GLACIOLOGY

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A Brief Review of the Recent History of the Science. By P. D. Baird

The science of glaciology is scarcely a century old. For many years it was treated rather lightly, mostly by geologists who happened to be also enthusiastic mountain climbers. It took a long time for men to realize that to explain some of the phenomena of past glaciation and the problems of Pleistocene geology a deeper study of the processes of existing glaciers was necessary. This concept was stimulated greatly during the past thirty years by the now classical investigations of Hans W:son Ahlmann (1948) in several areas around the North Atlantic Basin.

It can be argued that wherever perennial snow and ice is found in the form of ice cap or glacier we have a glacial climate, hence all glaciers in any part of the world are "arctic". Yet it seems that there are important physical differences between glaciers in temperate latitudes and those in polar regions, and Ahlmann has divided them in his geophysical classification on the basis of temperature and consistency of the upper parts of the glaciers.

Thus although many problems in glaciology, particularly those dependent on long-term observations, can most easily be studied in accessible, temperate glaciers, there are still some questions which can only be answered in the polar regions where strongly negative temperatures prevail in the glacial ice and in the firn snow above it.

In the North American Arctic the geographical extent of all land ice has still to be properly delimited. This would now be possible from a detailed study of existing air photographs, and a tentative classification of the glaciers could be made with the aid of spot field checks.

In recent years there has probably been more glaciological activity in Greenland than in Alaska or Canada. In 1939 Ahlmann's work in the North Atlantic area carried him as far as Greenland, to the Frøya Gletscher in latitude 74°N. on the east coast (1941). Immediately after the Second World War P.-E. Victor began organizing the Expéditions Polaires Françaises, which resulted in their large-scale Greenland project of the summers 1948–51 and the winters 1949–50 and 1950–1. A tremendous amount of glaciological work was achieved (Cailleux, 1952), and new ideas about the Greenland Ice Cap were formulated. Seismic soundings have now shown that at many places

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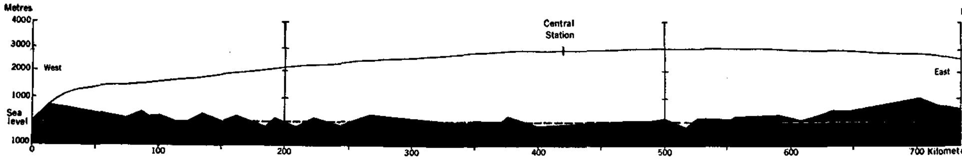

Fig. 1. The Greenland Ice Cap on a section approximately at 70°N., after the Expéditions Polaires Françaises 1948–51. From A. Joset reproduced by Cailleux (1952, p. 8).

the rock floor under the ice is at, or even below, sea level (Fig. 1). Based on these Greenland results J. F. Nye (1952) evolved a theoretical relationship between the thickness of an ice cap and its surface slope. By his calculations the rock floor in north Greenland, an area where British and American parties have recently operated, may be very greatly below sea level. We hope soon to have direct evidence on this point.

Next to Greenland Canada possesses most arctic ice, but until recently little glaciological work has been attempted. In 1950 the Arctic Institute's Baffin Island expedition investigated the Barnes Icecap (Baird *et al.*, 1951). This appears to be a relic of the Pleistocene age and is maintained chiefly by the refreezing of the annual meltwater on to the cold high Polar Ice, and not by normal accumulation of firn slowly changing to ice. There have been two further expeditions to Baffin Island. In 1952 a small party visited the Grinnell Glacier in southern Baffin Island, and in 1953 the Arctic Institute's expedition studied the Penny Highland, the second highest region of the Canadian Arctic.

Two other major projects in Canada should be mentioned. In 1952, under the direction of R. P. Sharp, a program of long-range investigation of many of the least known properties of glacial ice was started on the Saskatchewan Glacier, a readily accessible, temperate glacier in the Rocky Mountains. In 1953 G. Hattersley-Smith and R. Blackadar made a preliminary reconnaissance of the ice shelf off the north coast of Ellesmere Island in preparation for a joint Canadian/United States expedition the following year. This joint expedition spent the summer of 1954 making detailed studies of the shelf, which is believed to be the source area for the ice islands observed in the Polar Basin.

In the Alaska–Canada boundary area two large projects have been under way since 1948. The Arctic Institute, under the leadership of Walter Wood, has carried out work on the Seward–Malaspina system (Sharp, 1951), while the American Geographical Society has studied the Juneau Ice Field (Field and Miller, 1950). These projects were the first large three-dimensional surveys of glacial systems to be carried out in North America. On the Malaspina Glacier a bore hole 1,000 feet deep has been sunk, and inclinometer measurements should yield important results on glacial flow at depth. On the Juneau Ice Field core samples of ice have been obtained down to about 300 feet. Great fluctuations from year to year in precipitation and ablation have been recorded, and a start has been made in both areas on winter studies.

Recent North American work in the Polar Basin has largely concentrated on problems connected with ice islands. Since 1946 the existence of very

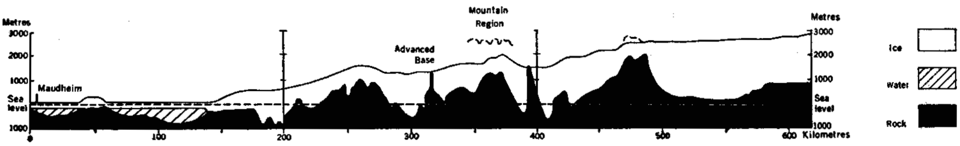

Fig. 2. The Antarctic Ice Cap on a section approximately southeast from Maudheim, after the Norwegian-British-Swedish Antarctic expedition. From Robin (1953, p. 57).

large stable ice masses floating in the Polar Basin has been known, and some of their tracks have been plotted by crews of the U.S.A.F. and R.C.A.F. (Koenig *et al.*, 1952). On 19 March 1952 the first landing was made on one of these ice islands, known as T3, in a position 103 miles from the north pole, and a semi-permanent base was subsequently established by the U.S.A.F. A program of scientific observations was carried out and regular weather observations were transmitted until May 1954 when the ice island was abandoned.[1] The thickness of T3 averages about 200 feet, and borings to 60 feet have shown a mainly freshwater origin, although at the lower limit there are traces of salt. There has been considerable Russian activity in the Polar Basin and some news of their work is just becoming available.

Outside the North American Arctic other glacial studies are being pursued and should be noted here because their evidence is essential in assessing such problems as "the warming of the Arctic". The Norsk Polarinstitutt now has a glaciologist on its staff who is responsible for investigations both in Norway and Svalbard. A clearly defined mountain glacier, Storbreen, and a swiftly moving tongue from Jostedalsbreen have been selected for continued study, as has Finsterwaldbreen in Vestspitsbergen.

In Iceland a glaciological society has recently been formed and has established a small research station on the Vatnajökull (*Jökull*, 1951).

Results from the large Norwegian-Swedish-British Antarctic expedition (Robin, 1952), in which a study of the glaciology of the antarctic continent was a principal consideration, have shown that the season 1950–1 was one of glacial equilibrium in Queen Maud Land and that there appears to have been no appreciable thinning of that section of the antarctic ice cap in the past decade. Seismic soundings showed over 2,000 metres of ice thickness inland, and borings were made with core examinations up to 70 metres deep on the ice shelf at the expedition base (Fig. 2).

From these widespread studies we are beginning to gain a picture of the extent of the recent rather alarming retreat of glaciers (*see* Figs. 3–6). This appears to be progressing violently in the European area and the Pacific coast, less violently in arctic North America, and scarcely, if at all, in the Antarctic.

The future, as R. P. Sharp points out, should lie with detailed examinations of selected accessible glaciers. At present there is tremendous activity on these lines in Switzerland. The volume of valuable detailed glaciological research carried out there probably exceeds that of the rest of the world.

[1]A small United States party reoccupied the station in April 1955, and planned to remain for the spring and summer months making scientific observations. *Ed.*

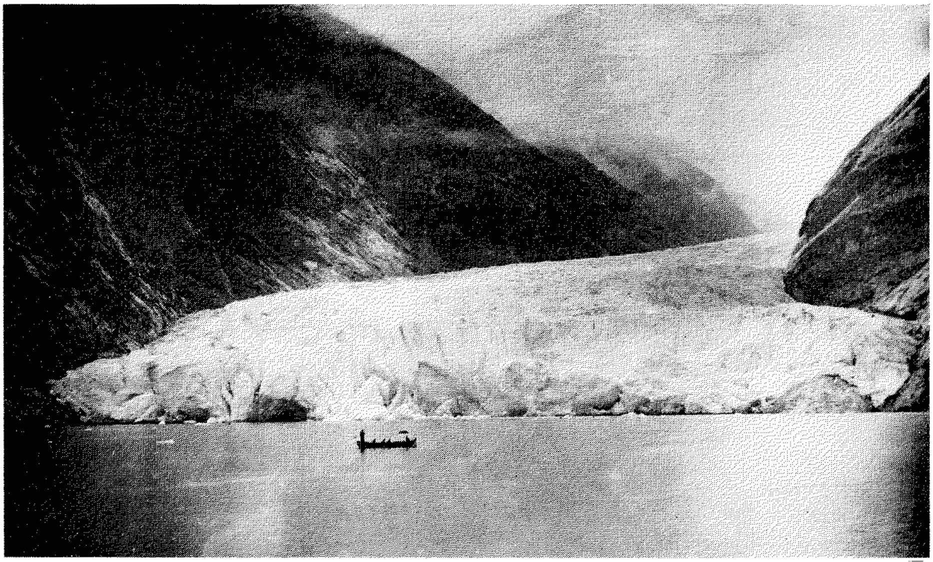

Photo: U.S. Coast & Geodet. Surv., Coll. Comm. on Glaciers, Amer. Geophys. Un.

Fig. 3. North Dawes Glacier, Endicott Arm, Alaska, in 1889, showing a party from the U.S. Coast and Geodetic Survey vessel *Patterson* which made the first determination of the position of the terminus of the glacier.

Photo: W. O. Field

Fig. 4. North Dawes Glacier in 1935, when the terminus had receded about 3,900 feet since 1889.

Photo: W. O. Field

Fig. 5. North Dawes Glacier in 1941.

Photo: Amer. Geogr. Soc.

Fig. 6. Valley of the North Dawes Glacier in 1950. Total recession from 1889 to 1950 was approximately 6,500 feet.

Most meticulous surveys have been made of some of the larger glaciers, and by means of tunnels, sponsored by hydroelectric concerns, much is being learned about internal structure of ice masses.

The polar explorer and scientist is intimately interested in the climate both present and past. The study of glaciers is one of the most valuable in the elucidation of climatic history. As we move back in time, glacial geology takes over from pure glaciology as the science concerned with collecting the evidence. We are back to the geologist again. But the fields of meteorology, physics, and botany have been drawn in, and the practical work of the engineer is required to assist the field investigator, who must still have a strong back and a love for snow and ice.

References

Ahlmann, H. W:son. 1948. 'Glaciological research on the North Atlantic coasts'. *R.G.S. Research Ser.* No. 1, 83 pp.

Ahlmann, H. W:son and B. E. Ericksson. 1946. "Revet station and the Fröya Glacier—north-east Greenland—in 1939–40". *Geogr. Ann.* Vol. 28, pp. 227–57.

Baird, P. D., W. H. Ward, and S. Orvig. 1952. "The glaciological studies of the Baffin Island expedition, 1950". *J. Glaciol.* Vol. 2, No. 11, pp. 2–23.

Cailleux, A. 1952. "Premiers enseignements glaciologiques des Expéditions Polaires Françaises 1948–1951". *Rev. Géomorph. Dynam.* Vol. 3, No. 1, pp. 1–19.

Field, W. O., Jr. and M. M. Miller. 1950. "The Juneau Ice Field Research Project". *Geogr. Rev.* Vol. 40, pp. 179–90.

Jökull (Year Book of Glaciological Society of Iceland). 1951. No. 1, 16 pp.

Koenig, L. S., K. R. Greenaway, Moira Dunbar, and G. Hattersley-Smith. 1952. "Arctic ice islands". *Arctic,* Vol. 5, pp. 67–104.

Nye, J. F. 1952. "A method of calculating the thicknesses of the ice-sheets". *Nature,* Vol. 169, pp. 529–30.

Robin, G. de Q. 1952. "Queen Maud Land. The scientific results of the international expedition". *Geogr. Mag.* Vol. 25, pp. 283–93.

——— 1953. "Measurements of ice thickness in Dronning Maud Land, Antarctica". *Nature,* Vol. 171, pp. 55–8.

Sharp, R. P. 1951. "Accumulation and ablation on the Seward–Malaspina glacier system, Canada–Alaska". *Bull. Geol. Soc. Amer.* Vol. 62, pp. 725–44.

Some Aspects of Glaciological Research. By Robert P. Sharp[1]

The following brief comments make no pretence at providing a complete survey of desirable research in glaciology. The aim is rather to "sign post" the beginnings of trails that might be followed by interested workers. These investigators must themselves become well informed on the basic principles, so they can independently evaluate the desirability of a specific program and determine the best means of carrying it forth. No one can or should try to tell someone else how to tackle a research problem. They can only indicate some of the areas that appear worthy of consideration, and that is the objective here.

Velocity relations in glaciers

Differential movements within glaciers, both in time and space, have been recorded for more than a century (Forbes, 1843, pp. 124–56). In view of this

[1]Contribution No. 666, Division of Geological Sciences, California Institute of Technology.

extended observation and the data obtained (Hess, 1904, pp. 115–50; Klebelsberg, 1948, pp. 80–9), it is truly surprising that so much remains to be done. Large, relatively untouched but highly promising areas of investigation in the field of velocity relations invite attack. For ease of discussion, differences in surface velocities are treated, first with respect to spatial relations and then with respect to temporal variations. This is followed by consideration of velocities at depth in glaciers.

Surface velocities: Many studies on different valley glaciers provide a reasonably good picture of velocity distribution along transverse profiles on the surface. More efforts should be directed toward obtaining data on velocities over the entire surface of the glacier, as only a little information of this type is available (Hess, 1904, p. 136). This will have to be done by means of carefully controlled measurements at a network of widely distributed points and not just along two or three profile lines. At the same time information should be obtained that will allow an evaluation of the influence on flow velocity of surface slope and channel characteristics, especially width and depth.

If velocity studies are possible only along profile lines, efforts should be focused on longitudinal profiles. Such data are of prime importance as a means of testing theoretical concepts bearing on extending and compressive flow in glaciers (Nye, 1952, p. 89). Little information is available on longitudinal velocity changes in North American glaciers (Matthes, 1946, pp. 222–5; Matthes and Phillip, 1943, p. 21). The situation is better for European glaciers (Hess, 1904, pp. 128–35, 148; 1933, pp. 37–8), but quantitative data are needed.

Nearly all measurements of surface velocity to date have recorded only the downvalley component parallel to the glacier surface. It has long been recognized that the absolute direction of movement is actually oblique to the surface and of different angles and different amounts from place to place (Hess, 1933, p. 41). The failure to build upon Reid's (1896, pp. 917–21; 1901, pp. 749–50) early work on this matter is a striking oversight, and this remains a promising and fertile line of investigation.

Variations of flow velocity in time constitute a closely allied subject for study. Although more and better quantitative data on seasonal velocity fluctuations would be useful, measurements over shorter periods provide an even more fruitful line of investigation. Such measurements must be carefully controlled or the data will be open to such question and uncertainty as to make them almost worthless. Some earlier investigations of short-period variations have not been rigorously controlled, and most, if not all, have been made with respect to a single station on the glacier surface. Indications are that the care and labour required to make reliable short-period measurements at a number of stations will be well worth the trouble. Preliminary studies on the Saskatchewan Glacier (Meier *et al.*, 1954, pp. 9–12), show that surprising and puzzling differences of velocity occur from day to day between stations located in the same flow-line as well as beween stations in different flow-lines. Adjacent flow-lines are not always coordinated in their periods of acceleration or deceleration, and different parts of the same flow-line behave differently during the same interval. It seems that much can be learned about the nature of glacier movement from short-period observations of a number of points on the glacier surface.

Instances of exceptional acceleration and deceleration show a definite but unexplained correlation with major meteorological events, especially periods of precipitation. Much more field data on this type of relation must be gathered before even the crudest type of analysis from the standpoint of physical mechanics will be possible. Whether the erratic velocity behaviours involve some sort of wave movement within the ice, or whether the normal processes of flow respond directly and sensitively to variations in the meteorological elements cannot be determined on the basis of present information.

The movement of waves or surges through a glacier needs more study. Such surges have been recognized (Hess, 1931, p. 240, 1933, pp. 94–5; Finsterwalder, 1937, p. 99; Streiff-Becker, 1938, pp. 18–19; Klebelsberg, 1948, pp. 87–8), and one is currently progressing down the Nisqually Glacier on Mount Rainier in Washington (Harrison, 1951, p. 11). It is of utmost importance that these phenomena be carefully observed and their various behaviours recorded. An understanding of the mechanics involved would certainly further our knowledge of glacier flow. In addition, they are obviously important in causing erratic advances at the terminus of a glacier.

Glaciology, like many other phases of earth sciences, is currently passing from a stage of general observation to one of more careful quantitative measurement. The temporal and spatial differences of velocities in glaciers are good subjects for this type of study.

Velocity relations at depth: Little is known about the distribution of velocity with depth in glaciers, although such information is even more essential to an understanding of glacier flow than surface data. Considerable information on stress–strain conditions at depth, and on the physical properties and behaviour of ice under confining pressures, as they occur under natural conditions, can be gained from the vertical velocity profile in a glacier.

Data on velocities at depth are scant because they are difficult to obtain, but their value justifies the effort. A bare beginning has been made, and more data should be gathered from ice streams on slopes and ice sheets on flats. Those interested in this type of investigation can learn of procedures previously used from the following references: Gerrard, Perutz, and Roch (1952) and Sharp (1953).

Structures in glaciers

Glaciology offers many problems for study, but if an attempt were made to select a few of basic importance, the subject of glacier flow would certainly be among them. Attacks on this problem can be made from various directions and should include both field and laboratory investigations. One avenue of field approach is through study of structures within glaciers. Since most of these structures have been created by or because of flowage, knowledge of them and their origin is bound to promote understanding of the mode and mechanism of glacier flow.

Planar structures: Crevasses and faults are surface features, to be sure, but they are the product of stresses generated in the crustal ice by movements deeper within the glacier. Field studies of crevasses have not kept pace with theoretical analyses of the stresses leading to their formation (Lagally, 1929; Nye, 1952, pp. 89–91). Brief field inspection shows that crevasses are more varied and complex than might be supposed. Many different types can be recognized, and each type must have a particular meaning with respect to stress conditions in the glacier. Crevasses need the attention of someone well versed in solid state physics and engineering principles dealing with stress, strain, and the behaviour of brittle materials. Faults should also be studied, for they are just as significant, and perhaps easier to interpret.

A thorough investigation of foliation in glacier ice would likewise be desirable. A satisfactory explanation of its origin, and an understanding of the attitude and structure of foliation planes in various parts of the glacier are lacking. Most investigators regard foliation as a secondary structure imposed on the ice by flowage, but a few look upon it as wholly or in part a relic of sedimentary layering inherited from the firn. However, even among those regarding foliation as secondary, the mode of origin is a subject of some debate. This is a matter intimately related to the mechanics of glacier flow, and an understanding of either is likely to be promoted by advances in the other. A satisfactory explanation is also lacking for the fact that the spoon-shaped structure of foliation planes, observed near the terminus of a simple valley glacier, does not extend any distance up the glacier, at least on the surface.

In recent years geologists have made considerable progress in understanding the form and emplacement of relatively homogeneous igneous bodies through careful mapping of all structures displayed therein. Similar investigations of glaciers might prove fruitful if all crevasses, faults, foliation planes, debris layers, sedimentary structures, lineation (if any can be recognized) and related features were mapped. This would be difficult to do because structures in glaciers are usually so profuse and locally so complex that detailed mapping leads more to frustration and confusion than to clarification and understanding. Anyone undertaking such a study should select the smallest, simplest glacier available as an initial subject.

Rhythmic banding (ogives) in steep valley glaciers deserves further investigation because it in turn can lead to an understanding of the mechanics and behaviour of these ice streams (Leighton, 1951). The interrelation of individual ice streams in compound valley glaciers, and the origin of the complexly deformed debris layers displayed by many ice masses present unsolved problems worthy of study.

Crystal fabrics: Investigations of crystal fabrics in glaciers are undergoing the same history as the earlier studies of fabrics in rocks. Strong orientation patterns have been demonstrated, but no satisfactory explanation for them has yet been evolved. This comes about in large part because knowledge of the behaviour of polycrystalline aggregates of ice under stress is so incomplete. Laboratory investigations are clearly called for, and a beginning is being made in this direction, particularly by J. W. Glen in England, and by D. T. Griggs and G. P. Rigsby in the United States.

It is entirely possible that the strong crystallographic orientations demonstrated in ice at the glacier's surface (Rigsby, 1951, 1953) are the product of an ordered recrystallization proceeding from an orientation earlier established by flowage at depth. A study of ice samples obtained from considerable depth by coring would be helpful in evaluating this hypothesis, if the relaxation rate is not too rapid and if the specimen is not too greatly disturbed by the coring procedure. Core drilling in glaciers has so far been too shallow for such purposes (Miller, 1953, p. 14), but this matter should be pursued further.

Much remains to be done with field studies of crystal fabrics, and a recent suggestion that shear planes of several different orientations in the glacier are involved merits further investigation (Schwarzacher and Untersteiner, 1953, pp. 121–4). However, the greater need at the moment is for controlled laboratory experimentation to establish the principles by which preferred orientations are developed in aggregates of ice crystals.

Phase relations in glacier ice

In 1950 H. Bader made an exploratory study of relations between the liquid, vapour, and solid phases of water in glaciers with respect to the conditions of temperature and pressure to which the ice had been subjected. This work was largely preliminary in nature, and the results obtained were different from those expected. Nonetheless, it appears that much can be learned concerning the properties and behaviour of ice at depth within a glacier from investigations of phase relations. Some of this work can best be done in the field, as the laboratory cannot reproduce wholly satisfactorily the conditions to which the ice in glaciers is subjected.

Oxygen-isotope studies in snow, firn, and glacier ice

Pioneer investigations of oxygen-isotope ratios (O^{18}/O^{16}) in waters of various origins reveal that water in glaciers is exceptionally light, that is low in O^{18} (Epstein and Mayeda, 1953). Furthermore, preliminary studies show sizeable differences in the O^{18}/O^{16} ratio within a single glacier. Data are still too scanty to demonstrate any consistent trends in the oxygen-isotope ratios in glaciers or to relate them to other factors, but these differences may well reflect environmental conditions at the point of origin of the ice, or they may be influenced by something within the subsequent history of the ice such as age, amount of flow and recrystallization, and temperature regime. This type of investigation is in its earliest stages, but it looks promising. Close cooperation between the geochemist and the field glaciologist will be required to produce results.

Micrometeorology and the regime of glaciers

Micrometeorology has been studied for some time with vigour and profit in Scandinavian areas (Wallén, 1948), but it has been largely neglected in North America, save for some work currently underway (Hubley, 1953). Glaciers are frequently referred to as "historians of weather", but weather records from glaciers cannot be interpreted without an understanding of how they respond to the various meteorological factors. Furthermore, the relative influence of the several meteorological elements involved displays such gross variation, depending upon environment, that detailed studies on many different glaciers in many different areas will be required before an evaluation of the basic relations will be possible.

A means of checking the reliability of micrometeorological studies is available if a correspondingly accurate determination of the ablation of firn and snow can be made. Measurements of ablation to date have been too crude and inaccurate to provide reliable values for balancing the ablation equation. It is not feasible to go into details here concerning the difficulty of making an accurate measure of ablation in firn or snow (Hubley, 1953, p. 18). It is a difficult matter, but one well worth considerable study and effort.

Micrometeorological studies on glaciers have significance outside the field of glaciology. The proper evaluation and understanding of climatic changes recorded by present and past glacier behaviours have a bearing on all activities of mankind affected by the climatic environment. The science of meteorology should also benefit, as a glacier surface furnishes an ideal subject for studies of heat exchange at the earth's surface.

Closely allied with the subject of glacier response to climatic change is the synchronism or non-synchronism of glacier behaviours in widely separated regions. When one deals with ancient fluctuations of glaciers the techniques of glacial stratigraphy and geobotany come into play, but even these ancient fluctuations should be interpreted on the basis of sound glaciological and micrometeorological principles. Eventually, Carbon-14 dating may be helpful in establishing the more ancient relations, provided the method can be properly refined and applied to the problem. A demonstration of closely synchronous glaciations in opposite hemispheres, with some degree of antiquity, would have major significance with respect to theories bearing on causes of glaciation.

References

Bader, Henri. 1950. "The significance of air bubbles in glacier ice". *J. Glaciol.* Vol. 1, pp. 443–51.

Epstein, S. and T. Mayeda. 1953. "Variation of O^{18} content of waters from natural sources". *Geoch. et Cosmoch. Acta*, Vol. 4, pp. 213–24.

Finsterwalder, Richard. 1937. "Die Gletscher des Nanga Parbat". *Zeit. f. Gletscherk.* Vol. 25, pp. 57–108.

Forbes, J. D. 1843. 'Travels through the Alps of Savoy and other parts of the Pennine Chain with observations on the phenomena of glaciers'. Edinburgh: Adam and Charles Black, 424 pp.

Gerrard, J. A. F., M. F. Perutz and André Roch. 1952. "Measurement of the velocity distribution along a vertical line through a glacier". *Roy. Soc. Lond.* Proc. A, Vol. 213, pp. 546–58.

Harrison, A. E. 1951. "Ice advances during the recession of Nisqually Glacier". *The Mountaineer*, Vol. 43, pp. 7–12.

Hess, Hans. 1904. 'Die Gletscher'. Braunschweig: Friedrich Vieweg, 426 pp.

1931. "Zur Strömungstheorie der Gletscherbewegung". *Zeit. f. Gletscherk.* Vol. 19, pp. 221–50.

1933. "Das Eis der Erde". *Handb. d. Geophys.* Vol. 7, Sect. 1, pp. 1–121.

Hubley, R. C. 1953. "Preliminary report on meteorological and glaciological studies on Lemon Creek Glacier". *Amer. Geogr. Soc.* pp. 16–21. (mimeo.)

Klebelsberg, R. v. 1948. 'Handbuch der Gletscherkunde und Glazialgeologie'. Vienna: Springer-Verlag, 403 pp.

Lagally, M. 1929. "Versuch einer Theorie der Spaltenbildungen in Gletschern". *Zeit. f. Gletscherk.* Vol. 17, pp. 285–301.

Leighton, F. B. 1951. "Ogives of the East Twin Glacier, Alaska—their nature and origin". *J. Geol.* Vol. 59, pp. 578–89.

Matthes, F. E. 1946. "Report of committee on glaciers, 1945". *Trans. Amer. Geophys. Un.* Vol. 27, pp. 219–33.

Matthes, F. E. and K. N. Phillip. 1943. "Surface ablation and movement of the ice on Eliot Glacier". *Mazama*, Vol. 25, pp. 17–23.

Meier, M. F., G. P. Rigsby, and R. P. Sharp. 1954. "Preliminary data from Saskatchewan Glacier, Alberta". *Arctic*, Vol. 7, pp. 3–26.

Miller, M. M. 1953. "Status reports of the Juneau Ice Field Research Project, Alaska, from 1948 to 1952". *ONR Task Order N9onr-83001*, Inter. Memo. 4, 24 pp. (mimeo.)

Nye, J. F. 1952. "The mechanics of glacier flow". *J. Glaciol.* Vol. 2, pp. 82–93.

Reid, H. F. 1896. "The mechanics of glaciers". *J. Geol.* Vol. 4, pp. 912–28.

1901. "De la progression des glaciers, leur stratification et leurs veines bleues". *Congrés Geol. Intern. 8th Session, Compt. Rendus*, Pt. 2, pp. 749–55.

Rigsby, G. P. 1951. "Crystal fabric studies on Emmons Glacier, Mount Rainier, Washington". *J. Geol.* Vol. 59, pp. 590–8.

1953. 'Studies of crystal fabrics and structures in glaciers'. *Calif. Inst. Tech.* Ph.D. thesis, 51 pp.

Schwarzacher, W. and N. Untersteiner. 1953. "Zum Problem der Bänderung des Gletschereises". *Sitz. der Oster. Akad. der Wiss. Math-Naturw. Kd.* Abt. IIa, Bd. 162, Heft 1–4, pp. 111–45.

Sharp, R. P. 1953. "Deformation of bore hole in Malaspina Glacier, Alaska". *Geol. Soc. Amer. Bull.* Vol. 64, pp. 97–9.

Streiff-Becker, R. 1938. "Zur Dynamik des Firneises". *Zeit. f. Gletscherk.* Vol. 26, pp. 1–21.

Wallén, C. C. 1948. "Glacial-meteorological investigations on the Kårsa Glacier in Swedish Lappland, 1942–1948". *Geogr. Ann.* Vol. 30, pp. 451–672.