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Structural geology of an Alpine glacier
(Griesgletscher, Valais, Switzerland)

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ABSTRACT

Griesgletscher (near the Nufenen pass, Valais, Switzerland) is a simple-shaped valley glacier, with a small ice-fall separating a broad accumulation area (to the west) from a narrow tongue (to the east). Aerial photography and detailed field mapping of the gently graded area at the base of the ice-fall, the Bättelmatthorn sector, revealed an earlier foliation (S_1), possibly related to some large-scale isoclinal folds, intersected by a later foliation (S_2) associated with widespread small-scale folding (F_2, axial plane parallel to S_2). Structures which postdate S_2 include crevasses and crevasse traces, boudinage features, and thin mylonitic or debris-filled shear zones, as well as a weak longitudinal foliation (S_3) near the snout. S_2 seems to develop near the top of the ice-fall, at or above the equilibrium line, and is related in some way to predominantly transverse crevasses. S_1 forms under the accumulation area, but its style, its longitudinal/subvertical orientation and its association with intense folding preclude the possibility that it is a purely sedimentary stratification. On reaching the base of the ice-fall, S_2 has attained a transverse arcuate distribution and it maintains this throughout the tongue region, although the arc axis rotates from subvertical through moderate up-glacier plunges to subhorizontal on being traced downstream. S_1 and S_2 intersect at high angles in the central part of the glacier but become indistinguishable from each other at the margins, where they coalesce into a composite longitudinal planar structure.

Some aspects of the kinematic framework of these relationships can be deduced from the annual stake measurements which are available from 1960 onwards. Estimates of cumulative surface strains from the base of the ice-fall downstream show that, in the centre of the glacier, S_2 first becomes intensified by flattening in a coaxial strain field and is then transported down to the snout in a more or less non-deforming plug. At the margins, the strain field approximates to simple shear and the composite foliation trace delineates the slip direction. Here, the long axis of the cumulative strain ellipse only becomes approximately parallel to the foliation trace after considerable transport. Although the boundary conditions of flow in a valley glacier are unlike those in most orogenic belts, some aspects of these observations may be of relevance in interpreting the effects of ductile rock deformation. In particular, they illustrate the complex conditions which may lead to foliation formation, and they show that the concept of "phases of deformation" may have more complicated ramifications than are generally admitted.

ZUSAMMENFASSUNG

Der Griesgletscher (Nufenenpass-Gebiet, VS) ist ein Talgletscher einfacher Form; ein kleiner Eisfall trennt ein breites Akkumulationsgebiet im Westen von einer schmalen Zunge im Osten. Eine Auswertung von Luftbildern und detaillierte Felduntersuchungen im flachen Bättelmatthorn-Abschnitt, der sich gerade unter dem Eisfall befindet, zeigt die folgende strukturelle Abfolge: 1. Anlage einer frühen, longitudinalen planaren Paralleltextur (S_1), möglicherweise in Zusammenhang mit einer Isoklinalfaltung auf grösserem Maßstab; 2. Anlage einer späteren planaren Paralleltextur (S_2), welche S_1 durchschneidet und in Zusammenhang mit einer verbreiteten Fältelung auf kleineren Maßstab (F_2) gebracht werden

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kann (S_2 ist parallel zur Achsenebene der F_2-Falten). Noch spätere Strukturen umfassen Spalten und Spaltenspuren, Boudins, dünne mylonitische oder debrisgefüllte Scherzonen sowie eine weitere, schwach entwickelte longitudinale Paralleltextur (S_3). S_2 scheint sich nahe der Oberkante des Eisfalles, bei oder über der Sommerschneegrenze, zu entwickeln und steht scheinbar in Zusammenhang mit hauptsächlich transversalen Spalten. S_1 hat seinen Ursprung im Akkumulationsgebiet, aber der Stil, die longitudinale und beinahe saigere Orientierung sowie der Zusammenhang mit Isoklinalfaltung sprechen gegen einen Ursprung als rein sedimentäre Schichtung. An der Unterkante des Eisfalles hat S_2 bereits einen bogenförmigen Verlauf quer über den Gletscher und behält diesen bis zuunterst an die Zunge. Die Bogenachse steht unter dem Eisfall fast senkrecht, neigt sich stromabwärts (mit progressiv kleinerer, stromaufwärts gerichteter Neigung) und liegt an der Zunge beinahe waagrecht. S_1 und S_2 kreuzen sich in der Strommitte unter hohem Winkel, der gegen den Rand hin jedoch zusehends kleiner wird, so dass sie nicht mehr zu unterscheiden sind und in eine zusammengesetzte longitudinale S überführen.

Jährliche, von der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich ab 1960 durchgeführte Pegelmessungen lassen Schlüsse bezüglich des kinematischen Rahmens dieser strukturellen Beziehungen ziehen. So zeigen Schätzungen der totalen Verformungsbeträge an der Eisoberfläche unterhalb des Eisfalles, dass S_2 in der Strommitte zunächst durch Plättung in einem koaxialen Verformungsfeld verstärkt wird, dann aber ohne wesentliche weitere Verformung passiv stromabwärts transportiert wird. Demgegenüber ist die Verformung am Rande nichtkoaxial und annähernd eine einfache Scherung, wobei die zusammengesetzte S-Fläche ungefähr der Gleitebene entspricht. Die lange Achse der Verformungsellipse wird hier erst nach beträchtlicher progressiver Verformung annähernd parallel zur Paralleltexturspur. Einige Aspekte dieser Beobachtungen könnten von Bedeutung sein bei der Interpretation von Effekten duktiler Gesteinsverformung, obschon die Randbedingungen des Fliessens von Eis in einem Talgletscher sicher anders sind als jene von Gesteinen in einem Orogen. Sie zeigen insbesondere die Komplexität der Vorgänge bei der Bildung einer einzigen Paralleltextur, sowie dass sich eine Reihe von klar unterscheidbaren «Deformationsphasen» aus einem kontinuierlichen Prozess bilden kann.

Introduction

Glacier ice can be regarded as a metamorphic rock which has been strongly deformed under temperature conditions very close to the melting point. A mass of ice now exposed at the surface near the snout of a typical glacier originated as a subaerial sediment a few centuries ago and subsequently suffered burial, diagenesis, regional high-grade metamorphism (occasionally even partial melting and crystallization), fracture and flow. Within a few years, this ice will have been removed by surface ablation, uncovering deeper levels of the evolving ice mass. In a typical Alpine glacier, the rock - ice - has gone around the geological cycle at a speed about six orders of magnitude faster than the Mesozoic sediments of the Alpine orogenic belt. This very rapidity enables glaciers to be used as huge rock deformation laboratories. However, it also complicates the application of ordinary geological techniques, since the "rocks" are no longer stationary on the human time scale, and are not always sufficiently deeply eroded to allow complete three-dimensional reconstructions.

In the present paper, the tongue of an Alpine glacier, Griesgletscher (for location, see inset, Fig. 1), will be described from a structural geology point of view, that is, the structural relations will be treated as though they were exposed in a stationary rock mass at the earth's surface. Large-scale vertical aerial photographs, taken in 1973 by the Eidgenössische Landestopographie (Bern), form the basis of this description; the detailed field work was carried out between 1974 and 1976. In the case of deformed rocks, the amount of deformation they have suffered (cumula-

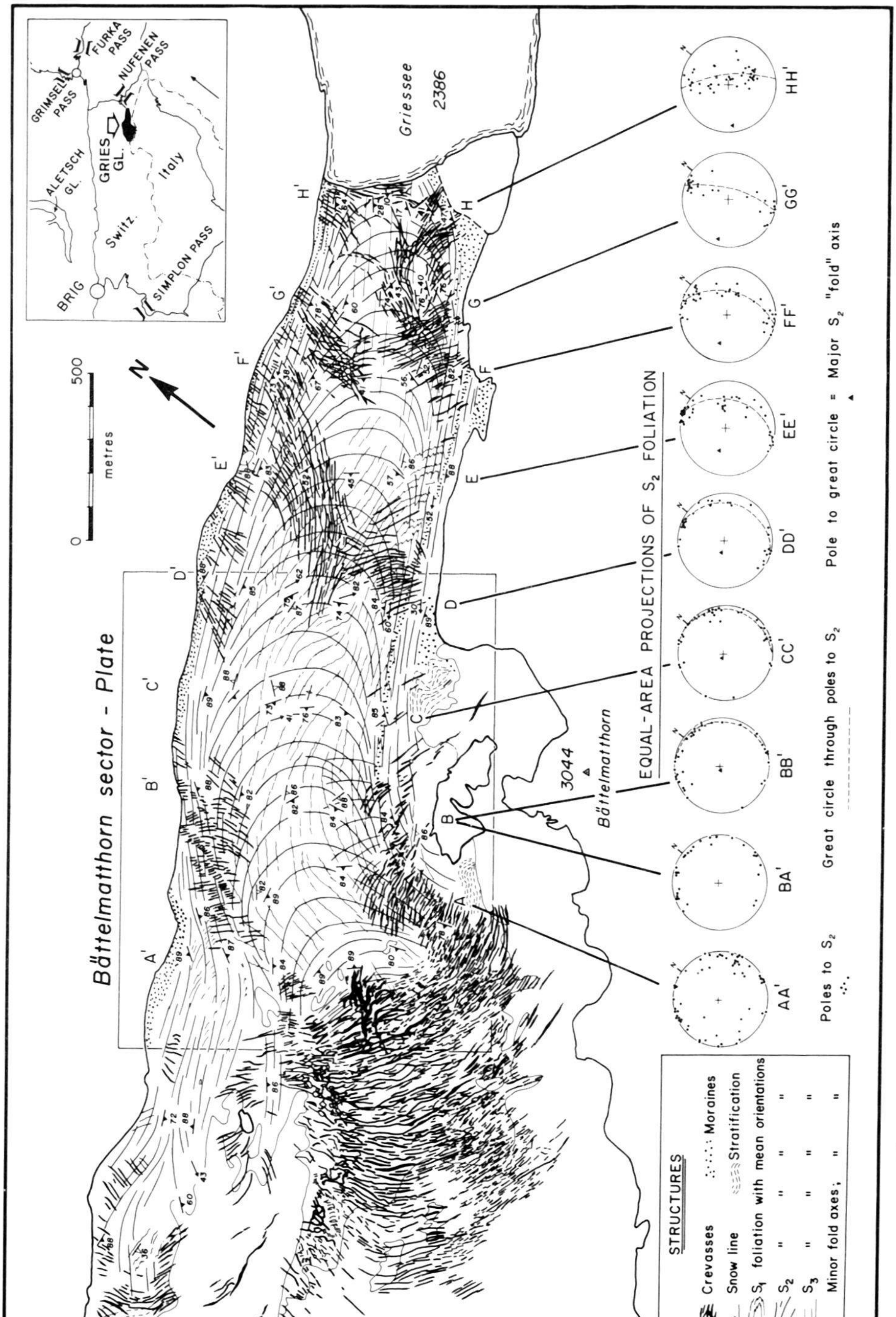


Fig. 1. Generalized structural map of the tongue of Griesgletscher (location of glacier shown on inset map).

tive strain) must be estimated from enclosed objects of known original shape. Such objects are absent in glacier ice, but some idea of the cumulative strain can be obtained from velocity contour / flow line maps (MILNES & HAMBREY 1976). Thus, although the approach is essentially geological - the kinematic picture being developed from the structural analysis - some aspects of the relation between structures and strain will be deduced from direct measurements of the movements involved. The possibility that strain can be determined from measured displacements is, of course, the area in which glacier dynamics can provide a major contribution to our knowledge of rock deformation. The ice-flow data used here was obtained by H. Siegenthaler (Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich) for the company operating the hydroelectric reservoir into which Griesgletscher flows (Kraftwerke Ägina AG) in the years 1971-1973. The geological picture assembled from these various sources is therefore a composite one for a five-year time period, 1971-1976.

Although it is well known that glaciers show a similar range of deformation phenomena and microstructures as tectonites in the world's metamorphic terrains, the number of structural analyses of glaciers is small compared with the innumerable geological studies (e.g. SCHWARZACHER & UNTERSTEINER 1953, ALLEN et al. 1960, MEIER 1960, RAGAN 1969, ANDERTON 1973, HAMBREY 1976). In particular, surprisingly little work has been carried out in the Alps since modern glacier flow theory was developed in the early 1950's. One of the earliest detailed studies was that of SCHWARZACHER & UNTERSTEINER on the Pasterzenkees in the Austrian Alps. This pioneer work specifically treated ice deformation from the petrofabrics point of view, as applied to deformed rocks by the Innsbruck school (cf. SANDER 1948-1950). Otherwise, structural studies on Alpine glaciers have concentrated on specific features, such as foliation in the "Mer de Glace" (VALLON 1967), crevasses in the Hintereisferner (AMBACH 1968), and ogives and associated foliation in various Swiss glaciers (KING & LEWIS 1961, FISHER 1962). The Griesgletscher was chosen for our study of all the macroscopically visible structures for its typical overall morphology, its simple shape and its easy accessibility. However, although the glacier shows fairly average bulk characteristics, its detailed structure is probably strongly influenced by local conditions, in particular by the shape of its bedrock. Hence, many such glaciers must be investigated before useful generalizations can be made. The internal structure of glaciers, like that of mountain chains, is typically untypical!

Griesgletscher is about 5 km long, with ice flowing WSW to ESE, from an extensive accumulation area into a gently curving tongue which narrows downstream from 1 to 0.6 km (Fig. 1). The accumulation area is separated from the tongue by a small ice-fall or steep ice-slope, which may or may not become snow-free by late summer. The tongue and the lower part of the ice-fall make up the ablation area, within which the structural relations can be observed. Below the ice-fall, there is a large, gently graded and little crevassed area, the Bättelmatthorn sector (Plate), which formed the main area of detailed study. Below this, the slope steepens and crevassing increases, until the glacier terminates in an ice-cliff in the recently impounded lake, Griessee (Fig. 2). This lower part will be referred to as the snout. The structural relations will be discussed with respect to these morphological parts of the glacier, together with a rough geographical notation (north, south, east,

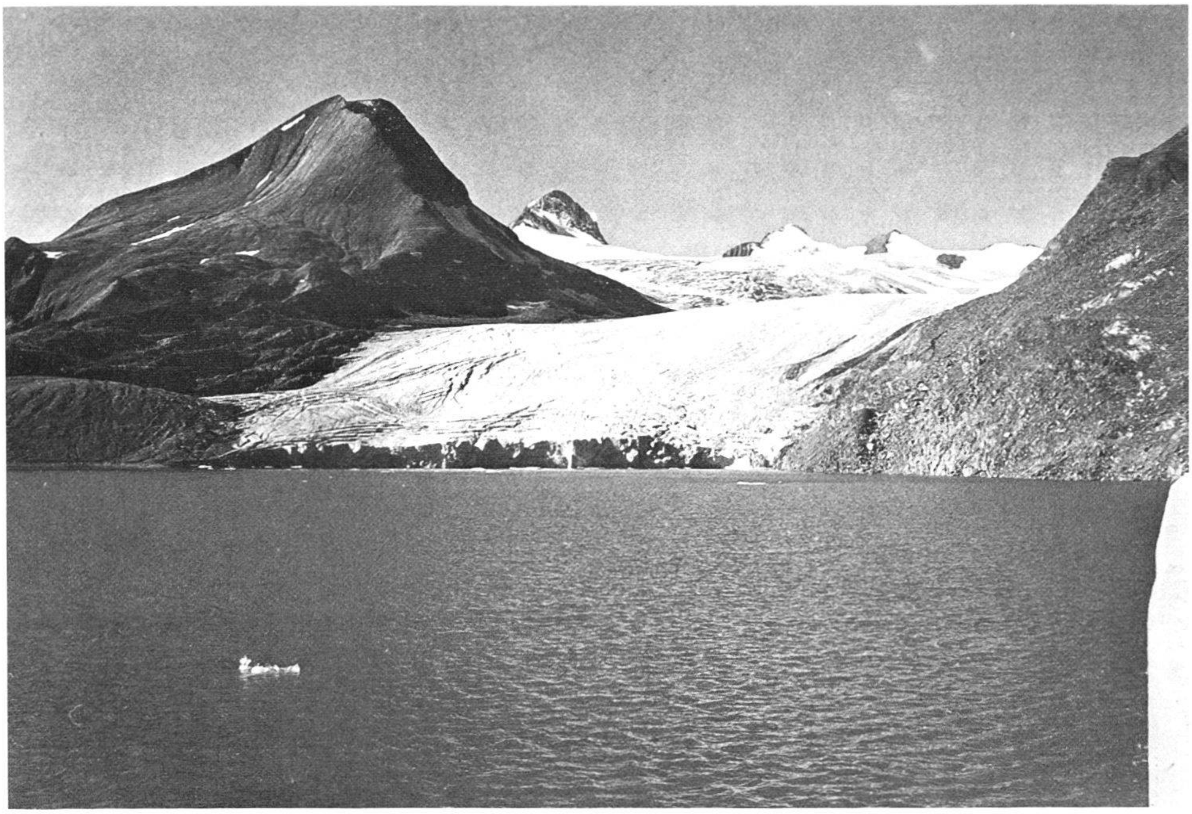


Fig. 2. View of Griesgletscher from Griessee dam. The snow-free peak to the left is Bättelmatthorn (3044 m). Above the ice-cliff, the crevassed snout of the glacier is well seen, and in the background the small ice-fall or steep ice-slope. Between the two, hidden by breaks in slope, lies the Bättelmatthorn sector, the gently graded area between 2600 and 2700 m, on which the structural relations are best exposed.

west being approximately left, right, downstream, upstream, respectively) and the terms transverse and longitudinal (high and low angle to the flow lines). Some details of the types of structures observed are given first, followed by a discussion of interrelationships and genesis.

Types of macroscopic structures

a) Crevasses

Widespread tensional fracturing occurs mainly in the ice-fall and snout regions, and along both sides of the Bättelmatthorn sector. In the ice-fall, the fractures form an irregular network, although the general trend is transverse (Plate). In the tongue, geometrically regular arrays occur which can be described as transverse, chevron, splaying or "en échelon" sets (Fig. 1, cf. MEIER 1960, p. 56–57). On the upstream side of any set of crevasses, the fractures tend to be straight or only gently curved, and they become more curved downstream. Their attitude also changes progressively, sometimes becoming *S*-shaped, and eventually they grade into a similarly orientated set of closed joints. These are obvious effects of progressive deformation of the original fractures, similar to those observed in rocks (cf. RAMSAY & GRAHAM

1970, Durney & Ramsay 1973, Fig. 15). In particular, "shear zones" delineated by "en échelon" sets of correspondingly curved crevasses ("feather joints") are well developed in the north part of the Bättelmatthorn sector (Fig. 3 and Plate). Although the original opening of a crevasse on the upstream side of a crevassed area is purely tensional, the progressive closing and/or rotation downstream invariably causes lateral displacements of the inter-crevasse blocks. Hence, the closed crevasses lower down often appear as small faults.

b) Crevasse traces

"Crevasse traces" consist of layers of coarse-grained, clear ice (frequently of dark blue appearance), which contrasts sharply with the bulk of glacier ice which is of the coarse bubbly variety (for definitions of ice types, see Allen et al. 1960). The clear layers often contain well defined planes of bubbles midway between the walls, and they are spaced at similar distances to true crevasses. In some cases, they are obviously either closed and healed equivalents of originally open fractures or the remnants of water-filled crevasses that are now frozen. In other cases, they occur as continuations of open fractures, or between and parallel to open crevasses, and may never have represented an open space in the ice. Which of these possible modes of

Fig. 3. Strongly developed marginal/longitudinal foliation (S_1/S_2) and "en échelon" crevasse zone near the north margin of the glacier in the Bättelmatthorn sector (cf. Plate). The dark layers in the crevasse walls are of coarse-grained clear ice; the remainder is bubbly ice of variable grain size. Flow is approximately parallel to the foliation, towards the camera.

origin applies in individual cases is often uncertain, however. Crevasse traces are not as well developed in the Griesgletscher as, for example, in Arctic glaciers (cf. HAMBREY & MÜLLER, in press). The clearest examples are to be found on the south side of the Bättelmatthorn sector, just below the ice-fall (Plate).

c) *Foliations*

As in most other glaciers, the ice of Griesgletscher contains one or more foliations with systematically varying orientations and intensities. In their most well developed form they consist of discontinuous layers of three main types of ice: coarse-grained bubbly, coarse-grained clear and fine-grained, in decreasing order of abundance. The layers are generally 1-10 cm thick but, apart from the planar arrangement, the variations in bubble content and grain size are unsystematic. Penetrative foliation of this type is best developed near the margins of the glacier (Fig. 3); in other areas, individual layers or groups of layers alternate with bands of unfoliated ice showing earlier structures (see below) and all gradations exist (cf. MILNES & HAMBREY 1976, Fig. 1C). Usually, the individual ice grains in foliated ice are not noticeably elongated but have interlocking boundaries and vary in diameter from 10 cm (coarse) to 0.1 cm (fine) (cf. HAMBREY 1977). Occasionally, the crystals have serrated boundaries and show subgrain structures and finer grained recrystallized aggregates.

Ice foliations of this type are generally considered to be metamorphic structures produced by deformation (ALLEN et al. 1960, MEIER 1960, GUNN 1964, RUTTER 1965, RAGAN 1969, ANDERTON 1973, HAMBREY 1977). They are to be strictly separated from the original "bedding" of the snow deposits, known as stratification, which consists, after diagenesis and metamorphism, of thick continuous layers of coarse bubbly ice (the original snow beds) and thin continuous layers of coarse clear ice (the summer melt surfaces and superimposed ice, cf. GROVE 1960, HAMBREY 1976). Stratification is not well exposed on Griesgletscher; it has been transformed out of recognition by the deformation suffered before it reaches the ablation area of the glacier. A layered structure observed locally just below the equilibrium line is of this type (Fig. 1; Plate). However, the layered structure described above as foliation is by far the dominant one. The most obvious proof of its secondary origin is its widespread association with minor folding in axial planar orientation (see below). It should be noted that, although secondary planar structures are typical of both glacier ice and high-grade regionally metamorphosed rocks, it is difficult to find precise equivalents in style. The characteristic feature of ice foliation is grain size lamination, whereas rock foliations are generally preferred orientations of grain shape, alone or combined with a compositional lamination. The only rocks which show a foliation similar in style to that in glacier ice are certain types of mylonite (cf. HIGGINS 1971; ROSS 1973, Fig. 7; WILSON 1975, Fig. 3).

In the Bättelmatthorn sector, two foliations are present, varying in relative importance in different parts (Plate). The earlier foliation, S_1, has a general longitudinal trend, and the aerial photograph suggests that it may be associated with large-scale isoclinal folds, although this is not apparent in the field. It has been affected by a later, small-scale folding (amplitudes of the order of 1-10 m, see Fig. 4)

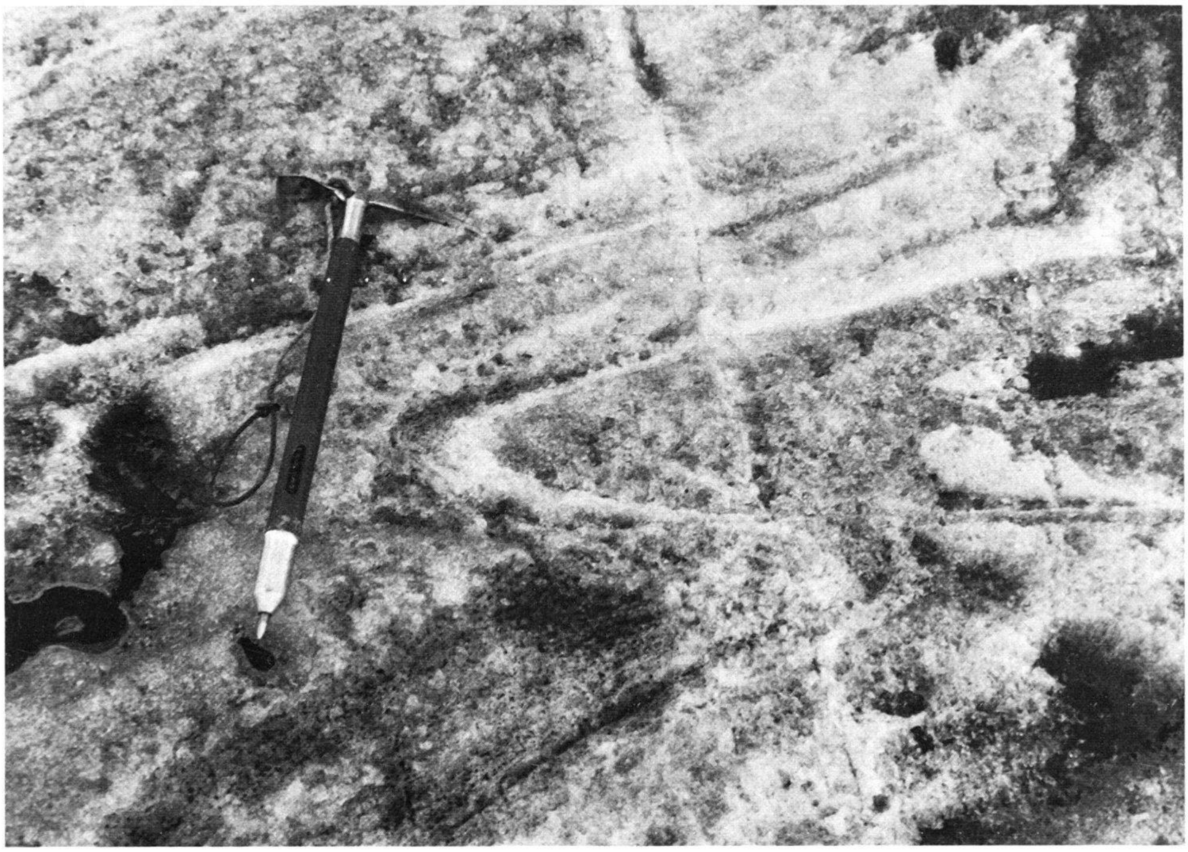


Fig. 4. Minor fold with approximately similarly folded layers defined by variations in grain size and bubble content, axial plane parallel to S_2. South margin of the Bättelmatthorn sector (south end of profile XY, see Plate). Flow is from left to right.

and an associated later foliation, S_2. The latter sometimes consists of groups of layers or individual layers, cutting through S_1 discordantly, along the limbs of the small scale folds (Fig. 5). These time relations are best observed in the centre of the glacier, where S_2 has a regional arcuate and transverse attitude. Towards the margins, the two foliations merge into a single longitudinal structure, with only occasional intrafolial folds indicating its composite origin. In the snout of the glacier, a weak longitudinal foliation, post-dating S_2, can be distinguished (S_3, see Fig. 1).

d) Minor folds and boudins

As noted above, S_1 is commonly folded on a small scale with S_2 developed along the fold limbs parallel to the axial planes (Fig. 5; see also Milnes & Hambrey 1976, Fig. 1C; Hambrey 1977, Fig. 5). The folded S_1 layers are generally of approximately similar type (Fig. 4), although they are too diffuse and irregular for precise classification. Most of the minor folding would be designated F_2 in a geological study - related to the development of S_2 - while F_1 would represent the earlier large-scale folding apparently associated with S_1. In contrast, all boudinage features observed are post-S_2 in age, since it is the S_2 foliation which is affected. Boudinage is confined to the margins and is mainly of the type known as "foliation boudinage" or "internal boudinage" (Fig. 6; see Hambrey & Milnes 1975 for details). A few fine-

Fig. 5. Minor fold with limbs truncated by axial planar structure S_2 (folded layers are S_1). Central zone of the glacier in the Bättelmatthorn sector. Flow is from top to bottom.

grained ice boudins, resulting from competence differences between coarse- and fine-grained ice, were observed, mainly at the northern margin.

e) Mylonite zones and debris-rich layers

Thin zones of fine-grained "mylonitized" ice are common in some areas, particularly in the central part of the glacier. These often cut through or sharply truncate the grains of the neighbouring coarse-grained ice, and in some zones they contain remnant large grains, similar to the clasts in many rock mylonites. The "mylonitized" ice seems to have formed by cataclasis, and the discontinuous fine-grained laminae in strongly foliated ice may have a similar genesis [see c) above].

Another type of structure, possibly related to the above, is thin layers of debris-rich ice, particularly well seen along the northern margin of the snout and in the ice-cliff (and standing out because the ice of Griesgletscher is otherwise remarkably clean). The trace of the debris layers in the ice-cliff is parallel to S_2; in other areas, it is clearly discordant to the surrounding foliation, although the angle of intersection is always small. In some cases, the layers are accompanied by discrete planar surfaces which give the impression of being active shear planes. Comparison with similar structures in other glaciers (HAMBREY & MÜLLER, in press) suggest that the layers are the remnants of thin shear zones which once extended to the base of the ice, but the mechanism of formation of these features is not fully understood.

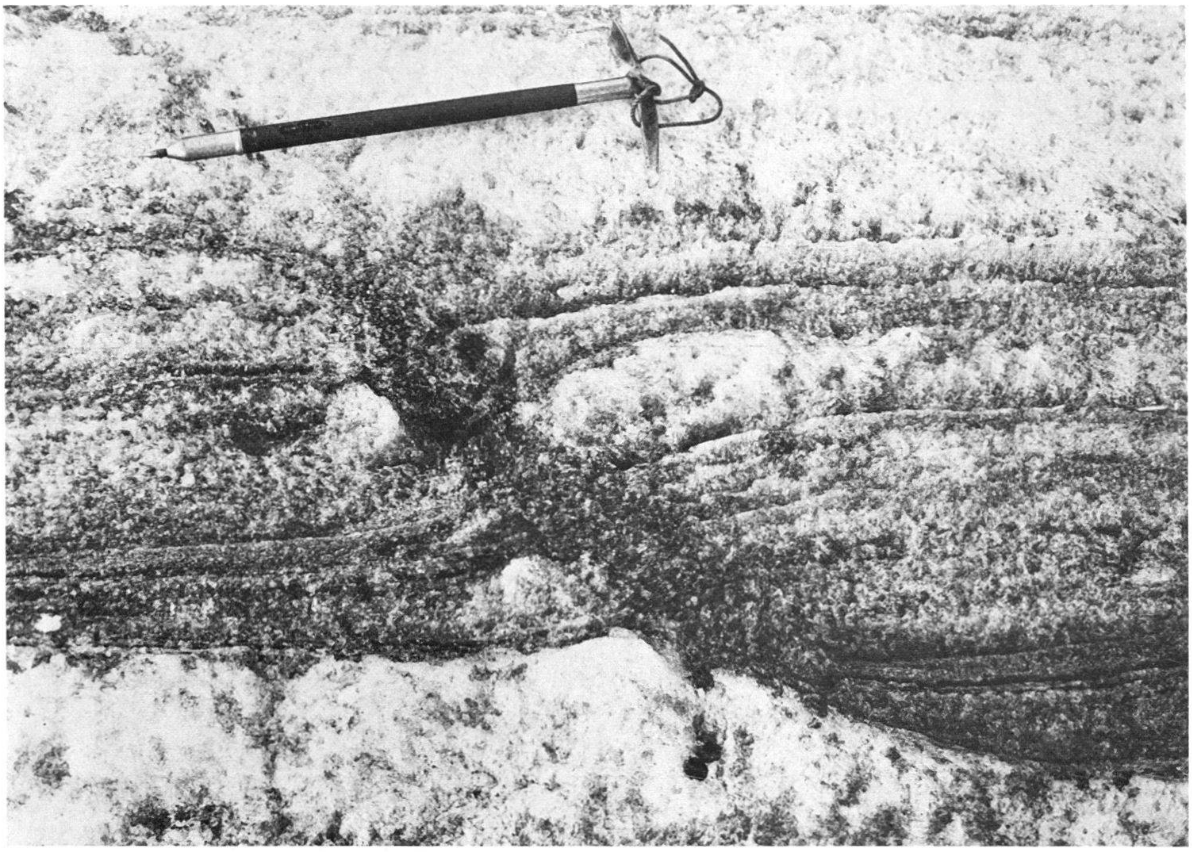


Fig. 6. Foliation boudinage of S_2 (cf. HAMBREY & MILNES 1975). North margin of the Bättelmatthorn sector. Flow is from left to right.

Foliation development

A detailed picture of the relations between some of these structures and of their spatial variations within the Bättelmatthorn sector is given on the Plate. From the structural geological point of view, the main problem here concerns the development and significance of the S_2 foliation, the arcuate structure which dominates the picture in this area. Although the structural map is a static representation, it should be borne in mind that, in contrast to many geological situations, we *do* have a qualitative idea of the kinematics, even without making a single flow measurement. We know, for example, that the flow is from west to east and that, because of progressive melting of the ice surface, the more easterly the outcrop on a given postulated flow line the longer the deformation and metamorphic history the ice has suffered, and the greater its maximum depth of burial.

The arcuate foliation can be followed continuously upstream through the ice-fall, almost to the top, where it is subvertical and transverse, paralleling the general orientation of the inter-crevasse blocks. As the ice descends the ice-fall, this rough foliation remains subvertical, as do the crevasses, but it progressively attains an overall arcuate shape. This is not well seen because the inter-crevasse blocks tilt and rotate somewhat during downward movement. The crevasses close up progressively on descending the ice-fall, and the ice enters the gently graded area below with a composite foliation consisting of subparallel crevasse traces and earlier foliation domains, still arcuate and subvertical (Fig. 7). Then follows rapid intensification of the foliation out into the middle of the Bättelmatthorn sector. Continuing downstream, along the centre line of the glacier, these relations are preserved. The arcuate trace of S_2 is maintained, but the foliation gradually becomes more diffuse and takes on an up-glacier dip which progressively becomes less steep. The S_2 foliation arc can be described as a major fold with a vertical axis at the base of the ice-fall (Fig. 1, profiles AA′, BA′, BB′), slowly rotating and attaining a gentle up-glacier plunge at the snout (Fig. 1, profiles GG′, HH′). The important points are that the S_2 foliation is composite, originating in the ice-fall, at least partly in association with the formation of transverse crevasses, and that it remains inactive from the base of the ice-fall onwards, being modified and rotated as a passive marker during its subsequent history. This passive nature is best demonstrated by tracing it through crevassed areas below the ice-fall. For instance, in the area of very regular curved crevasses near the south margin of the Bättelmatthorn sector (see Plate), the new crevasse traces show no sign of deformation which could be connected with continued development of S_2, although the inter-crevasse blocks contain well developed F_2 folds. In general, the remnants of crevasses formed below the ice-fall do not become folded on the scale of the F_2 folds - the S_2 foliation (axial planar to F_2) seems to have developed during a phase of heterogeneous deformation which has no equivalent in the lower half of the glacier. Below the ice-fall, the deformation

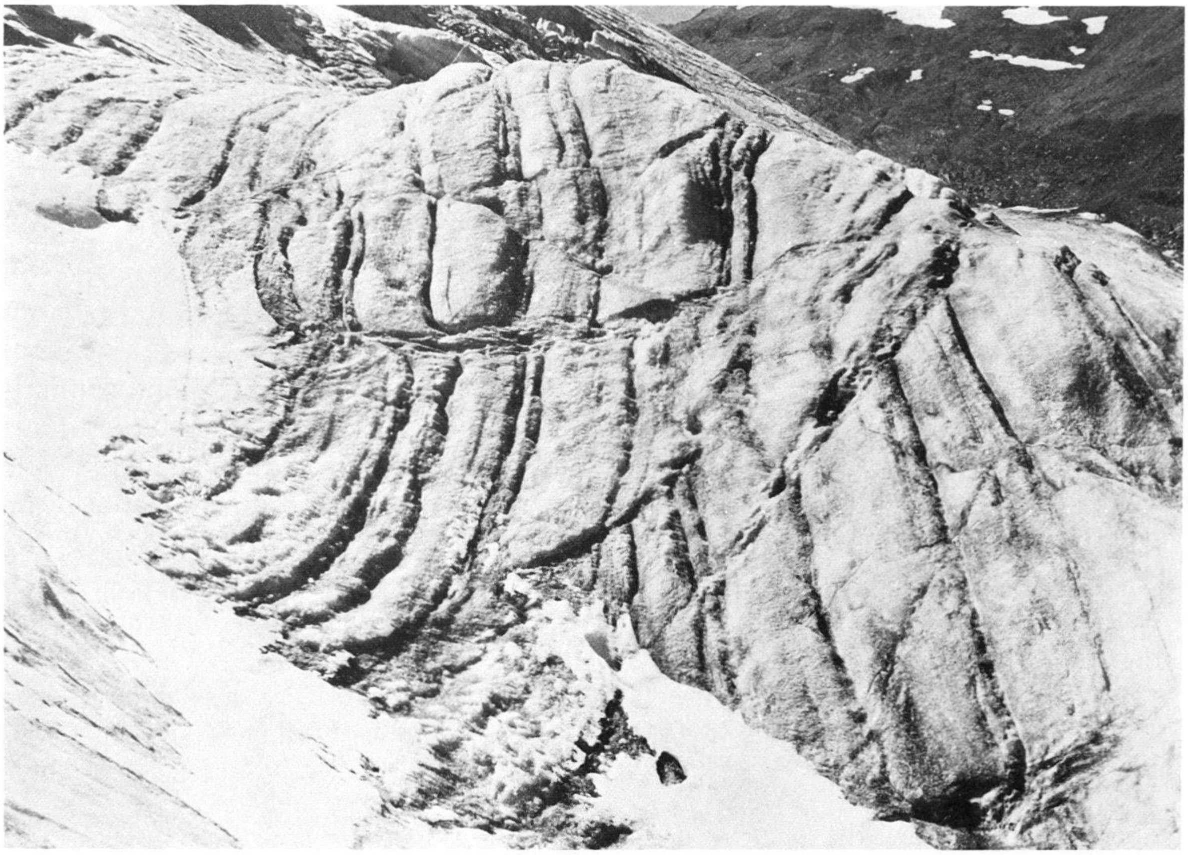


Fig. 7. Subvertical incipient S_2 foliation near the base of the ice-fall. The dominant layering structure is related to transverse crevassing near the top of the ice-fall and is cut through by crevasse traces developed at later stages.

is homogeneous on the scale of the F_2 folds, except where post-S_2 boudinage and mylonite structures have developed.

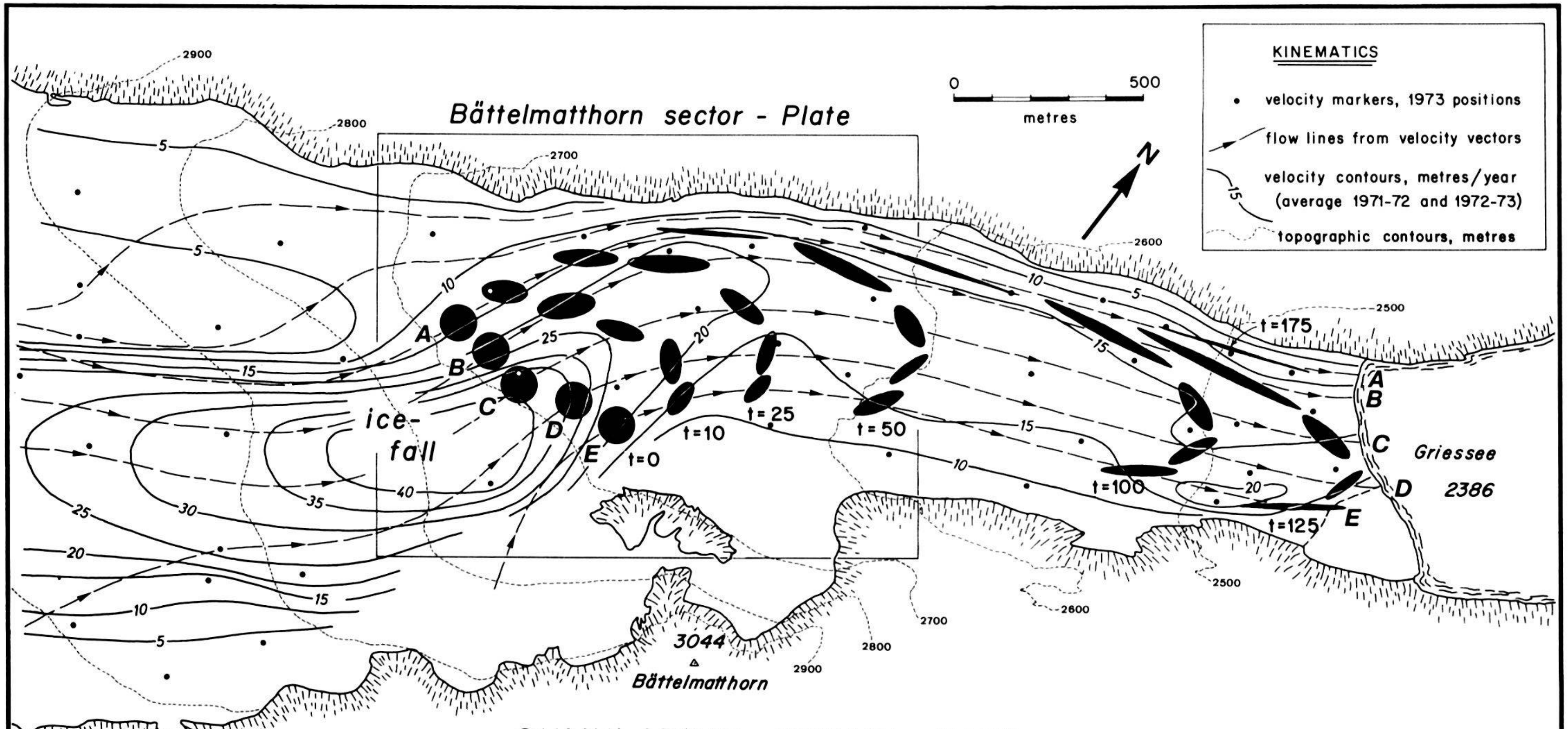
The above discussion concerns the central zone of the glacier. At the margins, the relations are less clear. The S_2 foliation swings into a longitudinal orientation at each margin, becomes more intensely developed and more completely overprints S_1, the latter remaining only as isolated isoclinal fold hinges (see MILNES & HAMBREY 1976, Fig. 1C). However, even at the margins there is little sign of continuing small-scale heterogeneous deformation, except for small displacements (by a few cm) of crevasse traces along discrete planes parallel to S_2; significant active development of this foliation (i.e. associated with intense isoclinal folding) cannot be proceeding below the ice-fall, only a more or less passive and homogeneous deformation of an already present structure. This longitudinal marginal foliation can, in fact, be followed upstream, particularly north of the ice-fall, as far as the transient snow line. It therefore originates beneath the firn of the accumulation area.

Kinematic framework

In contrast to most structural studies of rock bodies, the kinematics of deforming glacier ice are determinable. However, the building up of a full kinematic picture, involving extensive deep drilling and repeated detailed geodetic surveys, is usually impossible for logistic and financial reasons. Griesgletscher was chosen for this structural study partly because the positions of numerous stakes in a fairly complete network had been accurately surveyed annually since 1960. The latter provided us with a two-dimensional kinematic framework, which although only reflecting bulk relationships, can be used as the basis for a discussion of the development of structures in relation to strain conditions. The velocity distribution and flow line map (Fig. 8) has been constructed from the 1971/72 and 1972/73 data, which were the most complete and extensive. Approximate cumulative strains can be determined for any part of the glacier surface for any period of time by moving arrays of 3 or more points down the corresponding flow lines with the appropriate velocities (MILNES & HAMBREY 1976). This has been done for some flow lines from the base of the ice-fall downstream (Fig. 8). If we assume that the flow pattern has not changed over the time periods involved and that the movement of stakes at the surface reflects the movement at depth, then the strain ellipses constructed from the deformed point arrays provide an estimate of the deformation which ice now at the surface has undergone during its journey from below the position of the starting points. Both these assumptions become progressively less justifiable the greater the distance moved; the second assumption is anyway unreasonable at the glacier margins.

Bearing in mind the uncertainties and approximations of the method, the following points can be made concerning the strain pattern and structural development:

a) The highest strains occur along the margins of the glacier, where the strain ellipses rotate, rapidly at first, then progressively more slowly, until their long axes are essentially parallel to the margins. This type of strain history approximates to simple shear, and the trace of the composite longitudinal foliation S_1/S_2 maintains a



CUMULATIVE STRAIN DATA

(1) axial ratio of strain ellipse

t =	10	25	50	100	125	175
A	1.8	3.9	37	52		69
B	2.0	4.2	6.8	11	14	
C	2.4	2.8	2.2	2.6	3.4	
D	1.8	3.1	4.4	3.9	4.7	
E	2.0	2.8	3.3	8.6	17	

(2) rel. area of strain ellipse

t =	10	25	50	100	125	175
A	0.9	0.8	0.3	0.4		0.3
B	1.3	1.1	1.2	1.4	1.9	
C	0.8	0.8	0.8	0.8	0.8	
D	0.8	0.5	0.4	0.5	0.3	
E	0.5	0.3	0.6	0.5	0.4	

(3) angle: long axis/flow line

t =	10	25	50	100	125	175
A	45	20	6	3		2
B	18	11	14	13	8	
C	38	42	48	42	36	
D	81	72	51	42	43	
E	36	43	33	13	8	

(4) angle: long axis/S_2 trace

t =	10	25	50	100	125	175
A	25	7	3	1		0
B	39	10	6	3	1	
C	51	21	7	5	30	
D	19	9	32	32	4	
E	13	4	11	17	3	

Fig. 8. Summary of kinematic data for the tongue of Griesgletscher (*t* in years).

constant attitude parallel to the slip direction. However, the significance of this relation is difficult to interpret, since the three-dimensional picture is obviously more complicated. The marginal foliation maintains a constant *subvertical* attitude (except near the snout), at a considerable angle to the actual ice/rock interface which would be expected, in three dimensions, to control the orientation of the slip plane.

b) The estimates of horizontal cumulative strain along the central part of the glacier are more reliable. They show a rapid increase immediately below the ice-fall and then only slight changes in axial ratio and orientation down the whole of the rest of the glacier (Fig. 8). This is reflected in the structures by the sudden increase in the "intensity" of the S_2 foliation and the following stretch of constant relations noted above. The trajectories of the strain ellipse long axes closely follow the arcuate shape of the S_2 foliation traces everywhere along this central zone. This implies that the strain conditions were approximately coaxial here (incremental and cumulative strain ellipse axes parallel, as opposed to the non-coaxial, rotational strains in the marginal zones), and that S_2 already lay in the extensional strain field as it approached the starting points of the strain determinations (base of ice-fall).

Although the ice in the central zone seems to move down most of the tongue as an almost rigid plug, it should be noted that this is only an impression from the horizontal strain estimates. The rotation of the S_2 foliation arc from a subvertical to a subhorizontal plunge between ice-fall and snout implies considerable deformation in a vertical plane as the ice moves down-glacier.

Discussion and conclusions

The purpose of this study was to see what could be learnt from a structural study of a large-scale model of ductile rock deformation in which some control on the kinematic picture was available. Although the model is not realistic with respect to its boundary conditions from the geological point of view (flow of material in an inclined trough under gravity), two aspects may be of relevance to an understanding of rock deformation in orogenic belts, particularly in their deeper parts. Firstly, it is possible to study the development of some types of small-scale structure and relate them to their strain history. Secondly, it is possible to observe sequences of structures and to work out what caused one set of structures to stop developing and to be overprinted by another, in the course of an essentially continuous process. Although our investigation did not produce any clear solutions to these problems, we hope it may help to formulate the right questions.

a) Foliation and strain

A frequently discussed topic in both glaciological and geological literature concerns the origin and significance of foliation. In glaciology, several studies have attempted to determine the relationship between foliation and incremental strain axes (generally referred to as "strain rate tensors", the incremental strains over a one-year period), and the result has been that all possible mutual orientations exist (cf. MEIER 1960, ANDERTON 1973, HAMBREY 1977). One reason for this is clear - a foliation, once generated, can be transported and rotated as a passive marker over long distances, during which time its orientation will have no special relationship to the incremental strain or strain rate axes at any particular position. For such a study to be meaningful, one must first identify the regions in which the foliation is actively forming. The S_2 foliation in Griesgletscher originates at or above the transient snow line, within and below an area of extensive transverse crevassing at the top of the ice-fall or higher. Although this prevents close observation and measurement, there is evidently a close genetic relation between foliation formation and transverse crevassing (see earlier), which in turn implies that the foliation originates in an area of longitudinal tensile stress, normal to the extensional axis. However, this condition in itself is clearly not sufficient - its subsequent strain history (cumulative strain, or the way in which the strain increments accumulate) is equally important. It must be associated with small-scale heterogeneities causing lateral displacements (passage down the ice-fall) and it must enter a strain field in which the cumulative strain, even when homogeneous on a small scale, works in favour of intensification and preservation (passage through the Bättelmatthorn sector).

That such a special combination of conditions seems necessary for foliation formation and preservation explains why such structures are by no means ubiquitous in glaciers. Other combinations are obviously required to produce longitudinal foliations, and different ones for a marginal foliation, as on Griesgletscher, and for the longitudinal foliation found in some glaciers throughout their widths (MEIER 1960; HAMBREY & MÜLLER, in press). The Griesgletscher relations did not do much to illuminate the longitudinal foliation problem, except to indicate that it does not form parallel to the long axis of the strain ellipse in the general case, but rotates towards parallelism during progressive deformation. A solution depends on finding an area in which such a foliation is generated, on being able to determine the incremental strains (strain rates) in that area and on being able to show how the strain increments accumulate downstream to cause preservation (cumulative strain history).

An interesting aspect of these obviously complicated processes of foliation formation in glaciers is that, at least on Griesgletscher and on the basis of the two-dimensional horizontal picture, the results agree approximately with the most frequently observed relation in mylonitic rocks. The foliation trace is subparallel to the long axis of the cumulative strain ellipse, or, in three dimensions, the foliation is subparallel to the XY-plane of the strain ellipsoid (see JOHNSON 1967). The significance of foliation in mylonitic rocks has been the subject of some controversy in geology, since it is not clear whether it originally developed in this position (for possible mechanism, see RAMSAY & GRAHAM 1970), or whether it represents the slip plane in a simple shear strain field (e.g. BARBER 1965) which only becomes subparallel to the XY-plane at high strains. The same argument is found in the glaciological literature with respect to ice foliation (for review, see RAGAN 1969). Observations on glaciers in general, and on Griesgletscher in particular, however, tend to support the conclusions of WILLIAMS (1976), that foliations can have various original orientations, but in most situations rotate towards the XY-plane during progressive deformation.

b) "Phases of deformation"

Throughout most of the Bättelmatthorn sector, a pre-S_2 foliation can be distinguished, obviously intensely folded during the development of S_2. The vergence of the F_2 folds, together with the subvertical or steep attitude of the fold axes (Plate), indicates that the attitude of S_1 prior to the second phase deformation was longitudinal and subvertical. This, together with the nature of S_1 (similar to S_2 but with more diffuse layering) and its possible association with tight large-scale folds, indicates that it does not represent the original stratification. Processes in the accumulation area resulted in the destruction of S_0 (bedding stratification) and the generation of a new foliation S_1 (or, alternatively, the complete transposition of S_0 into an S_1 attitude). When the ice appears from beneath the snow cover, the generation of S_2 (or the transposition of S_1 into an S_2 attitude) is already under way. This situation reminds one of the geological adage, that the critical outcrops are always covered by drift.

With regard to S_3, we have the opposite state of affairs - the area is completely exposed, but the structure is so weakly developed that the casual observer may doubt its existence. It is a longitudinal foliation occurring with varying intensity across the whole width of the glacier snout and hence, geometrically, it can be considered as the "axial plane" foliation associated with the major "fold" in the S_2 foliation (see Fig. 1). However, this axial planar relationship may be coincidental: S_3 may in some way be related to the longitudinal/splaying crevasses developed just below the Bättelmatthorn sector. Although S_3 is generally weakly defined by planar discontinuities or variations of ice type, in many places it seems to be more of a linear feature. Nevertheless, a planar structure of similar orientation, also interpreted as S_3, can be observed faintly in parts of the ice-cliff (HAMBREY, in press, Fig. 2). Apparently it cuts through S_2, there in a near horizontal attitude, and the recumbent F_2 minor folds.

One of the most illuminating aspects of the present study has been the forced reappraisal of the meaning of "phases of deformation" in structural geology. On Griesgletscher, we have three clearly defined structural phases, a clear sequence of events producing successively S_1, S_2, and S_3. We can even define roughly what these events represent. A mass of snow deposited in the upper part of the accumulation area is first transformed to ice by burial and downstream movement. During passage through the accumulation area S_1 is generated or develops out of S_0. Passage through the ice-fall results in S_2 and descent to the snout in S_3. What is interesting is that these foliations develop in a continuously flowing mass, that one "phase" can run continuously into another in some areas and be clearly separable in others, that periods of passive and homogeneous deformation can occur between two "phases", leaving no structural imprint, and that the timing of the transition from one "phase" to another can vary from area to area. It is clear that many of our ideas on structural correlation in deformed rocks have been too simplistic up to now (see also PARK 1969), and that glacier studies may contribute to a better understanding of this important problem.

Note on access

The easy accessibility and weak crevassing of the tongue of Griesgletscher, and its location in a geologically interesting area, make it particularly favourable for field trips. Access is from the 2nd hairpin down on the west side of the Nufenenpass (height point 2303, ample parking). Walk along private road about 1.5 km to the dam (driving forbidden), cross dam to west side and ascend diagonally across boulder slopes and small slump blocks (rough path in places) keeping well above the lake, eventually reaching a point of easy access on to the ice at a height of about 2540 m. Walking time from the Nufenenpass road, without geology, is just over 1 hour. In late summer (August/September), the glacier surface can be walked across without special equipment (rope, ice-axe, crampons) so long as it is free of snow and due care is taken in circumventing the few crevasses.

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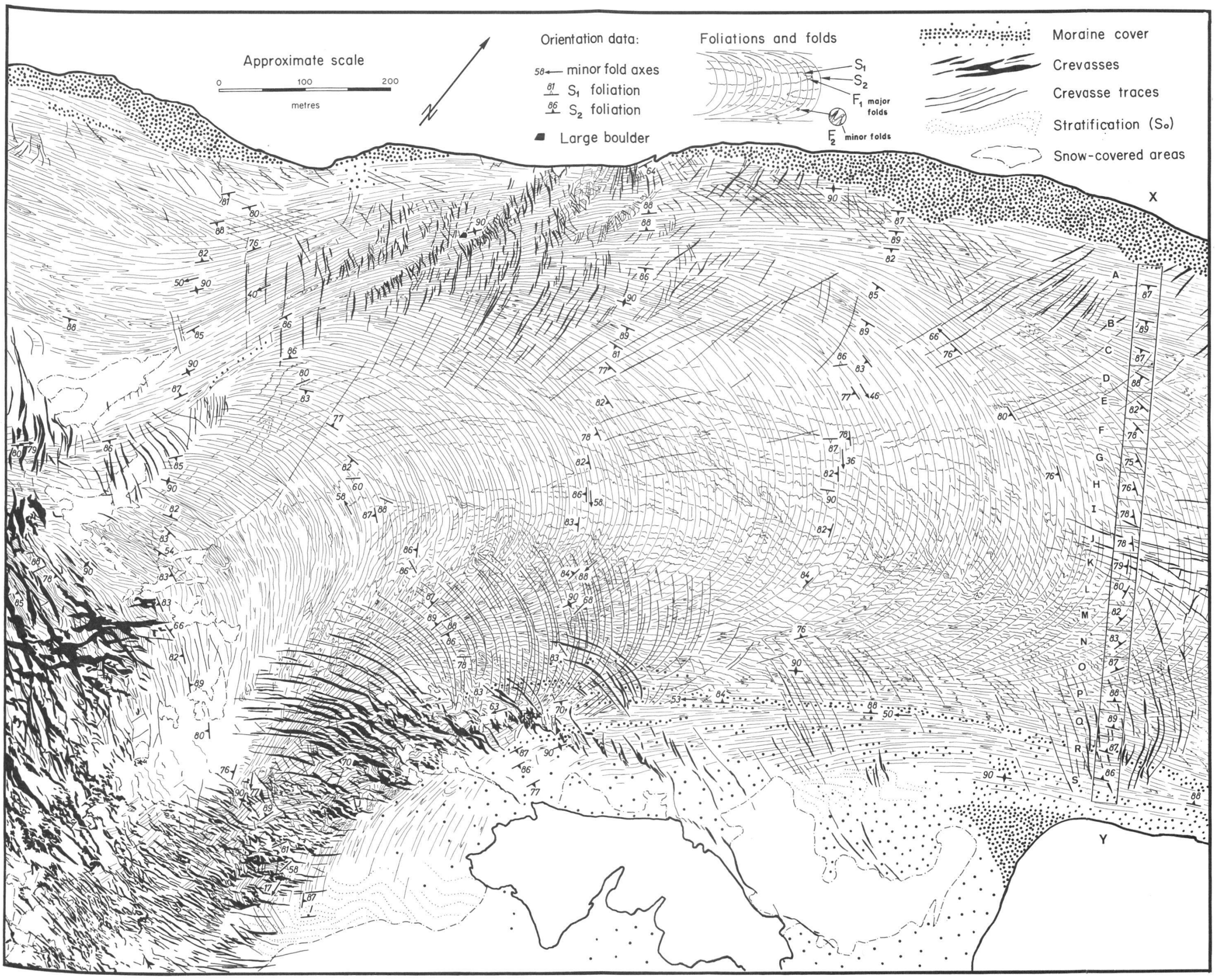

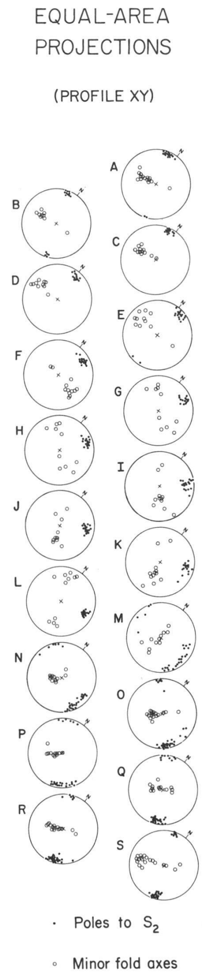

Structural relations in the Bättelmatthorn sector of Griesgletscher (Valais, Switzerland)

based on a vertical aerial photograph taken on 6 September 1973.