

SHORT NOTES

THE ORIGIN OF FOLIATION IN GLACIERS: EVIDENCE FROM SOME NORWEGIAN EXAMPLES*

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ABSTRACT. Studies of Norwegian glaciers indicate that foliation is frequently derived from sedimentary stratification. Shearing and accompanying recrystallization of the ice is most likely to occur in the planes of the sedimentary layers, particularly where they are steeply dipping and have a longitudinal trend. Foliation not related to pre-existing layering is uncommon. Steeply dipping transverse layers, often referred to as foliation, are believed to be simply the traces of former crevasses.

RÉSUMÉ. *L'origine du foliation des glaciers mise en évidence à partir d'exemples de glaciers norvégiens.* L'étude des glaciers norvégiens montre que le feuillage provient fréquemment de dépôts stratifiés. Les contraintes de cisaillement dans la glace, et la recrystallisation consécutive se produit principalement dans les plans des couches de dépôts, spécialement lorsqu'elles pénètrent profondément et sont orientés longitudinalement. Le foliation en l'absence de couches de dépôts préexistantes est rare. Les couches situées transversalement et à fort pendage, souvent prises pour du feuillage, sont considérées aujourd'hui comme de simples traces d'anciennes crevasses.

ZUSAMMENFASSUNG. *Die Entstehung der Bänderung in Gletschern: Aufschluss aus einigen norwegischen Beispielen.* Untersuchungen an norwegischen Gletschern weisen darauf hin, dass Bänderung häufig eine Folge sedimentärer Schichtung ist. Scherung und die damit verbundene Rekristallisation des Eises treten höchstwahrscheinlich in den Ebenen der Sedimentschichten auf, besonders dort, wo diese steil einfallen und längsgerichtet sind. Bänderung ohne Beziehung zu einer vorgegebenen Schichtung ist ungewöhnlich. Von steil einfallenden, quergerichteten Schichten, die oft als Bänderung bezeichnet werden, wird angenommen, dass es sich dabei einfach um Spuren früherer Spalten handelt.

INTRODUCTION

During the course of a structural investigation of the glacier Charles Rabots Bre in the Okstindan area of northern Norway (Fig. 1), it became apparent that the longitudinally trending lenticular structure, normally referred to as foliation, was closely related to sedimentary stratification. In view of earlier work on glacier structures this was rather surprising, and therefore several other glaciers in the Okstindan area were examined. In these glaciers also a close relationship between the two structures was frequently observed. On one glacier, transverse layering of high dip appeared to represent the closed or bottom remnants of crevasses formed in an ice-fall; similar structures in other glaciers have been termed transverse foliation.

DESCRIPTION OF LAYERED STRUCTURES

As in earlier studies (Untersteiner, 1955; Meier, 1960; Allen and others, 1960; Taylor, 1962), the term foliation is here used to describe intercalated layers of ice of varying crystal size or bubble content and translucency, and stratification refers to the original depositional layering preserved in the ice. In foliation there are two main types of ice, coarse bubbly and coarse clear, which form intercalated layers, each about 5–100 mm thick and up to about 4 m in length. Sedimentary stratification consists of alternating coarse clear ice layers up to 10 mm thick (representing the former ablation surfaces) and coarse bubbly ice layers often 3 m or more thick; individual layers are very regular and can be followed for several hundred metres across the glacier surface.

THE STRUCTURE OF CHARLES RABOTS BRE

This glacier is small, steep and narrow, and now largely stagnant (Hambrey, unpublished). Two main flow units, each distinguishable by a set of convex down-glacier arcs, are recognizable (Fig. 2). The arcs represent the surface traces of the original sedimentary layers which have been tilted and

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passively deformed as a result of flow. In each flow unit, the axis of the resulting fold is parallel to the former direction of movement. At the apices of the arcs, a down-glacier dip at the firn limit changes gradually to an up-glacier dip of about 20–30 degrees, while towards the margin of each flow unit, where the layer traces attain a longitudinal trend, the dip increases to over 70° inwards. In three dimensions each folded layer is trough-shaped. Between the two flow units and at the margins of the glacier, strong longitudinal foliation is in evidence (Fig. 2). This has a near-vertical dip, and a similar strike to that of the adjacent steeply dipping sedimentary stratification. A gradual progression from one structure to the other is apparent: towards the margins of the flow unit the individual layers of the stratification become increasingly discontinuous and the coarse bubbly ice layers narrower, until only an intercalated structure of the two ice types remains. A stereogram of the structure in one of the flow units (Fig. 2) indicates the close relationship between the two types of layering.

In the larger flow unit, the sedimentary layers become more tightly folded down the glacier (Fig. 2). They become stretched out and thinner at the limbs of the fold, and wider and less well-defined at the fold hinge. Longitudinal foliation, approximately parallel to the original bedding, is increasingly evident at the limbs. Transposition of bedding into foliation of a different orientation, similar to that which occurs in metamorphic rocks (Turner and Weiss, 1963, p. 92–94), has apparently taken place at the fold hinge. Thus the overall structure of the lower part of the glacier is a “composite foliation”, made up of strong longitudinal foliation parallel to the bedding at the limbs of the fold and weak “transposition foliation” at the hinge. Foliation completely unrelated to sedimentary stratification is uncommon at Charles Rabots Bre; this type of foliation is most easily recognized where it intersects the stratification, but in only a few places was this observed.

By definition, foliation must be the result of deformation. Recent studies of other glaciers (Schwarzacher and Untersteiner, 1953; Untersteiner, 1955; Meier, 1960; Allen and others, 1960; Taylor, 1962; Gunn, 1964; Rutter, 1965; Hashimoto and others, 1966; Ragan, 1969; Marangunic, 1972; Hooke, 1973) have shown that foliation develops as a result of shearing or compression. Longitudinal foliation forms between flow units and at the margins of a glacier, and transverse foliation forms below ice-falls and in zones of marked decrease in the longitudinal velocity component. The structures of Charles Rabots Bre in many respects are similar to those of other glaciers, but apparently the only previous references to the possibility that the development of foliation may be controlled by sedimentary stratification, and then only in a restricted sense, are in papers by Meier (1960), Taylor (1962) and Ragan (1969). However, it is clear that foliation can either be highly deformed stratification or a completely new structure. Most authors have regarded foliation as a completely new structure, but the extent to which it is related to stratification at Charles Rabots Bre indicates that it often may not be so.

OBSERVATIONS AT OTHER GLACIERS

The results from Charles Rabots Bre indicated the desirability of examining the structures of other glaciers. Thus seven other glaciers in the Okstindan area were visited with a view to determining the relationship between foliation and sedimentary stratification (for locations see Fig. 1). In all these glaciers stratification is clearly visible, and normally deformed and tilted in the same way as at Charles Rabots Bre. Longitudinal foliation of high dip sometimes occurs at the glacier margins and between ice streams, for example at Svartfjellbreen, Vestre Stekvassbreen and Bessedørbreen, and here it has the same attitude as the adjacent stratification.

At the snouts of Corneliussens Bre and Bessedørbreen, low dip transverse foliation was observed. Again, this is clearly related to the stratification, a gradual transition from the lenticular structure at the snout to a continuous and more regular layered structure higher up the glacier being observed. Similarly, basal foliation, approximately parallel to the glacier beds, has the same attitude as the stratification immediately above it. Only in one instance, on a part of Corneliussens Bre, was the foliation seen to intersect the stratification. Thus completely new foliation, that is foliation which would form whether the ice was stratified or not, is the exception rather than the rule in the Okstindan glaciers.

All the glaciers referred to above are relatively small. The nearest equivalent in the Okstindan area to the glaciers studied in other parts of the world is Austre Okstindbreen, a valley glacier with a large ice fall. According to the theories of earlier workers, the Austre Okstindbre ice fall was expected to generate steeply dipping transverse foliation. In fact, transverse layers of high dip do form, but they are too widely spaced to give a typical foliated structure; they represent the traces of the transverse crevasses in the ice fall. Faulting in the sedimentary stratification (Fig. 3) indicates that these layers are

not the result of recrystallization under compression in the way envisaged by other workers. Having the same initial orientation as the crevasses, the layers are deformed into arcs as a result of differential flow between the margins and the centre. An unsolved problem is the extent to which the ice must fracture, both laterally and vertically, in order to give rise to layers which persist almost as far as the snout.

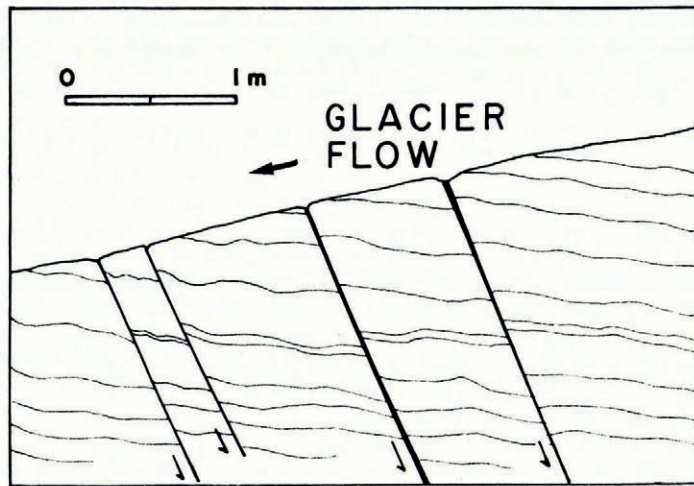


Fig. 3. Longitudinal section near the centre of Austre Okstindbreen below the ice-fall, showing slightly wrinkled stratification and transverse blue layers representing former crevasses. Arrows indicate down faulting.

CONCLUSIONS

It is clear from the study of the Okstindan glaciers that foliation either is highly deformed stratification which would not have developed if the ice had originally been unlayered, or a new feature which would have formed even if the ice was initially structureless. The latter type is uncommon in the glaciers examined in Okstindan, and foliation is most likely to develop when sedimentary stratification has a favourable attitude. Thus, for the development of longitudinal foliation, near vertical sedimentary layers at the margins of the flow units are most suitable; differential movement may cause shearing between the layers and subsequent recrystallization. Low-dip transverse foliation and basal foliation are most likely to develop by compression of the layers by the weight of overlying ice, or by shearing as a result of strong differential flow near the base of the glacier.

The origin of steeply dipping transverse layering at Austre Okstindbreen can be traced to crevassing in the ice fall. Studies of other glaciers are necessary to determine whether or not this is an isolated occurrence.

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