THE UNITED STATES GLACIOLOGICAL RESEARCHES DURING THE INTERNATIONAL GEOPHYSICAL YEAR*

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Abstract. The U.S. IGY program in glaciology is reviewed in two parts: Antarctica and northern latitudes. The objectives of the program are outlined and the results of each investigation are briefly summarized. A separate discussion of observations related to changes in the Earth's ice cover is included.

Résumé. Le programme glaciologique des États-Unis pendant l'AGI est présenté en deux parties: l'Antarctique et les latitudes du nord. Les buts du programme sont exposés et les résultats de chaque investigation sont brièvement indiqués. Une discussion séparée traite des observations liées à la variation de la couverture de glace de la terre.

Zusammenfassung. Das USA-IGY Programm für Gletscherkunde ist in zwei Teilen beschrieben: Antarktis und die nördlichen Breiten. Der Zweck dieses Programmes ist angeführt und die Ergebnisse dieser Untersuchungen sind kurz zusammengefasst. Eine gesonderte Diskussion der Beobachtungen befasst sich mit den Veränderungen in der Eisdecke der Erde.

It is convenient to consider the IGY glaciology investigations of the United States in two parts: Antarctica and northern latitudes. In the Antarctic, emphasis was necessarily placed on descriptive studies which are basic for more comprehensive glaciological research; some detailed programs were also conducted. In the Northern Hemisphere program, primary emphasis was placed on detailed studies of chosen glaciers, although some reconnaissance studies were also conducted.

Antarctica

Pre-IGY

Reference should be made here to a publication issued by the National Academy of Sciences (U.S. National Academy of Sciences, 1961, p. 38-41). Although the continent was sighted as early as the 1820's, the first recorded landing was not made until 1895. The inland ice was first seen in 1903 by Scott's party in Victoria Land, but the first wintering on the inland ice was not accomplished until 1956 at the U.S.S.R. Pionerskaya Station in East Antarctica. The progress of glaciological research and the general state of knowledge regarding the Antarctic ice cover prior to the IGY have been summarized in English by L. Gould and N. E. Odell, and in German by R. von Klebelsberg and H.-P. Kosack. The first truly international effort—the Norwegian-British-Swedish Antarctic Expedition of 1949-52—introduced comprehensive geophysical studies of the ice shelves of western Dronning Maud Land and the adjoining inland ice, based on the new concepts developed by H. W. Ahlmann and H. U. Sverdrup in the North Atlantic area. In many ways this expedition established the pattern of the IGY glaciology program.

The pre-IGY expeditions added much to the knowledge of the ice sheet and its special features. But, for the most part, it had not been possible before the IGY to do more than study one area, either in the vicinity of a base camp or on an overland trek. Expeditions were isolated in their own segment of the continent, and relatively little continuity or coordination of observations could even be attempted. As late as 1930, the interior of the continent, comprising

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the inland ice and protruding mountain ranges, was still unknown except for a wedge-shaped area between the Ross Ice Shelf and the South Pole. By 1955 this wedge had grown appreciably, and a number of sectors extending several hundred miles from the coastline had been visited. However, a vast region in the interior, measuring some 5,000,000 to 7,000,000 square kilometers and extending outward in three quadrants from the South Pole, had never been seen, and no station had yet been established for systematic observations on the inland ice.

The effectiveness of the IGY program in Antarctica was in part due to the application of modern techniques, instrumentation, and logistical methods on a scale never previously attempted. It was also the result of extensive planning and efforts to develop an integrated program on an international scale.

After much preliminary planning by its Technical Panel on Glaciology, the U.S. National Committee for the IGY proposed three basic principles to guide the United States' approach to Antarctic glaciological research: (1) investigations should concentrate on items which are peculiar to the Antarctic and which cannot be studied efficiently and effectively in more accessible areas; (2) attention should be given, in so far as possible, to basic principles and to matters of world-wide significance; (3) efforts should be made to learn as much as possible about the physical state, environment, and behavior of Antarctic ice bodies. To satisfy these principles, certain lines of investigation were recommended: (1) measurement of ice thickness leading to a reliable calculation of the volume of Antarctic ice primarily by the seismic-reflection procedure and gravimetric surveys; (2) observations of variations in the volume of Antarctic ice in the past and measurement of current rates of change; (3) deep core drilling as a means of obtaining data at depth in the inland ice and the Ross Ice Shelf; (4) determination of firn stratigraphy; (5) studies of thermal regime; (6) studies of crystal fabrics; (7) measurements of glacier movement; (8) measurements of rates of accumulation and wastage to determine Antarctic glacier regime; (9) micrometeorological studies; (10) determination of climatic fluctuations as recorded by changes in the size of Antarctic glaciers.

Traverses

Glaciological observations were conducted during the IGY by seven oversnow traverses and by airlifted research parties under the general direction of the Arctic Institute of North America. The IGY traverses and aircraft landings conducted by C. R. Bentley, R. Bradley, I. Cook, A. P. Crary, and E. C. Thiel penetrated a large part of West Antarctica as well as the Victoria Land Plateau of East Antarctica (Bentley, 1960; Bentley and Ostenso, 1959, 1961; Bentley and others, 1960; Crary, 1959) (Fig. 1). The traverse parties employed seismic, gravimetric, magnetic, and glaciological techniques to obtain information on the interior ice sheet. The information sought included: surface elevations through multiple altimetry methods; thickness of ice (and water, if applicable) by seismic soundings; character of large- and small-scale surface morphology; character of the rock underlying the ice by seismic refraction methods and magnetic correlations; geodetic information and ice thicknesses from gravity measurements; annual snow accumulation from pit, stake, and geochemical measurements; character of snow and firn (including temperature, density, grain size); average annual surface temperatures from englacial temperatures; and limited biological and geological collections and studies.

The principal results of the traverses were the delineation of surface elevations and ice thicknesses over a large portion of West Antarctica. In view of the numerous mountains protruding through the ice in West Antarctica, it had been supposed that the ice sheet in this area was relatively thin compared with the lofty ice plateau of East Antarctica. The IGY traverses revealed an average ice thickness of 2,000 m. in West Antarctica, from which the total volume of the Antarctic Ice Sheet may now be estimated to be in excess of 25,000,000 km.[3]. Much of the rock surface beneath the ice sheet of West Antarctica was found to be near, below, and in some cases, considerably below sea-level. The greatest thickness of ice yet reported, 4,270 meters, was measured near Byrd Station; the rock surface there is 2,490 m. below sea-level. The troughs below sea-level beginning at the Filchner and Ross Ice Shelves

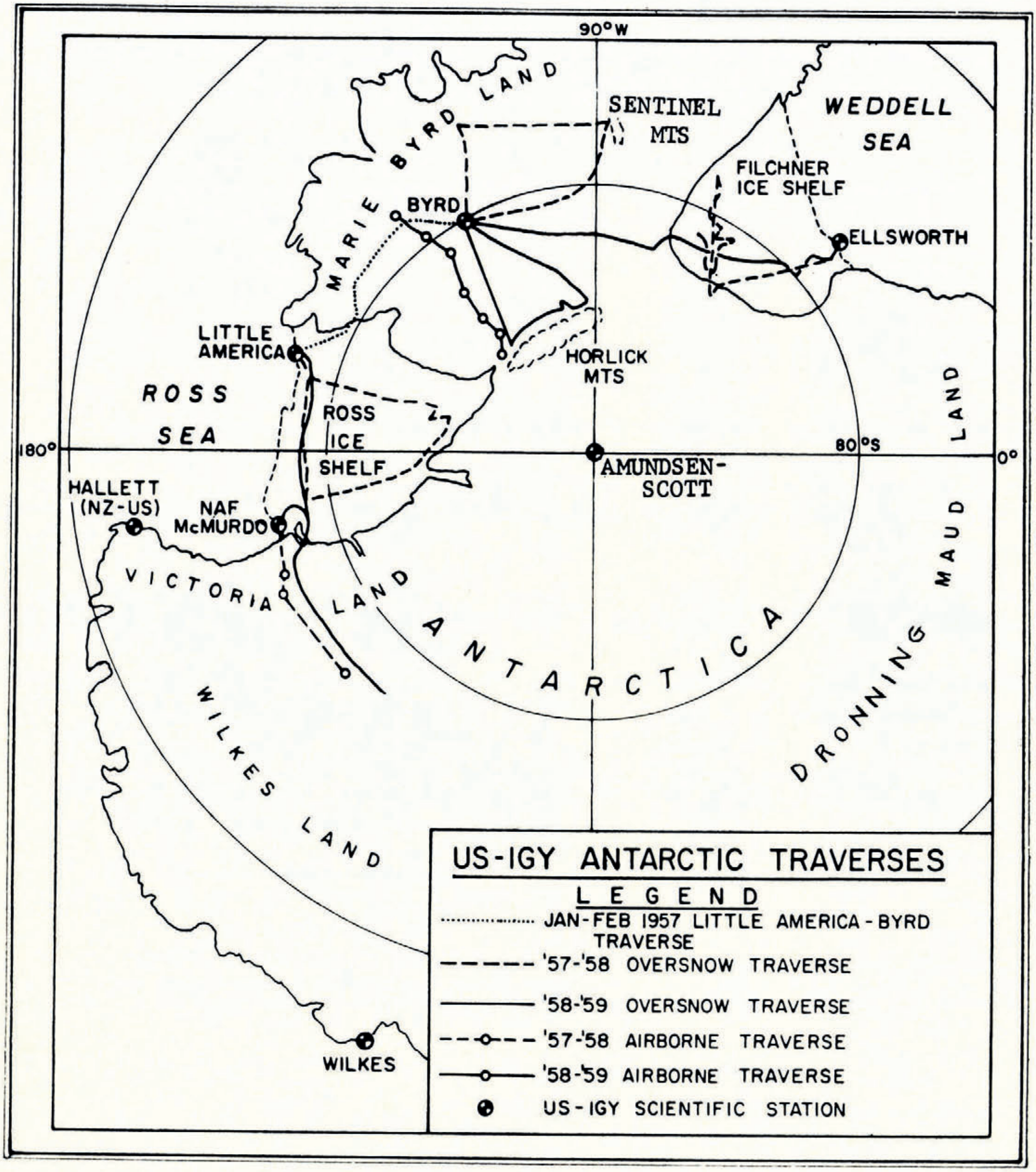

Fig. 1

were traced inland towards one another. It is now believed that, if these troughs are connected, they are connected at most by a narrow topographic low, expressing the break between the folded mountains of the Palmer Peninsula extension and the Antarctic horst; in any event, it is known that the ice in the troughs is grounded inland, thus precluding the

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possibility of circulation of water directly between the Ross and Weddell Seas. Another trough or under-ice channel has been traced from the Ross Sea into the Bellingshausen and eastern Amundsen Seas.

On the traverses, snow and ice stratigraphy was studied in some 250 pits dug to 3-meter depth; data on density were extended to 10-meter depth in the holes drilled for temperature measurements and seismic purposes. These data are now under study to determine the annual accumulation and to gain further insight into densification of snow and firn.

Station Glaciology

At Little America, Byrd, Ellsworth, Amundsen-Scott (South Pole), and Wilkes, snow stakes were set in for determination of accumulation and the character of surface snow and ice was monitored and logged. Glacial, meteorological, and surface heat exchange observations were made at Little America and Amundsen-Scott. Ice elevation and movement observations were initiated at all stations.

In addition, some special station programs were carried out. These included deep snow pits at all stations, ranging from 20 to 35 m. for the purpose of studying many ice characteristics. At Wilkes Station, these studies were made at an inland site, about 80 km. south of the station, at an elevation of 1,300 m. This inland site was established and occupied for short periods by station glaciologists; in the deep pit at this site a horizontal deformation tunnel (6 m. long and 2 m. in diameter) was constructed at the 30 m. level.

At all stations, personnel took advantage of opportunities to visit surrounding territory, photograph glacial features, acquire rock samples, make observations of glacier development, movement, and budget, and make as complete a survey as possible for future reference.

Deep Drilling

Reference should be made here to certain reports (Bender and Gow, 1961; Marshall and Gow, 1958; Patenaude, 1958; Patenaude and others, 1959; Ragle and others, 1960). Prior to the shipment of drilling equipment to Antarctica, test drillings were conducted in Greenland in the summers of 1956 and 1957. A Failing drill rig (used in the petroleum industry) was modified for deep drilling in ice and a hole was drilled to 430 m. depth. The cores recovered were estimated to have been laid down in the fifteenth century. The equipment was shipped to Antarctica for drilling at Byrd and Little America stations under the direction of E. W. Marshall, R. H. Ragle, and A. J. Gow. By January 1958, substantially complete core recovery had been achieved to 309 m. at Byrd. The drill hole was capped, the cores sent to CRREL (then SIPRE) for analysis, and the drilling rig was transferred to Little America, where drilling on the Ross Ice Shelf was begun in October 1958. A hole was drilled to a depth of 255 m. where a crack permitted sea-water to enter and rise to 189 m. After this water froze, the hole was rebored to 232 m. It was estimated that the ice shelf was about 260 m. thick in that area.

Stratigraphy of the cores from Greenland was examined in transmitted light to a depth of 140 m. Continuous density measurements were made to a depth of 90 m.; spot density measurements were made at greater depths. In the upper section, annual accumulation of snow was determined by visual stratigraphy observations, and densification measurements. Airborne particles were filtered (using membranes with retention of 0·8 microns). The particles included organic material, angular mineral grains, and magnetic spherules possibly of cosmic origin. At the 1912 (Katmai) horizon a discrete mineralogical horizon was found. It is hoped that stratigraphic correlation between glaciers of both hemispheres can be made for times of explosive vulcanism.

The cores at Byrd Station were similarly inspected for visual stratigraphy in transmitted light; distinctive layering was detected to 120 m. and thin ice bands (4 mm.) throughout the core. The stratigraphy consisted of alternating layers of coarse- and fine-grained snows. The approximate annual accumulation was calculated to be about 15 cm. water equivalent; if this rate is constant throughout the hole, the ice at the bottom is approximately 2,000 years old. $^{18}O/^{16}O$ analyses have not proved conclusive, presumably due to the low annual accumulation and drifting of snow. Petrofabric studies revealed no patterns of preferred orientation at any depth.

In December 1958, measurements of temperature, diameter, and inclination of the hole were made. Closure near the bottom of the hole was 2·8 cm.; no inclination was detected. Subsequent measurements showed that temperature had stabilized and that closure was accelerating.

Stratigraphy of the core at Little America was similarly studied. Layers of foreign material were observed at 172·1, 219·4, and 222·8 m. Microscopic examination of the first layer revealed aggregates of glassy, markedly angular material tentatively identified as volcanic ash.

The depth-density profile was accurately determined to the bottom of the drill hole. A density anomaly was found between 20 and 40 m., and there is evidence that the accumulation in this zone of anomalous density may have occurred at lower temperatures than now exist; alternatively, it may reflect some unique condition of the original site of accumulation. It is estimated that the average accumulation is 22 cm. of water equivalent and that snow now 18 m. below the surface was deposited 40 years ago. Since no saline ice was encountered in the core, it appears that fresh ice may persist to the bottom of the shelf (estimated 3-5 m. below the bottom of the hole) and that any sea ice that may have accumulated has subsequently melted.

Petrofabric studies showed more complex metamorphism below the firn-ice transition at Little America (55 m.) than at Byrd. Strained crystals and strongly developed fabric orientations, observed below 90 mm., probably reflect the deformation of the shelf ice.

It is hoped that final results of the core analyses and measurements of the holes will yield information on climate and volcanic activity for the past several hundred years, as well as basic information on the flow of ice. It is hoped that thermal drills now being tested can be used in the future to penetrate the entire thickness of the ice sheet.

Oxygen Isotopes

The effect of temperature on the $^{18}O/^{16}O$ ratio of rain and snow—a decrease in the ratio with decreasing temperature, hence also with increasing altitude—was tested by R. P. Sharp and S. Epstein, of the California Institute of Technology, as a method of identifying annual layers in glaciers (Epstein and Sharp, 1959). The method was tested with success in Greenland: good correlation was found between the seasonal variations at two sites 360 km. apart and the seasonal variation in a deep hole was clearly recognizable to a depth of 300 m. The method was then applied to samples for Byrd, Little America, and South Pole Stations with inconclusive results. It is supposed that the relatively small annual accumulation and the drifting of snow account for much of the uncertainty, and that the method may prove to be more effective in the future with the gathering of larger samples from each accumulation layer. It was noted that the $^{18}O/^{16}O$ ratio for samples from the South Pole are the lowest yet measured, which tends to confirm the basic premise of temperature control.

Ross Ice Shelf Deformation (Fig. 2)

A special project was undertaken by J. H. Zumberge of the University of Michigan, to study the deformation of the Ross Ice Shelf north of Roosevelt Island (Zumberge and others, 1960). The structural features of the ice were observed and related to the measured horizontal compressive stresses. Although most of the Ross Ice Shelf is a featureless plain, the area between Roosevelt Island and the Bay of Whales contains a system of parallel crevasses and intersecting ridges and troughs. The ridges and troughs are, in effect, anticlines and synclines found in strata of firn. Because the structural features are analogous to those of deformed

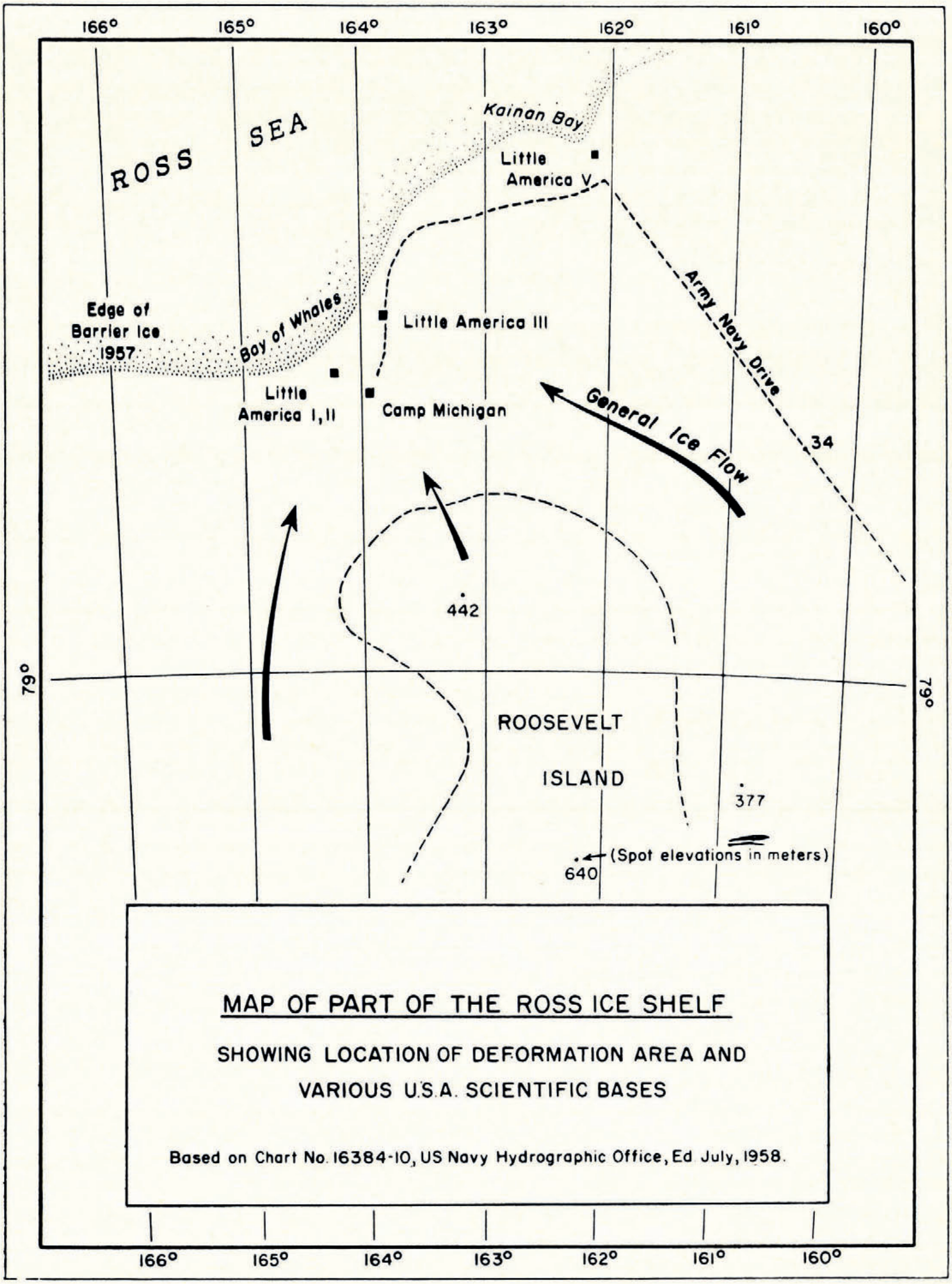
166°
165°
164°
163°
162°
161°
160°
ROSS SEA
Kainan Bay
Little America V
Army Navy Drive
Edge of Barrier Ice 1957
Bay of Whales
Little America III
Little America I, II
Camp Michigan
General Ice Flow
34
442
79°
ROOSEVELT ISLAND
377
(Spot elevations in meters)
640
MAP OF PART OF THE ROSS ICE SHELF
SHOWING LOCATION OF DEFORMATION AREA AND VARIOUS U.S.A. SCIENTIFIC BASES
Based on Chart No. 16384-10, US Navy Hydrographic Office, Ed July, 1958.

Fig. 2

sedimentary rocks, the project was designed as a scale model study of the deformation of conventional geological structures. The ice shelf north of Roosevelt Island is thinner than the ice which flows around the island; it is this relatively thin ice which is deformed. Because the ice is everywhere afloat in the area studied, the strong deformation in this area must be caused by the confluence of the two ice masses from either side of the island.

The observations included: triangulation, topographic mapping of special features, detailed snow stratigraphy, petrofabric analysis of deformed ice layers, temperature measurements daily at various depths, accumulation (by stakes), and measurements of strain in selected areas.

The crevasses, ranging in width from 0·5 to 8 or more meters, generally trend east-west. The average length is a few hundred meters, the greatest length about 1,000 m. The crevasses display a marked parallelism and regular spacing, which strongly suggest a uniform stress pattern. The firn folds are roughly parallel and trend north-south. (The anticlines are more pronounced than the synclines, which are readily filled and thus obscured by drifting snow.) The folds have amplitudes of 5-15 m., wave lengths of 100 m. or more. The axes of most, but not all, of the folds are orthogonal to the crevasse system and to the principal compressive axis. The crevasses are essentially perpendicular to the principal tension axis except in the immediate vicinity of the anticlinal crests. Ages of the anticlinal folds were estimated from strain data and from differential accumulation to be of the order of 30 years. The study of crystal fabrics and their correlation with stress patterns is continuing.

Strain Rate of Ross Ice Shelf

Horizontal ice strain or strain creep was measured by A. P. Crary (Crary, 1961[a], [b]) on the Ross Ice Shelf near Little America by repeated survey of a network of stakes in an area approximately 8×6 km. The principal horizontal creep rates were 129×10^{-5} and 81×10^{-5}, normal and parallel to the direction of absolute ice flow, respectively. The maximum strain rate is in good agreement with the rate deduced from Weertman's formula for the creep of floating ice, using acceptable flow law constants. The calculation of vertical strain yields an annual loss of ice thickness of 54 cm. by ice creep. The combined effect of accumulation, ice creep, and deduced bottom melting (80 m./yr.) yields an apparent annual loss of 108 cm., corresponding in the Little America area to an annual elevation decrease of about 18 cm.

Velocity of movement of 278 m./yr. has been calculated on the basis of the surface slope at Little America of 65 cm./km. and the annual elevation decrease of 18 cm./yr. given above. These values compare favorably with the movement (about 265 m./yr.) determined by comparison of the present location of Kainan Bay and the position reported by the Japanese expedition in 1912. Extrapolation of regime factors to the thicker ice and measured slopes suggest that the ice west of Roosevelt Island is moving three to four times as fast as the ice on the east side.

Measurements by C. R. Wilson and A. P. Crary (Wilson and Crary, 1961) on the Skelton Glacier (on the west side of the Ross Ice Shelf between the Worcester and Royal Society Ranges) showed that the annual volume of ice flowing from the Skelton is 712×10^6 m.^{3} water equivalent. Annual accumulation is estimated to be $1{,}018 \times 10^6$ m.^{3} water equivalent, of which some 30 per cent may be lost to adjacent areas by katabatic winds. From this, it is concluded that the Skelton now receives little or no contribution from the ice of the high plateau; it is further supposed that this condition is general on the west side of the Ross Ice Shelf and is the basis for the existence of the so-called "dry" valleys west of McMurdo Sound.

Radiation Studies and Micrometeorological Studies

A special project was conducted by Herfried Hoinkes to obtain records of all components of the radiation balance in Antarctica (Hoinkes, 1960, 1961). Measurements made at Little

America between February 1957 and February 1958 were supplemented by limited measurements at the South Pole and Byrd Stations. It was found that the albedo and net radiation could not be recorded directly in the polar regions where the sun remains at low angles for considerable periods of time. These quantities must be calculated from separate records of up-and-down-facing thermopiles with different calibration factors depending upon solar altitude, cloudiness, and temperature. The intensity of direct solar radiation at Little America (elevation 44 m.) was found to correspond to the intensity measured in the European Alps at 3,000 m. in June; the intensity at the South Pole (elevation 2,800 m.) corresponds to that of the European Alps at 3,000 m. in December. Albedo measurements at Byrd and South Pole gave a mean value of 89 per cent from a range of 84 to 93 per cent. The mean albedo for overcast days at Little America was 88·1 per cent in summer, 90·3 per cent in spring, and 89·8 per cent in fall. Studies are being made of the heat balance by turbulent and latent heat transfer and of the erosion and transportation of snow by wind.

The micrometeorological investigation of Dalrymple (1960) at the South Pole and Little America revealed similar wind and temperature profiles in the first eight meters, the contrasting environments and types of climate notwithstanding. The surface inversions within eight meters were larger than those at the South Pole: at Little America, the maximum inversion to eight meters was 19·2° C., the maximum to two meters was 14·0° C., occurring some six weeks after sunset. At the South Pole, the inversion rarely exceeded 11° C., in the first eight meters (maximum recorded was 14·7° C.). The surface inversion averaged 21° C. at a mean height of 3,350 m.; the maximum inversion was 33·4° C., the maximum height 4,300 m. At both stations, strong surface inversions were frequent during stable periods in winter ; at these times, the wind profiles were logarithmic only to two meters. During near isothermal temperatures characteristic of midsummer, the wind profiles were logarithmic to eight meters.

Glacial Geology

An extensive study of glacial geology was made in the ice-free area of McMurdo Sound, especially in Taylor Dry Valley (Péwé, 1960[a], [b]). T. L. Péwé found four major Quaternary glaciations with a relatively long time interval between the first and second. Glacial ice from the most recent, which occurred not less than 6,000 years ago, may still be found in the drift. Deposits from the previous glaciations are more subdued, those of the oldest being rare and preserved only on high ridges (above 550 m.). From the oldest to youngest, the following names have been proposed for these four glacial episodes: McMurdo, Taylor, Fryxell, and Koettlitz. Correlation between these glaciations and Pleistocene glaciations in the Northern Hemisphere or elsewhere in the Southern Hemisphere is uncertain at present.

Northern Latitudes

The U.S. IGY program in northern latitudes included observations of glaciers and sea ice on a more extensive and comprehensive scale than had previously been attempted. In Alaska, detailed studies of glacier regimen were carried out at three localities, eight glaciers were mapped, and the condition and behavior of the termini of many other glaciers were determined by ground and air reconnaissance. Detailed studies were made of the structure, flow, and mass budget of two glaciers in Washington State; less detailed studies were made on six other glaciers in Washington, Oregon, and Montana. In the Polar Basin, three drifting stations were occupied for various periods and detailed studies were made of the ice shelves of Ellesmere Island. In addition, a program of deep drilling and oxygen isotope analysis was carried out in Greenland, partly as a preliminary test of the application of these methods in Antarctica.

Alaska

Until the late 1940's, observations of Alaskan glaciers were confined largely to the terminal areas and were predominantly concerned with variations in length, changes in surface level, and the environmental and geological aspects. Detailed regimen studies were begun in 1948 on the upper Seward Glacier in the St. Elias Mountains of Yukon Territory and Alaska (Sharp, 1951[a], [b], [c], [1952]), and in 1949 on the upper Taku Glacier of the Coast Mountains of southeastern Alaska (Heusser, 1954; Heusser and others, 1954; LaChapelle, 1954; Miller, [1956]; Nielsen, 1957). Air photography performed during the 1940's and early 1950's provided a basis for more detailed topographic maps and a further record from which to determine the distribution and morphological characteristics of glaciers, their behavior,

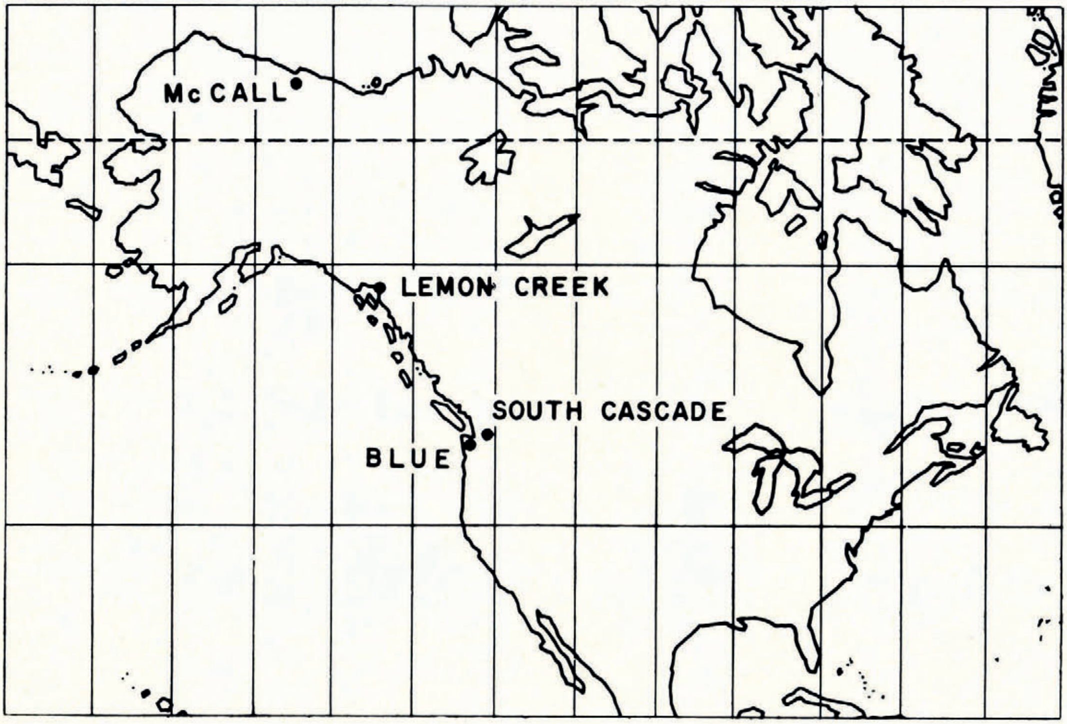

Fig. 3. Index map for Figures 4, 5, 6, 7

and the elevation of the firn limit in different areas. Concurrently, the development of radiocarbon dating and improved geobotanical techniques furnished new data on the chronology of glacier fluctuations prior to the period of direct observations.

The IGY program carried forward the various projects of study which were already under way and initiated new ones. The primary objectives were to determine the present state of the glaciers with respect to the current environment, and the speed of their response to climatic changes, to establish a basis for future measurements, and to gather further data for analyzing the various causes of glacier fluctuations.

Detailed observations which had been carried on since 1953 at Lemon Creek Glacier in the Coast Mountains of south-eastern Alaska were continued through 1958 as part of the Juneau Ice Field Research Project of the American Geographical Society, under the sponsorship of the Office of Naval Research (Heusser, 1958; Heusser and Marcus, 1960; Wilson, 1959). The Lemon Creek Glacier (Figs. 3, 4) was selected upon the advice of H. W. Ahlmann

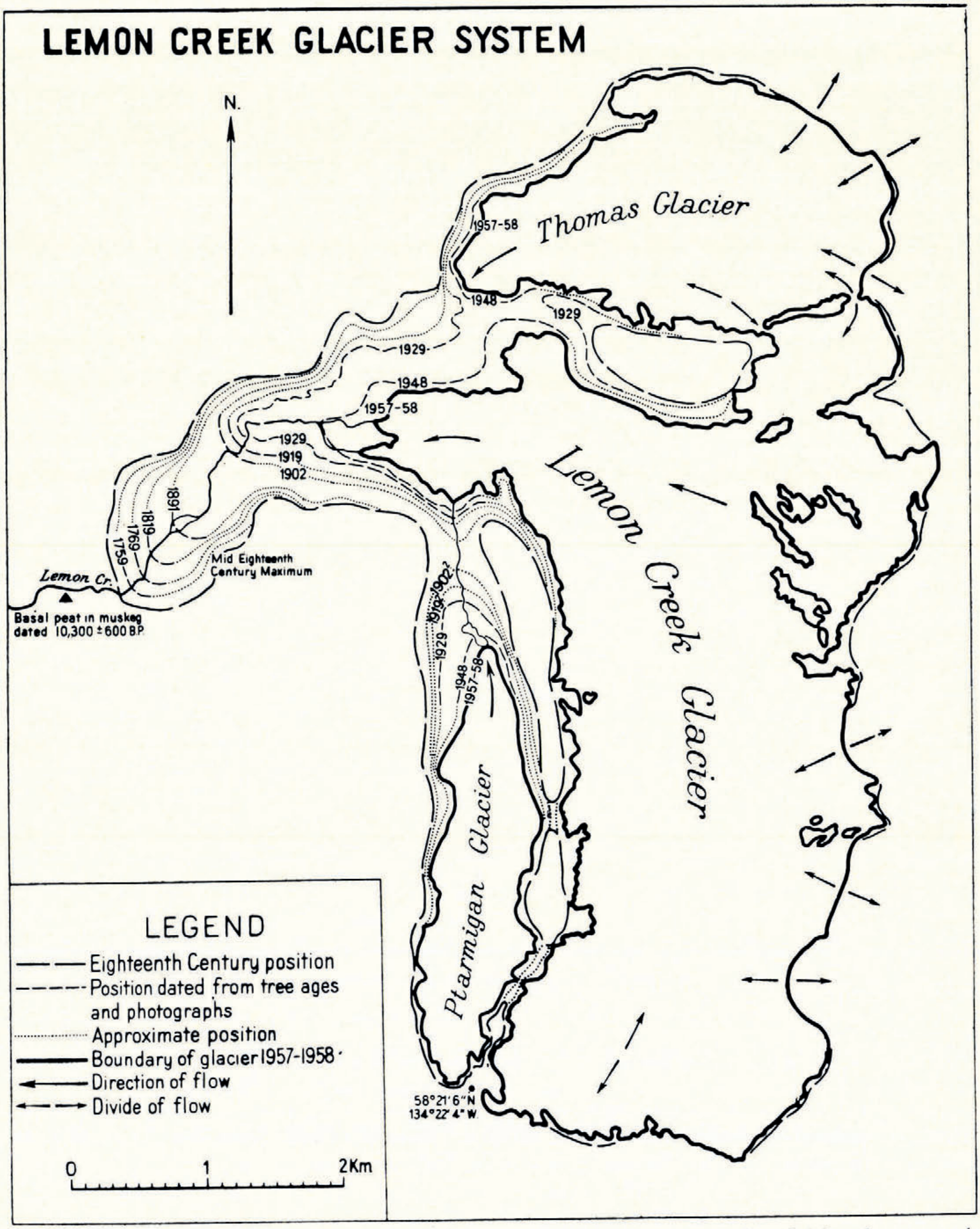

Fig. 4. Map of Lemon Creek Glacier system showing positions of the glacier margin between the mid-eighteenth century and 1957-58

as a representative glacier of north-western North America. The hydrological budget, surface movement, mass transfer of ice, and history of the glacier in recent centuries were studied. Negative budgets of $0 \cdot 92 \times 10^6$ and $8 \cdot 96 \times 10^6$ m.^{3} of water were determined for 1956-57 and 1957-58 respectively. A net deficit of 10 $\times$ 10^6 m.^{3} of water was determined for the period 1953-58; from photographs, a deficit of 16 $\times$ 10^6 m.^{3} is estimated for the period 1948-53. Relationships between the glacier budget and climate are complex; detailed annual correlations have not proved possible. From radiocarbon dating of wood and peat, it is concluded that the glacier has not advanced more than 375 m., if at all, beyond the maximum of 1750 during the past 10,000 years.

During the IGY detailed studies were initiated on two polar glaciers in the Brooks Range in northern Alaska. The Arctic Institute of North America established a station on McCall Glacier (Fig. 5) where observations were conducted from June to October 1957 under the leadership of R. C. Hubley and from February to August 1958 by Svenn Orvig (Keeler, 1958, 1959; Mason, 1959; Sater, 1959). The Geophysics Research Directorate of the AFCRC sponsored a program of studies conducted by G. W. Holmes in July and August 1958 on Chamberlin Glacier, some 40 km. west of McCall (Larsson, 1960). On both glaciers, primary emphasis was directed toward an understanding of the energy balance of the ice mass. The McCall is a relatively long and narrow glacier (length 8 km., average width 600 m.). The lower part of the glacier was free of snow throughout most of the summer of 1957. Ablation values were considered high (almost equal to those for Blue Glacier). It is thought that the 1957 ablation season was an unusually long and warm one. Peculiarities in the Chamberlin Glacier regime suggest that it may be difficult to relate the regimen of the glacier to the climate of the Brooks Range which may be determined largely by topography.

The American Geographical Society sponsored two programs concerned with recording the status and behavior of glaciers in various parts of Alaska. The first project dealt with preparation of detailed maps based on aerial photogrammetry of selected small valley glaciers in several different mountain ranges as a basis for future studies of morphological characteristics and mass balance (American Geographical Society, 1960; Case, 1958). These glaciers range in length from 3 to 6 km., in width from 0·5 to 2 km. Surveys, supported by aerial photography of the U.S. Navy and U.S. Coast and Geodetic Survey, were made by James Case and Austin Post of the following seven glaciers: West Gulkana and Polychrome (Alaska Range); Chikuminuk (Tikchik Mts.); Bear Lake (Kenai Mts.); Worthington (Chugach Mts.); Little Jarvis (St. Elias Mts.). In addition, similar surveys and aerial photographs were obtained by the respective research parties and the U.S. Air Force for McCall and Lemon Creek Glaciers. Maps on a scale of 1:10,000 with 5-meter contour intervals have been prepared and published by the AGS. It is anticipated that the surveys will be repeated after a suitable interval to detect whatever changes are taking place.

The principal objective of the second AGS project was the study of glacier behavior, both past and present, as revealed by changes in their terminal areas. Surveys of some 80 glaciers were conducted under the direction of W. O. Field (Field, 1958). Several glaciers were visited in the Alaska Range and Wrangell Mountains of interior Alaska, but the concentration of effort was within coastal ranges: the Kenai, Chugach, St. Elias and Coast Mountains. Such localities of former classical studies as Prince William Sound, Yakutat Bay, and Glacier Bay were visited. The localities included in the study were largely in the coastal and interior mountains of southern Alaska where comparable observations had been carried out since the last quarter of the nineteenth century. All termini were photographed from identifiable sites, including many established by earlier observers. Termini which had changed appreciably were surveyed.

United States South of Alaska

In that part of the United States called variously conterminous or contiguous (i.e., exclusive of Alaska and Hawaii), but in common parlance still called Western United States or United States south of Alaska, the IGY glaciology program was directed toward answering more specific questions: where do glaciers exist in the United States and what is their current

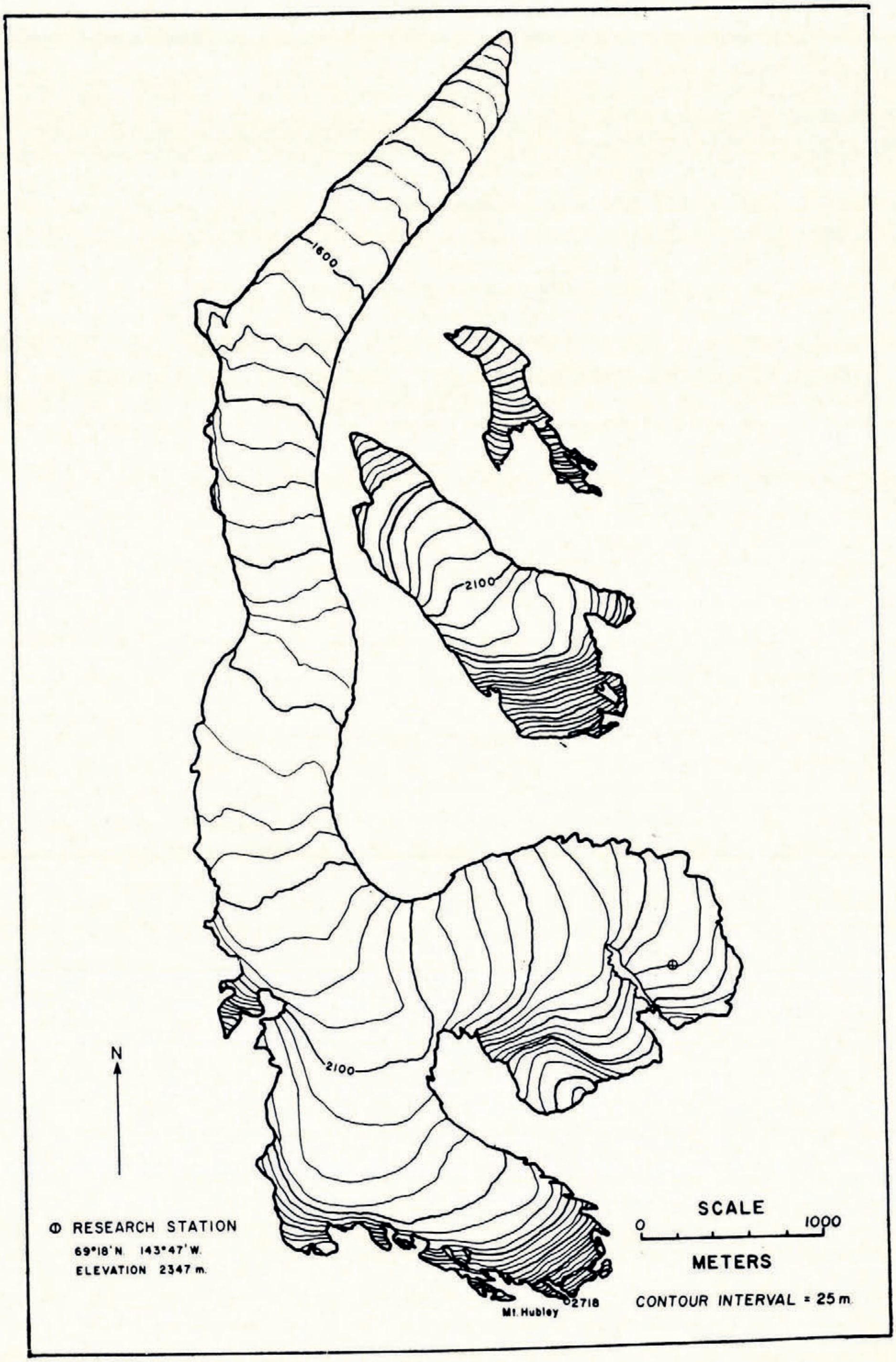

Fig. 5. Map of McCall Glacier

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metabolism and state of health? What are their climatologic environments? What processes are responsible for accumulation, firnification, and ablation of these glaciers? How does radiation penetrate and attenuate in ice and how significant is subsurface ablation? How do the unique hydrologic characteristics of a glacier influence the run-off pattern of melt water? How does the surface and subsurface ice velocity field adjust to changing climate, curvature of bed, a non-cylindrical channel, and other complications? What causes foliation and ice crystal orientations in a flowing glacier? Can isotope analysis lend insight into the genesis of different types of ice and structural features in glaciers? (Meier, 1960; Rigsby, 1958.)

Two projects were conducted on the Blue Glacier (Mt. Olympus). On the lower part of the glacier, a project led by R. P. Sharp of the California Institute of Technology, sought a clearer understanding of the flow dynamics and structural constitution of a typical valley glacier (Sharp, 1958) (Fig. 6). Attention was concentrated on the lower glacier, a tongue about 2 km. long. Seismic studies revealed a maximum ice thickness of nearly 300 m. near the firn edge and an irregular bedrock channel. Three components of velocity at 48 points on the glacier surface were determined by conventional triangulation techniques; values of 9–15 cm./day were found to be typical. The velocity at depth in the glacier was determined by the bore-hole method using 2,400-watt hotpoints which drilled holes about 6 cm. in diameter at a rate of about 10 m. per hour (Shreve, 1961). Holes were drilled to depths of 80, 110, 120, and 225 m.; none of these quite reached bedrock. Strain rates were determined on the surface and at depth in the vicinity of boreholes. These data have not yet been fully computed so few results can be given. The surface strain rates show a rather interesting adjustment between longitudinal extension and compression as the glacier travels around a sharp curve.

Foliation was mapped over the exposed area of the tongue, and was found to occur as two sets of nested arcs convex down-glacier (Allen and others, 1960). These are separated by a zone of strongly foliated, structurally complex ice termed the longitudinal septum. It is inferred that the transverse foliation and the longitudinal septum originate in zones of strong compression and shear immediately below a steep icefall. Three types of ice—fine, coarse bubbly, and coarse clear—combine to form the observed foliated structure. A petrofabric study of fine ice consistently revealed a strong maximum of *c*-axis orientations perpendicular to the foliation plane, but a diamond-shaped four-maxima fabric pattern is characteristic of the coarse bubbly ice (Kamb, 1959). Ratios of the oxygen isotopes ^{18}O and ^{16}O from Blue Glacier were found to be consistent with the relatively cool temperate environment of the Olympic Mountains, and with the principle that the ratio should decrease with increasing elevation (Sharp and others, 1960). Isotope ratios suggest that fine ice represents masses of firn or snow which have been recently incorporated into the body of the glacier through filling of crevasses or the infolding of firn in areas of severe deformation.

On the upper part of the Blue Glacier, a research station was established in the accumulation zone under the leadership of E. R. LaChapelle of the University of Washington; this station operated without interruption for 14 months during the IGY (LaChapelle, 1959[a]). Data on meteorology, snow accumulation and ablation, snow and firn temperature, and other records were collected continuously during this period. Intensive micrometeorologic and mass-balance studies were performed during the summers of 1958, 1959, and 1960. Blue Glacier is a temperate alpine glacier in a strongly maritime climate, and is nourished by what may be the heaviest annual precipitation in the United States south of Alaska. Solar radiation was found to be responsible for the major part of the ablative heat supply, although sensible heat was an important component during periods of heavy storm activity (LaChapelle, 1961). Sensible and latent heat transfer values could not be computed by conventional Bowen ratio and aerodynamic methods. Special techniques were developed to measure profiles of subsurface ablation and the radiation penetration into the snowpack (LaChapelle, 1959[b]) and the latter point was studied theoretically (Giddings and LaChapelle, 1961).

The mass balance of the whole Blue Glacier was measured during the 1957-60 budget years. The annual mass exchange was large—during the winter 1957-58 the specific accumulation (average depth) was 3·5 m. of water. This was followed by very heavy ablation, resulting in a large net loss (averaging 1·7 m. of water) (LaChapelle, 1959[a]). In 1959 and in 1960 the

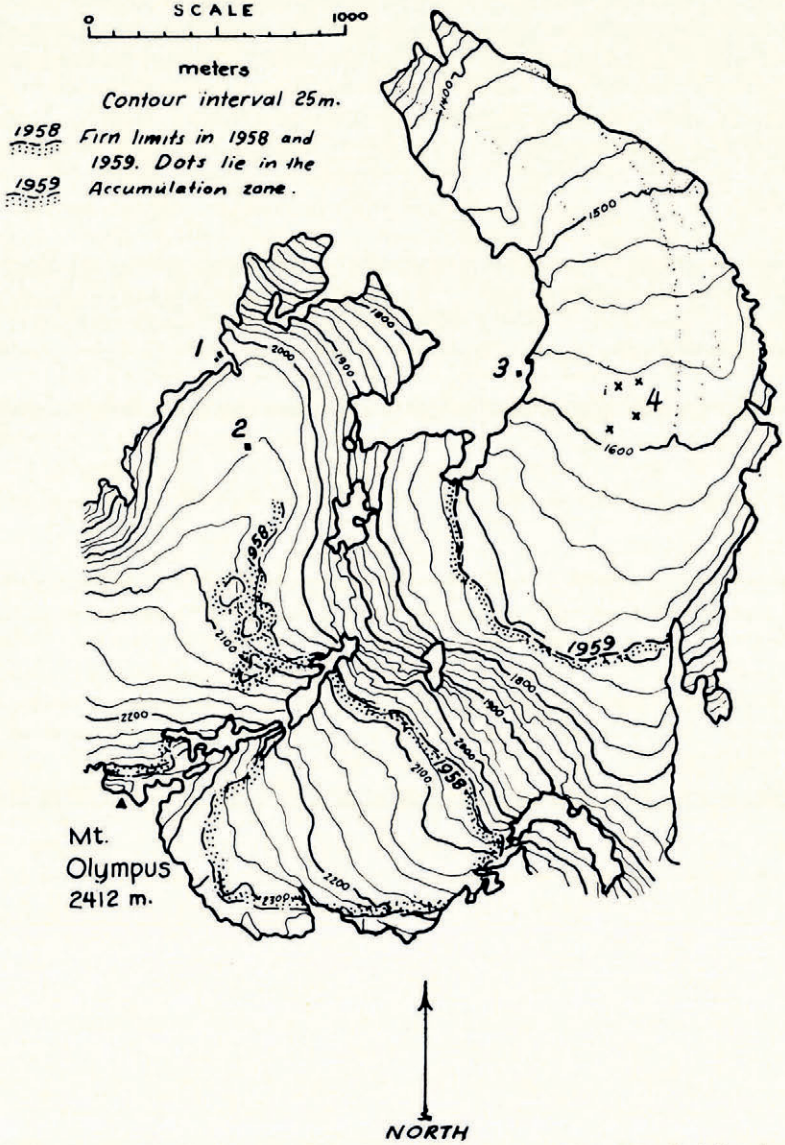

Fig. 6. Map of Blue Glacier, Olympic Range. 1, Research station buildings; 2, Micrometeorological station; 3, Lower Blue Glacier camp; 4, 1957-58 deep boreholes

winter snowfall was greater and the rate of ice ablation was less. The regimen as ordinarily measured in September was positive for both of these years but late fall storms caused additional ablation so that the mass balance became negative on 16 October 1959, and on 10 October 1960. Thus Blue Glacier lost mass and volume during each of these three budget years.

A project on South Cascade Glacier (Fig. 7) was undertaken by the U.S. Geological Survey under M. F. Meier to study the interrelationship between the climatological environment, the flow dynamics, and the water budget of a mountain glacier, and to analyze the hydrologic

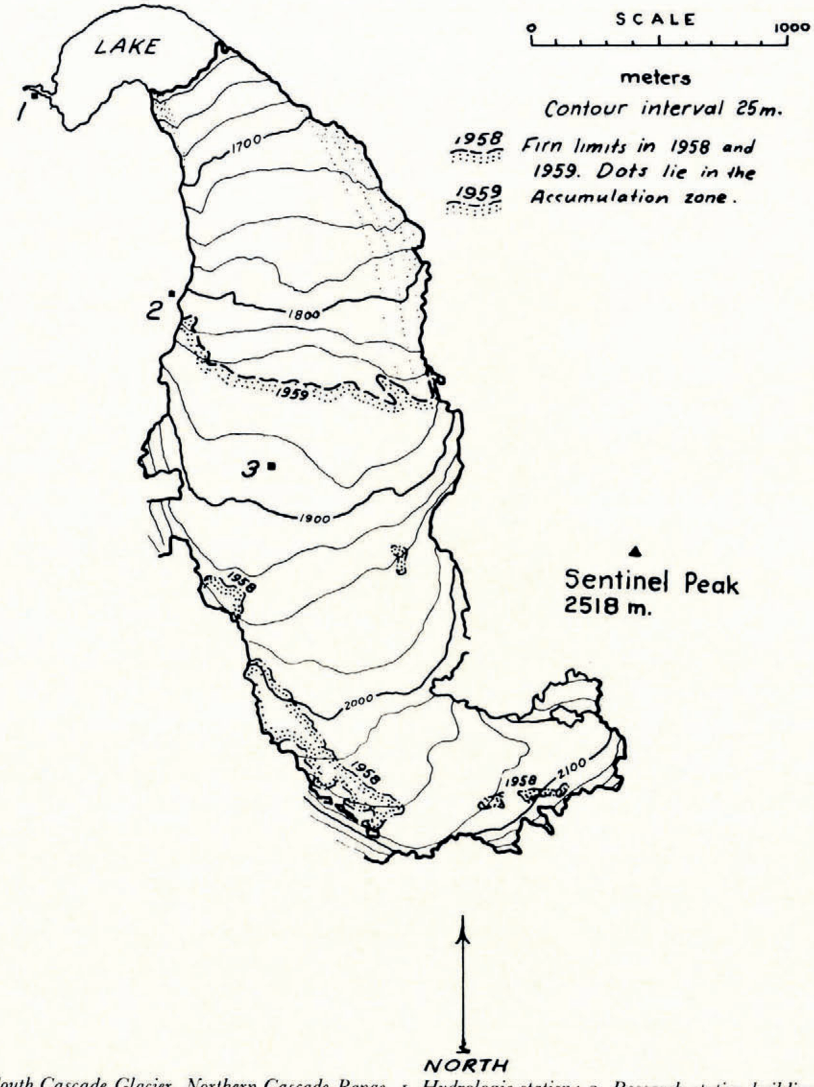

Fig. 7. Map of South Cascade Glacier, Northern Cascade Range. 1, Hydrologic station; 2, Research station building; 3, Main glaciological station

peculiarities of glacier run-off (Meier, 1958). South Cascade Glacier is located in the heart of the Northern Cascade Range, where recent observations of advancing glaciers have attracted considerable attention (Hubley, 1956). In size, orientation, and altitude, this glacier is rather similar to the Blue Glacier so that valid comparisons can be made. Precipitation, snow accumulation, ablation, and melt water run-off from this glacier were found to be large; e.g., in 1959 precipitation of 5·3 m. and specific (area-averaged) run-off of 4·9 m. was measured for the 6·15 km.[2] drainage basin. If the budget year 1959-60 is considered "normal", then the 1957-58 year was characterized by excessive ablation resulting in a strongly negative net balance ($-2 \cdot 15$ m.), whereas 1958-59 was characterized by high accumulation and decreased low-altitude ablation resulting in a positive net balance ($+0 \cdot 71$ m.).

The thickening or thinning of Coleman Glacier (Harrison, 1961) and Nisqually Glacier (Giles, 1960), Washington; Eliot, Coe (Phillips, unpublished), and Collier Glaciers, Oregon; and Grinnell and Sperry Glaciers, Montana (Johnson, 1958, 1960) was measured by personnel of the University of Washington, and the U.S. Geological Survey, National Park Service, and Weather Bureau. These studies showed that all glaciers lost volume during the 1957-58 budget year, but all glaciers either gained volume or remained close to an equilibrium position during the 1958-59 budget year (Meier, 1961). On Nisqually Glacier, a regular series of kinematic waves appears to travel down the glacier, which complicates determination of volumetric changes.

A reconnaissance study (Meier, 1961) of the extent of glaciers in the United States south of Alaska revealed that the total number of glaciers was about 1,000 and the area covered by glacier ice was about 513 $km.^2$. These studies also indicate that the recent advance of glaciers discussed by Hubley (Hubley, 1956) was largely confined to the States of Washington and Oregon, and it appears that glaciers in the other states have been very close to equilibrium since about 1950.

Polar Basin

In the Arctic Ocean north and northeast of Alaska, three drifting stations were occupied during the IGY period. These stations were operated under the direction of the AFCRC. Drifting Station B (an ice island called variously Bravo, Fletcher's Ice Island, or T-3) had been intermittently occupied since 1952 (Crary, 1958, 1960). Occupation was continuous throughout the IGY, but the activity has been greatly reduced since the island became firmly grounded in July 1960. Drifting Station A (or Alpha) was established on an ice-floe north of Alaska in June 1957 and was operated until November 1958 (Schwarzacher, 1959; Untersteiner and Badgley, 1958). Drifting Station C (Charlie) was established in June 1959 and was occupied until January 1960.

Programs in most of the disciplines of the IGY were conducted at these stations, including studies of the regimen of sea and micrometeorology by the University of Washington, the Arctic Institute of North America, and the AFCRC. Closely related to the work on Fletcher's Ice Island were joint studies by Canadians and Americans of the ice shelf along the northern coast of Ellesmere Island where the existing ice islands originated.

Greenland

The notable achievement of the CRREL in the development of deep drilling techniques was reported under the discussion of the Antarctic program, as was the confirmation of the $^{18}O/^{16}O$ method for detection of seasonal variations in snow. In 1956, in preparation for the forthcoming Antarctic program, CRREL organized a polar glaciology course for scientists from the United States and six other nations.

Changes in the Earth's Ice Cover

Because one of the principal objectives of the IGY glaciology program was to record the status of the earth's ice cover and to study its present and past fluctuations, a discussion of some observations bearing on changes in the earth's ice cover is appended.

The observations made on Fletcher's Ice Island and on the northern coast of Ellesmere Island shed further light on the changes in the glaciers and floating ice in that area during the last few millennia. Crary (Crary, 1960) suggests that the ice pack of the Arctic Ocean has been thinning for about 400 years following a period of over 1,000 years of growth, and that under present conditions the ice shelves "might very well become extinct". He also finds evidence indicating that there has been no appreciable advance of the glaciers along the northern shore of Ellesmere Island for at least 7,200 years. However, in other parts of the island some advances have been reported in recent decades (Sharp, 1956).

In Alaska, while most glaciers are now receding from end moraines formed within the last two to three centuries, instances of glaciers whose termini have made appreciable advances during the present century are not uncommon.

Of the 101 glaciers which were specifically observed between 1957 and 1959, no less than 46 are known to have had periods of advance during the present century and 15 since 1940. The termini of at least seven large valley glaciers were farther forward during the IGY period than in 1900, and of these, three were still invading vegetation which was at least several centuries in age. Many other glaciers have experienced spasmodic advances resulting from a wave or surge moving down the glacier. Some of these instances of terminal advance are very minor and of short duration while others have been major events in the history of the glacier and have completely transformed its terminal area.

In most cases, because of the dearth of information as to conditions and elevations in the areas of accumulation, it is not yet possible to determine in precise terms what regimen changes are involved or whether the advances represent a condition no longer existent in the *névé* area. Data on the elevation of the firn limit in different areas are also as yet too fragmentary to indicate what changes may have been occurring during the past half century. However, it is presumed that in most places the firn limit has been rising. As may be expected, many of the glaciers which are receding most rapidly have their sources at elevations only slightly above the firn limit while the advancing glaciers tend to derive their nourishment from the *névé* basins which are generally well above the firn limit. Further effort in correlating the information at present available may reveal new relationships, but to seek the causative factors involved, additional observations of regimen in the area of accumulation are needed.

An advance of special interest and significance occurred on Muldrow Glacier in the Alaska Range during 1956 and 1957 and was studied by several scientific parties, including those specifically concerned with IGY observations. According to Post (Post, 1960) this advance involved a rapid transfer of ice in the lower 41 km. of the glacier, during which surface movement amounted to over 6·6 km., accompanied by a surface lowering of up to 170 m. in the upper part of the glacier and a corresponding rise in the terminal area. Other glaciers in the vicinity were immediately examined by air reconnaissance, but up to the end of 1960 no other such unusual activity had been reported. Somewhat similar types of advance had been observed in the Alaska Range at Black Rapids Glacier in 1936-37, Yanert Glacier in 1943, and Susitna Glacier in 1952-53. Investigation of existing data by Post reveals no abnormal meteorologic conditions or earthquakes which can be assigned as causative factors, and he proposes that these advances were the result of an unstable dynamic condition between the middle part of the glacier and the virtually stagnant terminal portion.

Another occurrence of special interest was the potential effect on glaciers of the earthquake which occurred in the St. Elias Mountains in July 1958 (Miller, 1960[a], [b]). A resultant landslide (and shearing off of some 400 m. of the terminus of Lituya Glacier) caused a tremendous wave in Lituya Bay. North Crillon Glacier, 4·5 km. distant at the other end of the bay, was apparently not immediately affected by the shock and the wave. It is of interest that both these glaciers have advanced between 3 and 4·5 km. since they were first mapped by the La Pérouse expedition in 1786. In other nearby areas where the 1958 shock was known to be severe, subsequent observations have disclosed no appreciable change in the glaciers which can be assigned specifically to the earthquake. However, there may be delayed reaction as was believed to have occurred after the 1899 earthquake in Yakutat Bay (Tarr and Martin, 1914). With this in mind, extra effort was made after the 1958 earthquake to record the positions of as many glacier termini as possible along the Alaskan and Canadian slopes of the St. Elias Mountains. Flights were also made shortly after the earthquake to record by photography the position of rock slides which were visible on the surface of the glaciers in the Lituya Bay area. In future it is believed that the remnants of these slides will remain visible for some years as they are carried downglacier and their change in position will provide an indication of the approximate rate of flow of these ice streams.

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