SOME OBSERVATIONS ON GLACIER FLOW

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Abstract. The excavation of a tunnel by l'Energie Ouest Suisse (EOS) presented *inter alia* the opportunity to construct a longitudinal profile of the glacier speed and also to observe the speed of the transverse contraction of a circular section. The swift change of shape without fracture was noteworthy. A second tunnel driven from the glacier snout straight up the subglacial stream gave the opportunity to establish a definite connection between the form of the glacier sole and its surface. Finally, measurements of the glacier speeds on the surface and their variations from year to year gave a closer indication of the nature of Forbes's bands.

Zusammenfassung. Ein auf ca. 2400 m unter dem Sturz des Mt. Collongletschers bis zum Felsuntergrund vorgetriebener Stollen (EOS) bot u.a. die Möglichkeit, ein Geschwindigkeitsprofil längs der Stollenaxe aufzunehmen und andrerseits die Geschwindigkeit der Querkontraktion eines Kreisstollens zu beobachten. Bemerkenswert waren die raschen, bruchlosen Verformungen. Ein zweiter, beim Gletschertor, direckt über dem Gletscherbach vorgetriebener Stollen liess einen eindeutigen Zusammenhang zwischen der Morphologie der Gletschersohle und der Gletscheroberfläche erscheinen. Schliesslich ermöglichte die Messung der Fliessgeschwindigkeiten an der Gletscheroberfläche und deren jährliche Schwankungen einen besseren Einblick in die Ogivenbildung.

Two tunnels were driven into the Mt. Collon Glacier, Arolla in connection with the preliminary work for the Grande Dixence power station of S.A l'Énergie de l'Ouest-Suisse (EOS) (see Fig. 1, p. 499). The work was begun in the autumn of 1948 and finished in the early summer of 1949. Glaciological research was carried out in the tunnels, the relevant measurements being entrusted to the care of the representative of EOS, Monsieur Grosjean.

The upper tunnel was situated at the foot of an ice fall at about 2400 m. and was originally inclined upwards at 5 per cent. At about 202 m. rock was encountered in the shape of a vertical cliff towering some 60 m. above the tunnel. The glacier, flowing over the top of this cliff, detached itself from the upper edge, as does a waterfall, leaving a gap of 2–4 m. between ice and rock (see Fig. 2(*b*), p. 499). By contrast only a small gap between ice and rock was encountered in a branch gallery driven at right angles to the main tunnel. The bedding of the ice was approximately parallel with the polished surface of the rock, and close to the rock some of the strata were strongly impregnated with sand (see Fig. 3, p. 500).

In the principal tunnel the bedding of the ice, recorded by the geologists, showed a pronounced syncline with its axis at a distance of about 150 m. from the entrance of the tunnel, thus affording grounds for conclusion that at this point the vertical component of the velocity reaches a maximum. The speed of the ice at the point of contact with the rock bed (202 m. from the tunnel mouth) was of the order of 3 cm. a day, while at the surface, at the entrance of the tunnel, the glacier flowed at about 15 cm. a day. The section along the tunnel showing the glacier movement (in which the horizontal component of speed could be established more accurately than the vertical) corresponded well with the form of the ice bedding. A most surprising feature was the considerable extension of the ice along the length of the tunnel close to the rock. What was originally a length of 20 m. became stretched by some 4 m., *i.e.* by 20 per cent in 40 days, without the slightest sign of fracture. This steady lengthening, averaging 0·5 per cent a day, can be attributed to the plastic transverse stretching of the ice due to the heavy vertical loading caused by the steep slope immediately above.

In order to make a more detailed study of the relatively rapid plastic deformation in the tunnel cross-section, a cylinder of ice 5 m. long with a diameter of 220 cm. was broken out at 125 m. from the mouth of the tunnel. The progressive contraction of this was measured for one month. The fact that the tunnel section changed only slightly from its original circular shape (see Fig. 2(*a*)) shows that, in the plane at right angles to the axis of the tunnel, there was practically a state of hydrostatic pressure. The rate of the plastic contraction of the tunnel diameter was of the order of 0·82 per cent a day. From this relatively high value it may be concluded that here was a region in which the tunnel was exposed to greater pressure than the vertical pressure of the over-burden (pressure zone).

In similar conditions, such as those in a tunnel made later in the Z'mutt Glacier the measurement of the rate of contraction of a circular tunnel enables the calculation of the mean viscosity of ice to be made.

From this it can be shown that the rate of contraction of a vertical circular shaft decreases proportionately to the radius, so that theoretically the complete closing of the shaft would take an infinitely long time. But the closing of tunnels and shafts is the result not only of plastic contraction but of another process, whereby the fluid phase contained in the grain boundaries is squeezed out into the hollows. There it freezes as a result of the reduction in pressure, this being, of course, in addition to the freezing of melt water entering from outside. The filling of spaces with ice without air bubbles can play a decisive part in the last phase of the closing of any hollow cleft and results in a blue band. A similar development of a blue band with the closing of an artificially produced groove was demonstrated later in the Z'mutt Glacier tunnel.

The lower tunnel was started in the spring of 1949 from the snout of the Bas Glacier d'Arolla—as the tongue of the Mt. Collon Glacier is called on the new map—at 2120 m., and followed the subglacial stream for about 340 m. (see Fig. 4, p. 500). The angle of inclination of the stream bed cut through the moraine was 10 per cent at the glacier snout but showed a steady decrease to 6 per cent at the end of the tunnel. (From seismic soundings at this point Dr. A. Süsstrunk believes that below the stream bed there is a thick deposit of dead ice.)

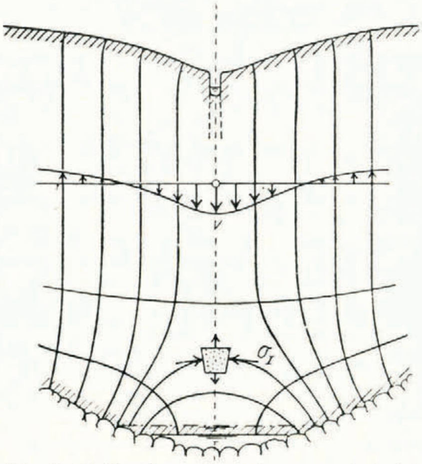

Fig. 6. Valley formation above a subglacial stream. The stress trajectories and distribution of the vertical speeds are diagrammatic only

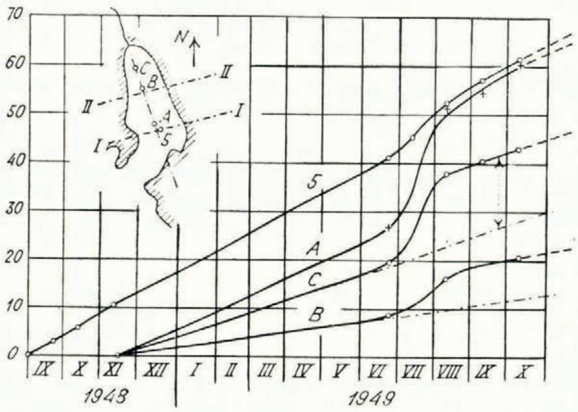

Fig. 7. Horizontal speeds in metres on the glacier surface

Surprisingly, the lower surface of the ice above the glacier stream was not arched but horizontal. Essentially, the ice moves vertically downwards here without sliding over the underlying rock. The glacier apparently plunges beneath the water level, and is melted in horizontal layers during periods of high water (see Fig. 5, p. 499). Should the stream rise suddenly after a period of low water the channel might act as a tunnel under water pressure so that the drag would be greatly increased. At the same time the melting process would become intensified so that the buttresses of the ice bridge would melt and collapse might occur.

If we consider the direction of the stress-trajectories and the strong concentration of forces in the buttresses of the invisible arch, the process of deformation of the base of the glacier above the stream becomes apparent (see Fig. 6, p. 497). Locally strong vertical movement may penetrate to the surface of the glacier and form a small valley corresponding to the course of the subglacial stream. In that case the course of this surface channel gives a valuable indication of the course of the subglacial stream. A fairly close connection, therefore, exists between the morphology of the upper and lower surfaces of the glacier. This applies more particularly when the course of the subglacial stream is sufficiently permanent.

The Mt. Collon Glacier broadly fulfils the above conditions, even though the glacier stream is cut into the moraine which, as suggested above, probably lies upon an accumulation of dead ice.

Vertical movement due to similar local causes result in trough-like depressions of the surface in the vicinity of such features, for instance, as the funnel-shaped holes ("*entonnoirs*") of the Gorner Glacier.

OGIVES (FORBES'S BANDS)

The horizontal movements shown in Fig. 7, p. 497, which were measured at four different points on the glacier surface, may be of some interest for the study of the formation of ogives which in English-speaking countries are referred to as Forbes's Bands. They are V-shaped like chevrons (see Fig. 1). In Fig. 7 the sudden acceleration of flow in July 1949 is very evident. This appears nearly simultaneously at all four points. It is also striking that the two points 5 and A, which are close together and of which the winter speed is practically identical, show considerable differences in speed in July. Finally, it is important to note that the average yearly speed of the glacier surface between the points A and C practically coincides with the average wave length of the ogives, from which it follows that in the pressure zone below the ice fall an ogive not unlike a pressure wave forms each year.

On account of the observations above, one is, on the one hand, inclined to feel that the formation of the ogives is due to differences in speed subject to a yearly rhythm. That is to say, that as soon as the diminution of speed between two points in the direction of flow reaches its maximum, effective pressure also reaches its highest value. The lateral expansion of the ice vertical to the glacier surface also shows a maximum at that moment, the ice spreading plastically upwards and forming a wave crest.* On the other hand, the tendency to form pressure waves on the glacier surface is increased by a certain instability reminding one of buckling (*Knickvorgänge*). Comparison with the formation of fine folds in the snow cover, as shown in Fig. 8 (p. 500), shows that even in the case of a more or less constant speed of creep a superficial wave formation may appear in the pressure zone of plastic layers.

As each year a new pressure wave is formed at the foot of the ice fall a system of bands results, which gives a very clear picture of the velocity distribution on the glacier surface. Provided that the speed of the glacier remains constant, the distance measured in the direction of flow between the axes of two adjacent bands should correspond to the average yearly velocity at that place. Thus, for example, it should be possible to read straight off the number of years required by a point on the glacier surface to travel from A to B by the number of bands between A and B. These preliminary reflections, based so far on single observations only, are put forward for discussion and as an introduction to further observations on ogives. It would be too early to generalize until more accurate measurements become available.

Nevertheless it should be noted that Professor R. von Klebelsberg in his *Handbuch der Gletscherkunde* (Vol. 1, p. 120) also expresses the basic view that these bands are caused by the intermittent and, as it were, jerky feeding down or falling down (*stossenweisen Nachschüben bzw. Nachbrüchen*) of ice from above.

Finally the author takes the opportunity on behalf of the glaciologists of thanking the Board of EOS for their initiative and for their permission to publish the above work. His thanks go equally to all workmen and others who risked their lives in this research.

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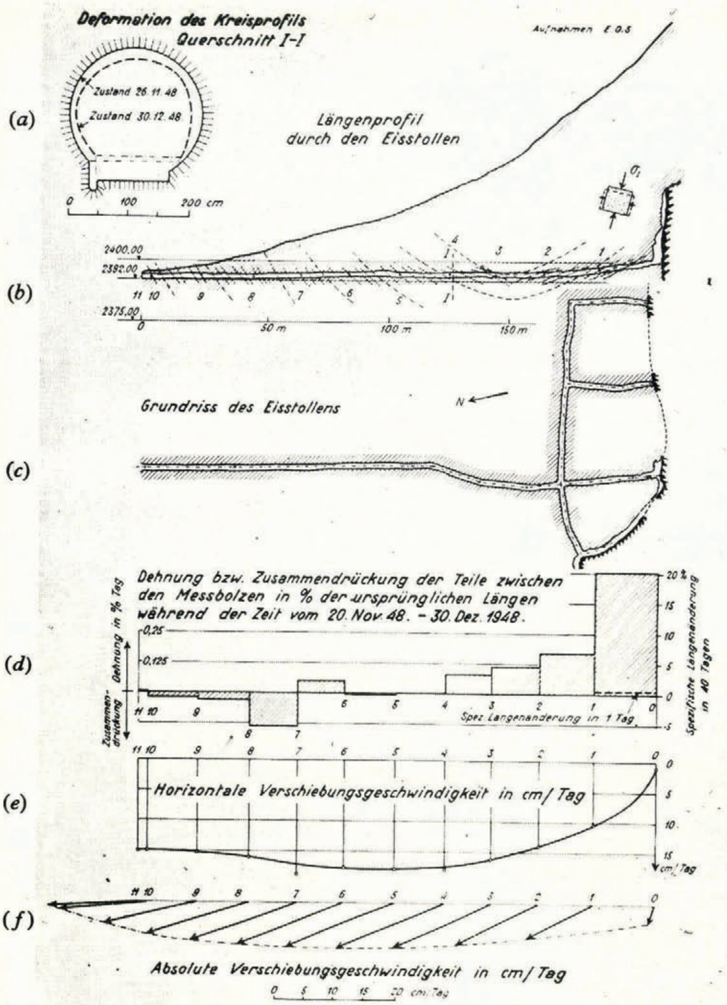
* Cf. Streiff-Becker, R. *Denkschr. Schw. Natf. Ges.*, Bd. 75, Abh. 2, 1943, p. 129.



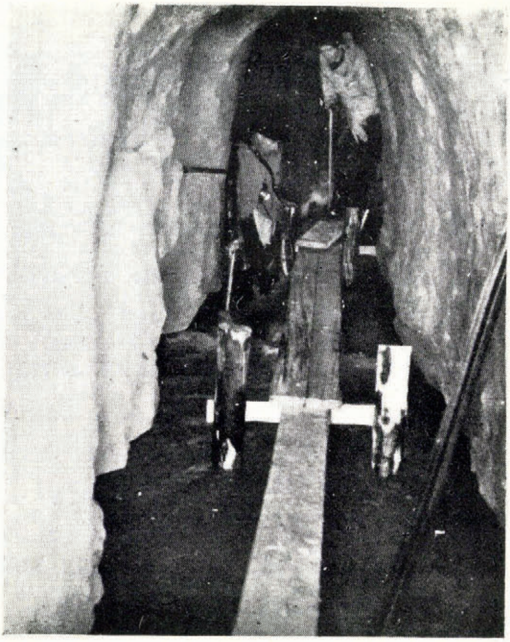


Fig. 5. The lower tunnel excavated above the subglacial stream

Photograph by P. Kasser

Fig. 2. Experimental tunnel in the Glacier du Mt. Collon

(a) Top left; deformation of a circular tunnel section between 26/11/48 and 30/12/48
(b) Longitudinal section through the tunnel
(c) Plan of the tunnel showing auxiliary galleries
(d) Expansion and compression between datum points from 20/11/48 to 30/12/48 expressed in percentages of the original lengths
(e) Horizontal speed of displacement in centimetres a day
(f) Actual speed of displacement in centimetres a day

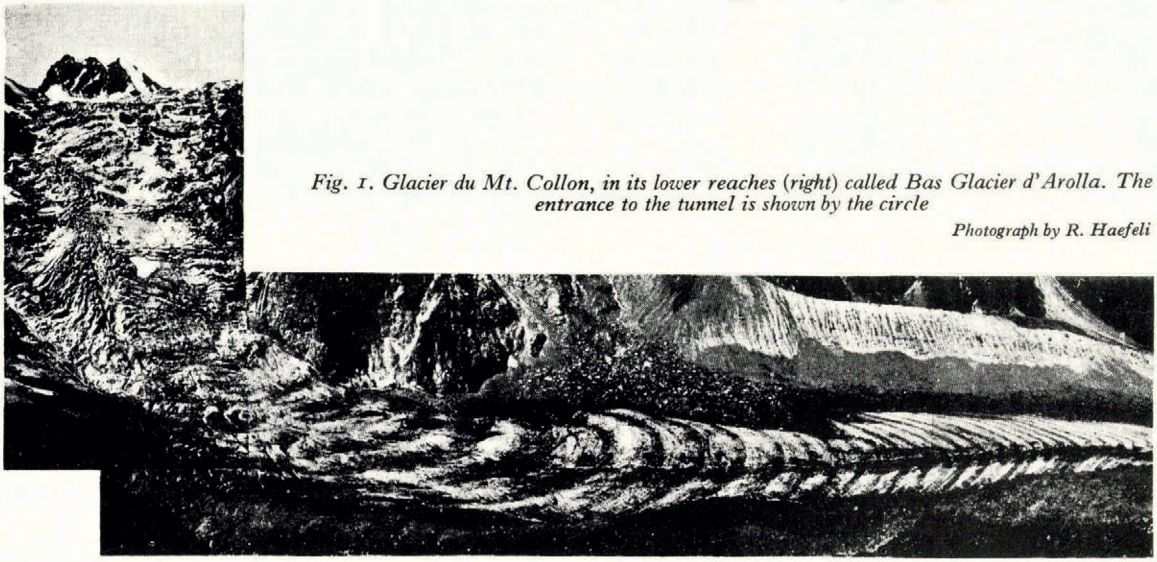


Fig. 1. Glacier du Mt. Collon, in its lower reaches (right) called Bas Glacier d'Arolla. The entrance to the tunnel is shown by the circle

Photograph by R. Haefeli

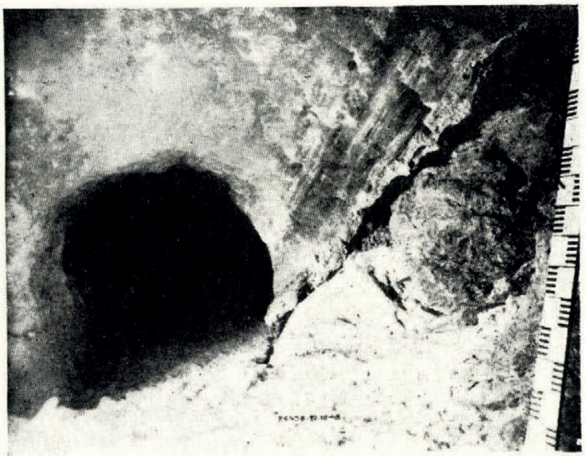


Fig. 3. Contact between ice and rock (right) in the upper tunnel. Flashlight photograph taken approximately on the double dotted line shown in Fig. 2 (c) (p. 499) a few metres to the west of the main tunnel

Photograph by EOS

Fig. 4. The entrance to the lower tunnel of the Bas Glacier d'Arolla

Photograph by R. Haefeli

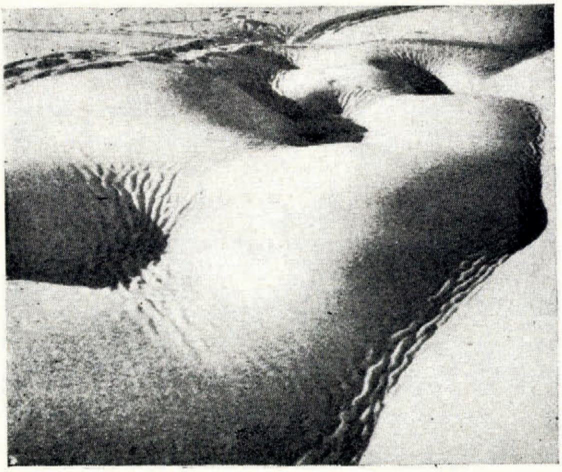


Fig. 8. Surface folds in snow showing pressure zones

Photograph by R. Haefeli

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