EXTRUSION FLOW IN GLACIERS

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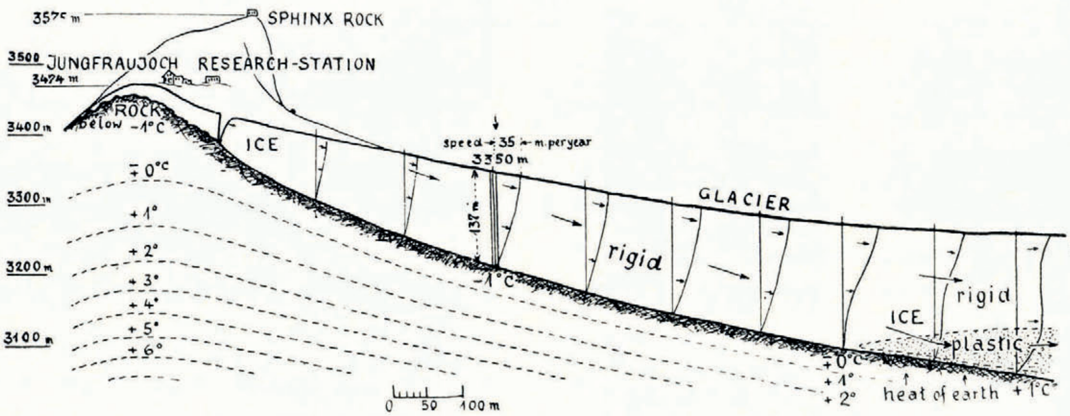
In 1948–50 a research group led by Dr. M. F. Perutz made a bore hole and took measurements on the Jungfraufirn (Bernese Oberland) and published their results.[1, 2] A vertical bore was made in the ice about 500 m. distant from the Jungfraujoch, at an altitude of 3350 m. above sea level. Rock was reached at a depth of 137 m. The firn ice that was bored through was found to be in a rigid state; no plastic ice layer was encountered anywhere. At the upper surface the speed of the ice amounted to 35 m. per annum, but diminished continuously from the surface to the rock (see drawing below).

These interesting results appear to be in contradiction to the theory of the writer,[3] who postulated that in the firn region a fluid-plastic layer occurs at a certain depth, this layer moving downhill at the time of accumulation, but remaining relatively steady during ablation. He supported his theory by measurements and calculations made on the Claridenfirn. The writer believes that his assumption of plastic layers under rigid ones is rendered probable by the morphology of the firn and glacier surfaces, by the path—first descending and then again ascending—of the



stones from the bergschrund to the tongue of the glacier, and further by the excavated basins and rock dams (*Riegel*), hollows, forced up seracs, descending ice steps, many "flow-forms," ogives and other phenomena. The ice movement caused thereby is just as easily possible as the movement of dry, granular material in a technical silo. We know how grain, coal and hard rubble flow through a silo, and we see how big areas of land at times creep downhill (solifluction). Why should a differential movement within the ice not be possible, where indeed another favourable feature has to be taken into account, namely that the ice can easily alter its aggregate condition, *i.e.* it melts where pressure and friction are great, and refreezes where pressure diminishes?

The investigations of the Perutz research group did not show a plastic layer, because they were undertaken at an altitude of 3350 m. above sea level where, for climatic reasons, the ice cannot reach a fluid-plastic state even at great depth. In the Alps the altitude range in which the average ground temperature of the year amounts to zero Centigrade lies between 2800 and 3000 m. above sea level. According to particulars furnished by the Swiss Central Meteorological Office, the average annual temperature on the Jungfraujoch amounts to $-8{\cdot}5^\circ$ C., and the temperature in the warmest month (August) is still below zero, being $-1{\cdot}7^\circ$ C. Consequently the snow here falls at very low temperatures and it piles up on rock which is always at a temperature far below zero.

Under the insulating layer of firn, the line of zero rock temperature will be somewhat higher—possibly at 3100 m. From here, downhill, the increasing thickness of the firn layer and the heat of the Earth will have the effect that a fluid-plastic deep-lying layer is very easily possible. From 3100 m., uphill, the ice remains rigid and adheres firmly to the cold rock. At the surface, however, a downhill movement of 35 m. per annum was measured. This movement is a consequence of the increasing thickening of the granular substance of the firn on an inclined base, and also of the withdrawal of ice on the downhill side where the plastic deep-lying layer moves on.

If similar soundings could be made much lower down on the Jungfraufirn instead of in the neighbourhood of the Joch, the results would certainly be different. The measurements of Haefeli and Kasser [4] on the middle of the Aletsch Glacier and in galleries in other glaciers, have confirmed the existence of plastic ice layers.

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DEFORMATION OF A VERTICAL BORE HOLE IN A PIEDMONT GLACIER

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The well-conceived and nicely executed British plans for measurement of velocity distribution along a vertical profile in the Jungfraufirn [1, 2] provided inspiration and guidance for a similar experiment in the Malaspina Glacier, Alaska. A repetition of the earlier experiment seemed desirable because it was not entirely certain that the Jungfraufirn provides the best conditions for extrusion flow,[3, 4] the concept it was desired to test. The Malaspina Glacier appears to offer conditions ideally suited for extrusion flow. It is a piedmont glacier, a sheet of ice with gentle surface slope, covering more than 1000 square miles on the flat coastal plain of southern Alaska. From seismic reflections, the glacier's floor is known to slope northward toward the mountains in opposition to the southward flow of ice.

In the summer of 1951 a vertical hole approximately 5 cm. in diameter was bored to a depth of 305 meters near the center of the glacier by an electrically heated hot-point. Boring stopped at this point because the hot-point ceased to function. The glacier at this point is 595 meters thick, its surface slopes southward at 6·6 meters per kilometer, and its floor, 183 meters below sea level, slopes gently northward. The bore hole was cased with aluminum pipe, 3·5 cm. inner diameter and 4 cm. outer diameter.

Orientation of the pipe was determined by a small-diameter inclinometer, kindly loaned free of charge by the Parsons Survey Company of South Gate, California. This instrument gave reproducible measurements of inclinations accurate to 0° 05′, and of bearing accurate to 2° or 3°. Readings were made at 15-meter intervals. Curve A (Fig. 1, p. 183) shows the initial orientation of the pipe, projected on to a vertical plane bearing S. 25° E., the direction of flow as inferred from structures in the glacier. A resurvey $3\frac{1}{2}$ weeks later showed no perceptible deformation.