COMMENTS ON PROFESSOR HAEFELI'S PAPER

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Professor Haefeli's beautiful results are interesting both in themselves and as a corollary to our own measurements in the field[1] and in the laboratory.[2] We have found in both cases a rapid increase in the rate of shearing as a function of increasing stress, somewhat like that shown in the full curve of Haefeli's Fig. 1 (p. 95). In the field experiment the ice was at the pressure melting point, whereas in the laboratory pressure melting was excluded by carrying out the experiments at $-1\cdot5°$ C. Nevertheless, the dependence of the rate of shearing on shear stress was similar in the two cases, and possibly differed by no more than a scale factor due to the different temperatures at which the two experiments were done.

Haefeli rightly stresses the importance of distinguishing between the intrinsic effect of the shear component of the stress and the effect of hydrostatic pressure, and suggests that the latter should not be left out of consideration. Our experience rather seems to indicate that the first factor is overwhelming in cases like the one investigated by Haefeli, and that thermo-dynamic effects, *i.e.* pressure melting leading to the presence of a liquid phase at the grain boundaries, may only have a secondary influence.

In conclusion, we should like to make a plea that the time has come to abandon the term "viscosity" in discussions of glacier flow, because it has little value in relation to plastic materials showing the kind of behaviour that ice does.[2] In cases where complicated stress systems are involved, such as the closing of a tunnel or the penetration of a ball, a curve of deformation rate against depth or load might be more informative and be more easily applied to other cases.

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SHEAR-STRESS FABRICS OF ICE AND QUARTZ

SOME COMMENTS ON A PAPER BY DR. H. BADER*

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Dr. Bader's purely glaciological paper, based in part on studies of the Malaspina Piedmont Glacier in Alaska, should prove of great interest to those concerned with petrofabric work on ice and on metamorphic rocks, and to non-specialist glaciologists and metamorphic petrologists. The author deals with (1) the size, shape and mutually interlocked nature of Malaspina ice crystals, and (2) preferred orientations of the principal crystallographic axes of such crystals. These ice characteristics are dealt with in relation to (*a*) so-called "dead" ice (of the glacier fringe) that was flowing to some extent owing to deformation under the stress of its own weight, and (*b*) "living bubbly ice" near the outer edge of the glacier. In addition, the author gives a valuable account of ice-fabric research methods, including both field and laboratory techniques, and provides descriptions and photographs of the instruments employed.

* Introduction to ice petrofabrics. *Journal of Geology*, Vol. 59, No. 6, 1951, p. 519–36.

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Early in the paper (p. 519) it is stated that the crystallographic basal plane is the only reported plane of lattice slippage in ice. In this connection [6] it may be mentioned (1) that Matsuyama [7] and Rigsby [10] have independently put forward evidence indicating or suggesting the presence, in ice, of glide-planes other than the basal plane; (2) that, according to Hawkes,[3] slip within ice crystals takes place in part along the basal plane and in part along internal fracture surfaces; (3) that Turner and Ch'ih,[14] in a recent petrofabric account of the artificial deformation of dry marble, state that some type of intra-crystalline movement in calcite, other than that connected with the development of optically detectable twin-plane gliding, has played a part in deformation, *and has left no visible internal evidence of its activity*.

Dr. Bader (p. 523–26) emphasizes the high degree of interlocking of individual crystals, both in "dead" and living Malaspina ice. Like Buchanan,[1] he found that a block of glacier ice, when exposed to solar radiation, melted preferentially along its irregular intergranular boundaries and attained the condition of a loosely-articulated three-dimensional jig-saw puzzle. The preferential intergranular melting is attributed either to (1) the ice at the intergranular boundaries being in a non-crystalline state,[3] or (2) the ice at the intergranular boundaries being relatively impure.[1, 9] Hawkes [3] has mentioned "itacolumite" or flexible sandstone in connection with "flexible jig-saw" or "rubber" ice. Thin slabs of "flexible sandstone," although quite coherent, can be bent repeatedly. Such stone [15] consists of highly sutured, interlocked quartz grains [6]; the interlocking of the grains has developed owing to renewed growth of clastic (detrital) quartz fragments under unspecified metamorphic conditions. The origin of intergranular mineral films, and their elimination (which has produced the loosening of the fabric), are apparently not fully understood. Such flexible stone, whatever may have been its geological vicissitudes, provides a suggestive analogy between crystallization histories of ice in glaciers and of quartz in metamorphic rocks.

In view of preferred crystal orientations Dr. Bader (p. 520, 525), tentatively suggests that in the production of interlocked ice "intra-crystalline deformation (lattice translation) is the main flow mechanism, with phase changes according to Riecke's principle (pressure melting and regelation) as important contributors." Pressure melting and "regelation" (as generally understood) [3] can however take place in the absence of shearing stress, while Riecke's principle invokes the operation of such stress to bring about local differences in solubility of crystalline material in a state of elastic strain.* Dr. Bader thus appears to combine regelation with Riecke's principle, and to assume the presence of liquid intergranular films (*cf.* the saline liquid films believed by Renaud [9] to be produced by the melting of "saline skins" on glacier crystals, and to be important as a lubricant). Apart from the mention of regelation, the suggested dynamo-chemical process seems to be very closely comparable with that recently postulated to account for the development of strained and highly sutured (interlocked) quartz-aggregate in Scottish psammitic granulites.[6] In relation to ice/quartz analogies, the resemblances between these quite independent suggestions would appear to be of some significance.

Another point mentioned (p. 526), in connection with clear living Malaspina ice, is the alternation, in an apparently haphazard manner, of ice masses with highly developed interlocking structure, and of masses less well interlocked and composed of more or less equidimensional grains. This observation recalls the close association, in Scotland, of psammitic granulites with and without sutured, strained quartz-aggregate [5]; all stages of transition between the two types of aggregate are known.

Dr. Bader illustrates very strikingly the great elongation of interlocked crystals in the "dead" ice; he believes that some crystals may have linear dimensions of several feet (p. 525 and Fig. 2). Seligman [11, 12] and Mercanton [8] have attributed the very large crystals of dead glacier ice to alternate melting and refreezing (due mainly, perhaps, to daily fluctuations of temperature caused by radiation from the banks) and to the relatively great age of these apparently homogeneous crystals that grew by successive enlargement at the expense of others. Elongated quartz crystals in meta-

* Views on Riecke's principle, and on its application to metamorphic rocks, have recently been accorded fully documented discussion by Turner.[13]

morphic granulites, though of course on a much smaller scale, are well known to petrographers.[4] Here we may recall that, according to Seligman,[12] crystals in flowing glacier ice are not, as a rule, markedly elongated. Dr. Bader suggests that, if elongation of interlocked quartzes occurs in metamorphic rocks, it could be revealed only by serial thin-sectioning (the technique he used in studying elongated ice crystals). The scale of metamorphic crystallization is, however, relatively so small that sections of the same rock specimen cut in different directions may give a good general idea of crystal size, shape and orientation.[4]

At the outer edge of the Malaspina Glacier, in living bubbly ice, there are many clear parallel bands dipping at approximately 45 degrees away from the edge (p. 534). Dr. Bader considers that these clear bands are unlikely to be active shear-zones, but he appears to be doubtful as to their origin. In the bubbly ice, orientation of crystals was estimated (by the use of his own technique) from the orientation of enclosed "disks" (air bubbles and water). Dr. Bader thus found four very clearly preferred orientations of main crystal axes, as follows: (1) normal to the glacier surface; (2) parallel to the glacier surface in the direction of flow; (3) and (4) situated symmetrically in the plane defined by the normal to the plane of banding and the strike of the banding, each set making angles of approximately 20 degrees with the normal to the plane of banding. The symmetrically located axes (3) and (4) would thus appear to constitute an imperfect "girdle" *in a plane perpendicular to the local direction of flow*. Even if such an interpretation of Dr. Bader's statements is not fully justified, it is worthy of note that the orientation of this plane, in relation to direction of flow or movement, agreed with (1) the orientation established by Perutz and Seligman for an ice-girdle plane in the ice apron on the north wall of the Sphinx ridge at the Jungfraujoch, and (2) with the orientation (*according to the tectonic ideas of E. M. Anderson*) of quartz-girdle planes in dynamically metamorphosed psammitic granulites.[6] In connection with optic axis girdle-plane orientation, petrofabric workers should note the last paragraph of the paper by Turner and Ch'ih [14] mentioned earlier in this commentary.

In view of the comparisons made above between ice and quartz, it is only fair to state that Dr. Bader, at the time he wrote his paper, obviously regarded such comparisons with considerable suspicion (p. 535). It is to be hoped that this attitude will be modified, or at least that it will not prevent him from giving due consideration to tectonic quartz-fabrics.

Dr. Bader (p. 535) is also suspicious of analogies drawn between the behaviour of ice and of metals. It therefore seems worth directing attention to two photomicrographs just published by Gifkins [2]; they illustrate the microscopic appearance of polished surfaces of a lead-thallium alloy: Fig. 1 after slight strain, and Fig. 2 after 372 per cent extension in 221 days. The texture shown in Fig. 1 very closely resembles the tessellate mosaic of ice in the *névé* region of a glacier [6]; Fig. 2 bears a remarkable resemblance to cross-sections of the irregular, interlocked ice-aggregate of the glacier tongue, as illustrated in Dr. Bader's paper, and elsewhere.[6] If the figure captions, including the statement of magnification, were removed, it would be impossible to say whether Gifkins' photographs represent metal, ice or quartz.

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A COMPARISON BETWEEN THE THEORETICAL AND THE MEASURED LONG PROFILE OF THE UNTERAAR GLACIER

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ABSTRACT. The measurements by seismic sounding of the long profile of the Unteraar Glacier reported by Mercanton and Renaud are compared with theoretical calculations. By taking the valley to be a cylinder of parabolic cross-section a theoretical curve for the surface is deduced which depends on one unknown parameter only, the average shear stress on the bed. If his parameter is given the value $0{\cdot}77 \times 10^6$ dynes/cm.^{2} the theoretical curve agrees well with the measurements.

RÉSUMÉ. Les mesures obtenues par sondages sismiques, présentées par Mercanton et Renaud, concernant le profil en longueur du Glacier d'Unteraar sont comparées aux resultats calculés par la théorie. En assimilant la vallée à un cylindre de section parabolique, on obtient une courbe théorique pour la surface, qui ne dépend que d'un seul paramètre inconnu: la tension tangentielle moyenne exercée par la glace sur le lit du glacier. Si l'on attribue la valeur $0{\cdot}77 \times 10^6$ dynes/cm^2 à ce paramètre, la courbe théorique correspond bien aux mesures citées.

THE publication by Mercanton and Renaud [1, 2] of the long profile of the Unteraar Glacier measured by seismic sounding makes possible a rough comparison between theory and observation. The measured profile based on 750 soundings over the glacier surface is reproduced from reference 2 in Fig. 1.

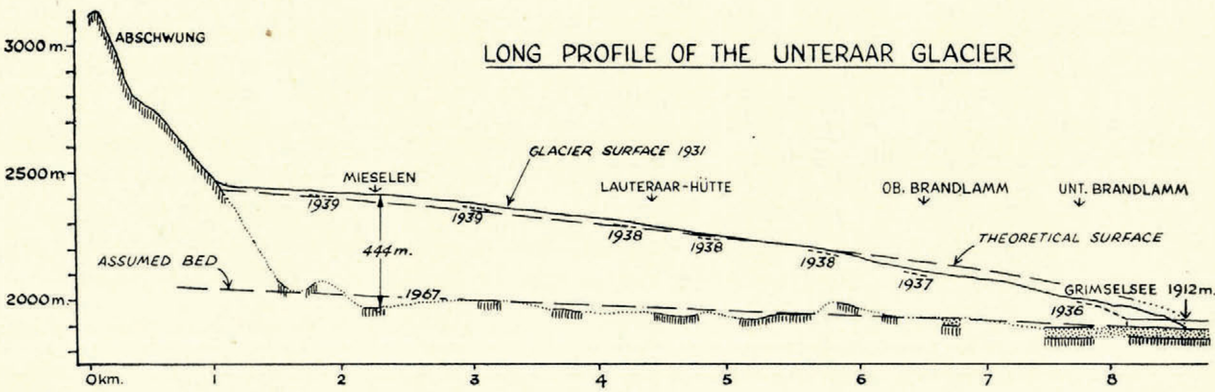

Fig. 1. Long profile of the Unteraar Glacier measured by seismic sounding, reported by Mercanton and Renaud. Vertical scale exaggerated by a factor of two. The observed curve is compared with one calculated by assuming a constant slope of the bed, $\beta = 0{\cdot}0213$ radians

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