In order to guide the Committee in formulating a detailed programme and in devising suitable methods of research, Dr. Perutz has written a report summarizing the present state of the problems of Glacier Physics. This summary is published below.

REPORT ON PROBLEMS RELATING TO THE FLOW OF GLACIERS

By M. F. PERUTZ (Cambridge)

Viscous Flow : Experiments and Theory

The great naturalists of the nineteenth century discovered glacier flow and described its main features. They showed that the flow properties of glaciers resemble those of highly viscous fluids, and attributed the ductility of the apparently brittle substance ice to the effects of regelation or to the relative motion of individual ice crystals.

Accurate measurements of glacier flow were begun in the Alps in the 1890's and continued for several decades.[1] Surface velocities were measured at many points on glacier tongues, bore-holes reaching down to the rock bed were drilled and their progression was carefully recorded. Finally, in the 1930's, reliable and less tiresome methods of measuring glacier depths became possible with the introduction of seismic soundings.

Many of the experiments and observations were accompanied by attempts at theoretical interpretation. One of the earliest of these was Finsterwalder's geometric streamline theory,[2] which correlated accumulation and ablation with glacier flow and explained the periodic advance and recession of glaciers. Finsterwalder's theory is mainly descriptive and free from all arbitrary assumptions; on the other hand, this makes the theory so general that it is difficult to derive from it any quantitative predictions. Hess actually employed it to obtain equations for the total mechanical energy of a glacier, involving integration over six dependent variables which cannot be evaluated without a host of dubious assumptions. The solutions of these equations led him to some exceedingly improbable conclusions concerning the stress distribution in glaciers. More important are Weinberg's and Somigliana's attempts to formulate a quantitative theory of glacier flow on a hydrodynamic basis.[3, 4] Somigliana treats the stationary flow of a viscous liquid in an evenly inclined cylindrical channel under the influence of gravity. His work is outstanding for the clear exposition of the underlying assumptions and important because it leads to a relation between the depth and surface velocity of a glacier. Lagally extended his theory and used it to derive the average viscosity of glacier ice from the change in flow velocity between the edges and the centre of a glacier surface[5]; he obtained a value of $\mu = 1 \times 10^{14}$ *g.* cm.$^{-1}$ sec.$^{-1}$. Taking the cross-section of the glacier bed to be a semi-ellipse whose major axis is very large compared to the minor one, and the velocity of flow on the rock bed to be negligibly small, he obtains the equation

$$z = \sqrt{\frac{2\mu V_0}{\rho g \sin \alpha}}$$

where z is the depth of the glacier, μ the viscosity of ice, V_0 the surface velocity at the centre of the glacier, ρ the density of ice, g the acceleration of gravity and α the inclination of the

https://doi.org/10.3189/S0022143000007541 Published online by Cambridge University Press

rock bed. On the Pasterze (Austria), where the ideal conditions of Somigliana's theory seem to be very nearly fulfilled, Lagally was able to predict a value for the depth of the glacier which was verified by the subsequent seismic soundings of Mothes and Brockamp.[6] This remarkable success established beyond any reasonable doubt that the theory of continuous, stationary, viscous flow is substantially correct provided that all external conditions liable to lead to discontinuities are absent. The experiments of Blümcke and Hess had shown that the temperatures in Alpine glacier tongues remain at the pressure melting-point throughout the year [7] except for an insignificant surface layer affected by the winter cold wave. Crevassing is confined to the top 50–100 ft., and the distribution of crevasses can easily be interpreted on the basis of the stresses introduced by differential flow and the changes in direction and inclination of the rock-bed.

Limitations of Simple Theory.

(a) Extrusion Flow

Thus apparently nothing remained to be explained, apart from the microscopic mechanism of flow as it affects the individual crystals, a field which was left almost untouched until the work of the Jungfraujoch Research Party.[8] Nevertheless, recent observations have made it increasingly evident that the simple picture outlined above is merely one aspect of usually far more complex behaviour. In the first place it fails to account for the regime of the Greenland Ice Cap. In order to explain the fact that the centre of the ice cap does not continuously increase in height through the accumulation of new snow, Hobbs proposed a theory of anti-cyclonic winds which reduce precipitation in the central regions of the ice cap to a minimum. He claims that most of the snow is deposited near the margins, from where it is carried to the sea by essentially the same flow mechanisms as in the Alps. Hobbs' theory was discredited by the observations of Koch and Wegener, Sorge [9] and others, who showed that there exists a definite and substantial annual accumulation of snow even near the centre of the ice cap. An explanation of the apparent paradox was recently put forward by Demorest,[16] who postulated that the enormous ice streams of the Greenland fjords must be fed by extrusion from the interior of the ice cap. Shortly before this, Streiff-Becker [10, 17] published some observations from which he inferred a similiar extrusion mechanism to be operative in certain large flat alpine firn fields. He measured the annual accumulation of snow on the Claridenfirn (Switzerland) and determined the superficial velocity of flow at the outlet of the firn basin. He further assumed this velocity to be the same at all depths. On that assumption his figures show that the total amount of snow accumulation in the firn basin is three times larger than could be removed by flow through the outlet at the observed rate of surface flow.

Since the firn level did not rise during the twenty years covered by the observations, the disappearance of the missing balance of accumulation could only be explained by extrusion from the interior.

(b) Variation in Flow Rate

Some of the most interesting observations recently made relate to periodic, short-term variations in the rate of glacier flow. Washburn and Goldthwait found that day-time speed was different from night-time speed in the South Crillon Glacier and believed that short spasms of motion at about twenty-minute intervals also occurred.[18] At least two independent observers have reported that in winter the superficial velocity of flow in the firn region of alpine glaciers is about twice as great as in summer.[10, 11] Since the winter snow layer constitutes not more than 1 to 2 per cent. of the weight of the glacier, it appears that flow in the firn region must be very sensitive to small variations in the applied force. R. Finsterwalder[12] actually measured daily variations of the order of 20 per cent. in the velocity of a large glacier tongue in the Nanga Parbat massif. His careful photogrammetric studies indicate a progression of waves along the glacier, involving changes in surface level as well as velocity. The stresses introduced by such waves may well account for the extraordinarily rugged surface structure of many fast moving ice streams.

The Plastic Properties of Ice

Clearly, explanations of these diverse phenomena must be sought from the point of view of the general mechanism of deformation of plastic bodies. Such attempts are not likely to be successful, unless account is taken of the peculiar plastic properties of ice itself. In this connection Höppler's recent measurements of the apparent viscosity of ice under various conditions are of the greatest interest.[13] As expected, Höppler found the apparent viscosity to be a function of the applied shear stress, the temperature and the crystal orientation in his specimens. The actual figures, however, are surprising and allow a revealing insight into some of the more puzzling features of glacier flow. At a constant shear stress of 63 Kg./cm.^{2} the apparent viscosity at $-20°$ C. was 1000 times greater than at $-1°$ C.; at a constant temperature of $-1°$ C. an increase in the shear stress from 10 to 63 Kg./cm.^{2} reduced the apparent viscosity by a factor of 200. In a sample of frozen snow, possessing no preferred crystal orientation, the apparent viscosity was 70 times greater than in a multicrystalline block where all the crystal glide planes were parallel to the direction of shear. (This last result shows the enormous gain in plasticity of local regions, e.g. blue bands, brought about by preferred orientation.) Unfortunately, none of Höppler's actual viscosity measurements can be applied to glacier problems directly, since he did not determine the viscosity at the pressure melting-point and all but one of his test specimens consisted of crystals in preferred orientation. His observations do point the way, however, to the kind of experimental data that will have to be collected before some of the peculiarities of glacier flow can be fully explained.

One important factor not considered by Höppler concerns the probable changes in viscosity with increasing depth below the glacier surface, due to hydrostatic pressure. This causes the melting of

$$\nu = 5{\cdot}7 \text{ p} \times 10^{-4} \, gm. \, H_2O/cm.^3$$

where p is the pressure in Kg./cm.^{2}. Thus at a depth of 500 m., say, over 3 per cent. of the glacier mass at pressure melting-point will consist of water, whose presence should greatly reduce the viscosity.

Micro-mechanism of Flow

Very little is known as yet about the micro-mechanism of flow in glacier tongues, since the work of the Jungfraujoch Research Party was concerned chiefly with the firn region. There are indications that locally, at any rate, crystals tend to assume a preferred orientation with their glide plane parallel to the direction of shear stress, and that large scale thrust planes do not consist of actual cracks but rather of thin strata of large crystals in preferred orientation.[8] Plastic flow is probably the main factor responsible for the astonishing growth of the glacier crystals, though, as Seligman has pointed out, regelation or thaw-freeze processes on the surface may also play a part. Winterhalter's recent studies of ice sections under tension are interesting in this connection.[14] The internal stress, orientation and growth of each crystal in a test strip can be observed between crossed nicols while tension is being applied. The method thus offers an almost unique opportunity for the study of the micro-mechanism of plastic deformation in a *transparent* polycrystalline material. Again observations have been too few to permit any definite deductions, but the general potentialities of the method are obvious.

Conclusions

For a more complete understanding of the mechanism of glacier flow, advances are needed along three main lines; first, there is a call for precise data on the actual flow mechanism in glaciers, so far as it can be made accessible to observation; second, studies of the plastic properties and the micro-mechanism of flow of polycrystalline ice at the pressure melting-point are required; and third, theoretical and experimental work on the behaviour of large masses of ice in gravitational fields will have to be done. The first is a matter for field work on alpine and arctic glaciers, while the second and third are subjects for laboratory work. I shall not discuss the possible forms of attack upon these problems in detail, but rather give an outline of the separate points which, in my view, merit investigation. For the sake of completeness I shall also include lines of work which have only an indirect but nevertheless important bearing on the subjects discussed above.

Proposed Research

1. *Laboratory Work*

Measurement of the quasi-viscous creep rate of ice near 0° C., as a function of shear stress, crystal size, crystal orientation and hydrostatic pressure.

Study of the mechanism of crystal growth and re-orientation under the influence of continued strain.

Study of the behaviour of ice masses in gravitational fields, both in theory and experiment.

2. *Field Work on Alpine or Norwegian Glaciers*

Development of a method for the direct measurement of stresses and flow rates in the interior of glaciers.

Observations of glacier flow from day to day by photogrammetric methods, allowing short-term variations in flow rates to be discerned.[12, 15, 18]

Observations on crystal growth and orientation in glacier tongues (in continuation of the work of the Jungfraujoch Research Party, 1938).

Development and application of seismic sounding methods.

Observations on the interplay between continuous viscous flow and flow along large scale thrust planes.

The relationship between glacier flow and erosion.

https://doi.org/10.3189/S0022143000007541 Published online by Cambridge University Press

3. *Field Work in the Arctic and Antarctic*

General glaciological research along classical lines.

Application of new or improved methods of research, developed and tried on alpine glaciers.

REFERENCES

1. Blümcke, A. and Hess, H. *Zeit. Gletscherkunde*, Vol. 13, 1925.
2. Finsterwalder, S. Der Vernagtferner. *Wissenschaftliche Ergänzungshefte D. Oe. A.V.*, Vol. 1, No. 1, 1897, p. 112.
3. Somigliana, C. The Viscosity of Glacier Ice and the Determination of the Depth of Glaciers, reported by S. Finsterwalder in *Zeit. Gletscherkunde*, Vol. 15, 1927. (See also *Rend. R. Acad. Linc. Math. Phys. Class* 30, 1921.)
4. Weinberg, S. *Zeit. Gletscherkunde*, Vol. 1, 1906–7, p. 322.
5. Lagally, M. *Mechanik u. Thermodynamik d. stationären Gletschers*, Leipzig, 1934, p. 94. *Zeit. Gletscherkunde*, Vol. 18, 1930, pp. 1–8.
6. Brockamp, B. and Mothes, H. *Zeit. Geophys.* Vol. 6, 1930, pp. 148 et seq.
7. Blümcke, A. and Hess, H. Untersuchungen am Hintereisferner. *Wissenschaftliche Ergänzungshefte D. Oe. A.V.* Vol. 1, 1899.
8. Perutz, M. F. and Seligman, G. A Crystallographic Investigation of Glacier Structure and the Mechanism of Glacier Flow. *Proc. Roy. Soc.* A, Vol. 172, 1939, pp. 335–360.
9. Sorge, E. Glaziologische Untersuchungen in Eismitte. *Wiss. Erg. d. D. Grönland Exp. Alfred Wegener*, Band 3. Leipzig: Brockhaus, 1935.
10. Streiff-Becker, R. Zur Dynamik des Firneises. *Zeit. Gletscherkunde*, Vol. 26, 1938–9, pp. 1–21.
11. Haefeli, R. Private communication.
12. Finsterwalder, R. Die Gletscher des Nanga Parbat. *Zeit. Gletscherkunde*, Vol. 25, 1937, pp. 57–108.
13. Höppler, F. *Kolloid Zeit.* Vol. 97, 1941, pp. 154 et seq.
14. Winterhalter, U. Private communication.
15. Finsterwalder, R. *Zeit. Gletscherkunde*, Vol. 19, 1931, p. 251. Pillewitzer, W. *Zeit. Erdkunde*, No. 9–10, 1938.
16. Demorest, M. Ice Sheets. *Bull. Geol. Soc. Am.* Vol. 54, 1934, pp. 363–400.
17. Seligman, G. Extrusion Flow in Glaciers. *Journ. Glaciology*, Vol. 1, No. 1, 1947, p. 12.
18. Washburn, B. and Goldthwait, R. Movement of South Crillon Glacier, Crillon Lake, Alaska. *Bull. Geol. Soc. Am.*, Vol. 48, 1937, pp. 1653–64.

GENERAL INFORMATION

Matthes, F. E. Glaciers: a short account in *Physics of the Earth, Vol.* 9; *Hydrology*. Ed. by O. E. Meinzer, McGraw-Hill Book Co., 1942, Chapter 5.

MEETINGS

ANNUAL GENERAL MEETING

held at the Royal Geographical Society's House, Kensington Gore, London, on THURSDAY, 28 November 1946 at 4.30 p.m.

23 members and 5 visitors were present

The President informed the meeting that the Minute book was available for inspection and if no objections were raised the Minutes of the last meeting would be signed in the ordinary way.

1. *The President's Report.* The President reported that the Snow Survey of Great Britain was now in operation. There were about 100 volunteer observers and 61 from the Meteorological Office. Valuable results were to be expected.

Membership of the Society had increased satisfactorily during the year and was now 128, 102 in the United Kingdom and 26 abroad. These figures were higher than when the Society ceased its activities at the beginning of the war.