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BOUDINAGE IN GLACIER ICE—SOME EXAMPLES

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Abstract. Boudinage structures have only rarely been reported in glacier ice, yet they seem to be widespread in Swiss glaciers. They form in debris-free, strongly foliated ice by the stretching, necking and rupture of layers or groups of layers, when the principal compressive strain axis lies at a high angle to the layering. Two main types of boudinage are distinguished. The first results from the difference in competence between fine-grained and coarse-grained ice, and indicates that the former is more resistant to flow than the latter. The second occurs in more equigranular ice which shows a strong planar anisotropy; associated with the necking of such ice is the development of shear planes, along which the layers are displaced. As in deformed rocks, it is not possible to determine the directions of the finite principal strain axes from the boudinage structures alone. Although the boudins described here all occur in longitudinal foliation, it is suggested that they are likely to form in other situations also.

Résumé. *Boudinage dans la glace de glacier—quelques exemples.* L'existence de structures de boudinage dans la glace de glaciers n'était guère reconnue auparavant; cependant, ces structures semblent être répandues dans les glaciers suisses. Elles étaient formées dans la glace fortement feuilletée par tension, amincissement périodique ("necking") et rupture des strates ou groupes de strates, quand les directions principales de raccourcissement sont inclinées à un angle fort par rapport à la stratification. Deux types principaux de boudinage peuvent être distingués. Le premier est un résultat de la différence de compétence entre les glaces fines et grossières et indique que la glace fine est plus résistante à l'écoulement que la glace grossière. Le deuxième type se produit surtout dans de la glace à composition homogène qui montre un plan d'anisotropie bien développé; associé au "necking" d'une telle glace, on trouve souvent le développement de plans de cisaillement le long desquels les strates sont décrochées. Comme dans le cas de déformation de roches, on ne sait pas, à partir seulement des structures de boudinage, déterminer les directions des axes principaux de l'effort qui a été subi. Bien que les boudins ci-décrits se produisent tous dans une foliation longitudinale, nous émettons l'hypothèse qu'ils peuvent probablement se former aussi dans d'autres situations.

Zusammenfassung. *Boudinage in Gletschereis — Einige Beispiele.* Bisher ist Boudinage in Gletschereis kaum beschrieben worden, obwohl Boudinstrukturen in Schweizer Gletschern weit verbreitet sind. Sie entstehen in reinem stark laminiertem Eis und zwar durch Streckung, Einschnürung und Zerreissen von Lagen oder Verbänden von Lagen, wo die kurze Achse des Verformungsellipsoids mit einem hohen Winkel zur Laminierung liegt. Zwei Typen von Boudinage können unterschieden werden. Der erste ist durch Kompetenzunterschiede zwischen Eislagen verschiedener Korngrössen bedingt und zeigt, dass das grobkörnige Eis eher fliesst als das feinkörnige. Der zweite Typ kommt in mehr äquigranularem Eis vor, das aber eine ausgeprägte Planarparalleltextur besitzt. In diesem Fall entwickeln sich Scherflächen, an denen die Lagenverbände verschoben werden, an der Stelle, wo das Zerreissen stattfindet. Aus diesen Strukturen allein ist es nicht möglich die Lage der Hauptachsen des Verformungsellipsoids zu bestimmen, wie dies bei deformierten Gesteinen auch der Fall ist. Obwohl die hier beschriebenen Boudins alle im Zusammenhang mit longitudinaler Laminierung vorkommen, können sie unter gewissen Bedingungen auch in anderen Teilen von Gletschern entstehen.

Introduction

Boudinage is a widespread feature in deformed rocks, and most authors agree that it results from the extension and pulling apart of competent layers in a matrix of ductile material (see, for instance, Lohest and others, 1909; Adams and Bancroft, 1917; Wegmann, 1932; Holmquist, 1931; Cloos, 1947; Ramberg, 1955; Rast, 1956; Sitter, 1958; Coe, 1959; Ramsay, 1967). The ductile matrix flows into the spaces between the individual competent fragments, or boudins (from the French for blood sausage), often rounding the corners, so that cross-sections of boudinaged layers look like strings of sausages (cf. Ramsay, 1967, figs 3-40, 3-41, 3-42; see Fig. 1). There is little reference to such features in the glaciological literature, in spite of the many similarities between glacier ice and deformed rocks. Boudinage involving debris-laden ice has been observed (Gow, 1972, fig. 2), although it has not been described as such. That boudin-like structures may be quite common in ice, however, became clear during structural studies of several Swiss glaciers during the summer of 1974, and this prompted the following discussion, with examples.

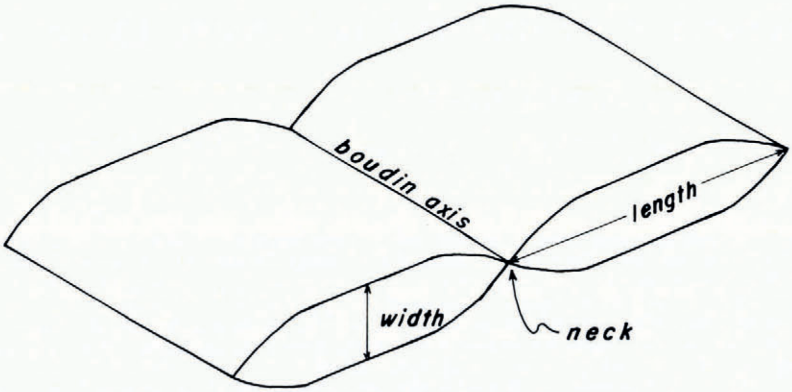

Fig. 1. Cut-away block diagram of a typical boudinaged layer, showing the terminology used in the text.

Boudinage in deformed rocks

Boudins, like folds, are found in deformed rocks in many different styles, depending on the mechanical properties of the materials involved as well as on the relation between the boudinaged layer and the deformational environment. These variations can be briefly summarized as follows:

(a) *Boudinage in a multi-layer system*

A whole range of boudinage styles result from differences in "competence" (a loose, ill-defined term used in geology to designate relative apparent resistance to flow, i.e. "competent" indicates high resistance and "incompetent" low resistance to deformation under the local flow regime), which in turn are related to compositional differences between the layers in multi-layer systems. These variations have been described qualitatively by Ramsay (1967, fig. 3-44) and are summarized in Figure 2. Blocky, square-ended boudins are taken to

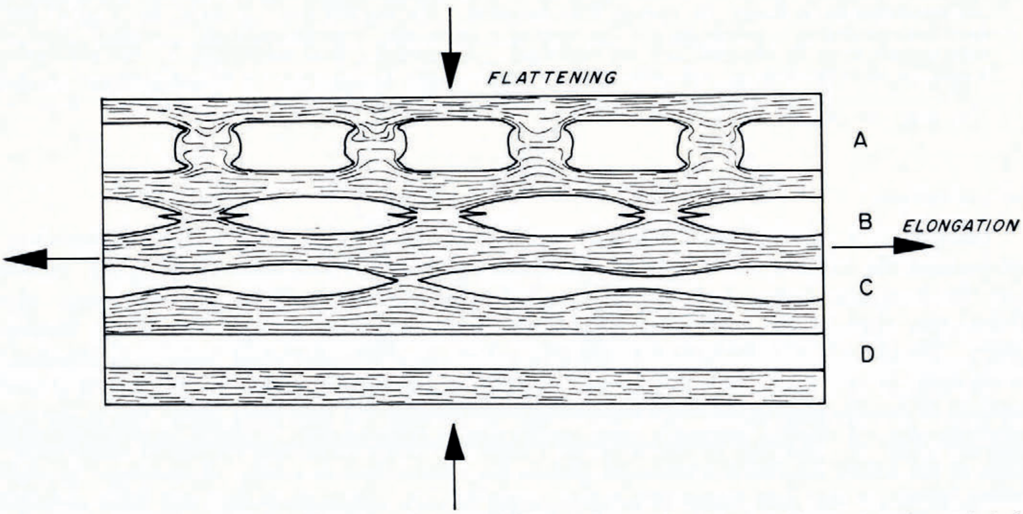

Fig. 2. Boudinage and pinch-and-swell structures in layers of different degrees of competence with respect to the matrix (after Ramsay, 1967, fig. 3-44). Layer A is much more competent than the matrix (barrel-shaped boudins), layer B moderately more competent (sausage-shaped boudins), layer C slightly more competent (pinch-and-swell), layer D is the same as the matrix.

indicate a high competence difference between the brittle, more competent boudinaged layer and the less competent material on each side deforming by ductile flow. At low competence differences, when all the layers deform by ductile flow, boudinage degenerates to a pinch-and-swell structure, with necking or even complete thinning out of the more competent layer at regular intervals (Fig. 2). In all cases, there seems to be an empirical relationship between the thickness of the boudinaged layer and the length of the resulting boudins (see Fig. 1 for terminology), corresponding to the thickness/wavelength ratio in folds and equally difficult to interpret (cf. Ramberg, 1964, fig. 2). The neck regions may be partially or completely occupied by mineral nodes, if the spaces (low pressure areas) between the boudins could be more easily filled by deposition of minerals from migrating fluids than by flow of the surrounding rock (e.g. Ramberg, 1955; Coe, 1959). Although one of the main differences between rock and ice masses is the general lack or weak development of compositional banding in the latter, some examples of these types of boudinage have been observed in Swiss glaciers and are described below.

(b) *Boudinage in a homogeneous, mechanically anisotropic medium*

Deformation of compositionally homogeneous rock bodies often results in a strong planar and/or linear anisotropy (e.g. cleavage in slates, foliation in granitic gneisses) which is not accompanied by a corresponding compositional banding. Subsequent deformation of such a homogeneous, mechanically anisotropic body leads to structures which cannot be understood in terms of competence differences. The effect of mechanical anisotropy on fold and boudin development has only recently been studied theoretically and experimentally (Cobbold and others, 1971), but boudinage effects which probably formed under these conditions are recorded sporadically in some earlier literature (e.g. Coe, 1959; Milnes, unpublished). These have been referred to as "foliation boudinage" (Milnes, unpublished) or "internal boudinage" (Cobbold and others, 1971). In these cases, it is not yet known what determines the thickness of the boudinaged layer, since there is generally very little difference in bulk composition between it and its surroundings (Fig. 3). Structures of this type are probably widespread in glaciers, particularly in volumes of ice which have previously become strongly foliated, and some possible examples are given later.

(c) *Boudinage and states of strain*

All types of boudinage may be symmetric or asymmetric ("rotated"), a relationship probably determined by the orientation of the layering or foliation relative to the principal bulk strain axes during boudin formation (Fig. 3; see also Ramsay, 1967, p. 103–09). Boudinage can be taken to imply

(i) that the layering or foliation maintained an orientation at a high angle to (for symmetrical boudins, perpendicular to) the short axis of the strain ellipsoid during boudin formation, and

(ii) that, if folding related to the boudinage is absent, the strain ellipsoid was of flattening type (i.e. $1 < k < 0$, where k is a parameter for describing different types of ellipsoid, see Flinn, 1962).

Apart from these generalizations, little can be deduced from the geometry of the boudinaged layer concerning the corresponding states of finite or infinitesimal strain, or about the related stress fields. In particular, it can be shown that the orientation of the boudin axes is of little kinematic significance, since extension in the plane of the layering generally takes place in all directions (see Ramsay, 1967, p. 112; Sanderson, 1974). With these difficulties of interpretation in mind, the examples from Swiss glaciers will now be briefly described and then the significance of boudinage in understanding glacier flow will be discussed.

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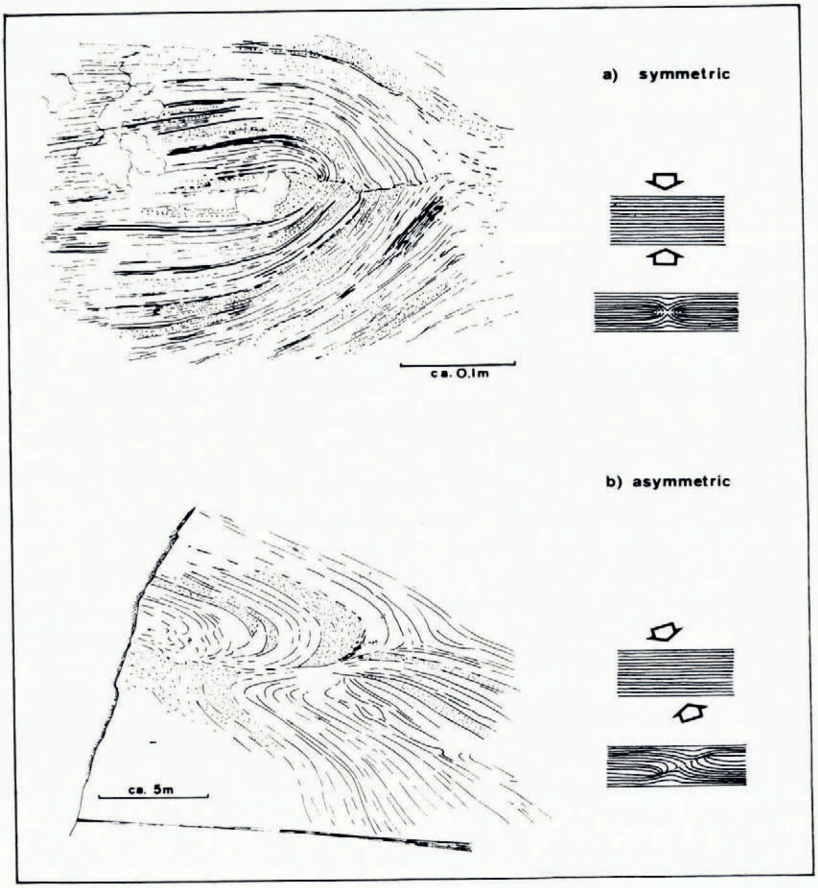

Fig. 3. Sketches and interpretation of foliation boudinage in rocks, (a) in green schists, Tittelsnes, Hardangerfjord, Norway, (b) in colour-banded marble, Piano di Peccia (quarry), Ticino, Switzerland.

Examples of boudinage structures in Swiss glaciers

Vadret da Morteratsch, Val Bernina, Grisons

The tongue of this glacier is structurally composite, involving three flow units. Several large boudins occur near the east margin of the main (central) flow unit, about 1.8 km from the snout (Fig. 4). The general structure of this flow unit consists of a strong transverse foliation, made up of intercalated layers of coarse bubbly, coarse clear, and fine-grained ice, cropping out parallel to weak ogives which are formed in a large ice fall below the peak of Bellavista. Initially, the foliation is near-vertical throughout, although with a marked down-glacier curvature (cf. Allen and others, 1960; Ragan, 1969). Downwards, a decreasing up-glacier dip develops at the apex of the foliation outcrop, and a centreward dip at the limbs (compare stereograms XX′ and YY′, Fig. 4). The boudins occur on the east limb of the arcuate foliation system, where the strike is longitudinal and the dip about 65°. In effect, they have formed on the limb of a fold which now, as a result of differential flow, plunges at about 27° up-glacier (see Fig. 4).

The boudins, observed in the walls of a sub-longitudinal crevasse, are of the order of 1–2 m in width. They exceed 5 m in length, but their exact dimensions could not be determined because of incomplete exposure. Internally, the boudins are composed of many

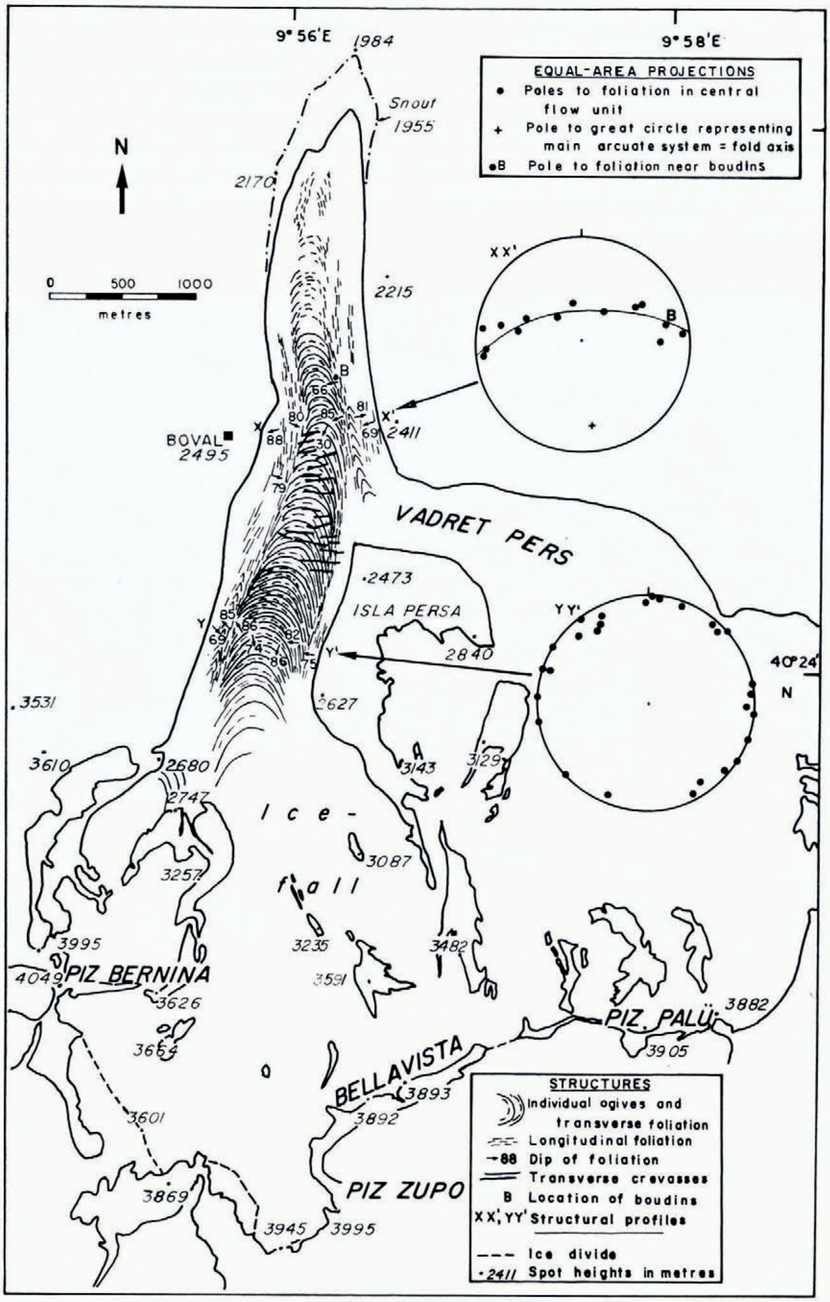

Fig. 4. Sketch map of structures in the tongue of Vadret da Morteratsch, based on vertical air photographs (18 August 1971) and field measurements, showing location of the described boudinage features. The stereograms are lower-hemisphere equal-area projections of poles to foliation on the two transverse profiles XX′ and YY′.

layers of foliation (here mostly coarse bubbly ice with thin coarse clear layers), and there are no visible differences with the ice surrounding them. Shear planes have formed at a moderately high angle to the layering, displacing it at the boudin necks by up to half a metre, while layers about two metres above and below the necks are continuous (Fig. 5). These boudins are apparently analogous to asymmetrical "foliation boudinage" in rocks (cf. Fig. 3b). Symmetrical foliation boudinage in rocks often results in voids near the ends of the individual boudins which become simultaneously filled with new minerals (e.g. Coe, 1959). A similar situation appears to have arisen between one pair of boudins in Vadret da Morteratsch; water has filled such a void and subsequently frozen, producing a concentration of large radiating crystals of clear ice.

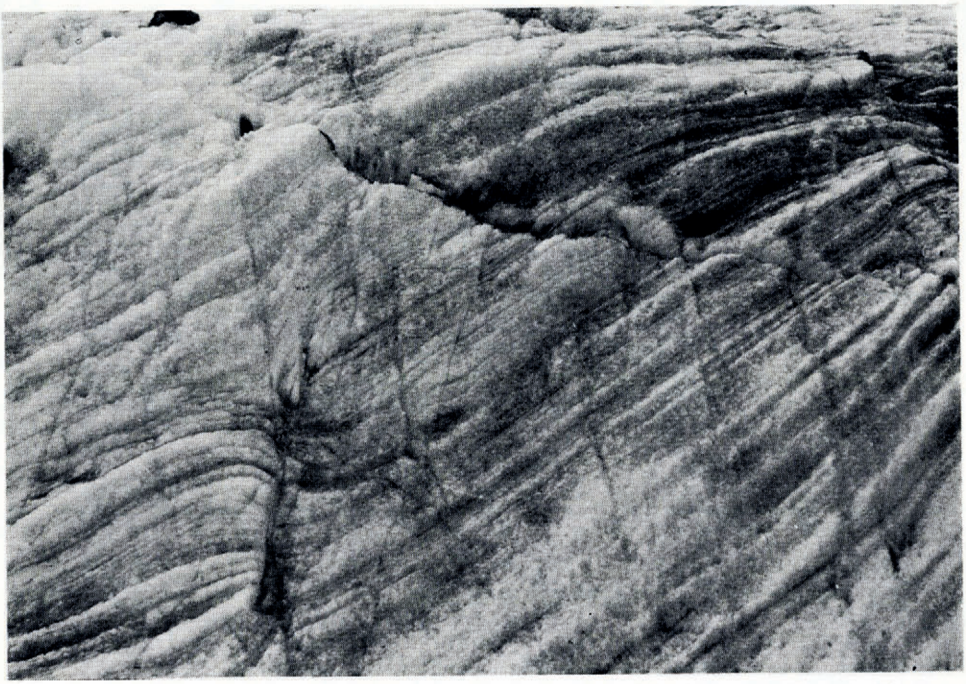

Fig. 5. Foliation boudinage in the wall of a crevasse, Vadret da Morteratsch (for location, see Fig. 4). The near-vertical joints are the traces of former crevasses. Note the displacement of foliation by a shear plane at the boudin neck. Glacier flow is from left to right.

The deformational history of the glacier below the ice fall is indicated by the spacing of the ogives and from the traces of former crevasses. Assuming that each ogive represents a year's movement, and taking groups of five to even out annual fluctuations, it can be seen that the ice in the centre of the glacier passes through two zones of longitudinal compression between the base of the ice fall and the site of the boudins (Fig. 4). Between these zones is an area of extension, indicated also by the transverse crevasses. The joints shown on Figure 5 are probably the traces of former crevasses formed in this zone. The necks of the boudins often coincide with such joints, suggesting that boudinage occurred as the ice passed through the crevassed zone, that is, under conditions of "extending flow" (see Nye, 1952). This conclusion can be supported by considering the expected strain conditions at the margins of the glacier in the different flow regimes. Figure 6 illustrates the orientations of the incremental strain

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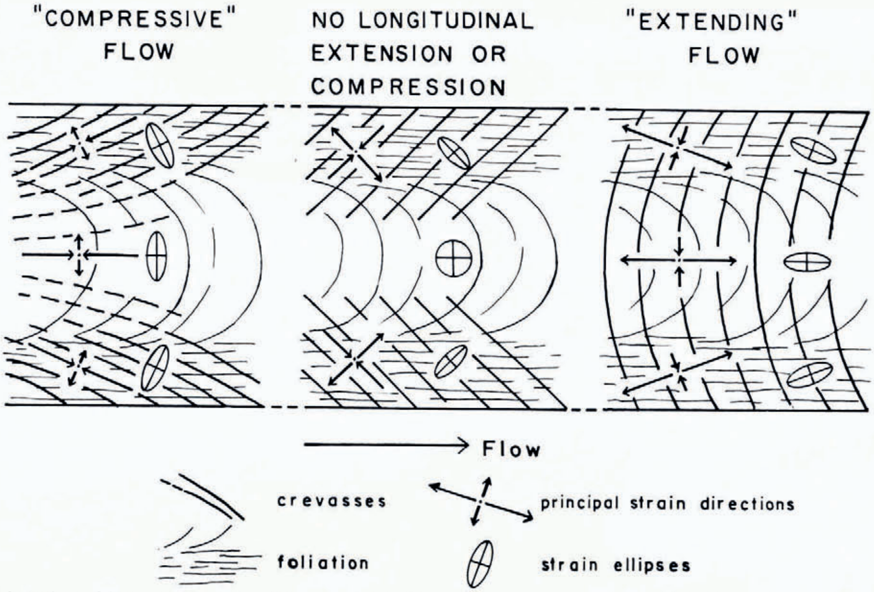

Fig. 6. Orientation of incremental strain ellipses and principal strain axes in the plane of the ice surface under different flow conditions in an idealized valley glacier (based on Nye, 1952, fig. 9).

ellipses in the plane of the glacier surface under conditions of ideal "compressive" and "extending" flow (after Nye, 1952, fig. 9). It can be seen that the foliation trace in the latter situation subtends a high angle to the short axis of the strain ellipse (the condition for boudinage formation), whereas in the compressive flow regime this is not the case.

A similar boudinage structure was also observed on a horizontal surface in steeply dipping longitudinal foliation near the centre of the lower Grosser Aletschgletscher, Valais (Fig. 7). In this case, the shear plane cuts the boudinaged layer at a rather high angle, compared with those associated with foliation boudinage in rocks. However, the boudins contain numerous layers of finer-grained ice and are surrounded by ice of coarser grain, so competence differences may have played a role in this example (see below).

Vadrec del Forno, Val Bregaglia, Grisons

The main structure of the straight, gently graded Vadrec del Forno is an approximately vertical longitudinal foliation throughout its width and for most of its length. Small boudinage structures were observed at a number of localities. The boudins, exposed on horizontal surfaces, are composed entirely or mainly of fine-grained ice, while the matrix consists mostly of coarse-grained ice (Fig. 8). These structures seem to be more comparable with the results of deformation of a multi-layer system, in which the fine-grained ice is the more competent material (cf. layer B, Fig. 2). If we consider the shape of the valley and the absence of transverse crevasses, it seems that the boudins formed as a result of transverse shortening where the valley narrowed. Small boudins of similar shape and size were also observed in longitudinal foliation in Glacier de Saleina (Val Ferret, western Valais), Oberaargletscher (Grimselpass, canton Bern) and Griessgletscher (Aegintal, eastern Valais).

Vadrec da l'Albigna, Val Bregaglia, Grisons

Irregularly shaped fine-grained ice layers of width approximately 0.2 m in a matrix of granulated coarse-grained ice were observed near the snout of the structurally complex

Fig. 7. Boudinaged zone in longitudinal foliation, lower Grosser Aletschgletscher, made up of numerous fine-grained ice layers surrounded by coarse-grained ice. A shear plane at a high angle to the layering displaces the layering at the boudin neck. Glacier flow is from right to left.

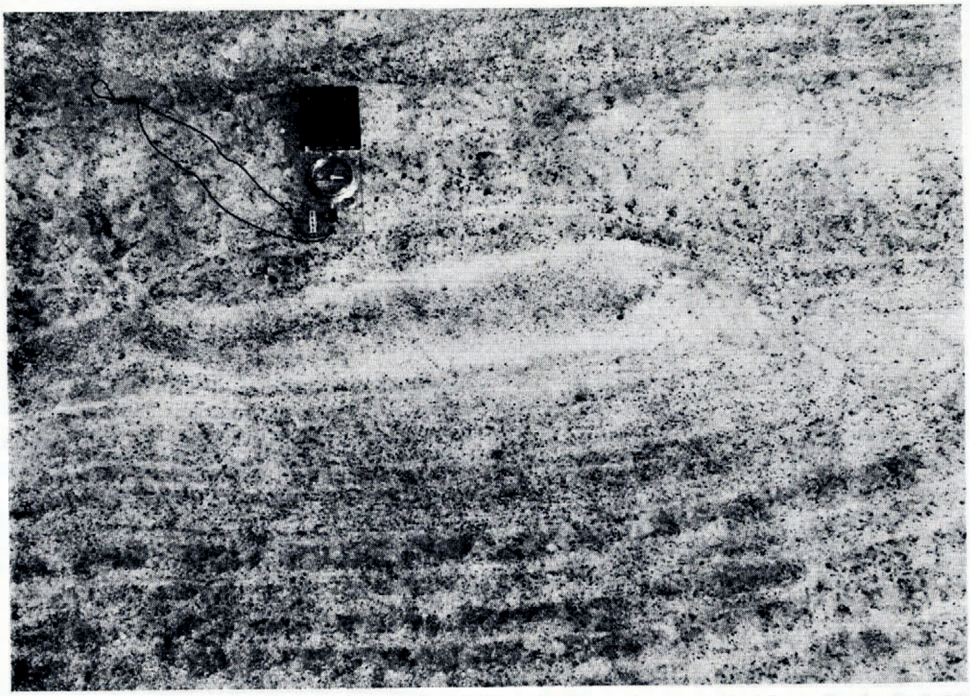

Fig. 8. Boudinaged layer of fine-grained ice in a matrix of alternating fine and coarse-grained layers (longitudinal foliation). Vadrec del Forno. Glacier flow is from right to left.

Vadrec da l'Albigna, and showed occasional strong necking, reminiscent of "pinch-and-swell" structures in rocks (cf. layer C, Fig. 2). A good example was exposed in the vertical walls of a transverse crevasse, in near-vertical longitudinal foliation, in the centre of the glacier (Fig. 9). It would appear that extension took place in a vertical longitudinal plane, where a tributary generated a strong transverse compressive strain in the main part of the glacier. The pinch-and-swell structure and the foliation are also slightly folded in this case. As in the previous examples, the fine-grained ice appears to have been more competent than its matrix, although the competence difference seems to have been less here.

A larger but more irregularly developed pinch-and-swell structure is displayed in basal ice on the steep left lateral face of the snout of Glacier de Tsijiore Nouve (Val d'Arolla, Valais). Here, at least one of the light coloured, mainly fine-grained ice layers in the alternating sequence of approximately 2 m thick light and dark layers has been pulled apart by extension parallel to the bed.

Fig. 9. Pinch-and-swell structure in a layer of fine-grained ice in a matrix of coarse clear ice, Vadrec da l'Albigna. The structure is exposed in the wall of a transverse crevasse and is slightly folded. Glacier flow towards the viewer.

Discussion

Boudinage in glacier ice develops in structurally anisotropic but compositionally homogeneous material. Sometimes it involves the extension, necking and rupture of fine-grained ice layers in a matrix of coarser-grained ice, sometimes of groups of layers in a matrix of identical structure. The first type implies that coarse-grained ice is markedly less resistant to ductile flow than the fine-grained ice, and can be compared with competence-dominated boudinage in rocks. The competence contrast seems to vary and is greater in the example described from Vadrec del Forno than in that from Vadrec da l'Albigna, possibly because of variations in crystal size, shape and orientation. Although the examples given here are developed in clean ice (the debris illustrated in Figures 3, 7 and 8 being only surficial), competence differences

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between clean and debris-laden ice may also enable boudinage to develop, as the photograph of Gow (1972, fig. 2) illustrates. While several workers have determined the flow law for ice artificially produced in the laboratory, little work has been done on the flow law of actual glacier ice. Colbeck and Evans (1969) experimentally deformed "typical" (i.e. coarse-grained bubbly) ice from the Blue Glacier, Washington, and obtained a flow law from the resulting creep curve. However, no experimental work has been carried out to compare the flow properties of the different types of ice found in glaciers, as is clearly desirable in the light of the above observations.

The second type of boudinage involves bundles of laminae in strongly foliated ice, whereby a comparison with foliation boudinage in homogeneous, mechanically anisotropic rocks seems more appropriate. In these cases, the laminated structure is the same both inside and outside the boudinaged layer and thus competence differences in the sense of differences in bulk mechanical behaviour probably did not exist. A characteristic feature of the asymmetric variety of foliation boudinage (see Fig. 3b) is the displacement of the lamination along shear planes cutting through the necks between adjacent boudins. Interesting in such cases is the relationship between the sense of displacement on the shear plane and the curvature of the lamination towards it. This is the opposite to that expected if the curving had been caused by "drag" during movement. Although foliation boudinage was recognized as such in only a few glaciers, it may be a widespread feature, and other examples of displacements along shear planes may represent the same phenomenon.

The boudinage structures described here have all developed in longitudinal foliation near the margins of flow units, but there is no reason to suppose that they should not develop in other types of layering or in other situations. For example, one would expect boudins to develop in ice subject to longitudinal compression in the centre of a glacier where the foliation is transverse. In general, a closer observation of these structures should lead to a better understanding of the mechanical behaviour of natural ice bodies and provide additional information concerning strain conditions in different parts of a glacier.

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