# SOIL DEVELOPMENT AND ECOLOGICAL SUCCESSION IN A DEGLACIATED AREA OF MUIR INLET, SOUTHEAST ALASKA
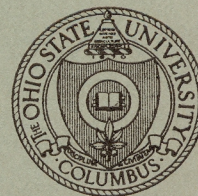
by

R. P. Goldthwait, F. Loewe, F. C. Ugolini, H. F. Decker, D. M. DeLong, M. B. Trautman, E. E. Good, T. R. Merrell, III, and E. D. Rudolph

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INSTITUTE OF POLAR STUDIES

Report No. 20

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A DEGLACIATED AREA OF MUIR INLET, SOUTHEAST ALASKA

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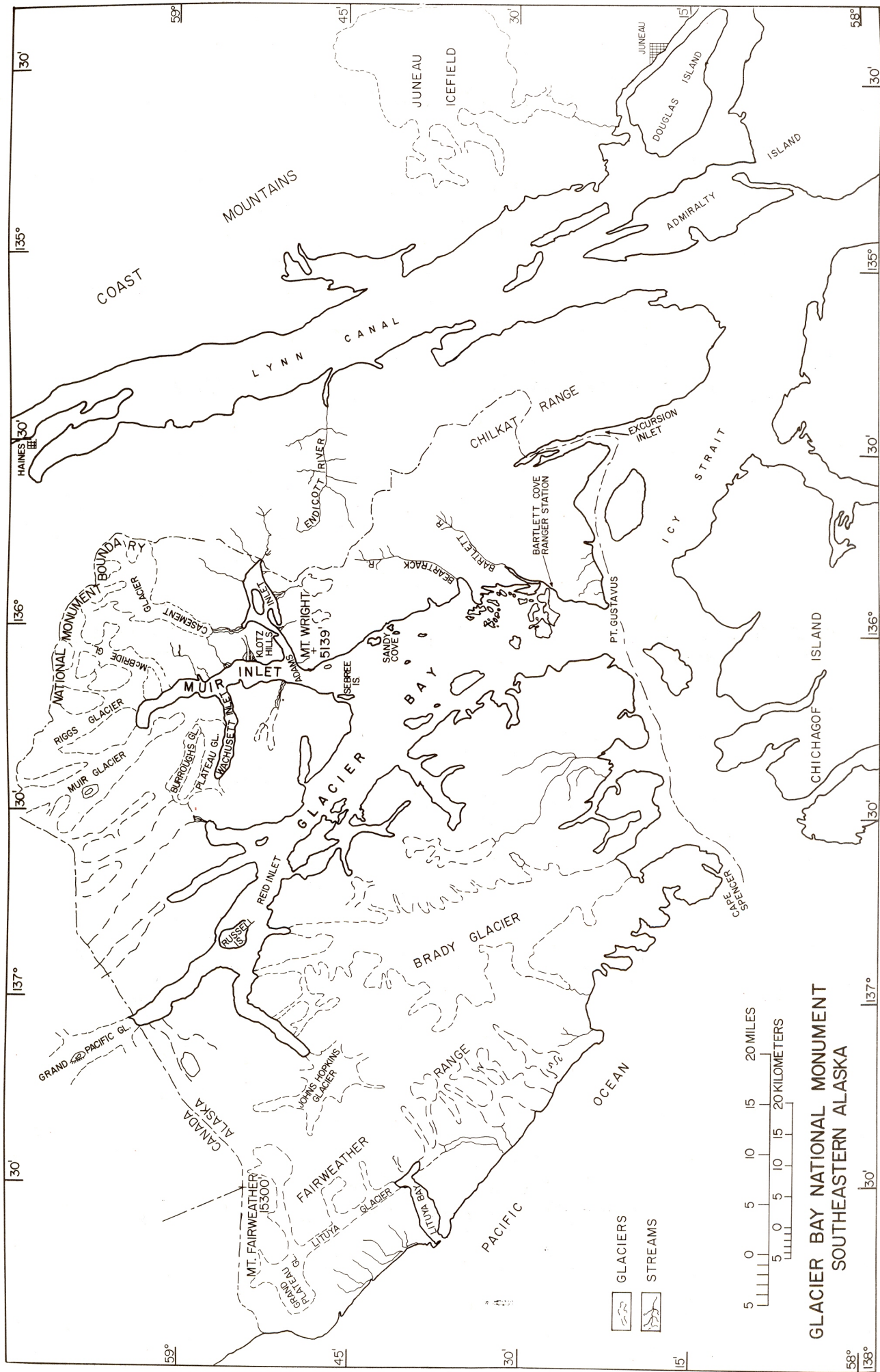M. B. Trautman, E. E. Good, T. R. Merrell, III, and E. D. Rudolph

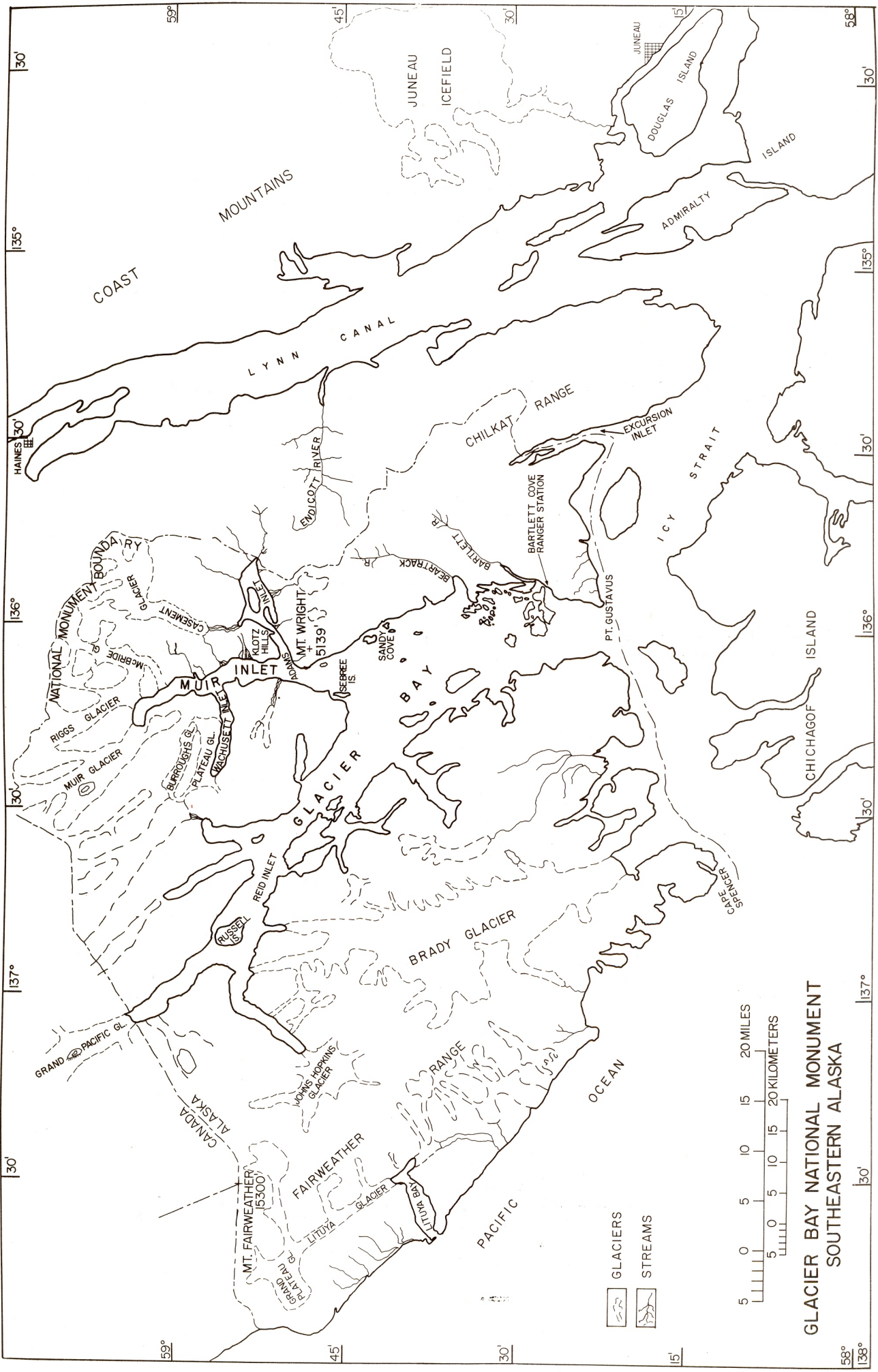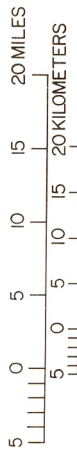Edited by Arthur Mirsky

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GLACIER BAY NATIONAL MONUMENT
SOUTHEASTERN ALASKA

GLACIERS
STREAMS

20 MILES
20 KILOMETERS

COAST MOUNTAINS

JUNEAU ICEFIELD

JUNEAU

DOUGLAS ISLAND

ADMIRALTY ISLAND

LYNN CANAL

HAINES 30'

CHILKAT RANGE

ENDICOTT RIVER

EXCURSION INLET

BARTLETT R.

BEARTRACK

BARTLETT COVE RANGER STATION

ICY STRAIT

PT. GUSTAVUS

CHICHAGOF ISLAND

NATIONAL MONUMENT BOUNDARY

CASEMENT GLACIER

McBRIDE GL.

RIGGS GLACIER

MUIR GLACIER

BURROUGHS GL.

PLATEAU GL.

WACHUSETT INLET

ADAMS INLET

KLOTZ HILLS

MT. WRIGHT +5139'

SEBREE IS.

SANDY COVE

MUIR INLET

REID INLET

RUSSELL IS.

GLACIER BAY

BRADY GLACIER

CAPE SPENCER

GRAND PACIFIC GL.

CANADA
ALASKA

JOHNS HOPKINS GLACIER

FAIRWEATHER RANGE

MT. FAIRWEATHER 15300

GRAND PLATEAU GL.

LITUYA GL.

LITUYA GLACIER

LITUYA BAY

PACIFIC OCEAN

PACIFIC OCEAN

30'  35'  45'  30'  15'  58°

59°  45'  30'  15'  138°

137°  136°  135°

Muir Inlet in Glacier Bay National Monument, southeastern Alaska (Frontispiece) offers an unparalleled opportunity for studies of soil development and repopulation by plants and animals in a recently deglaciated area. Historical records of ice positions of the Muir Glacier date from 1794, and the receding ice fronts have been accurately mapped frequently since 1892. Of particular note are the repeated visits by W. O. Field since 1926, resulting in maps of ice cliff positions in tidewater, and in approximations of the dwindling ice thickness. Glacier Bay is unique because nowhere else in the world are there glaciers retreating with such rapidity that have been so well studied and for which the rate of retreat and positions for given dates are so accurately known. Although most of this retreat has been in sea water, sizable tracts of land which were freed from ice within a short span of time have well-defined habitat types representing successional stages, from the barren ice front to mature forest. Thus, the area offers outstanding opportunities for dating an ecological succession, and for correlating this succession with known vegetative and soil types. W. S. Cooper, in 1923, began pioneer studies along these lines with his descriptions of forest successions; he also established stations and plats, a work continued in later years by D. B. Lawrence.

Since 1959, through several National Science Foundation grants, members of the Institute of Polar Studies under the direction of Dr. Richard P. Goldthwait, have been systematically studying the glacial geology of Muir Inlet and adjacent areas, so that the glacial and post-glacial history is very well known. During the summer of 1962, as a by-product of a study of glacial geomorphology, preliminary ecological observations were made on the habitat, species, and general successional stages of the plants and animals in the central part of the area. Although the observations were very general only, there appeared to be a clear indication of an ecological development in the deglaciated area in terms of repopulation. As a result, a long-term study was proposed to examine in detail the re-establishment of soils, plants, and animals, and their temporal relationships to the glacial history.

The first year of the intended long-term study began with the summer 1965 field season. The Institute party, consisting of specialists, made a detailed study of the development of soils and the successional re-entry of plants, insects, birds, and mammals. Also, some peripheral observations were made of freshwater fish, and some weather records were available from other Institute projects in the area. Finally, additional data were collected on details of the glacial geology, especially in the southern part of the Muir Inlet area.

The Institute's field parties have been based at several tent camps in the Muir Inlet area. Camp 1 was located on the shore about 50 meters west of Muir Cabin. Camp 2, set up on an outwash delta on the coast just north of Klotz Hills, and Camp 3 at the northeast corner of Nunatak Cove,

are also the sites of meteorological stations now designated respectively as Delta and Nunatak Cove.

The field party consisted of the following personnel, who had the indicated responsibilities:

Dr. Richard P. Goldthwait:  party leader and glacial history
Dr. Henry F. Decker:  plants
Dr. Dwight M. DeLong:  insects
Dr. E. Eugene Good:  mammals
Dr. Milton B. Trautman:  birds
Dr. Fiorenzo C. Ugolini:  soils
Mr. Roger K. Burnard:  field assistant
Mr. Donald Frickie:  field assistant
Mr. Thomas Goldthwait:  field assistant
Mr. Theodore R. Merrell III:  field assistant

Mr. Merrell also made a few observations on freshwater fish, which are included as a short section at the end of the report.

Other persons connected with the project include Mr. Frank Preston, who spent about a week at the field camp, Dr. Fritz Loewe, who compiled and evaluated the available meteorological data pertaining to the project, and Dr. Emanuel D. Rudolph, who analyzed the ecological data.

This report contains the results of the 1965 field season.  It is noteworthy that a definite successional development can be documented for each aspect studied.  Moreover, differences in climate are insignificant over the deglaciated area, and the ecologic development is clearly related to length of time since deglaciation.

reviewing the individual reports.  Particular thanks are due to Mr. Henry Brecher, who aided greatly in the general editing of this volume.

Arthur Mirsky
Assistant Director
Institute of Polar Studies

SOIL DEVELOPMENT AND ECOLOGICAL SUCCESSION IN
A DEGLACIATED AREA OF MUIR INLET, SOUTHEAST ALASKA

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OF

SOIL DEVELOPMENT AND ECOLOGICAL SUCCESSION IN
A DEGLACIATED AREA OF MUIR INLET, SOUTHEAST ALASKA

## Part 1.  Glacial History by R. P. Goldthwait

The origin of the materials on which soils and ecosystems have developed in the 25-kilometer-long triangular lowland of Muir Inlet north of Mts. Wright and Case involves the last two glacial invasions and pro-glacial waters since 8,500 B. C.  The lowest unit, which is rarely seen, consists of gray marine clay full of shells more than 10,000 years old; this is the Forest Creek clay.  It represents a mid-Wisconsin (or pre-Wisconsin?) sea at least 65 meters (200 feet) above the present bay.  At 11 localities, the lower of two tills lies on bedrock, or on these marine clays; it is a compact sandy loam, stained yellow to orange near its surface, and bracketed by stumps and logs which date from 8,000 to 5,100 B. C.  For more than 2,300 years of Hypsithermal time retracted glaciers filled all the side valleys with outwash (Van Horn gravels) at 1 to 2 meters per century and the forests these gravels buried were just like climax forests today.  Apparently, northwestern Glacier Bay (to Reid Inlet) had ice, and no forests.  The early Neoglacial advance by 2,800 to 2,200 B. C. came from this west side and blocked the Muir Inlet area, for widespread rhythmite clays cover the gravel and bedrock even up to 270 meters (900 feet). The lake lasted 2,000 years until deposition of upper Van Horn gravels, dipping gray outwash layers, killed trees between 400 B. C. and 300 A. D. Neoglacial (Glacier Bay) till covers everything.  The first stumps annihilated by this ice were on higher slopes to the northwest (800 B.C.), then to  the north (100 B. C.) and finally to the south (500 A. D.).  At the climax of this Little Ice Age it covered mountains like Red Mt., 1250 meters (4,100 feet), and lay at 800 meters (2,600 feet) against the slopes of Mt. Wright, with a terminal moraine along Bartlett Cove about 1700 A. D.

From this slowly gained advance position there has been phenomenal retreat.  Ice thinned near the edge at rates generally from 3 to 12 meters per year.  The sea ice cliff probably calved back to Beartrack Cove by 1780 A. D., to Sandy Cove by 1830 A. D. and up Muir Inlet to its first mapped positions west of Mt. Wright in the 1880's and 1890's.  In broader stretches, recession of 300 to 600 meters per year took place, well charted after 1892; in narrow parts of Muir Inlet 150 to 300 meters per year with two 3-year halts.  The triangular lowland area invaded by plants and animals first appeared as nunatak knobs (Klotz Hills 1892, the Nunatak 1911), then as belts of new lowland 30 to 150 meters wide each year, and concentric to still-active side glaciers or to stagnant residual ice masses (Adams Inlet to 1935; McBride Remnant to 1966).  Gently sloping channels, floored with recent Seal River outwash gravels, became available some decades after the ice left, as floodwaters ceased in each route.

Shores are emerging at over 4 centimeters per year as the great ice load is removed from the land, so the shore environment area has widened several meters each century. These are the rates at which new land became available to plants, animals, and soil-forming processes.

## Part 2.  Climate by Fritz Loewe

The summer observations at different points around Muir Inlet show no notable differences except the obvious lower midday temperatures at the Casement station. Any physiographic or biological differences among the sites are likely to be due to factors other than those of the summer climate.

## Part 3.  Soils by Fiorenzo C. Ugolini

A sequence of ecosystems has developed in the Glacier Bay area along the deglaciation stages that began at the end of the Little Ice Age. A pedological study along a transect from the terminus of Casement Glacier to the terminal moraine of Bartlett Cove has revealed a number of soils whose historical sequence corresponds to the ontogeny of a Podzol. However, time is not the only variable along the transect. After 100 years the alder forest has been replaced by a spruce-hemlock community and, consequently, the biotic factor ceases to be constant. It is recognized, however, that during the time the alder forest has prevailed the soils could approximate a chronofunction. This implies that among the five soil-forming factors, four are reasonably constant and time is the only variable. The maritime climate prevailing in Glacier Bay, with its moderate temperatures and high rainfall, is very conducive to a vigorous plant growth, to maintaining a high leaching potential and to an accelerated rate of soil development.

Following the deposition of glacial deposits by the retreating glacier, the fresh till is immediately attacked by a number of processes. While the surface is still barren the carbonates are readily depleted and the cryopedological processes attain their maximum. With the establishment of plants, organic matter enters into the mineral soil and a surficial horizon Al, is formed. The pH of the soil is lowered and the cation exchange capacity is increased. With more plants growing a thin litter layer, the O1 horizon, is formed. These initial transformations occur during the first 40 years. Following the densification of the plant cover a humified layer, the O2 horizon, appears. About 55 years after deglaciation, the pH is lowered from 8.2 to 5.9. Cation exchange capacity has doubled and the exchangeable hydrogen has increased five times. An incipient B horizon appears in the lower part of the Al horizon. During the next stage, from 55 to 250 years after deglaciation, the pH is further lowered and the exchangeable acidity increased more. The exchangeable bases are considerably depleted and the carbonates almost exhausted. Free iron oxides show a maximum accumulation in the B horizon.

Then, 150 years after deglaciation, the A2 horizon makes its first appearance. The thickness of the forest floor increases from 2 centimeters after 12 years to 20 centimeters after 150 years. The C/N ratio increases with time. The depth of the solum increases from 0.5 to 11.0 centimeters during the first 60 years, but it then increases to 15 centimeters during the next 165 years.

The soil sequence along the 250-year-old transect can be represented schematically as follows:

Regosols → Podzolic soils → Brown Podzolic → Podzols

However, because it is not known whether the Brown Podzolic soils are eventually going to disappear in the course of the ontogeny of a Podzol, the following representation could also be valid:

Regosols → Podzolic soils → Brown Podzolic → Podzols
                                        → Brown Podzolic

The Podzols found at the end of the recessional sequence are shallow and lack both an illuvial humus and a clay horizon. Because they show an illuvial iron horizon they have been included among the iron podzols of Kubiena.

Turf-hummocks and other patterned ground features occur above 900 meters (2800 feet). Frozen ground was also detected in the turf-hummock areas. The recently deglaciated areas are also cryopedologically active, and sorted nets and sorted stripes were observed.

## Part 4. Plants by Henry F. Decker

Plant succession in Muir Inlet, Glacier Bay, Alaska can be divided conveniently into eight intergrading stages: I, early pioneer, consisting largely of Dryas and Salix seedlings; II, mat stage, in which the Dryas forms extensive mats 0.1 to 4 meters in diameter; III, late pioneer, in which the terrain has scattered alder, willow, and poplar shrubs; IV, open thicket stage; V, closed thicket stage; VI, poplar-line stage, in which poplar emerges above the alder canopy, forming a clearly discernible line on the horizon; VII, spruce forest; and VIII, spruce--hemlock forest stage. In the Muir Inlet region, the first three stages (I, II, III) occupy the deglaciated terrain for 20 to 25 years; 10 more years are required for the transition of open thicket (IV) to closed thicket (V). The poplar line (VI) along the east and west sides of Muir Inlet closely follows the 1920 positions of the McBride, Casement, and Plateau Glaciers, indicating it forms 40 to 45 years after deglaciation. It takes at least 75 to 90 years after deglaciation for a spruce forest (VII) to supplant the alder--willow--poplar closed thicket (V).

## Part 5.   Insects by Dwight M. DeLong

A study of the insects in the Muir Inlet area following glacier re-
cession for a period of some 70 years showed a rather definite pattern of
succession in both the aquatic and terrestrial forms.  The first aquatic
insects to appear behind the melting glaciers are larvae of certain mos-
quitoes and black flies.  Associated with these are small predaceous
diving beetles and a species of water boatman.  As vegetation appears in
the smaller ponds and organic matter accumulates in the larger pools,
more.species belonging to more families are found.  The early terrestrial
species are usually found some 15 to 20 years after glacier recession.
Usually the plants begin to appear in that length of time, and plant lice
and jumping plant lice occur on the early alders and willows.  The ground
beetles apparently appear soon after recession but are difficult to find
because of the loose gravel in which they hide.  Some blossom-feeding
flower flies are found upon these early plants.  More species occur in
rapid order with each older recessional zone until a climax is reached in
the spruce forest and strawberry meadow some 70 years after glacier re-
cession.  A number of herbaceous plant- and blossom-feeding species occur
in the meadow.

During this ecological survey, the most interesting ecological problem
observed was the normal occurrence of a species of leafhopper, Macrosteles
fascifrons (subspecies) living on a tidal flat, on a salt grass which is
submerged twice daily for a considerable period with salt water containing
icebergs and testing about 2°C.  The insect has no known adaptation to
either aquatic respiration or cold resistance.

## Part 6.   Birds by Milton B. Trautman

Since 1882 the rate of retreat (deglaciation) of the Muir Glacier and,
after 1900, of some of its major glacier tributaries, has been documented.

In June of 1965 several transect lines were established from the melt-
ing edge of Casement Glacier (formerly a tributary of Muir Glacier), each
radiating outward across terrains whose dates of emergence are known.  Ob-
servations were made along these transect lines at intervals between June
10 and August 2.  Studied were the lengths of time necessary for develop-
ment of habitat types and their bird associations, beginning with the
least vegetated type nearest the glacial front and its Snow Bunting
Plectrophenax nivalis - Rock Ptarmigan Lagopus mutus association, through
several distinctive, increasingly complex, vegetative types and their more
diverse bird associations, to the maturing Sitka spruce Picea sitchensis
(Bong) Carriere - western hemlock Tsuga heterophylla (Raf.) Sarg. forest
type and its Chestnut-backed Chickadee Parus rufescens - Varied Thrush
Ixoreus naevius - Pine Grosbeak Pinicola enucleator bird association.

Data, primarily concerning nesting species, substantiated the inference
that a species moves in immediately or shortly after establishment of its
habitat, provided there is a nearby population of that species.

Part 7.  Mammals by E. Eugene Good

A study of mammal distribution in recently deglaciated terrain was conducted on the east side of Muir Inlet in Glacier Bay National Monument during the summer of 1965.  Small mammals were trapped.  Large forms were located from tracks or signs and by direct observation.

The first mammals invade new terrain about 25 years after deglaciation.  The first species to appear are the wandering shrew, Sorex vagrans and the deer mouse, Peromyscus maniculatus.  The shrew persists at least for several centuries and was common in the oldest vegetation sampled.  The deer mouse declines in numbers as the hardwood species are replaced by Sitka spruce and hemlock.  It was not present in mature stands of spruce.

The red-backed vole, Clethrionomys rutilis, which is one of the most characteristic mammals of the climax forest of the region, invades when spruce groves establish a thick needle carpet on the forest floor.  In the area studied this occurred about 100 years after the recession of the ice.  A second insectivore, the masked shrew, Sorex cinereus, invaded at about this same time.

Two species of voles were present.  Microtus pennsylvanicus, occupied specialized marshy or grassy habitats of a variety of ages.  The youngest such habitats were 30 years old.  Microtus longicaudus, the long-tailed vole was a common species above timberline on the mountains around the inlet.  It was also taken on the lower foothills and in beach grass Elymus mollis near the north end of the area.

Larger mammals of several species moved freely throughout the area.  Mountain goats, Oreamnos americanus, were widely distributed and abundant.  Coyotes, Canis latrans, were common.  Wolves, Canis lupus, visited the inlet rather infrequently.  Tracks of both brown and black bears were seen in various parts of the area and black bears were definitely resident in the extreme southern portion where the terrain approached a century in age.  Tracks of the Wolverine, Gulo gulo, were noted once and the river otter, Lutra canadensis, ranged freely near the coast.  Most of the larger forms moved widely and freely and were not good indicators of habitat change.

The red squirrel, Tamiasciurus hudsonicus, and the pine marten, Martes americana, were present a few kilometers south of the study area.  The harbor seal, Phoca vitulina, was plentiful in the inlet and was abundant near the glaciers at the north end.  The harbor porpoise, Phocoena vomerina, was observed rather frequently and on two occasions northern sea lions, Eumetopias jubata, were heard.

Additional changes in the mammalian fauna were noted in the older terrain south of the study area but there was no opportunity to investigate these in detail.

## Part 8.  Freshwater Fish by Theodore Reed Merrell, III

In the summer of 1965 collections were made of freshwater fish in the Muir Inlet area.  Numbers of species and individuals were small, presumably because of a lack of freshwater fish from adjacent waters.  Only four species were recorded, all tolerant of salt water: Dolly Varden trout (Salvelinus malma), Chinook salmon (Oncorhynchus tshawytscha), Silver salmon (O. kisutch) and Threespine stickleback (Gasterosteus aculeatus).

A sexually maturing female salmon, presumably O. tshawytscha, was captured in a freshwater lake.  It was only 40 cm.  in length and contained 2,444 eggs.  Abnormal maturation in fresh water may have influenced fecundity.


## Part 9.  Ecological Succession: A Summary by Emanuel D. Rudolph

Information about succession of biota and development of soil in time after deglaciation for the last hundred years has been compiled into a table.  Using this representation, it is possible to ascertain some interrelationships that link soil development, plant succession, and invasion and population by various animal groups.  The insects and spiders show the most striking increase in number of species as the vegetation changes from the Dryas mat stage finally to the spruce forest stage, with bird increase being less great and small mammal and fish increase least.

# PART 1.  GLACIAL HISTORY

by

Richard P. Goldthwait
Department of Geology
and
Institute of Polar Studies

## ABSTRACT

The origin of the materials on which soils and ecosystems have devel-
oped in the 25-kilometer-long triangular lowland of Muir Inlet north of
Mts. Wright and Case involves the last two glacial invasions and pro-glacial
waters since 8,500 B. C.  The lowest unit, which is rarely seen, consists
of gray marine clay full of·shells more than 10,000 years old; this is
the Forest Creek clay.  It represents a mid-Wisconsin (or pre-Wisconsin?)
sea at least 65 meters (200 feet) above the present bay.  At 11 localities,
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more than 2,300 years of Hypsithermal time retracted glaciers filled all
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The lake lasted 2,000 years until deposition of upper Van Horn gravels,
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Neoglacial (Glacier Bay) till covers everything.  The first stumps anni-
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From this slowly gained advance position there has been phenomenal
retreat.  Ice thinned near the edge at rates generally from 3 to 12
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ice masses (Adams Inlet to 1935; McBride Remnant to 1966).  Gently sloping
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some decades after the ice left, as floodwaters ceased in each route.

Shores are emerging at over 4 centimeters per year as the great ice load
is removed from the land, so the shore environment area has widened
several meters each century.  These are the rates at which new land be-
came available to plants, animals, and soil-forming processes.

## BASIC STRATIGRAPHIC SEQUENCE

The substrate in which soils developed, and on which the biota re-
occupied the area, consists of glacial debris left by two well-documented
advances of former glaciers down Muir Inlet to or beyond the mouth of
Glacier Bay (Frontispiece).  These drifts comprise eight formations of
glacial, glacio-fluvial, and glacio-marine deposits, produced in episodes
from the latter part of Wisconsin time to the most recent decade (Fig. 1).
These were first described by Cooper (1923 and 1937), and Lawrence (1958).
The geological sequence and significance was presented by Goldthwait
(1963) and by Price (1964).  Detailed studies and additional units were
contributed by Haselton (1966) who introduced most formation names.  The
present study adds to the occurrences and distribution of the formations,
adds radiocarbon datings, and greatly extends the interpretation.

### Wisconsin stage

Early marine deposits. - The lowest and oldest unconsolidated forma-
tion is the Forest Creek Formation.  It consists of blue-gray marine clay
and silt with massive structure or thin bedding (Fig. 1).  These lie
directly upon unweathered glaciated bedrock and contain abundant pelecy-
pods, such as Macoma and Chlamys, and gastropods, such as Colus or
Neptunea.  Barnacle plates are most numerous; some are attached to pebbles.

These marine beds were discovered in 1963 at 24 meters (78 feet)
altitude in lower Forest Creek north of the recent terminus of Casement
Glacier.  Later small areas were found (1964) far up Forest Creek at 59
meters (194 feet) and (1965) southeast of Casement Glacier at near 30
meters (100 feet).

All three small areas were uncovered by the receding edge of Casement
Glacier during the late 1930's and 1950's.  The vegetation which has grown
on these patches is dominantly composed of horsetails owing to the great
moisture retention of the clays and silts.

The Forest Creek Formation is an enigma in the age determinations
thus far.  One radiocarbon date for the marine shells gave 10,000 ± 220
years B. P. (I-1303), but logs immediately above this marine formation
gave the date 10,400 ± 260 years B. P. (I-1615).  All subsequent forma-
tions, even at elevations down to sea level, consist of sub-aereal de-
posits, and indeed, the deposits from 7,000 years B. P. onward indicate a
sea level substantially lower than that at the present time.  Studies and
dates at many shores all around the world indicate a much lower (30 meters,

2

100 feet plus) sea level 10,000 years ago. One could explain these marine deposits above the present sea level only if one postulated a very strong uplift (100 meters, 300 feet or more) between 10,000 and 7,000 years B. P. following the Forest Creek marine invasion. Alternatively, it might turn out that the marine shell date (I-1303) is wrong, and that the marine invasion is mid-Wisconsin (interstadial).

Late Wisconsin till. - The Muir till is the lower of two tills, and thus is well hidden at most places. It has been discovered at five localities on the east side of upper Muir Inlet (Haselton, 1966) and at three localities on the north side of Wachusett Inlet (Goldthwait, 1963). Three new localities were found south of Adams Inlet, and just south of Casement Glacier. The material is a compact gray, sandy loam with few cobbles and boulders. In many places this till is oxidized on its upper surface and stained a bright orange-red, which grades downward from organic material at the top. Needles, cones and bark make up the material of the organic layer, and stumps are still rooted.

Because the oldest stumps are in place under the next younger gravel and date in excess of 7,000 years ago (Goldthwait, 1963), the interpretation is that the last phase of Wisconsin glaciation occurred after 10,000 years ago and well prior to 7,000 years ago, leaving sufficient time for soils to develop to 30 or 60 centimeters depth before sandy gravel outwash deposits inundated the forests and this initial soil.

This older till has been identified only on steep exposures cut by streams; it was exposed and cut primarily in the 1940's and 1950's. Steep sands slumping above it keep it unvegetated at this time.

## Hypsithermal time

Hypsithermal gravels. - Two sandy gravel units, called the Van Horn Formation, form a local substrate near most creeks and valleys. They have been noted by all scientific visitors, and especially discussed by Russell (1892). They range from medium-sized gravels to coarse sands in layers which sometimes contain local cross-bedding. Although the original surface is not preserved, these have the very gentle dips suggesting deposition as an outwash, and as they occur in matching levels with matching dates on both sides of Muir Inlet, and on both sides of Wachusett Inlet, it appears that the whole area was filled by these gravels from 50 to 100 meters (150 to 300 feet) above sea level. Cooper preferred the interpretation that these were kame terraces lateral to a continuously present but fluctuating central ice stream (1937 and personal communication 1961). The lower gravel, 5 to 50 meters thick, is generally stained from yellow to rusty brown or reddish-brown, especially beneath the numerous thin organic horizons at several levels in this gravel deposit. This darkening is prominent on bluffs along the west shore of Muir Inlet (Bull triangulation point) and in all valleys leading northward from Mts. Wright and Case.

In Wachusett Inlet a large number of radiocarbon dates show that this lower Van Horn accumulation had developed from some level below present sea level to the position of present sea level about 7,000 years ago. Then it continued to thicken at the rate of 1.4 meters per century (Goldthwait, 1963). The leaves, cones, and stumps in these organic layers suggest temporary forests of small Sitka spruce trees and alder bushes advancing across the outwash from time to time as happens in the same situation today. At the valley side slope against which these gravels rest, a more mature forest of large Sitka spruce and occasional hemlock form the material on the soil of the underlying Muir till. A great many tree stumps have been exhumed, both on these marginal slopes and in terraces cut into the buried outwash (particularly at Forest Creek). The rounded condition of the tops of these trunks and the scarred surfaces on one side suggest that they were killed during inundation by washing gravels and not, as was first suggested by Cooper (1923), by many successive glaciations. Radiocarbon dates from these lower gravels indicate a span of accumulation beginning before 7,050 ± 250 years ago (I-84 and I-91) and ending with the formation of a lake on the last forest beds approximately 4,200 years ago (3,290 to 4,775 years ago by ten dates: I-80, 83, 123, 124, 126, 164, 1613, 1616, and Y-301, 303).

## Neoglacial time

Early Neoglacial lake. - Interbedded in the gravels of the Van Horn Formation is a series of lacustrine silts and very fine sands found at most, but not all, localities on both sides of upper Muir Inlet, on both sides of Wachusett Inlet, and on the south side of Adams Inlet (Fig. 1). In a few instances it rests directly on bedrock with no Van Horn gravels or Muir till beneath it. The highest of these lacustrine deposits occurs at 60 meters (200 feet) above sea level in upper Muir Inlet, at 80 meters (260 feet) in Wachusett Inlet, and up to 270 meters (886 feet) in valleys into Adams Inlet. With such widespread distribution in almost every cut throughout an area 16 kilometers long and 10 kilometers wide, and with many radiocarbon dates all giving the drowned forests (of which there are 10) near the bottom dates of 4,200 ± 500 years B. P., it seems almost certain that this was one lake extending the full length of Muir Inlet and its tributaries from the main open part of Glacier Bay south of Sebree Island. It was as much as 450 meters (1,500 feet) deep because its surface had to be near the 270 meter (900 feet) contour, and it lasted 2,000 years because the three logs on the upper clays have dates within 2,200 ± 200 years B. P. There is no reasonable or logical way in which to dam such a lake in the valley of Muir Inlet without placing ice down the main body of Glacier Bay. This must mark the initial phase of the coming of ice from the northwestern end of Glacier Bay and the Fairweather Range at about 2,200 B. C. (Fig. 2B).

Advancing Little Ice Age outwash. - The upper member of the Van Horn Formation, as defined by Haselton (1966) and seen on the west shore of lower Muir Inlet, or the east shore of upper Muir Inlet, is a gray gravel, from 3 to 75 meters thick, generally resting on top of the lacustrine sediments (Fig. 1). This upper unit has poorer bedding and sorting and is

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distinguished from the lower unit by its cleaner, unstained gray color. The materials are coarser and include some cobble beds; here and there they are dipping beds or poorly bedded gravel, suggesting the proximity of ice. On the south side of Adams Inlet, these beds are very sandy and both there and north of Minnesota Ridge these upper sands rise to more than 140 meters (450 feet) above present sea level.

The nine buried forest samples in upper Muir Inlet range from 2340 ± 115 years B. P. (I-1612) to 1,660 ± 110 years B. P. (I-1304). This may represent a gradual ice advance from 400 B. C. to 300 A. D.

Because these gravels are the uppermost part of the Van Horn Formation, and are only very thinly covered by till in many places, there are numerous localities today where this gravel forms the surface and upon which sequences of plants, insects and birds are developing. The gravel surfaces differ somewhat from the adjacent till surfaces which retain their moisture, for they are so well drained as to be dry in spite of the very wet climate.

Little Ice Age till cover. - The ubiquitous cover of till which lies over the undulating eroded surface of the underlying gravel and lacustrine formations, and rises well above 300 meters (1,000 feet) on bedrock slopes, was deposited by the last advance of the ice, which is only now retreating (Fig. 2C). This is the Glacier Bay Till and has a much darker gray color than underlying gravels (Fig. 1). The lower (Muir) till is lighter gray and frequently colored yellow. Haselton (1966) shows that the upper Glacier Bay Till is more bouldery and stony but has a slightly lower sand content than the underlying Muir Till: 10 percent clay, 36 percent silt, and 54 percent sand. The embryonic soils described by Ugolini (this volume) and the various forms of life described in subsequent chapters of this volume invaded mostly on this material. Cuts along creek sides may remain open for many decades if once over-steepened, but the original depositional till surface forms an undulating area of low hills, extending from the sea back to where the present glaciers end or up against the steep rock slopes at about 150 to 300 meters (500 to 1,000 feet) altitude. It became exposed gradually, in belts, as outlined in the next section (Fig. 3).

This widespread till cover rises well above the earlier subjacent lacustrine and fluvial formations and near its upper limit covers or partially inundates the forest which occupied these slopes at the time the Little Ice Age began. Two wood samples which are dated by radiocarbon indicate the coming of Little Ice Age ice into upper Muir Inlet (1) 2,735 ± 160 years B. P. (I-122) from the northwest via present Burroughs Glacier at a point 220 meters (720 feet) above present sea level, and (2) 2,120 ± 115 years B. P. (I-1610) from the north in upper Muir Inlet against the west side of White Thunder Ridge at about 450 meters (1,475 feet) above sea level. Forests were not destroyed at Forest Creek (I-1302) and Adams Inlet (I-162) until 1,420 years ago. Clearly the Neoglacial ice expanded first from the northwest into other parts of Glacier Bay (Reid Inlet) before 2,200 B. C., forming the lake, but then ice did not expand from the lower peaks of the Canadian boundary area

until the proglacial outwashes were deposited from 400 B. C. to 300 A. D. By 500 A. D. it had thickened to cover all Muir Inlet and to 250 meters (800 feet) against Mt. Case. Lack of any other stratigraphic evidence suggests that the ice cover of Muir Inlet and its tributaries, Wachusett and Adams Inlets, was continuous from this time until the deglaciation of the century just ending.


## Recent deposits

Ablation moraine. - During the last hundred years, retreat over the gently-rolling surfaces, both east and west of central Muir Inlet, has left a thin coating (up to 30 centimeters thick) of angular and sub-angular sandy debris which slipped and slid off the last melting ice. Where we watch this process as ice continues to disappear today, there is a collection of lower englacial materials or a medial moraine let down on the melting ice surface, and spread and washed by small rills each summer. These sandy materials with very angular stones and blocks ultimately come to rest as thin "ablation moraine" on the sub-glacial Glacier Bay Till. Price (1964) found this covering material sufficiently sandy and washed to label it "upper gravels" in spite of the very sharp angular (non-rounded) coarse clasts; he indicated its usual thickness was a matter of a few centimeters but occasionally as much as 20 meters.

Washed deposits. - Obviously in this last association the recent surface "gravels" represent a stratified washed deposit of ablation materials accumulating in a kame mass along the retreating ice edge. For plants and animals these few deep hummocky spots afford a substrate similar to that of the underlying Van Horn outwash when exposed. Far more widespread and important as such a hilly gravel habitat are the eskers, ice-contact deposits made on the decaying ice of Casement Glacier. Price studied a series of eskers in two major chains from the southeast edge of the present Casement Glacier extending across Seal River into the great drainage channels sloping westward into Muir Inlet. These eskers were recorded in 1941 on aerial photos and interpreted as superglacial stream deposits. Under the gravel ridges remaining today are masses of buried protected glacier ice, exposed where Seal River cuts in, but hammer-blow seismic exploration west of Seal River in 1965 showed that nearly all the ice is now gone. These ice channel gravels have come to rest as steep-sided ridges; slowly they become stabilized and tenable for plants. Because the water table is deep, they dry quickly after a rain, and there are no silts or clays to hold soil wetness.

An even more widespread gravel habitat is the gently sloping glacial outwash plains, more than a kilometer wide, like that of Seal River that drains Casement Glacier into Adams Inlet. About 30 percent of the present-day land surface exposed by retreating glaciers at altitudes below 300 meters (1,000 feet) is floored by the gravels of these channels. These gravels are referred to herein as the Seal River Formation. They contain rounded pebbles washed out from under the present glaciers and may be derived in part from the Van Horn Formation, but in all cases they

are uniformly bedded, well sorted and fairly deep gravels. They provide a dry substrate for the development of certain plants and animals.

So long as glacial streams fed onto each sloping outwash plain, the braided channels contained broad, shallow rushing currents which constantly built new gravel bars and shifted course daily. With repeated violent flooding and bar building, little can grow until fluvio-glacial feeding is diverted or ceases. The effective date of biological invasion then is when the glacial stream abandons the channel surface and pioneer plants begin to take hold. Of course this post-dates by one or two decades the time when the immediate area was uncovered by ice. It makes these outwash surfaces younger in origin than the adjacent till surfaces. Stratigraphically they are "on top of" all other deposits, but topographically they are inset into channels cut through the whole series of earlier formations (Fig. 1).

## POSITIONS OF THE LAST ICE

### Source of ice

*Two centers of flow.* - The singular absence of stumps in place on the valley slopes, or logs in outwash gravels at any level, in the northwest portion of Glacier Bay (west of Carroll and Reid Glaciers), suggests that the glaciers emanating from the Fairweather and Crillon Ranges (Frontispiece) extended into the western end of Glacier Bay, perhaps as far as Russell Island, throughout Hypsithermal time, 7,000 to 4,000 years ago (Fig. 2A). Elsewhere buried climax forests are abundantly recorded on both sides of Muir Inlet, Queen Inlet, Hugh Miller Glacier and Geikie Inlet. It becomes unreasonable to explain a lake, or lakes, which endured for at least 2,000 years in Muir Inlet and began in Goose Cove (I-80) by 2,800 B. C., unless the first extension of glaciers in the cooling period of early Neoglacial time was from the glaciers already existing in the west. A 4,680 ± 160-year-old log (Y-9) reported in Reid Glacier moraine, and a 4,755 ± 180-year-old log (I-89) on Carroll Glacier outwash suggest destruction by such an advance from the west just after 2,800 B. C. The first half of Neoglacial time (2,800 to 500 B. C.) was characterized by increased net snow accumulation among the 3,000 to 4,500 meter (10,000 to 15,000 foot) high peaks of the Fairweather Range west of Glacier Bay.

When, then, did the second and lower ice center develop and extend glaciers into Muir Inlet from the north? The present Rendu, Carroll and Muir glaciers are distributed as transection glacier systems across the international boundary east of Mt. Barnard between peaks of 1,500 and 1,800 meters (5,000 and 6,000 feet) altitude. This suggests that this moderately high mountain complex finally sufficed to gather increasing snows which resulted eventually in the one connected great ice field seen by Reid in 1892 and by the first Boundary Survey (1907). Glaciers were not generated anew here for small glaciers must have supplied the gravels

of the lower Van Horn Formation to Muir Inlet all through Hypsithermal time (Fig. 2A). They simply became enlarged as a major ice center and covered the early Neoglacial lake deposits with proglacial outwash and (Glacier Bay) till between 400 B. C. and 300 A. D.

The dated logs pushed over by advancing ice or buried in till suggest that glacier growth may have progressed from west to east. About 785 B. C. (2,735 ± 160 B. P., I-22) Burroughs Glacier crept in from the northwest to an elevation of 220 meters (720 feet), but Muir Glacier to the north did not reach 450 meters (1,470 feet) altitude on the west side of Thunder Ridge until 150 B. C. (2,100 ± 115 B. P., I-1610). The logs at Forest Creek and Adams Inlet just under the till which are dated at 510 to 550 A. D. (I-1302, I-162) complete the southeastward expansion over this basin. This advance must have continued until all the moderately high peaks between 760 and 1070 meters (2,500 and 3,500 feet) above Muir Inlet were completely covered: Minnesota Ridge, Idaho Ridge, and Red Mountain. Each of these high ridges is slightly rounded and bears thin drift comparable to that on the lower slopes. The ice covered the area for 1,000 years and more (Fig. 2D).

A third high area containing Mts. Wright and Case respectively at about 1,500 and 1,700 meters (5,000 and 5,500 feet) elevation above Muir and Adams Inlets, certainly contained its own glacier sources. White Glacier is now covering all the upper slopes and has ice divides in the vicinity of 1,200 meters (4,000 feet). On the other hand, checks of the pebbles in the deposits of Van Horn (Hypsithermal) gravel and Glacier Bay (Neoglacial) till, both in Dirt Glacier Valley and in shorter valleys to the east past Mt. Case, showed lithologies found to the north across Adams Inlet. Medial moraines on one picture taken eastward into Adams Inlet in 1929 and H. F. Reid's map of 1892, suggest only a very small contributing ice stream from this arm of the Chilkat Range. Cooper (1937) notes undisturbed climax forest up to 760 meters (2,500 feet) on the south slope of Mt. Wright. Apparently there was an insufficient area of accumulation to provide important feeding to the main glacier system via Adams Inlet during the Little Ice Age. Each small glacier from here to the Juneau Icefields did register its own short expansion and advance, however (Lawrence, 1958; Heusser, 1960).

Climax of Neoglacial advance. - Several lines of evidence indicate that this last and greatest advance of post-Wisconsin ice down Muir Inlet reached its southernmost point just south of Bartlett Cove (Frontispiece) between two and three hundred years ago. Lawrence (1958) found stumps excavated by the waves on the south shore of Bartlett Cove and buried in the intertidal mud. Radiocarbon dates show that these may be as much as 300 years old. The oldest spruce trees growing on the moraine were 121 years old (cored by Lawrence, 1957) or 125 ring years (Goldthwait, 1963), or 175 years (Decker, this volume). Allowing 50 years or more for these to get started, it seems that the disrupting ice left the moraine some 250 years ago. On the occasion of the first recorded visit in 1794 by Vancouver, the ice front was said to stretch from one side of Glacier Bay to the other "near its mouth." It is not clear whether the ice front was still near Bartlett Cove or a few kilometers north of that among the islands near Beartrack Cove (Cooper, 1937).

The position of outermost Neoglacial ice is marked by a sharp moraine 30 to 50 meters high stretching through the woods northeast to southwest along the south side of Bartlett Cove. The National Park Lodge is built upon the north slope of this moraine. The moraine extends southward along Glacier Bay for over one kilometer and the ice edge may have reached Point Gustavus itself. The late Don Miller of the U. S. Geological Survey reported (oral communications, 1959) that a similar moraine trends northwestward into the hills on the west side of Glacier Bay just north of its mouth. The critical moraine on the east side has been traced from the air by following the trimline in the high spruce trees to the northeast into the region next to Salmon River and northward between it and Bartlett River to the area three kilometers east of Beartrack Cove, where it swings northwestward across the river into the mountainside at 120 meters (400 feet) above sea level. Cooper (1937) continued this line as undisturbed climax forests 300 meters (1,000 feet) above Beartrack Cove. Certainly, if these tracings are correct, the Beartrack River valley was blocked during the presence of the ice at its outermost position and it contained a glacial lake (Fig. 2D).

Changing snow line. - The first photograph taken from near the top of Mt. Wright (Reid, 1896) shows the white snow accumulation limit on August 19, 1892, near the end of the melting season. Around the end of Minnesota Ridge, and in the area on either side of Black Mountain, it was 640 to 730 meters (2,100 to 2,400 feet) high. Medial moraines shown on Reid's map (1892) fade out into snow cover at 550 to 760 meters (1,800 to 2,500 feet) above sea level; usually these show above the snow line for some distance. We have no direct clue how much lower the snow line may have been in the 1700's.

Careful measurements on the Casement Glacier by Donald Peterson in 1965 show a snow line slightly above 900 meters (3,000 feet) at the close of summer after rather heavy snow fall in the preceding winter. Medial moraines on 1948 vertical photography fade out at 950 meters (3,100 feet). Field concluded in 1947 that the firn line had been rising and was then above 900 meters (3,000 feet) on the average. Goldthwait (1963) concluded that the snow line or accumulation limit had risen about 300 meters in the half century between 1892 and 1942. It seems certain that the sudden rise has reduced the accumulation area by at least 50 percent and has caused the great retreat of these glaciers.

Disappearance of the ice

Considering that it took about 1,000 years for the last ice to slowly invade all Muir Inlet, and that this covering endured more than another 1,000 years, it is all the more amazing that retreat to its present position has taken only about one century. Lawrence (1958) notes that this is about 15 times as fast as most glaciers elsewhere in the world today, and this rate was sustained for more than two centuries. However, radiocarbon dates in central United States and Ontario suggest equally fast post-Wisconsin retreats.

Thinning. - The rolling lowland area north of Mts. Wright and Case
is triangular in shape and 25 kilometers on a side. It has been wholly
deglaciated since the first photograph and careful topographic map in
1892 (Reid). Everywhere that Reid's contours show 300 to 600 meters
(1,000 to 2,000 feet) elevation on the ice there is now low rolling
ground or narrow inlets (Muir, Wachusett, Adams).

In 1892 the ice surface wrapped around the north slopes of Mts.
Wright and Case, beginning at sea level on the west and climbing to
approximately 300 meters (1,000 feet) toward the east. Ugolini found the
highest erratic material on the northwest shoulder of Mt. Wright at just
over 600 meters (2,000 feet) above sea level. It seems possible that
with the ice fully extended to the Bartlett Cove moraine, ice wrapped
around the west side of Mt. Wright at an elevation 760 meters (2,500 feet)
above that sea level position. It was nearly 760 meters high on slopes
five kilometers farther south, and it was 300 meters (1,000 feet) high
on slopes 13 kilometers south above Beartrack Cove (Cooper, 1937). Using
200 years as the approximate time of retreat from the terminal moraine
at Bartlett Cove to the known ice position of the 1890's, early deglacia-
tion lowered the ice surface about 4 meters per year.

As rates of thinning are easy to measure against nunataks or ridges
near the termini of glaciers, this method for determining the rate of
thinning has been carefully read from photographs by Reid (1894), Field
(1947), Taylor (1962), Price (1964), and Haselton (1966). The average of
15 such figures is 8.5 meters of lowering of ice surface per year. On
the south side of Casement Glacier, Price (1964) gives 18 and 20 feet
(5.5 and 6.1 meters) per year from photographs of 1929, 1948, and 1962.
On the McBride Remnant Glacier east of Nunatak Knob, Field (1947) gives
22 feet (6.7 meters) per year, and Haselton (1966) gives 6.4 meters per
year. On the main Muir Glacier itself, John Muir gave 20 feet (6.1
meters) per year during the 1880's and 1890's, and Field calculates 38
feet (11.6 meters) per year between 1907 and 1941. Temporarily, between
1941 and 1946, the thinning was accelerated to 30 meters per year. Muir
Remnant, an isolated mass west of Muir Inlet, has disappeared between
Minnesota Ridge and White Thunder Ridge at the rate of 9.8 meters per
year between the 1892 and the 1948 mapping. Burroughs Glacier, on the
south side of Minnesota Ridge, lowered 3.4 meters per year higher up but
6.5 meters per year near the southeastern edge (Taylor, 1962), and Field
(1947) gives 15 feet (4.6 meters) per year for Plateau Glacier, which
formerly was attached to Burroughs Glacier.

From the point of view of repopulation by plants and animals, it is
clear that there were refuges on some high peaks and ridges all around
this basin throughout Neoglacial time. But these refuges were high and
the climate severe; thus, it is clear that nothing but tundra-type plants
and animals could have inhabited these places, and there is a lower
climatic limit for tundra today near 760 meters (2,500 feet) altitude
which cuts off egress through the lowlands.

Retreat of ice cliffs in sea. - The prehistoric retreat of the very
long ice cliff which stretched across Glacier Bay in Vancouver's time can

be estimated by prorating distances. Assuming that the ice started to disappear up the bay between 1660 and 1760 A. D. (Cooper, 1937, calculates 1735 to 1785 A. D.) it had to retreat 43 kilometers along the east shore to arrive at the recorded 1880 position. If so, the rate of retreat was 200 to 370 meters per year, which is well within the range of retreatal rates in Muir Inlet in historic time. The ice edge may have stood opposite Beartrack Cove, where the high mountain cliffs begin, between 1730 and 1830 A. D. The latter is a calculation of Cooper and Lawrence (Lawrence, 1958) based on tree rings. It would have backed up to Sandy Cove, (Frontispiece) 15 kilometers farther north, between 1805 and 1850 A. D. The Muir Inlet ice stream would have been separated from the Reid Inlet ice to the northwest between 1840 and 1860.

Certainly, the shore plants and birds and animals invaded Muir Inlet from the south to the north as the ice edge vacated this area horizontally. The record of the sea level position of the ice edge is most precise. Field (1947) has recorded these photographically and triangulated them from 1926 to the present. From his maps and photographs, terminal positions were interpolated for the present study (Fig. 3). These start across the narrow part of Muir Inlet one kilometer south of Muir's Cabin in 1880. As Field (1947) points out the wider and deeper the inlet, the more the ice front is exposed to warm water, and the more rapid the retreat up to 800 meters per year (1892 - 1907). As the exposed end of the same ice stream narrowed to the north, its retreat decreased to 335 meters per year from 1936 to 1946, and for a few short years (1926-31, and 1940-42) it almost held its own.

Shore plants and birds are particularly abundant up Adams Inlet on the east. Ice retreat was regular from 1900 to 1930 here, but when the local inflow of ice ceased about 1935, the whole residual mass of ice over the island and central parts of Adams Inlet suddenly decayed. In Wachusett Inlet to the west inflow of ice has continued, so that the rate of retreat beginning in 1913 was 252 meters per year, but where the valley broadened from 1948 to 1960 the rate increased to 554 meters per year (Taylor, 1962).

Sea level has changed measurably even in the short period since the land has been exposed. Because the land is coming up at a rapid rate, it is presumed to be due to the rapid unloading of the earth's crust from Muir Glacier. Hicks and Shofnos (1965) showed from U. S. Coast and Geodetic markers that uplift was 4 cm/year in Muir Inlet and that the regional center of uplift was just southeast near Bartlett Cove. The following measurements of highest raised beaches found in the present study (3 to 5 at each location) tend to confirm this, although the most rapid uplift would center near Klotz Hills and amount to 4.5 cm/year.

| Area | Year exposed approximated | Total uplift beach above highest tide in 1965 | Rate of uplift calculated |
|------|------|------|------|
| Bartlett Cove north shore | 1780 A. D. | 5.0 m | 2.7 cm/yr |
| Sandy Cove | 1830 | 3.8 | 2.8 |
| Muir Cabin and south | 1885 | 3.0 | 3.5 |
| Morse River, south-west shore | 1887 | 2.3 | 3.0 |
| Klotz Hills, north to Delta Station | 1910 | 2.5 | 4.5 |
| Goose Cove south | 1920 A. D. | 2.0 m | 4.4 cm/yr |

This means that shore plants are gaining a beach area one meter high and 5 meters to 20 meters broad each quarter century; indeed, the plants clearly show this (Decker, this volume).

Retreat of ice edge on land. - This triangular area, 25 kilometers on a side, seems to be typical of most hilly areas where deglaciation has occurred. As with the outer region of most ice sheets, the ice surface slope in the late 1800's was moderately steep, 31 meters per kilometer (Cooper, 1937, estimated 150 feet per mile, or 28.5 meters per kilometer, for climax trimline) and through the lowering of this sloping surface, circular hill tops are first to appear (Fig. 3). Red Mountain, 1,250 meters (4,100 feet) high between Casement and McBride Glaciers, has erratics and striae showing it was covered by Neoglacial ice. From 1892 to 1935, a period recorded by photographs, lowering on the steep south slope of this mountain has been at the has been at the rate of 6.1 meters per year; applying this same rate to the uppermost parts, one might construe that the top was poking through somewhere about 1810 A. D. Klotz Hills at 341 meters (1,118 feet) were just being exposed through the ice at the time of the first picture (1892). The hills on the west side just northeast of Morse Glacier were projecting at this time, and presumably first appeared somewhere just after 1800. Bruce Hills at 670 meters (2,200 feet), which divided Cushing Plateau Glacier into the Plateau and Burroughs Glaciers appeared about 1929, but Curtis Hills, at 429 meters (1,406 feet) near the entrance to Wachusett Inlet, first appeared in 1906. The west end of Van Horn Ridge at 648 meters (2,124 feet) first projected above the ice in the 1907 picture but the prominent 368-meter (1,205-foot) landmark just to the south of it, the Nunatak, was not visible until 1911. In the early 1930's, White Thunder Ridge began to project through as a long rising isthmus of land between what has become Muir Remnant Glacier and the main Muir Glacier.

Last to be exposed are four large side valleys, distinctly shallower than the main Muir Inlet, where the flow of ice was cut off at an early date. Concentric lines mark each decade (Fig. 3). The first and most irregular ice mass remained in upper Adams Inlet in the 1929 photographs and it wasted from all sides (Bndicott and Berg Lakes undermined it on the east) until the sea, buoying it up from the west, caused sudden disintegration and annihilation evident in the 1935 pictures and consummated by 1941. McBride Remnant in the broad valley east of the Nunatak was 520 meters thick in 1892, 280 meters thick in 1910, 140 meters thick and beginning to be surrounded by exposed land in 1935, 45 meters thick and completely isolated as a long oval in 1950, and 3 meters thick but essentially gone in 1965 (Haselton, 1966). Retreat of the feather edges of ice at 40 to 150 meters per year is a quarter as fast as ice cliffs in the sea. Similarly, Burroughs Glacier slopes in two directions; since 1916 it has no longer been fed by new ice and so has been disappearing at both ends at 30 to 100 meters per year. Muir Remnant between White Thunder and Minnesota Ridges has a similar rate of retreat at its lowest edge.

Casement Glacier (and earlier, Morse Glacier) is the prime example of a still-active long ice mass with a considerable accumulation area, which however, has been retreating regularly at rates of 30, 95, 98, 113 and 24 meters per year in successive decades since 1910. The two slowest periods of retreat represent the retreat where the ground slopes toward the west. The more rapid rates involve undulating or easterly slopes against the ice.

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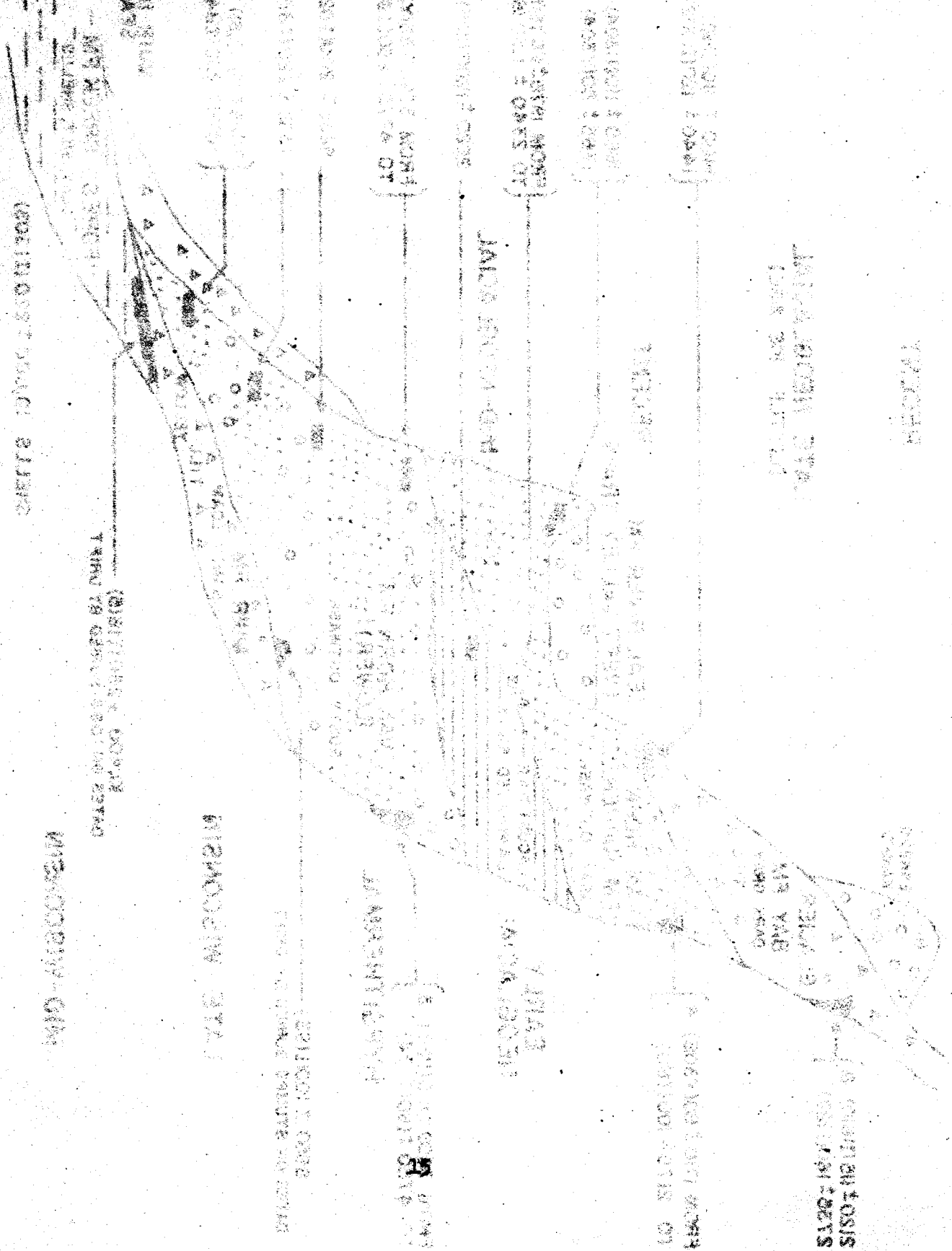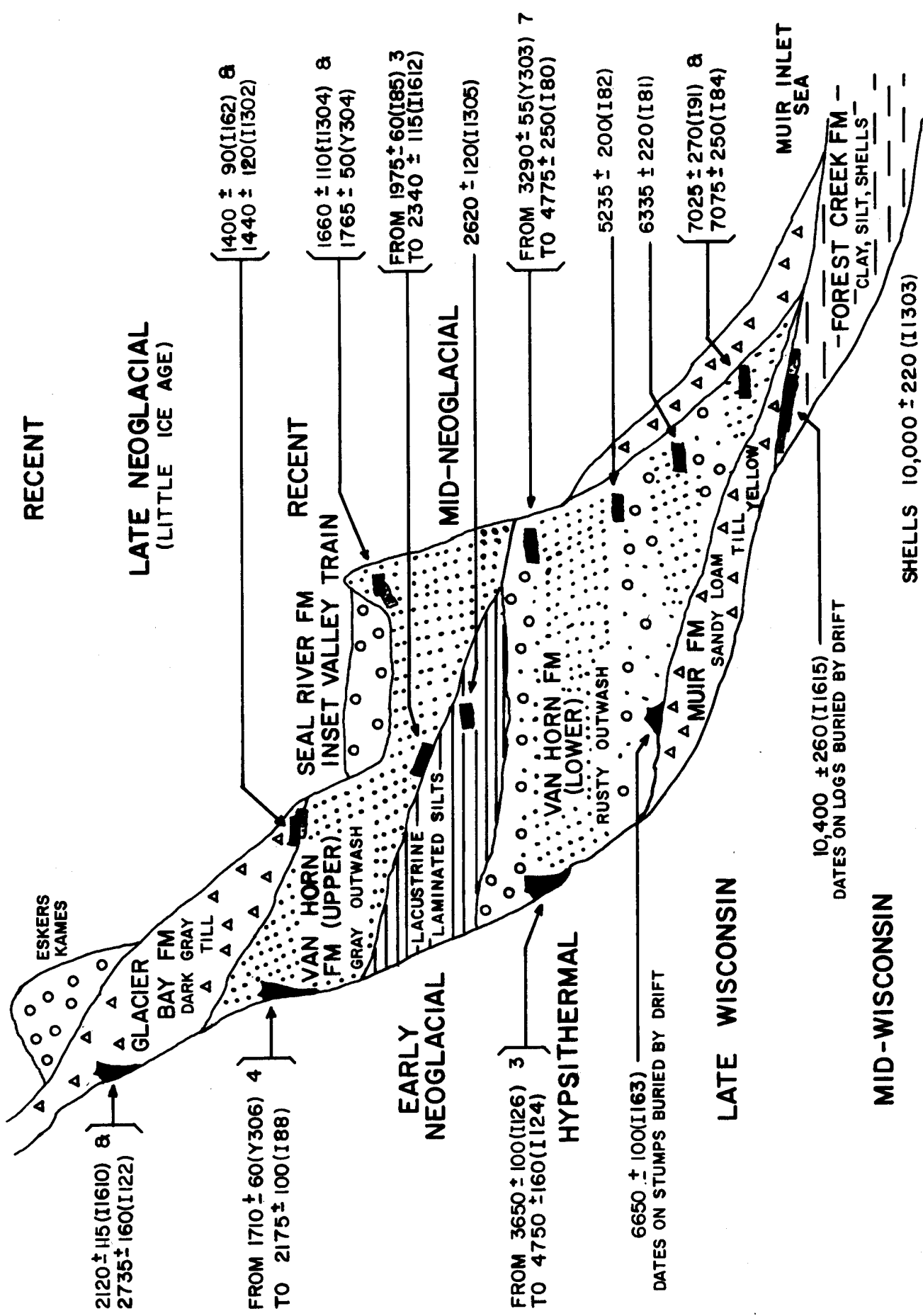
RECENT

LATE NEOGLACIAL
(LITTLE ICE AGE)

RECENT

MID-NEOGLACIAL

EARLY
NEOGLACIAL

HYPSITHERMAL

LATE WISCONSIN

MID-WISCONSIN

ESKERS
KAMES

GLACIER BAY FM
DARK GRAY
TILL

SEAL RIVER FM
INSET VALLEY TRAIN

VAN HORN
FM (UPPER)
GRAY OUTWASH

LACUSTRINE
LAMINATED SILTS

VAN HORN FM
(LOWER)
RUSTY OUTWASH

MUIR FM
SANDY LOAM
YELLOW TILL

FOREST CREEK FM
CLAY, SILT, SHELLS

MUIR INLET
SEA

2120 ± 115(I1610) 8
2735 ± 160(I122)

FROM 1710 ± 60(Y306) 4
TO 2175 ± 100(I88)

FROM 3650 ± 100(I126) 3
TO 4750 ± 160(I124)

6650 ± 100(I163)
DATES ON STUMPS BURIED BY DRIFT

1400 ± 90(I162) 8
1440 ± 120(I1302)

1660 ± 110(I1304) 8
1765 ± 50(Y304)

FROM 1975 ± 60(I85) 3
TO 2340 ± 115(I1612)

2620 ± 120(I1305)

FROM 3290 ± 55(Y303) 7
TO 4775 ± 250(I80)

5235 ± 200(I82)

6335 ± 220(I81)

7025 ± 270(I91) 8
7075 ± 250(I84)

10,400 ± 260(I1615)
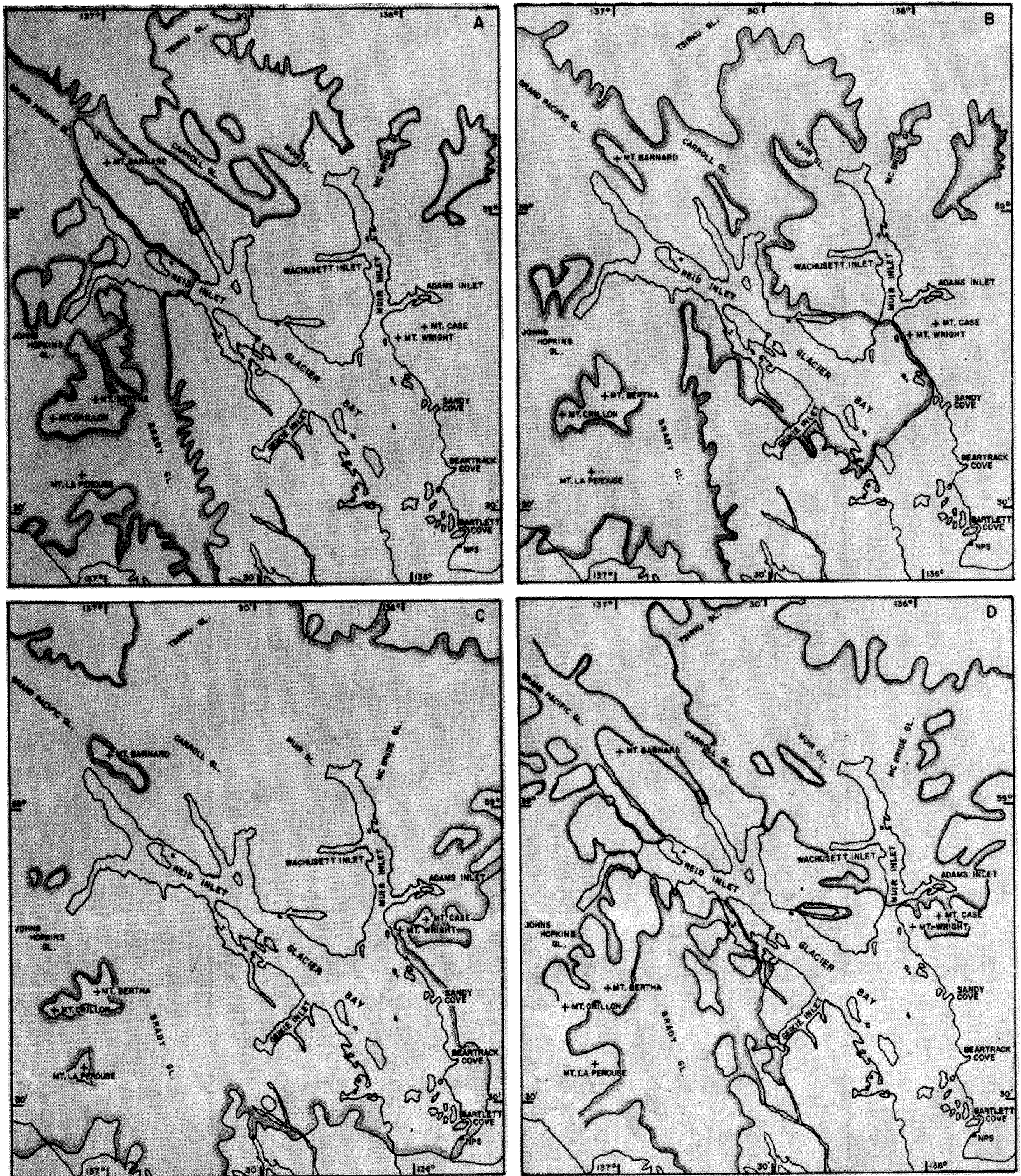DATES ON LOGS BURIED BY DRIFT

SHELLS 10,000 ± 220(I1303)

Figure 2 - Maps showing probable extent of glacier ice
in Glacier Bay area, Alaska, and adjacent
Canada, between 5200 B.C. and 1892 A.D.

A. Hypsithermal Time, 5200 to 2900 B.C.
B. Early Neoglacial Time, 2800 to 950 B.C.
C. Little Ice Age Climax, 1700 A.D.
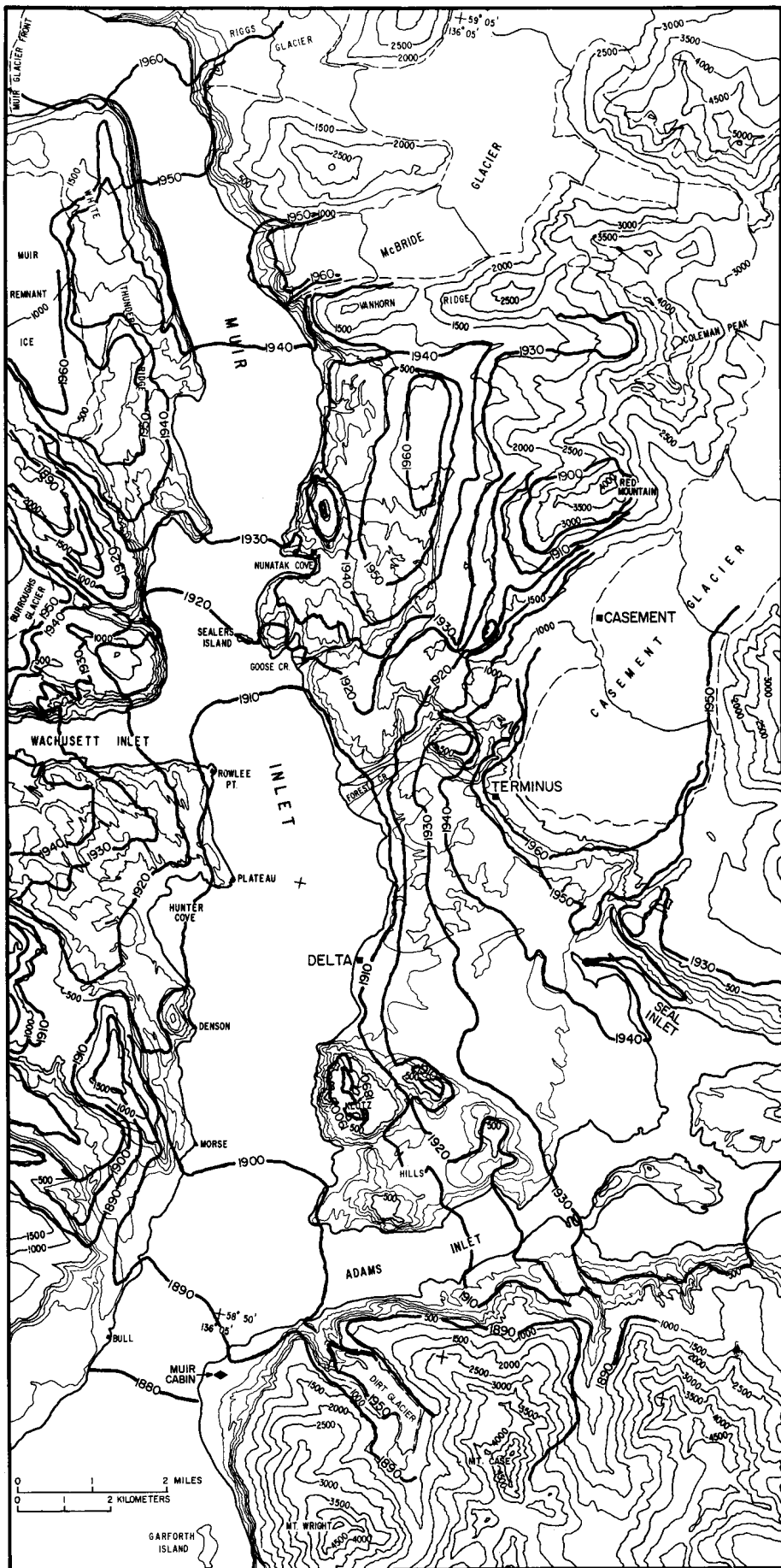D. First maps and photos (Reid), 1892 A.D.

Figure 3 - Map of Muir Inlet area showing retreat of glacier fronts by
decades since 1880. Black squares indicate locations of
meteorological stations.