Cameron and Dr. John H. Mercer of the Institute of Polar Studies. Discussion with them and with Dr. Colin Bull and Dr. Sidney E. White of the Institute and Department of Geology is gratefully appreciated. Special thanks are given to Dr. Mirsky for his many hours of help in the final preparation of this report.

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INTRODUCTION

Purpose

The purpose of the 1963 and 1964 field investigations was (1) to study in detail the Pleistocene stratigraphy in the Muir Inlet area as it relates to Late Wisconsin, Interstadial and Neoglacial times; (2) to examine ice contact, subglacial and englacial features, in relation to the deglaciation of this area; and (3) to use radiocarbon dating in determining the late glacial history of this area.

Location

Muir Inlet is in the northeast corner of Glacier Bay National Monument in southeastern Alaska. The region investigated is between latitude 58° 54' and 59° 04' north, and between longitude 136° 00' and 136° 07' west. It is 135 km northwest of Juneau and 40 km southwest of Haines (Fig. 1).

Physiographic Setting

Glacier Bay National Monument comprises an area of about 8,000 km^2. It is flanked on the east by the Chilkat Range and Takinsha Mountains, with maximum elevations of 2,200 meters. These mountains form the drainage divide between the National Monument and Lynn Canal to the east. Névé fields for Muir, McBride and Casement glaciers are on the west side of this range. Elevations decrease southward to an extensive outwash plain that leads into Icy Strait. The western two-thirds of Glacier Bay Monument is composed of deep fjords and high mountains of the Fairweather Range, culminating in the 4,673-meter peak of Mount Fairweather. The most extensive glaciers are in this region; some are advancing and many are tidal. The Fairweather Range decreases in elevation southward and ends at Cross Sound. The Brady Glacier, the largest ice mass in the Monument, is a transection glacier lying along the east side of the Fairweather Range. The southern half of the Monument is less rugged, with low rounded peaks, 600 to 900 meters high. These are covered by dense vegetation, which includes a climax forest with a dense understory. The regions near the head of the tributary inlets of Glacier Bay National Monument are, for the most part, still unvegetated because of recent glacial retreat.

Filling of the inlets by outwash is taking place rapidly, and numerous gravel deltas are the typical modern outwash features. Outwash gravel and sand, in addition to till, can still be seen throughout the Glacier Bay National Monument, but are best developed and preserved within the Muir Inlet area. Fluvial erosion has developed, and is now developing, an intricate, gully pattern on the till and gravel, and will continue as long as remnant ice exists to provide melt-water, and there is a lack of vegetation cover.

The grain of the topography runs northwestward. Recent faults control ice and stream drainage. The region is tectonically unstable with frequent minor earthquakes, and occasional major shocks.

Wildlife is abundant and varied, including mammals such as moose, coyote, porcupine, wolves, wolverine and various species of bear, and many species of sea and land birds. The region abounds in fish. The alpine animals observed include marmot and goat.

Climate

The climate is a maritime West Coast type. Small daily and seasonal temperature variations, high humidity, high fog frequency, considerable cloudiness and precipitation are characteristic. Temperature (Fig. 2) and precipitation (Fig. 3) are controlled largely by topography and proximity to the Pacific Ocean. Summer winds in Muir Inlet are usually light and southeasterly, with infrequent gales. Rapid downslope, or gravity, winds called "Takus" are frequent during some winters.

Summers are cool and winters are mild. The highest temperatures occur in July and August, and the first frost is usually in late August or early September. Pancake ice may form in the upper inlets by early September.

Total rainfall is variable, but annual precipitation varies from 150 to 250 cms (Goldthwait, 1963). Early spring is usually the driest time, and in some springs there is clear and rainless weather for as long as two consecutive weeks. Heavy rains occur during most summers, increasing in abundance by early fall. The summer seasons of 1963 and 1964 were exceptionally dry. Recent measurements by the National Park Service, in gauges near sea level, indicate snowfall is heaviest near sealevel in the western part of Glacier Bay National Monument.

PREVIOUS INVESTIGATIONS

The earliest recorded observation in the Glacier Bay area was made in 1794 by Vancouver (1801). At that time an ice front stretched across Glacier Bay somewhere north of the present National Park Facility at Bartlett Cove (Fig. 1).

John Muir (1893) made several early visits to the Muir Inlet area in 1879, 1880 and 1890. Although he was a naturalist, he spent a great deal of time studying the successive retreat positions of Muir Glacier in the inlet that was later named for him. During the late 1880's the ice front position extended as far south as Oberlin Ridge, which lies directly west of Mount Wright. In 1886, Wright (1887) established the position of the Muir Ice Front south of Adams Inlet (Fig. 1), and also made a study of the motion of Muir Glacier. His results showed that the surface velocity was 18.3 to 21.6 meters per day. Muir's later study in 1895 showed similar figures for the movement. However, the ice front was still retreating.

The first detailed map of Muir Glacier was begun in 1890 by Reid and completed in 1892 (Reid, 1892 and 1896). The terminus was then just south of Adams Inlet, and the area later investigated by the present writer in 1963 and 1964, was overlain by about 600 meters of ice at the time of Reid's study. Reid also indicates that Muir Inlet was entirely filled with gravel when the glaciers were farther back than they are today. This same idea has been more fully substantiated by Goldthwait (1963).

Field (1947, p. 371) states that the Muir Glacier receded about 2,750 meters from 1880 to 1899; yet between 1890 and 1892 there was an advance caused in part by heavier snowfall. Major glacial recession began after 1899, and between that year and 1913, it amounted to 12.8 km (Field, 1947, p. 374).

Tarr and Martin established the position of Muir Glacier in 1911, (Martin, 1913).

Cooper (1923, 1931, 1937) foresaw many of the stratigraphic subtleties that have since been investigated in Muir Inlet. His work showed amazing insight; his field studies were ahead of their time, and many of today's findings substantiate his early predictions. For example, the climax forest which he predicted was buried by ice is still appearing from the retreating ice fronts.

Valuable contributions that deal with ice retreat, vegetation changes, and stratigraphic problems include those of Field (1947), Lawrence (1958), and Goldthwait (1963). Goldthwait (1963), in particular, has helped to clarify the complex glacial history of Muir Inlet by giving a firm base to the glacial chronology through radiocarbon dating of trees, especially those in position of growth. The most recent and thorough study of ice structures on stagnating ice has been made by Taylor (1962). Price's report (1964) on the morphology and development of eskers and drainage changes in front of Casement Glacier is also an important contribution.

GEOLOGIC SETTING

General

Rossman (1963) reports that rocks on the west side of Glacier Bay, east of the Fairweather Range are predominately sedimentary, consisting of thin-bedded and massive limestones and some argillaceous rocks. The total exposed thickness is about 7,930 meters, and the rocks range in age from Late Silurian to Middle Devonian. Paleozoic metasedimentary and sedimentary rocks similar to those on the west side of Glacier Bay, east of the Fairweather Range, are also found on the east side of Glacier Bay, where they are intruded by Jurassic and Cretaceous stocks of diorite and granodiorite. Figure 4 is a generalized geologic map of the Muir Inlet area.

Sedimentary Rocks

The sedimentary section in Glacier Bay Monument includes the Willoughby Limestone at the base, believed to be Late Silurian; the Tidal Formation, a widespread unit of argillaceous rocks; the Pyramid Peak Limestone, also believed to be Late Silurian; the Rendu Formation, a unit composed of thin argillaceous beds and limestone of uncertain age; and the Black Cap Limestone with Middle Devonian marine fossils (Rossman, 1963).

In upper Muir Inlet, the basal rock unit is composed primarily of variegated, highly indurated thin-bedded to thinly laminated argillaceous metasedimentary rocks of Paleozoic age, and minor shale and limestone. Fine structural detail, such as cross-bedding, can be seen, and much of the sequence is calcareous. These basal rocks are folded, faulted and intruded by dikes of probable Cretaceous age. They may possibly be a northward extension of the Rendu Formation.

Twenhofel and others (1946) have subdivided these basal metasedimentary rocks at Nunatak Knob, where they have been intruded by quartz monzonite with which is associated molybdenite and other sulphides. The oldest rock unit is composed of dark blue, fine-grained, thin-bedded limestone and a few shale beds. Overlying this basal limestone is a thick section of hornfels, ranging in color from green to pink to brown, which is differentiated into three units. All are fine-grained, hard, dense, and closely resemble chert; but the lower hornfels unit is thin-bedded and contains a few limey beds, the middle unit is characteristically thin-bedded, and the upper hornfels unit is thick-bedded. A Devonian age has been suggested for this basal unit. Many light and dark-colored dikes cut these Paleozoic metasediments.

Above the basal argillaceous rocks lies the Black Cap Limestone, a thick unit of light-to dark-gray, fossiliferous, marine limestone. This formation is thin-bedded at the base and becomes progressively thicker-bedded upward. In the lower, thin-bedded part of the Black Cap Limestone, fossils are abundant and include corals, bryozoans, trilobites, gastropods, and pelecypods, which probably represent a fauna of Middle Devonian age (Dr. Edwin Kirk, in Rossman, 1963). The upper part of the section is pale gray and is cut by calcite veins. The thickness of the Black Cap Limestone was not measured. The rocks within the formation are mildly folded, strike in a northwesterly direction, and dip gently to steeply to the southeast.

Intrusive Rocks

Stocks of granite, granodiorite, and diorite, the latter being most common, intrude the Paleozoic sediments in Upper Muir Inlet. Idaho Ridge constitutes one of the largest intrusive masses of this kind in the Muir Inlet area. Reed and Coats (1941) believe that the diorite was formed in Late Jurassic or Early Cretaceous time.

Rossman (1963) has reported a small pipelike intrusion of gabbro within the Black Cap Limestone on the east side of Muir Inlet.

The older dikes that have intruded the metasedimentary rocks in the Muir Inlet area are basaltic in nature and have been folded and faulted. More recent intrusive dikes are lighter in color and much greater in number. They have been identified by Twenhofel and others (1946) as andesite porphyry and dacite porphyry. They may be Cretaceous in age.

Near the very head of Muir Inlet, on White Thunder Ridge, Van Horn Ridge, and at the base of Mount Brock, the number of dikes greatly increases. There appear to be as many as three stages of intrusion. At scattered localities around Muir Inlet both quartz veins and pegmatite dikes cut the basal metasediments.

Volcanic Rocks

An intermediate porphyritic volcanic rock, colored various shades of red, crops out with breccia boulders between Red Mountain and Coleman Peak. Based on megascopic field identification this rock is classified as andesite porphyry; albite-twinned, euhedral plagioclase phenocrysts make up about 50 percent of the rock, and quartz phenocrysts make up about 5 percent. The field relationships of this volcanic rock and its extent are still not known.

Ore Minerals

Disseminated sulfide minerals occur in most rock types in the Muir Inlet area. Pyrite occurs as scattered blebs and veinlets within the Black Cap Limestone and in the thin-bedded siliceous argillites. Bornite, chalcopyrite and malachite are associated with the pyrite.

Several pieces of "float" with this mineral assemblage were found along the south side of Van Horn Ridge. Deposits of molybdenite have been found on Nunatak Knob on the east side of Upper Muir Inlet. It occurs in spotty concentrations as thin films or platelets within or parallel to quartz veinlets that cut quartz monzonite.

GLACIAL STRATIGRAPHY

General

The Late Pleistocene stratigraphy in the Muir Inlet area can be subdivided into six units. These are, in ascending order, the Forest Creek Formation, the Muir Till, the lower, middle, and upper units of the Van Horn Formation and the Glacier Bay Till. Figure 5 is a composite stratigraphic section for this area; Figures 6 to 9 are general correlation diagrams of the sections measured around Muir Inlet, and Figure 10 illustrates the detailed stratigraphic relations of these units.

Late Wisconsin Strata

Forest Creek Formation

The Forest Creek Formation, ranging in thickness from 0 to 7 meters, is a blue-gray, thin-bedded, fossiliferous marine clay and silt which appears massive in fresh exposure. Pebbles in the clay and silt suggest that the ice was nearby when these fine clastics were being deposited. At Forest Creek gorge, at 24 meters above present sea level it rests on a striated, crystalline basement composed of porphyritic dike rock. Irregularly on top of the clay and silt are lenses or pods of clean white, fine-to-medium-grained, thin-bedded sand which probably represents a former beach deposit. In places the upper sandy part has been oxidized to a brilliant orange, and the clay below it has a blocky fissile structure. The exposure of the Forest Creek Formation at the gorge is covered in part by recent talus composed of angular boulders from the neighboring slopes to the east. Pebble counts made in the talus material confirm the local nature and proximity of the source.

Another exposure of the Forest Creek Formation was examined near the headwaters of Forest Creek (Fig. 4). Here it overlies an igneous basement rock at 59 meters above present sea level, and is only a few centimeters to a meter in thickness. The formation is directly overlain by the oxidized Muir Till, containing pebbles and boulders, which is believed to be of Late Wisconsin age.

The Forest Creek Formation contains abundant marine fossils, particularly, pelecypods, gastropods, and barnacles. Identification of many of these fossils has been made by Dr. Aurele LaRocque, Department of Geology, The Ohio State University. Gastropods include *Colus spitzbergensis*, *Trichotropis borealis*, and *Neptunea lyrata*. The pelecypods identified are *Trachycardium quadragenarium*, *Mya arenaria*, *Macoma sp.* and *Hiatella artica*. The pecten *Chlamys islandicus* is rather common as are numerous barnacle plates, some of which are found in their holdfast position on pebbles.

The shells in the upper part of the Forest Creek Formation are dated as 10,000 ± 220 years B.P. (Sample I-1303). It is entirely possible that shells at a greater depth may be older. Wood at the interface between the Forest Creek Formation and the overlying oxidized and indurated Muir Till is 10,400 ± 260 years B.P. (Sample I-1615), showing that the area was above sea level at that time.

Muir Till

The Muir Till, the lower of two tills in the section, is named for its several exposures along the east side of Muir Inlet. This lower till is a sandy loam in which cobbles and boulders make up a minor percentage of the coarse constituents. It is underlain by bedrock or by marine clay and silt of the Forest Creek Formation. It is overlain either by fine sand and lacustrine silt or coarse gravel of the Van Horn Formation. The color of the Muir Till contrasts strongly with the dark gray to drab brown, unoxidized younger Glacier Bay Till. The Muir Till is yellowish-brown to reddish-brown in its oxidized parts. The depth of oxidation ranges from 1 to 5 meters. Below the oxidized zone, the till may appear bluish-gray with yellow mottling. In most exposures it is well indurated and has not been leached, except in the exposure in upper Forest Creek.

The Muir Till, crops out at only five localities in Upper Muir Inlet. It lies directly on bedrock in a deep stream gully at the north end of Nunatak Knob, or 1.6 km north of Nunatak Cove (Fig. 4), where it is overlain by sediments which make up the middle member of the Van Horn Formation. It is also overlain by the middle member of the Van Horn Formation at Two-Till Creek, about 0.3 km farther north of Nunatak Knob. Its most northerly exposure is at Orange Creek, about 0.6 km north of Nunatak Knob, where it is directly overlain by the lower member of the Van Horn Formation; the base of the till was not seen here. The only other exposures of Muir Till seen in outcrop, or exposed by trenching, are near the head of Forest Creek. All of the above mentioned localities are on the east side of Upper Muir Inlet. Goldthwait (1963) has reported the existence of similar basal till in Wachusett Inlet.

Only five pebble counts were made in the Muir Till because it cropped out at only five localities (Table I). These limited pebble counts show the following average lithology: 22% diorite, 29% igneous dike rocks, 27% metamorphic rocks, and 22% calcareous rocks. Table I compares the pebble lithology of the Muir Till with those for the Glacier Bay Till and the gravel members of the Van Horn Formation. Figure 11 compares the mechanical analyses of fractions less than 2 mm for these same units. A typical mechanical analysis for the Muir Till shows: 61% sand, 32% silt, and 7% clay (0.002-0.0002 mm).

Five fabric analyses were made on the Muir Till. The fabric at Orange Creek demonstrates that ice moved directly down Muir Inlet during Late Wisconsin time. The fabric maximum at Two-Till Creek was N 50° W, whereas at North Creek it was E-W. West of the Casement Glacier, 0.4 km from the present ice front, the fabric maximum was E-W.

TABLE I

PEBBLE LITHOLOGY OF TILLS AND GRAVELS IN
UPPER MUIR INLET

	Muir Till (5)	Glacier Bay Till (34)	Lower Gravel Member of Van Horn Fm. (13)	Upper Gravel Member of Van Horn Fm. (25)	Average of Both Tills	Average of Both Gravels	Recent Gravels (10)
Diorite and Granite	38%	25%	26%	32%	27%	27%	12%
Metamorphic Rocks	23%	22%	24%	18%	22%	20%	16%
Calcareous Rocks	13%	23%	23%	21%	22%	22%	22%
Dike Rocks	26%	30%	27%	29%	29%	31%	0%
Volcanic Rocks	0%	0%	0%	0%	0%	0%	50%

(5) Numbers in brackets indicate number of pebble counts made.

TABLE II

RADIOCARBON DATES ON WOOD AND SHELLS
UPPER MUIR INLET
(Additional Dates in Goldthwait, 1963)

UNIT NAME	C-14 DATE & NO.	-METERS- Above Base Unit	-METERS- Above Sea Lev.	-METERS- Other	LOCATION	COLLECTOR
Forest Creek Fm. Muir Till	10,400 ± 260 B.P. (I-1615) (wood)	Top Forest Cr. Fm. Base Muir Till	59 meters		Upper Forest Cr.	Haselton
Forest Creek Fm.	10,000 ± 220 B.P. (I-1303) (shells)	5 meters	27 meters		Forest Cr. Gorge	Haselton
Van Horn Formation Lower Member	7,075 ± 250 B.P. (I-58-4) (wood)		9 meters		Westdahl Point	Goldthwait
Lower Member	7,025 ± 270 B.P. (I-58-20) (wood)		6 meters		Nunatak Cove	Goldthwait
Lower Member	6,335 ± 220 B.P. (I-58-1) (wood)		26.5 meters		Nunatak Cove	Goldthwait
Upper Member	2,175 ± 100 B.P. (I-58-9) (wood)		60 meters		Forest Creek	Goldthwait
Upper Member	1,660 ± 110 B.P. (I-1304) (wood)	At base of unit.	114 meters		No. side Nunatak Knob	Haselton
Glacier Bay Till	2,120 ± 115 B.P. (I-1610) (wood)		427 - 488 meters		West Side White Thunder Ridge	Field & Janda
Glacier Bay Till	2,735 ± 160 B.P. (I-59-15)		220 meters		Wachusett Inlet Station 7 Hill	Goldthwait

TABLE II (CONT'D)

UPPER MUIR INLET

RADIOCARBON DATES ABOVE AND BELOW LAKE DEPOSITS

Wood above lake deposits (age)	Elev. above sea level	Wood below lake deposits (age)	Elev. above sea level	Location	Collector
----------	---------	4,775 ± 250 B.P. (I-58-5)	15 meters	Goose Cove Muir Inlet	Goldthwait
2,265 ± 80 B.P. Y-301	Not given	-----------	--------	Goose Cove Muir Inlet	Lawrence
1,765 ± 50 B.P. Y-304	41 meters	------------	--------	Hunter Cove, Muir Inlet*	Lawrence
----------	---------	3,655 ± 100 B.P. (I-59-1 D)	41 meters	Camp Creek Wachusett Inlet	Goldthwait
2,340 ± 115 B.P. (I-1612)	54 meters	4,640 ± 160 B.P. (I-1613)	50 meters	Canyon Creek Muir Inlet	Haselton
----------	---------	4,560 ± 140 B.P. (I-1616)	34 meters	Two Till Creek Muir Inlet	Haselton
2,620 ± 120 B.P. (I-1305)	31 meters	-----------	--------	Forest Creek** Muir Inlet	Haselton

*Sample taken 10 m above lake sediments.

**Sample 1 m below top of lake sediment.

These E-W fabric directions are the result of local topographic control. Pebbles in the till have a gentle northerly dip in the direction from which the ice advanced. In general, the till fabric of the Muir Till (lower till) has a more westerly maximum than that for the Glacier Bay Till (upper till).

A thin, compressed peat layer occurs between the top of the Forest Creek Formation and the base of the Muir Till. This organic material, which could consist of fresh-water or wet-forest plant types, has been dated at 10,400 ± 260 years B.P. (Sample #I-1615) (Table II), which is closely equivalent to Valders time. This dates the death of the plants and suggests a maximum age for ice invasion here.

Van Horn Formation

The Van Horn Formation, named for exposures on the south side of Van Horn Ridge on the east side of upper Muir Inlet, consists of three members. These include a lower and upper gravel unit, and lacustrine deposits which normally occur between the gravel units but which may occur within the gravels. The Van Horn Formation ranges in thickness from 3 to 90 meters. It overlies the Muir Till and is in turn overlain by the younger, unweathered, bouldery Glacier Bay Till (Fig. 12). Although the lower contact relationships are obscured in many areas, the Van Horn Formation overlies bedrock in some exposures. Radiocarbon dates of 7025 ± 270 years B.P. (Sample I- 58-20) and 1765 ± 50 years B.P. (Sample I-304) were obtained from trees in their original position of growth in the lower and upper parts respectively of the Van Horn Formation (Fig. 13 and Table II). This 5000-year interval has been referred to as Hypsithermal time (Goldthwait, 1963, p. 37).

Lower Gravel Member. The lower gravel member ranges in thickness from 0 to 57 meters; it is more highly weathered than the upper gravel member, and has been oxidized to a characteristic yellowish color. This lower member is not seen in all exposures. It overlies the Muir Till immediately south of Canyon Creek, but overlies bedrock on the north side of the Westdahl Hills. It is exposed best between Van Horn Ridge and Goose Cove on the east side of Muir Inlet. One of the thickest exposures is in Canyon Creek midway between Van Horn Ridge and Nunatak Knob (Figs. 4 and 6).

Groundwater percolation is an important factor in the weathering of the lower gravel unit. Weathering in this member is also due in part to overlying organic layers which have released organic acids to the ground water. Support for this is seen by a noticeable increase in the amount of weathering in the pebbles towards the base of an overlying organic layer or forest horizon. However, at one exposure on the north fork of the Muir Remnant River, north of the Westdahl Hills, the lower member was more weathered and oxidized even though organic material was missing in the section. This is probably the result of a longer interval of wetting and drying since the lower gravel was deposited during early Hypsithermal Time, or perhaps of organic material which has since been removed by erosion.

TABLE III

MECHANICAL ANALYSES OF LACUSTRINE DEPOSITS OF VAN HORN FORMATION, UPPER MUIR INLET

Sample Number	Location	Particle Size Distribution in (mm) (Per Cent)									Textural Class
		Very Coarse Sand 1-2 mm	Coarse Sand 1-0.5 mm	Medium Sand 0.5-0.25 mm	Fine Sand 0.25-0.1 mm	Very Fine Sand 0.1-0.05 mm	Total Sands	Silt 0.05-0.002 mm	Clay 0.002 mm	Fine Clay 0.0002 mm	
M-1	North Creek	0.7	1.7	2.3	9.6	20.7	35.0	58.6	6.4	0.8	Silt Loam
M-3	McBride Remnant River	0.0	0.3	0.2	0.2	0.2	0.9	77.2	21.9	2.9	Silt Loam
M-4	Two-Till Creek	0.0	0.0	0.0	0.3	4.8	5.1	92.0	2.9	1.0	Silt
M-5	Westdahl Hills	0.0	0.1	0.0	0.1	0.2	0.4	80.4	19.2	2.6	Silt Loam
M-6	Canyon Creek	0.0	0.1	0.1	0.5	0.3	1.0	83.9	15.1	2.2	Silt Loam
M-2	Nunatak Cove Delta	0.0	0.0	0.1	7.9	46.9	54.9	41.8	3.3	1.3	Sandy Loam

The gravels of the lower member of the Van Horn Formation are poorly sorted and poorly bedded. Some beds or lenses of coarse cross-bedded sand occur in most exposures. The bedding in the gravel is horizontal, or essentially so. In some stream cuts, but not all, the gravels appear to coarsen upward.

Sands and silts are particularly well-developed beneath forest beds which are traceable through the lower gravel from Nunatak Cove to Goose Cove (Fig. 6). Soil developemnt appears to have just started beneath the forest horizons, but apparently was halted by burial.

Lacustrine Member. The lacustrine member of silt, very fine sand and clay is exposed along the shore and in many stream cuts on both sides of Upper Muir Inlet (Fig. 14). These lake sediments range in color from blue-gray to brown to yellow, depending on the amount of sand and the degree of oxidation. This lacustrine member ranges in thickness from a few centimeters to 12 meters, and individual laminae range in thickness from 1 to 5 centimeters. Very fine cross-bedding and occasional ripple marks occur in the coarsest sand layers; this suggests that the lake or lakes may have been shallow. In some exposures, fine cross-bedded sands, which may represent the first stage of lake filling, occur as the uppermost meter of this lacustrine unit. Locally, branches, twigs, or small logs are buried in the lake sediments.

The results of iceberg rafting may be indicated by the occurrence of cobbles and pebbles in lake laminae, especially near the terminus of the McBride Glacier and at an exposure one km upstream from the mouth of the Muir Remnant River. Pockets of till are present in the upper part of the lake silts, where they have been deformed by ice shove. Another example of this kind of deformation also occurs in lake sediments in front of the McBride Glacier (Fig. 15). At many places, folding and overturning have occurred in the silts, whereas the laminae above have been undisturbed. Where gradients were very gentle, much of this deformation may have resulted from density currents.

Laminae in pairs of light and dark layers occur in several exposures. Although these laminae resemble varves, they will be referred to as rhythmites because the length of time represented by each pair is uncertain. Moreover, at Two-Till Creek, about 0.8 km north of Nunatak Knob (Fig. 6), beds of gravel occur within these laminae, and show graded bedding.

Mechanical analyses were made on five lake samples and the results are shown in Table III. All except one of the lacustrine samples are silt loam. For comparison, a separate analysis was made of surface deltaic material which is a sandy loam.

Normally, this lacustrine member lies between the lower and upper gravel members of the Van Horn Formation, but in an exposure on the north side of Nunatak Knob, it rests directly on Muir Till. The most continuous exposure of lake sediments is from Canyon Creek, north of Nunatak Knob, southward to Goose Cove Creek (Fig. 6). North of Nunatak Cove similar lacustrine deposits occur higher in the section near the top of the upper gravel. Along the west side of Muir Inlet, south of Wachusett Inlet, lake silts occur at the top of the upper gravel sequence, in addition to their normal occurrence between the lower and upper gravels (see sections 23 and 24, Fig. 9), suggesting two separate lake deposits.

Radiocarbon dates of pieces of wood from near the top and bottom of these lacustrine sediments at various localities in Muir Inlet are shown in Table II. Additional dates are given in Goldthwait (1963). Most of the wood that has been used to date the lakes was not in its original position of growth, but had been washed into place. The assumption is that the wood was probably buried in these outwash deposits soon after death.

Goldthwait (1963) has suggested that these lakes began to fill simultaneously, perhaps as Muir Inlet became damned by an interstadial ice advance down Glacier Bay. He says (p. 43), "One indication that the latter may have occurred is that all dates just under silts indicate that these lakes existed after 1400 B.C." The radiocarbon dates on collections of wood made most recently by the present writer (Table II) show that these lakes began to form more than 1,000 years prior to 1400 B.C. The span of time for lake development is about 2,300 to 2,500 years, as indicated by the dated wood above and below the lacustrine sediments at Goose Cove and Canyon Creek (Table II). The similarity of radiocarbon dates at or near the top and bottom of the lacustrine deposits at Canyon Creek and at Goose Cove strongly suggests that these deposits here represent part of one large lake. If so, the lake must have had a very undulating bottom in order for the lake deposits to be so widely distributed stratigraphically in the Van Horn Formation.

The alternative is to interpret the occurrence of the lacustrine deposits at different stratigraphic levels as indicating the presence of two or more lakes. Thus, one lake may have developed early in Hypsithermal time and another one near the close; or the valley train deposit which extended down Muir Inlet during Hypsithermal time may have dammed side tributaries causing streams to become impounded. From the stratigraphic evidence in Upper Muir Inlet it is impossible to demonstrate conclusively that a single lake once filled all of Muir Inlet and its tributary arms.

<u>Upper Gravel Member</u>. The upper gravel member, which ranges in thickness from 0 to 75 meters, overlies the lacustrine sediments. This upper unit is crudely-bedded, poorly-sorted, and whitish-grey. Cross-bedded channel sand deposits as much as one meter thick occur throughout the unit (Fig. 16). Locally, pebbles in the gravel exhibit imbricate structure.

At sections 7A and 18 (Fig. 7 and 8) this upper unit contains unusually thick amounts of cross-bedded, well sorted sands. The exposure on the north side of Minnesota Ridge (section 18) exhibits many beds of deformed sands with other beds above still undisturbed. Because the sands here are not directly overlain by till, it is suggested that they were deformed soon after deposition.

The upper gravel member is very similar in lithology to the lower member. Pebble counts indicate that the upper member is richer in diorite than the lower member (Table I), yet this is in part a result of weathering.

Neoglacial Strata: Glacier Bay Till

The Glacier Bay Till was previously called the "Little Ice Age Till," by Goldthwait (1963), Taylor (1962), and Price (1964). The name, Glacier Bay Till, is proposed for the youngest till because it is a rock unit that is exposed not only around Muir Inlet but also throughout the bays and inlets of Glacier Bay National Monument.

The Glacier Bay Till, the highest stratigraphic unit in the Muir Inlet area, rests on the Van Horn Formation (Fig. 12). It is a dark gray boulder-to-pebble-rich loam or sandy loam, is unweathered and unleached, and shows little or no oxidation. It is composed of the re-worked upper gravel member of the Van Horn Formation, and the contact between the two is gradational in some areas. It ranges in thickness from less than one meter to 33 meters, and crops out high up on the sides of ridges and bedrock knobs up to 130 meters above sea level. Streams and slope wash are rapidly removing it from unvegetated slopes.

Twenty-six mechanical analyses were made of the Glacier Bay Till; a typical mechanical analysis in the sand-clay range is as follows: 54% sand, 36% silt, and 10% clay (0.002-0.0002 mm). Its sand content is less than that of the older Muir Till (Fig. 11).

Also, a number of pebble counts were made. It is interesting to note that there is no outstanding difference in the lithology when all pebble counts are averaged for the upper and lower gravels and the upper and lower tills (Table I). When only the lower (Muir) and upper (Glacier Bay) tills are compared, a greater percentage of granitic rocks is seen in the lower till. This reflects large areas of uncovered basement rocks and an abundant talus accumulation which was available for the Late Wisconsin ice.

On a rock knob near the south end of Burroughs Glacier, wood covered by the Glacier Bay Till and therefore overridden by the last ice advance has been dated at 2,735 ± 160 years B.P. (Sample I-59-15) (Goldthwait, 1963). This last ice advance was probably under way several decades before this. Wood from a stump in place, high up on the west side of White Thunder Ridge has been dated at 2,100 ± 115 years B.P. (Sample I-1610). It was collected by W. O. Field and C. V. Janda near Field's photographic station 13. This date indicates thickening of the ice to 500 meters above sea level by this time. Presumably it covered all except the highest peaks; its upper limit, however, has not been determined.

Post-Neoglacial Deposits

The most recent deposits now accumulating in Muir Inlet consist of the thick outwash gravels forming deltas and alluvial fans (Figs. 17 and 18), and a skim of recent gravel that Price (1964, p. 7) reports resting on Hypsithermal gravels or on Littel Ice Age Till (equals Glacier Bay Till).

The outwash gravel and sand is once again rapidly filling the inlets as it did in Hypsithermal time. Small ponds that have developed on the Glacier Bay Till or on gravel of the Van Horn Formation are rapidly filling with clay and silt. Many of these are ice marginal lakes that frequently contain numerous icebergs (Fig. 19).

FEATURES OF NEOGLACIAL ICE

In determining the direction of Neoglacial ice movements, a number of related features were studied. They included till fabric, grooved till, drumlins, crag-and-tail, and striae. Figure 20 is a plot of all these directional features.

Till Fabric

Till fabric analyses were made mostly in the Neoglacial Glacier Bay Till, because there are few Late Wisconsin Muir Till exposures in Muir Inlet. Also, fabric in grooved till ridges in the McBride Remnant area was studied by digging one-meter pits on the crests of several ridges in an attempt to get below the zone of frost disturbance.

Pebbles selected for fabric study had a long axis, ranging from one to 10 cms in length, which generally was three times greater than the short axis. The strike of 100 pebbles was measured to the nearest five degrees and the dip directions were recorded. The average direction of pebble orientation, and the dips to the north indicate that the last ice invasion, which deposited the Glacier Bay Till, moved across the McBride Remnant area from N 25° W (Fig. 21). Fabrics in the Muir Till show a more westerly orientation, with an average direction of N 60° W.

Fabrics also indicate that the direction of Neoglacial ice flow was parallel to ridges of grooved till in the McBride Remnant area, that is, the long axes of pebbles in the till are oriented parallel to the long axes of the ridges. Although the angle of dip of each pebble was not recorded, it was noted that dips were at low angles.

The up-glacier dip suggests it may be the result of movement of basal ice along flow planes that were inclined up-glacier at moderate angles, or the accretion of basal till. The absence of prominent transverse patterns in most fabrics suggests that pebble transport by rolling along long axes was not important.

Toward the eastern edge of the McBride Remnant area, the fabric study shows that ice moved across this sector from a direction N 10° W to N-S. Diverging ice directions occurred along the western base of a group of limestone hills that flank the east side of the McBride Remnant area. Here basal ice must have been diverted around these numerous bedrock knobs.

Streamline Glacial Forms

Grooved Till and Gravel

On the east side of Muir Inlet, extending from McBride Glacier southward to Forest Creek, streamlined till and gravel are molded into the form of narrow elongate ridges. These ridges are also well developed on the west side of Muir Inlet south of Wachusett Inlet. They are drumlin-like (Fig. 22), and even where covered by vegetation these parallel ridges are outlined by the alignment of trees. These ridges were produced by the most recent ice invasion since they are composed of the upper gravel member of the Van Horn Formation and the Glacier Bay Till.

In the McBride Remnant area, these parallel ridges are up to 1.5 km in length and range in height from 2.5 to 23 meters, with an average height of 9.5 meters. The distance between ridges is not regular, but ranges from 30 to 410 meters and averages 180 meters. Ridge forms are long and narrow being from 10 to 50 times their widths.

The ridges appear symmetrical in cross-section, and their form is locally accentuated by meltwater channels which have developed between many of the ridges. Nowhere in the McBride Remnant area was bedrock observed within the ridge forms except along the edge of Muir Inlet.

Drumlins

A small area of grooved till and gravel on the south side of Washusett Inlet has several drumlins, some of which are rock-cored (Fig. 23). Here the forms are steepest on the west, the side from which the ice advanced (Fig. 20). Wright (1957) has suggested that the preferred up-glacier dip of stones at moderate angles is connected with upward rising shear planes in basal ice. He has also suggested that perhaps drumlins are formed by a combination of the movement of debris along shear planes dipping up-glacier, and longitudinal vertical flow layers tending to localize the deposition.

Crag-and-Tail Features

The crag-and-tail features here consist of either a knob of resistant bedrock or more commonly, an individual boulder with an elongated body of till on the lee side. These features are common throughout the McBride Remnant area and their trend, for the most part, parallels that of the grooved till and gravel ridges. Those tails developed in the lee of boulders are commonly 30 to 90 meters in length, one-half to one meter in height, and one to three meters in width (Fig. 24). The tails developed in the lee of bedrock knobs may be as long as one kilometer. Detailed measurements of crag-and-tail features made one kilometer northeast of Nunatak Knob showed that the spacing between the ridges in this one area ranged from 1.5 to 4.5 meters and averaged 2.3 meters.

Just east of Nunatak Knob, near a chain of small ponds, crag-and-tail features suggest a slight convergence of the ice. West of the ponds, these features have a bearing that ranges from N 30° W to N 45° W, whereas east of these ponds, they bear N 30° E to N 23° E. Along the east side of McBride Remnant area crag-and-tail features and grooved till have a north-south bearing which confirms that past ice motion was over the top of Van Horn Ridge and southward into the McBride Remnant area.

These crag-and tail features give the till sheet surface a fluted aspect. It appears as though the tails have been formed by debris that had been pressed up into channel cavities under the ice on the lee sides of the boulders. Dyson (1952) thinks that these parallel ridges represent filling of subglacial tunnels that formed in the lee of boulders. He reasons that the weight of the overlying ice forces material upward into the tunnel, making a ridge. The moraine surface is a cast of the grooved base of the ice. He found that in some cases tunnel formation occurs beneath actively moving ice with a thickness of 60 meters. In 1963, the relict features observed by the present writer at the base of the McBride Remnant ice block were still under 20 meters of ice.

Hoppe and Schytt (1953) have suggested two modes of formation of fluted moraines. First, the surface of the ground moraine can be grooved by the uneven lower surface of the ice or by pebbles and boulders imbedded in the ice. Second, debris can be pressed up into channel cavities within the ice. Their evidence supporting this second idea is that ridges or tails often terminate at a boulder fixed in the surface of the moraine. If the ice is not too thick, long channels in the ice appear in the lee of the boulders owing to the plasticity of the ice. Such conditions have been observed by the present writer in basal ice in the McBride Remnant area, where boulders at the head of tails were always oriented parallel to these tails, and the grooved till ridge on which they were superimposed.

Striae

Striae on Sealers Island bear N 5° W, and on bedrock hills just east of this island most striae have a bearing close to N 10° W (Fig. 20). This reflects the direction from which the main ice stream moved down Muir Inlet. At higher elevations, such as the top of Nunatak Knob, Red Mountain and Van Horn Ridge, striae directions are close to north-south. On the west side of Muir Inlet, just north and west of the Westdahl Hills, striae directions range from N 60° W to N 70° W which demonstrates the convergence of tributary ice feeding into Muir Glacier from the north side of Minnesota Ridge and through a gap near the southern terminus of White Thunder Ridge. Striae directions in the other arms of Muir Inlet reflect past ice convergence.

Thickness of Neoglacial Ice

Early photographs give a basis for estimating minimum thickness of Neoglacial ice. Between 1890 and 1892 the McBride Remnant area was still covered by about 450 to 600 meters of ice (Reid, 1892). Striations made by Neoglacial ice are on the summit of Red Mountain at an altitude of 1,220 meters, indicating that Neoglacial ice reached altitudes at least as high as this in the Muir Inlet area.

Nunatak Knob first appeared through the ice between 1910 and 1911 (W. O. Field, oral communication). At this time there was still approximately 300 meters of ice over the McBride Remnant area. From photographs taken in 1935 there appears to have been about 150 meters of ice over the McBride Remnant area. Even in the early 1930's ice from Coleman Cirque was feeding this area and the ice from Muir Inlet extended over this part of the valley.

Sometime between 1935 and 1941 the Muir Glacier ice separated from the ice over the McBride Remnant area. Once this separation had taken place, shrinkage and downwasting were accelerated. By 1950 residual ice covered only about half of the McBride Remnant area, and by this time, was about 30 to 60 meters thick. By the fall of 1964 only small blocks of ice covered by gravel and ablation moraine were left. The largest of these blocks was from 240 to 300 meters long, about 90 meters wide and 12 meters thick (Fig. 25).

The dimensions of McBride Remnant ice block, when measured by pacing by Dr. Richard P. Goldthwait during the summer of 1965, was only 110 m long, 15 m wide, and about 3 m thick (Goldthwait, oral communication).

A comparison of plane table measurements of grooved till forms, just east of Nunatak Knob, with U. S. Geological Survey stereo-mapping on the ice in 1948 indicates that ice over these grooved till ridges in 1948 was 50 to 60 meters thick.

DEGLACIATION OF THE McBRIDE REMNANT AREA

Wasting of McBride Remnant Ice

Using old photographs, Price (1964) plotted the 1919 position of the Casement Glacier. It was then about 0.8 km east of Muir Inlet, but Muir Glacier was still connected with the expanded piedmont lobe of Casement Glacier, and the tidal terminus of Muir Glacier was at what is now Sealers Island (Fig. 26). Between 1919 and 1928, Muir and Casement glaciers separated.

The ice that covered the McBride Remnant area became separated from the main Muir Inlet valley glacier sometime between 1935 and 1941. Photographs taken in 1941 indicate that the McBride Remnant area was still covered by ice except for a narrow strip along its western edge near Muir Inlet (Fig. 26); at that time it contained about 19 km^2 of ice. By 1948, the ice cover had been reduced to about 7.5 km^2 (Fig. 27). When the writer first visited the area in 1963, only about 1 km^2 of ice remained along the eastern edge of the McBride Remnant area (Fig. 28), and the ice was protected by a blanket of ablation till and gravel.

Rate of Ice Wastage

In 1948 the highest elevation on the McBride Remnant Glacier was about 180 meters above sea level. In 1963, the maximum elevation in the McBride Remnant ice, as determined by plane table mapping, was 84 meters above sea level. This represents 96 meters of downwasting in 15 years, or 6.4 meters per year.

Lateral wastage was determined by measuring, with tape and alidade, distances to key boulders on the McBride Remnant ice. During the summer of 1963, the average amount of lateral wasting was 0.21 meter a day and the maximum amount was 1.0 meter a day. Measurements were also made of lateral wasting between Flag #2 and the ice edge (Fig. 25). The average lateral melting at this locality was 0.93 meter a day with a maximum of 1.2 meters a day and a minimum of 0.12 meter a day.

Lateral ice wastage in this area has been accelerated by streams flowing along the edge of the residual ice blocks. Ponding of meltwater along the sides of the ice has caused undermining, which is followed by calving.

Drainage Changes During Deglaciation

From about 1930 to 1935 Goose Creek, south of Nunatak Cove, was the principal meltwater channel at the south end of the McBride Remnant ice. (Fig. 17). Sometime between 1935 and 1941, most of the meltwater from the south end of the McBride Remnant ice began to flow westward into Nunatak Cove via a new channel north of Goose Creek. By 1948, McBride

Remnant Creek, a stream a little farther north that still empties into Nunatak Cove today, had become the principal new outlet for meltwater along the southern boundary of the McBride Remnant ice.

About 1937, two large meltwater streams flowed west, draining the western and northern parts of the McBride Remnant ice. In this report, these streams are named Canyon Creek and Van Horn Creek (Fig. 6). Both of these creeks served as major drainage channels until the middle 1950's. Groundwater still drains into these old channels, but the volume is small. Compared to the rest of the stream cuts in this area, Canyon Creek is the most impressive, with a deeply eroded channel. In 1958, there was a lake at the head of this meltwater channel (Goldthwait, oral communication).

By the late 1950's, practically all of the McBride Remnant drainage was carried southward by McBride Remnant Creek. Today this is the principal stream in this area. It is nourished mainly by snow melt and residual ice that is left in Coleman Cirque.

Marginal Drainage Channels

The successive positions of marginal drainage channels quite clearly cut across the grooved till and gravel ridges near the south end of the McBride Remnant area. These channels follow the outline of the former ice, but do not necessarily mark the exact boundary of the ice edge. The channels are not necessarily annual as two or more channels may form at or close to the ice edge in one summer season, as seen by the writer in 1960 when he was a field assistant working on the Burroughs Glacier near the head of Wachusett Inlet.

Eskers

During downwasting of the McBride Remnant ice, one englacial esker developed near the present position of Coleman Creek. This esker is ice-cored throughout its length and is composed of stratified sand and rounded gravel. It apparently formed near the base of the residual ice when there was little or no motion; Figure 29 shows an esker forming under these conditions today. Other very small eskers are scattered across the McBride Remnant area. Some of them cross the tops of till ridges, and one terminates against a ridge of stratified drift, which undoubtedly represents a crevasse filling. These small eskers ranged from 90 to 120 meters in length, from 1 to 3 meters in width, and from 1 to 2 meters in height.

Two large complex esker systems exist in front of the Casement Glacier. Details of the size, shape and origin of this system are discussed by Price (1964).

Kames

Groups of small, mound-like hills composed of thin-bedded, well sorted sands are scattered throughout the eastern and southeastern parts of the McBride Remnant area. These are kames, many of which developed as a result of small deltas or fans that built outward against residual ice. They can be seen in the process of formation in photographs taken from the summit of Nunatak Knob in 1950. Deep trenching revealed that many of these are still ice-cored.

Residual Movement of Remnant Ice

After its separation from the Muir Glacier, the McBride Remnant ice continued to have a slight residual flow until thinning prohibited further movement. Evidence for this residual movement is seen in the reverse direction of crag-and-tail features at the north end of Nunatak Knob (Fig. 17). From the photographic record, it is known that ice at this place moved from northwest to southeast, yet the ridges extending outward from individual diorite boulders demonstrate that ice later moved from the southeast toward the west and northwest, following the steep gradient toward Muir Inlet. Such changes in flow directions of stagnant ice masses also occur around the Burroughs Glacier north of Wachusett Inlet (Taylor, 1962).

MINOR RIDGES

Throughout the McBride Remnant area a system of long, narrow transverse ridges is well developed. Few of these ridges exceed a height of 2 meters. These ridges, which are composed mostly of till, can be differentiated genetically into crevasse fillings (Fig. 30), shear plane ridges (Fig. 31), and ice-disintegration ridges (Fig. 32).

Crevasse Fillings

There is a network of crevasse-filling ridges north and east of Nunatak Knob. A comparison of these crevasse ridge patterns with the crevasse pattern in the McBride Remnant Glacier seen on the 1948 aerial photographs shows a strong similarity between the two. Figure 33 is a plane table map diagrammatically showing part of the network pattern of these crevasse-filling ridges.

There are two sets of ridges, one set overlying the other, so that the upper set crosses the lower at angles varying from 90 degrees to 10 degrees (Fig. 30). Both sets of ridges lie on top of crag-and-tail and grooved till features.

Toward the northeast corner of the McBride Remnant area, ridges are higher and can be traced more continuously. This is partly due to the youth of the ridges here, as they have emerged from the ice only within the last few years. Most of these minor ridges are composed of till having the same composition as the ground moraine, and boulders are commonly encountered in many ridges. Some ridges are composed of stratified sand and gravel, which supports an origin by crevasse filling.

Where erosion has not dissected them, the ridges can be traced continuously for as much as 0.8 km. The highest ridges range from 3.6 to 8.0 meters, but most are only about one meter in height. Their width varies from a few centimeters up to nine meters.

The average strike of the ridges is N 70° E, but they range from N 40° E to E-W. Distances between the ridges are quite variable, ranging from three meters up to a maximum of 150 meters, but the average is 24 meters.

In aerial photographs, crevasse-filling ridges now in the process of formation can be seen along the east edge of the Muir Glacier. A well developed pattern of criss-cross ridges exists in front of the rapidly retreating Plateau Glacier near the head of Wachusett Inlet (Fig. 34). Similar ridges formed from crevasse fillings are now appearing from within the ice along the margin of the Plateau Glacier, and it is assumed that the ridges in front of the ice terminus were also formed by material that was dropped or deposited in crevasses.

Shear Plane Ridges

Other ridges in the McBride Remnant area have developed as a result of material being released from steeply-dipping shear planes in remnant ice blocks. Some of these ridges can be traced to the edge of the residual ice and can be seen continuing to develop as till is released from shear planes during melting (Fig. 35).

Many of the shear plane ridges that were observed in the process of formation in the field are asymmetrical when formed. They are steep on the south or lee side with the angle of repose varying from 50 to 60 degrees (Fig. 31), and are gentle on the north or stoss side with the angle varying from 10 to 12 degrees. During melting, the material in the shear planes absorbs more heat and in time a recess develops along the plane of the shear. Meltwater flowing down the shear trace also enlarges this re-entrant. Material released from the shear plane moves down the plane in this re-entrant or "shoot" following the angle of the shear plane. The shear plane becomes the gentle or stoss slope for the material released. The overhanging ice wall above the shear plane acts as a barrier as material is released from the shear plane, causing it to turn, roll, slide, or flow down the steeper lee slope. The surface of these shear plane ridges is generally covered by a blanket of angular, ablation boulders.

Ice-Disintegration Ridges

Small, circular, oval or irregular ridges have formed around isolated ice blocks which were separated from the main mass of dead ice in the McBride Remnant area (Fig. 32). These ridges were best developed around ice blocks that were heavily laden with ablation debris, which slides off the blocks in all directions and accumulates in such quantities at the base of the ice blocks, that the ridge form is preserved after the ice blocks melt. Where these ridges do not completely close, it is because ablation debris was incompletely deposited around the margins of the ice blocks, or because of post-deposition erosion. In some cases, the ridges may be pentagonal or hexagonal in outline. Irregularities in form reflect the shape or outline of the ice block around which they were deposited. In one small area in the central part of the McBride Till plain, the ice-disintegration ridges are concentric and occupied a shallow depression.

These ice-disintegration ridges are not as conspicuous as the linear ridges that have been described above. These ridges seldom exceed one meter in height, and if they do, they are ice-cored or lie against the side of the ice block around which they are forming.

For the most part, the closed ridges consist of angular boulders with occasional patches of finer material where till has flowed down the side of an ice block (Fig. 32). Small gravel ridges forming along the flanks of ice-cored eskers have somewhat similar characteristics, but they are linear rather than circular in form.

Theories for Ridge Development

Work by Hoppe (1952) has attempted to demonstrate that dead ice features are the result of basal till that has been squeezed into openings on the underside of the ice. His conclusions are:

(1) The till does not show any evidence of washing, as would be the case with superglacial material that has fallen from the ice surface or from side walls into an open crevasse.

(2) The till is compact and has all the characteristics of basal till.

(3) The till contains pebbles and cobbles that show a distinct fabric with their long axes oriented at right angles to the long dimension of the ridges. He regards this fabric as a primary characteristic caused by the lateral pressure of the ice blocks which squeezed the till up into the "basal crevasse".

All of these factors hold for many of the ridges that have been examined in the McBride Remnant area. In places, the till in the shear planes has a fabric that is normal to the trend of the ridges. Upon its release from these shear planes, most of the material moves out as a till flow (mud flow), resulting in a secondary fabric which may be parallel to the trend of the ridge. The till itself is so water-saturated that a man crossing it sinks in as far as his knees. Certainly Hoppe's "squeeze-up" hypothesis could account for the compact character of the till in these ridges.

Gravenor and Kupsch (1959) have suggested that, once the ice has acquired a thin layer of ablation debris on its surface, further downwasting becomes very slow and the clayey nature of the till might be preserved. They have suggested also that the compactness of the till can be the result, not of squeezing, but of the till's original texture, structure and fabric. They have stated, however, that the character of till in ridges or in hummocky moraine cannot be used as strong evidence in determining the origin of the feature.

Harrison (1957) stated that the bulk of till in ground moraine originated as englacial material and was deposited by debris which was slowly melting from the basal zones in the ice.

GLACIAL HISTORY

From the study of the glacial stratigraphy in the Muir Inlet area, a sequence of glacial events has been determined. No evidence was found for any glaciation older than Late Wisconsin. The glacial history from Late Wisconsin time to the present can be enumerated as discussed below.

Prior to 10,400 years B.P. (Sample I-1615), glaciers in the Muir Inlet area had retreated at least as far back as where they are today. The outwash, which must have accompanied this temporary glacial recession, may have been mostly removed by subsequent glacial advance and erosion. If this Late Wisconsin gravel is present it was not recognized in the stratigraphic exposures. During the Late Wisconsin, while the ice was as far back as it is today, marine deposits, the Forest Creek Formation, accumulated in Muir Inlet.

About 10,400 years B.P. ice advanced down Muir Inlet, but the thickness of the ice is not known, nor how far it advanced. This Late Wisconsin ice which deposited the Muir Till, may have covered all but the higher peaks in the Muir Inlet area.

Following this Late Wisconsin advance, the climate became warmer and during this interstadial time, the glaciers retreated farther up Muir Inlet than they are today. This is demonstrated because interstadial gravels and stumps are still appearing from beneath present day glaciers.

During this warm interval, or Hypsithermal time, Muir Inlet and its tributary arms were filled with outwash. This outwash which buried much of the mature forest that had been developing since the time of Late Wisconsin ice retreat, includes the lower and upper gravel members of the Van Horn Formation.

From radiocarbon dates of trees in place, Goldthwait (1963) has shown that Muir Inlet and its tributary arms were filled to sea level about 7,000 years B.P. (Sample I-58-20). He was also able to demonstrate that this outwash had reached 60 meters above sea level approximately 2,200 years B.P. (Sample I-38-9). Plotting radiocarbon dates from samples taken from trees in place in the outwash gravels, against their elevation, he calculated the rate of inlet filling. He found that sediments accumulated in Muir Inlet at an average rate of 1.4 cm a year, with a minimum rate of 1.0 cm and a maximum of 5 cm a year.

Most of the wood in the outwash gravels consists of stumps of mature hemlock and spruce. The majority were not overridden by ice, but were buried in place by gravel and sand. The root systems can be seen extending through a forest mat of needles and twigs into a soil which had developed before burial.

Oscillations of valley glaciers may have taken place during this interstadial interval, but if so, the tills that accompanied such advances have not been detected within the outwash gravels, or have been so completely reworked that they have lost their original character.

The span of Hypsithermal time (interstadial) was about 5,000 years, or from about 7,500 years ago to about 2,500 years ago. During Hypsithermal time, either one large lake developed with an undulating bottom and a life as much as 2,000 years, or several smaller lakes existed during this time but were not necessarily contemporaneous. These lacustrine deposits constitute the middle member of the Van Horn Formation.

During the 5,000-year Hypsithermal interval, rebound from ice unloading was undoubtedly taking place, and at the same time sea level was probably rising slowly as Late Wisconsin ice was shrinking rapidly throughout North America.

Radiocarbon dating of samples taken from trees that were overridden by ice indicates that another glacial advance, which deposited the Glacier Bay Till, occurred in Muir Inlet approximately 3,000 years B.P. during Neoglacial Time. A date from an overridden tree north of Wachusett Inlet, on the west side of the Curtis Hills, demonstrates that ice had already reached this position 2,735 ± 160 years B.P. (Sample I-59-15). Further evidence for this Neoglacial advance comes from dated wood in place on the west side of White Thunder Ridge (W. O. Field and C. V. Janda, oral communication) near the head of Muir Inlet, where ice was starting to bury the lower ridges 2,120 ± 150 years B. P. (Sample I-1610). Near the present terminus of Casement Glacier, where the Van Horn Formation is missing, a prone log buried between the Muir and Glacier Bay tills is 1,400 ± 120 years B.P. (Sample I-1302). This transported wood reflects thickening and advance of Casement Glacier during Neoglacial time.

Neoglacial ice advanced at least as far south as Bartlett Cove, where it built a large terminal moraine. It is entirely possible that the first Neoglacial advance, which has been dated at about 3,000 years B.P. was followed by a second advance, that reached the mouth of Glacier Bay to build a terminal moraine in the 17th century.

The climax of the "Little Ice Age" was about 300 years ago as Lawrence (1958, p. 101) states that, "On the shores of Bartlett Cove near the mouth of Glacier Bay stand the youngest fossil groves of all, the wood well preserved even with bark still in place below the surface of the beach from which the stumps protrude. Radiocarbon dating of this forest by Preston, et al (1955: stumps Y 132 - 83 and Y 132 - 86) and by Barendsen, Deevey, and Gralenski (1957: stump Y-308) shows that these erect stumps were living trees less than 300 years ago; they were dated "modern". Lawrence also said, (1958, p. 101); "Less than 300 years ago when the fossil stumps were living trees the ice advanced from some unknown line of retreat to the mouth of the bay, overwhelming the forest as it moved ahead and depressing the land as the load of ice increased where none had been immediately before."

Goldthwait (1963, p. 45) said that "Forests growing on the terminal moraine are old, but are not the oldest type of forest; because they lack numerous Tsuga, and there are relatively few large prostrate logs. The oldest tree cored by Lawrence was 121 years old, and the oldest Picea cut at the time of our visit in 1958 was 125 years. Allowing up to 50 years for young spruce seedlings to get started, this means a minimum of 175 years since the ice ceased to contribute to the moraine. Either 1650 or 1750 A.D. may be the appropriate date, and it is entirely possible that the ice was building the moraine during that whole century."

It is known from historic observations that this ice was still in the lower part of Glacier Bay in the late 1700's. Since then, Neoglacial ice has retreated about 70 km up Glacier Bay and into Muir Inlet. During the last 300 years it has retreated a maximum of 100 km from Icy Strait at the mouth of Glacier Bay to its present position at Grand Pacific Glacier (Fig. 1); this is the greatest observed recession anywhere in the world. The mechanism for the essential instability of fjord glaciers has been discussed by Mercer (1961). Rapid retreat of glaciers is still continuing in upper Muir Inlet now; Muir Glacier, which is still tidal, receded about 1 km from 1963 to 1964, and from 1964 to 1965 Muir Glacier retreated another kilometer (Goldthwait, oral communication). There are, however, several glaciers in the western part of the Glacier Bay National Monument which are re-advancing (Goldthwait, McKellar, and Cronk, 1961, p. 65).

Following this ice retreat in historic time, vegetation has rapidly re-established itself. A mature spruce and hemlock forest is now developing near the mouth of Muir Inlet, and alder and willow thickets are common near the termini of several valley glaciers in Muir Inlet.

Meltwater streams are once again rapidly filling the arms of Muir Inlet with post-Neoglacial deposits and small lakes and ponds are developing along the edges of dead ice masses such as Burroughs Glacier in Wachusett Inlet and along the present terminus of the Casement Glacier.

A study by Hicks and Shofnos (1965) has shown that a maximum rate of land emergence of about 4 cm a year relative to sea level is taking place at Bartlett Cove. They believe (p. 3318) this uplift is the result of rebound from present localized deglaciation or possibly the combination of present localized and general post-Wisconsin deglaciation. Pierce (1960) has shown that from the period 1940 to 1959, the land in the Muir Inlet area has been rising at a rate of 3.5 cm a year relative to sea level. This uplift is demonstrated by tree stumps and rocky shoals that continue to emerge from tidewater. Tectonic uplift is also affecting this region, but its rate is not known.

SUMMARY

The purpose of the 1963 and 1964 field studies in the Muir Inlet area, Glacier Bay National Monument, was to determine the recent glacial history of this area and to study the development and possible causes of various glacial features.

The stratigraphic succession represents deposits of Late Wisconsin and more recent sedimentation. These include:

Post-Neoglacial:	recent sand and gravel deposits
Neoglacial :	Glacier Bay Till
Late Wisconsin :	Van Horn Formation
	Muir Till
	Forest Creek Formation

The Forest Creek Formation consists of silt, sand, and clay with an abundant marine fauna. The Muir Till is the older of two tills in the section, and is distinguished by being more indurated but also more oxidized and weathered than the upper till. The Van Horn Formation is composed of a lower and upper outwash gravel with lacustrine beds commonly between them. The upper and most recent stratigraphic unit is the Glacier Bay Till. Recent deposits include outwash gravel and sand with local accumulations of clay in small ponds and lakes.

The late glacial and recent history in Upper Muir Inlet can be summarized as follows:

(1) Prior to about 10,400 years ago glaciers in Muir Inlet were probably as far back as those of today. During this recessional position, marine deposits accumulated in the arms of Muir Inlet.

(2) About 10,400 years ago, in Late Wisconsin, glaciers in Muir Inlet advanced, but their maximum extent is not known.

(3) Following this Late Wisconsin advance, the climate became warmer, glaciers retreated, outwash began filling the arms of Muir Inlet, and a forest re-established itself. This interstadial interval (the Hypsithermal) lasted about 5,000 years, during which time lakes were established.

(4) A Neoglacial advance in Muir Inlet may have started about 3,000 years ago because radiocarbon dates indicate that ice had reached the 200 m level on the Curtis Hills about 2,700 years ago, and was well up the side of White Thunder Ridge 2,200 years ago. No information is available about the next 2,000 years, but in the 17th century the ice reached its maximum post-glacial position in Bartlett Cove at the lower end of Glacier Bay. This may have been an entirely separate but greater advance from that beginning 3,000 years ago, the terminal position of which is unknown.

(5) Ice may have started to retreat from the lower reaches of Glacier Bay in the early 1700's, because it was already north of Bartlett Cove in 1794. Since then, ice has retreated from lower Glacier Bay back up Muir Inlet about 70 kms.

(6) Forests are once again re-establishing themselves on the deglaciated terrain around Muir Inlet. The arms of Muir Inlet are once again filling with outwash. Small ponds and lakes are forming along the edges of several glaciers in this region.

(7) Uplift from ice unloading that started in Late Wisconsin time is continuing today. The maximum rate of land emergence relative to sea level is at Bartlett Cove. Here the annual rate of uplift is about 4 cm a year. In Muir Inlet between 1940 and 1959 uplift was calculated to be 3.5 cm a year.

Till fabric, streamlined glacial forms, striae, and the aerial photographic record are helpful criteria for determining past directions of ice motion in the McBride Remnant area. These indicate that ice advance in the McBride Remnant area was from the northwest and north. The general direction of Neoglacial ice advance in Muir Inlet was from north to south, following the orientation of the inlet. The entire Muir Glacial System during its maximum development probably had a dendritic pattern.

Between 1890 and 1892 the McBride Remnant area was still covered by about 600 meters of glacial ice, which did not become separated from the main Muir glacial ice until between 1935 and 1941. By 1948 there was still about 7.5 km^2 of ice left in the McBride Remnant area, but by 1963 this had been reduced to only about 1 km^2. The rate of ice downwasting in this remnant area was in the order of 6.4 meters per year. From the orientation of crag-and-tail features it is suggested that after separation from the Muir Glacier, the residual McBride Remnant ice reversed its direction of flow near Nunatak Knob.

A succession of large glacial meltwater stream channels, now abandoned, can be traced northward from Goose Creek to Van Horn Creek. A series of much smaller abandoned marginal drainage channels is near the south end of the McBride Remnant area. The principal stream in this region today is McBride Remnant Creek, which empties into Nunatak Cove.

Several small eskers are scattered throughout the McBride Remnant area. The largest esker is still ice-cored. Kames composed of thin-bedded, well-sorted sand are particularly well developed in the north-central part of the McBride Remnant area, and many of them also are still ice-cored.

Minor linear ridges in the McBride Remnant area were developed by filling of crevasses with washed material, or by till that may have been forced upwards along shear planes or into openings at the base of the ice and later released to form ridges. In the central part of the McBride Remnant area, small circular ridges are present as ice-disintegration features around the edges of small ice blocks.

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