Dr. Cwilong: In the case of freshly evaporated zinc and cadmium surfaces (hexagonal) this was the case; but neither the evaporated silica surface nor other surfaces covered with fine crystalline silica dust showed any power to induce sublimation, although it was expected that the dust would "seed" the surface. Surfaces were coated by evaporation *in vacuo* in order to ensure their being clean. Mica was cleaned when placed in the observation chamber just before observation. During experiments on evaporated surfaces in the absence of air the surfaces were certainly free from oxide.

Dr. Perutz: What were the sizes of the nuclei?

Dr. Cwilong: They were very small; so small in fact that those parts of the surface on which sublimation was taking place did not appear different from other parts of the surface even under a magnification of 500 times. On all surfaces except those of evaporated zinc and cadmium the nuclei were sufficiently few in number to enable me to observe that they kept their ability to induce sublimation during consecutive depositions. It was only after the test plates had been heated to about 100° C. below their melting points for several hours that the loci of crystal formation shifted to other points on the plate.

Dr. Perutz: You are speaking of extraneous nuclei and not of nuclei in supercooled water?

Dr. Cwilong: Yes. In supercooled water the original point from which the solid phase spreads is difficult to locate owing to the high velocity of spreading. In supercooled water in a test-tube the addition of dust usually raises the semi-permanent freezing point of a sample, but a crystalline dust (silica) is not more effective in this respect than an amorphous one (glass powder).

Dr. Perutz: Do you consider that the crystals obtained in the German experiments were carbon dioxide or ice?

Dr. Cwilong: Rau's crystals, melting at −72° C. were, I think, a solution of water and some organic contamination. In König's experiments temperatures were very much lower and in spite of precautions contamination by carbon dioxide cannot be excluded.

The discussion was then closed by the Chairman with a tribute to the brilliant work of the lecturer.

THE FORMATION OF *Roches Moutonnées*

By Hans Carol (Zürich)

(This paper in addition to its main theme gives observational evidence of plasticity and faster flow in the lower strata of a glacier under pressure. The conditions it describes provide additional support for the Extrusion Flow hypothesis. Ed.)

Roches moutonnées, the rounded rock hummocks found in glaciated regions, vary somewhat in shape according to the nature of the rock, its stratification or cleavage planes and the action of the ice. Usually they have a smooth, rounded back pointing uphill, while their downhill face is rough and often steep.

There are many theories to account for their development. Some authorities attribute them to highly resistant rock masses which have persisted after the erosion of the rest of the glacier bed; others believe them to have been rugged protuberances of pre-glacial times which the glacier has not been able to remove entirely.

I believed that controversy could perhaps be stilled by direct observations in the bed of a living glacier. In the years 1940, 1941 and 1942 I several times found it possible to make my way from 20 to 50 m. down into the interior of both the Upper and Lower Grindelwald Glaciers by means of the marginal crevasses between the ice and the glacier banks. The photographs in Figs. 1 and 2, Pl. II, were taken on the Upper Glacier. In 1941 a system of subglacial caves led back from B (Fig. 1, Pl. II) to a point below the camera. The arrow in Fig. 2, Pl. II, marks the entrance to another series of caverns. By making my way into these I was able to reach the bed of the ice stream and there to watch the physical state of the ice and its action upon the rock.*

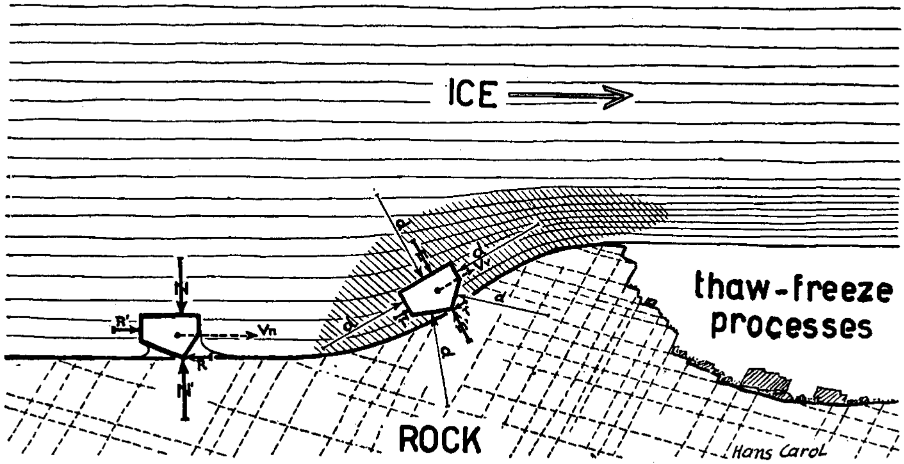

Fig. 7. Diagrammatic representation of a roche moutonnée forming under a living glacier. The hatching indicates the area of semi-fluid conditions

N pressure of superincumbent ice upon eroding stone
R, frictional resistance
Vn, normal speed of ice-flow
dd, hydrostatic pressure
n, reduced pressure upon stone
r, reduced frictional resistance

Under a pressure equivalent to a depth of 50 m. or less the glacier ice is rigid and brittle; it fractures easily on bending (see Fig. 3, Pl. II). If it flows over a large rock it does not immediately re-conform to the shape of the glacier bed after it has passed the obstruction (see Figs. 4 and 5, Pl. II). Instead a cavity is formed through which the observer may succeed in penetrating. It is more difficult to force access to the uphill side, but here too, by unusually good fortune, I was able to make a few observations and even measurements.

The problem was: did the upper layers of ice, which I found to be moving at the rate of 36·8 cm. a day against the obstructing rock, glide over the lower layers arrested by it? I found that this was not the case. The lower layers, squeezed by the narrowing of the vertical section, lost their rigidity and became plastic (see Fig. 6, Pl. II, also Fig. 8, p. 59). They assumed, so to speak, the character of a semi-viscous fluid. I measured their speed. The result was striking. The maximum rate of flow was 71·8 cm. a day—double the normal (see Fig. 8, p. 59).

* Carol, Hans, (1) Beobachtungen zur Entstehung der Rundhöcker. *Die Alpen*, 1943, pp. 173–80.
(2) Beschreibung einer Gruppe von Gletscherrandklüften am Obern Grindelwaldgletscher. *Mitteilungen der Geogr. Ethnogr. Gesellsch. in Zürich*, 1943–45, pp. 12–51.

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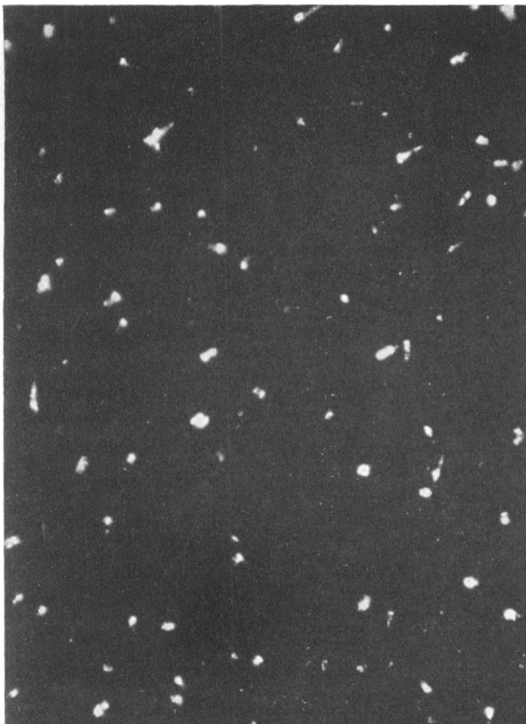

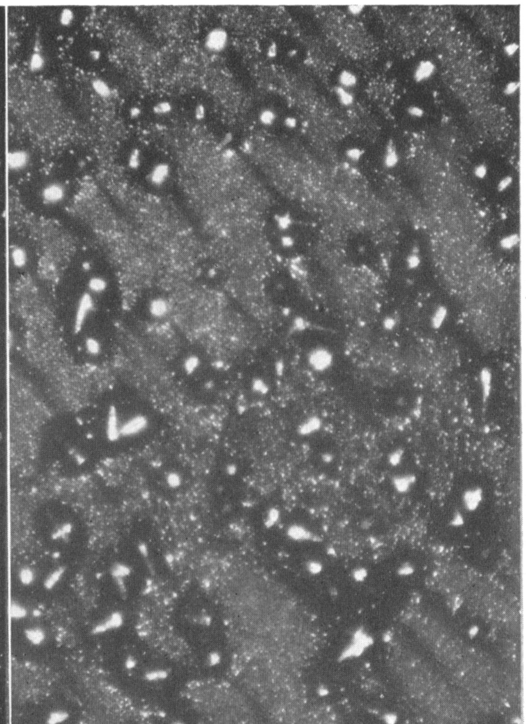

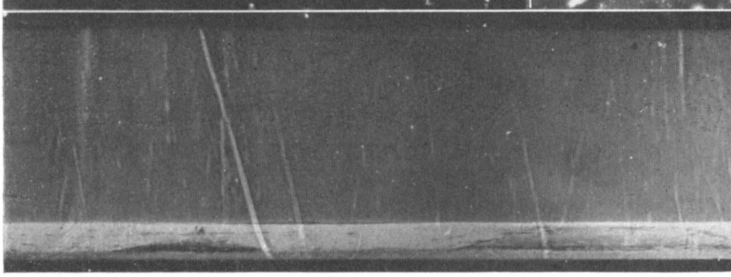

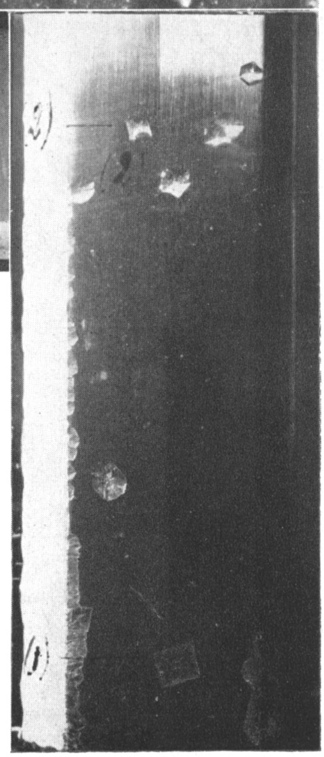

Fig. 1 (top left). Sublimation in presence of air on a surface of Al *deposited by evaporation* in vacuo*; an "old surface" prepared twelve days beforehand and kept in a desiccator. Frost point* $-52{\cdot}1°$*C. First ice crystals appeared at* $-54{\cdot}0°$*C. Photograph taken 15 minutes afterwards at* $-54{\cdot}5°$ *C. (× 50)*

Fig. 2 (top right). Same experiment 5 minutes later. When surface was cooled to $-58{\cdot}0°$ *C. supercooled water drops covered it, leaving free spaces round previously deposited ice crystals, owing to the decrease of water vapour pressure in their vicinity. To compare with Fig. 1 this photograph should be inverted*

Fig. 3 (left centre). Sublimation in absence of air. The surfaces of a thick layer of Cd *and "thin" layer of* Zn*. When the evaporation of* Cd *was completed half the surface was screened longitudinally and a thin layer of* Zn *was deposited on the other half. Frost point* $-38{\cdot}0°$ *C. Temperature of test plate* $-39{\cdot}1°$ *C. On the* Cd *side water vapour is subliming vigorously, none on the* Zn*. Natural size*

Fig. 4 (right bottom). Sublimation in absence of air on Cd *(left) and* Zn *(right) polished surfaces. Frost point of air* $-15{\cdot}0°$ *C.* $\pm$ $0{\cdot}1°$ *C. Temperature of test plate when first crystal appeared* $-16{\cdot}7°$ *C. Ice crystals of various shapes are shown (1) and (2) similar to those observed by Rau and classified by him as cubic*

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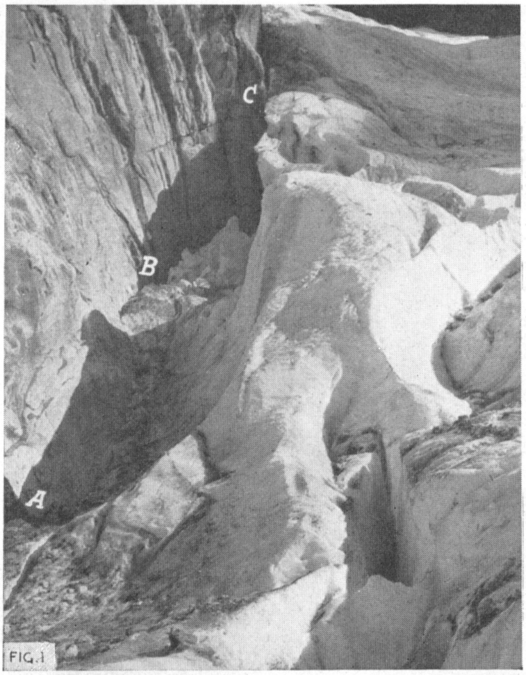
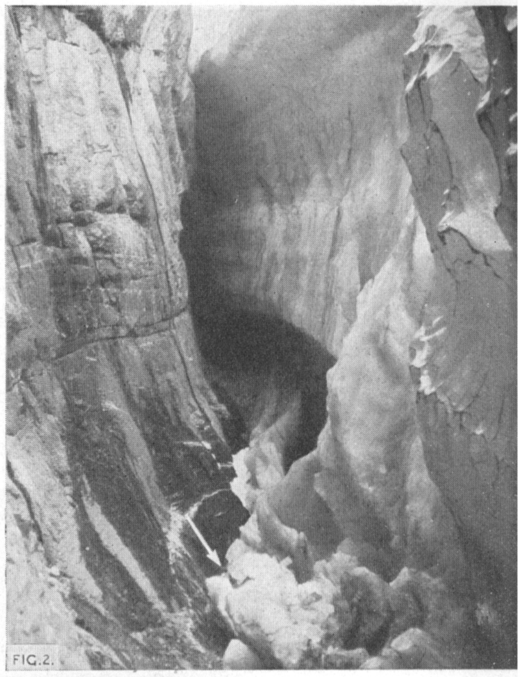
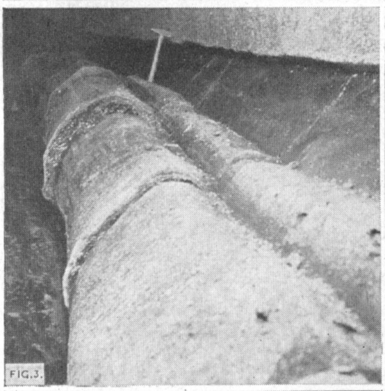
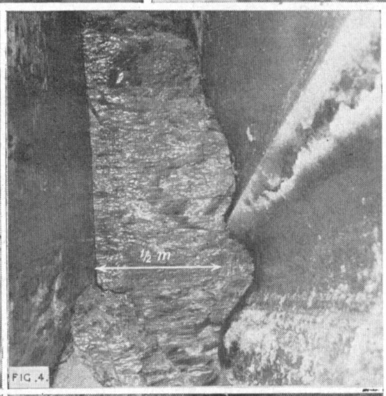
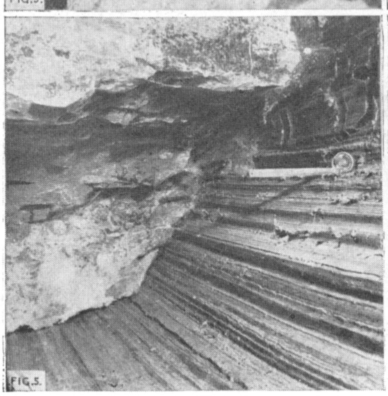
PLATE II











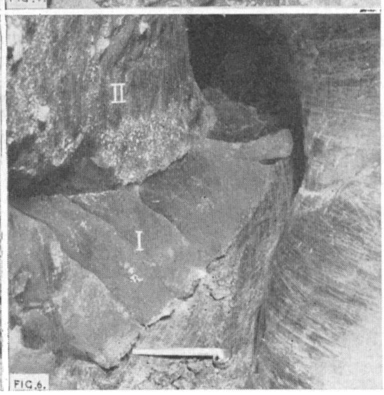


Fig. 1. Marginal crevasse. A C measures 160 m.

Fig. 2. Taken from B in Fig. 1. Ice 40 m. thick

Fig. 3. Roll of expressed plastic ice subsequently hardened. Figs. 3–6 Flash-light

Fig. 4. The rock mass (centre) has moulded its contour on the ice (right). Camera is pointing uphill

Fig. 5. The jagged downhill side of a roche moutonnée. Note grooves in ice. Rule extended 20 cm. 50 m. below surface

Fig. 6. Ice flowing over a rock. Camera pointing downhill. Layer (I) has been pressed out between an obstructing rock and the 20 m.-thick layer (II) above it

It was not surprising to find that water exuded from countless capillaries and that pieces of ice hacked out had almost the consistency of cheese. These two very different conditions of the ice—the plastic, through being dammed up on the uphill side of the obstruction, and the rigid, under normal conditions—must have a determining influence in the fashioning of rock forms.

Let us imagine that a stone the size of a man's fist is frozen into the ice moving parallel to the direction of flow over the glacier bed. In the unyielding ice, where each grain is frozen firmly to its neighbours, it is pressed on to the rock bed by the vertical (static) pressure (N, Fig. 7, p. 58). The observations I made showed that under these conditions it can scratch striae 4 mm. deep and 20 mm. wide. But as soon as the region in front of the obstruction is reached the increased pressure causes the surfaces of the ice grains to melt. The result is that the plastic mixture of ice and water flow round the stone; the pressure is no longer transmitted downwards from ice grain to ice grain, but is communicated to the fluid which

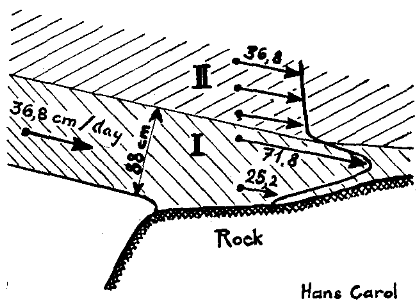


Fig. 8. Longitudinal section of Fig. 6, Pl. II, showing the measured speeds of layers I and II

now permeates the ice. The stone is therefore subjected to what amounts to hydrostatic pressure (dd, Fig. 7) from all sides and becomes practically a floating body. The pressure upon it is therefore much reduced and with it its power to erode.

The sequence of processes can be likened first to heavy scratching by a strong hand followed by a more gentle burnishing touch. In this way differential erosion acts upon an uneven rock surface and intensifies any irregularities irrespective of whether these existed preglacially or were caused by contemporaneous subglacial action (breaking and washing out).

As soon as the mixture of water and ice has passed the region of pressure it becomes rigid at once, as pointed out above, and retains the shape impressed upon it by the hummock. In the subglacial hollow so formed the temperature is always close to freezing-point. It seems probable, therefore, that the melt water penetrates through crevices and cleavage planes on the downhill side of the rock, where, the pressure being released, it refreezes and bursts off fragments.

I suggest therefore that reduced erosive power on the uphill side of the rock followed by thaw-freeze processes on the downhill face are the agencies which mould the typical shape of *roches moutonnées*. Differential resistance of the rocks forming the glacier bed is, in my view, of secondary importance in that it only appears to modify the individual forms.