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FABRIC ANALYSIS OF SURFACE ICE NEAR CASEY RANGE, EAST ANTARCTICA

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ABSTRACT. Forbes Glacier, one of the outlet ice streams from the Antarctic ice sheet, is located 20 km west of Mawson, Mac.Robertson Land, east Antarctica. In the uppermost part of the glacier near Casey Range, the velocity at the centre of the glacier is 59 m $year^{-1}$ and the strain-rate at seven strain grids ranges from -6.7 to 6.7×10^{-3} $year^{-1}$ on the surface of the glacier. The fabric types of this area are characterized by single-maximum and small-girdle fabrics. It is confirmed that the single-maximum fabric is an original pattern which changes gradually to a small girdle fabric about the maximum compressive axis in association with grain growth. The patterns predicted by Brace (1960) can be adapted to the small-girdle fabrics of this area.

RÉSUMÉ. *Analyse de fabrique de la glace de surface près de Casey Range, Antarctique Oriental.* Le Forbes Glacier, l'un des effluents de l'Indlandsis Antarctique, se trouve à 20 km à l'ouest de la Station Mawson, Mac.Robertson Land, Antarctique Oriental. Dans la partie supérieure du glacier près de Casey Range, la vitesse au centre du glacier est de 59 m an^{-1}, et la vitesse de déformation à sept grilles de déformation se trouve entre $-6{,}7$ et $6{,}7 \times 10^{-3}$ an^{-1} à la surface du glacier. Les types de fabrique de cette zone sont caractérisés par des fabriques à simple maximum et à petite couronne. Il a été confirmé que la fabrique à simple-maximum est une forme originale qui change graduellement en celle d'une petite couronne près de l'axe de compression maximum en association avec la croissance des grains. Les figures prédites par Brace (1960) peuvent être adaptées aux fabriques de petite couronne de cette zone.

ZUSAMMENFASSUNG. *Gefügeanalysen von Oberflächeneis nahe der Casey Range, Ost-Antarktika.* Der Forbes Glacier, einer der Eisströme aus dem antarktischen Eisschild, liegt 20 km westlich von Mawson, Mac.Robertson Land, Ost-Antarktika. Im obersten Teil des Gletschers nahe der Casey Range beträgt die Fliessgeschwindigkeit in der Mitte des Gletschers 59 m pro Jahr, während die Deformationsgeschwindigkeit — gemessen an sieben Deformationsgittern — zwischen $-6{,}7$ und $6{,}7 \times 10^{-3}$ pro Jahr schwankt. Die Gefügetypen dieses Gebietes sind durch Einzelmaximum- und schmale Gürtelgefüge charakterisiert. Es steht fest, dass das Einzelmaximumgefüge eine ursprüngliche Struktur ist, welche sich in Verbindung mit dem Kornwachstum allmählich zu einem schmalen Gürtelgefüge (um die Hauptkompressionsachse herum) verändert. Die Strukturen, die Brace (1960) voraussagte, können den schmalen Gürtelgefügen dieses Gebietes angepasst werden.

INTRODUCTION

It was a conclusion of a fabric study of ice in the Mawson area (Kizaki, 1969) that syntectonic crystal growth was one of the most effective factors in producing the variety of fabric patterns of glacier ice undergoing a moderate stress field. Here, the ice with coarser crystals tended to have various multiple-maximum fabrics such as three- and four-maxima patterns which were typical of the well-recrystallized coarse ice in active glaciers. The ice with smaller grains generally had fabrics with a smaller number of maxima.

However, the fabric patterns from the newly formed ice which was found in small accumulation basins caused by drifting snow in the area of general ablation near the coast of the Mawson area, differed from that of the ordinary glacier ice. Similar fine-grained ice with a polygonal texture also occurs at the boundary zone between the accumulation and ablation areas about 15 km inland from the coast. Such is the area east of the Casey Range where this study was carried out (Fig. 1).

Seven strain grids were set up to measure the strain-rates at the surface over this area and several samples were collected to analyse the orientation patterns of the ice-crystal axes. The strain-rates obtained were to be correlated with the fabric patterns from each grid but unfortunately more than half of the area was found to be an accumulation area covered with snow or firn so that samples were collected for fabric study from only three grids.

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This paper presents the data obtained from ice east of the Casey Range which bears on the problems of the strain-rates and fabrics of the fine polygonal ice and their variation over the area. Furthermore, the evolution of the fabrics associated with grain growth of the ice is briefly discussed. The observations and measurements given in this paper were made during 1966 as a part of the glaciological programmes of the Australian National Antarctic Research Expeditions (A.N.A.R.E.) at Mawson station, located at lat. 67° 36′ S., long. 62° 52′ E. near the head of Horseshoe Harbour in Mac.Robertson Land, Antarctica.

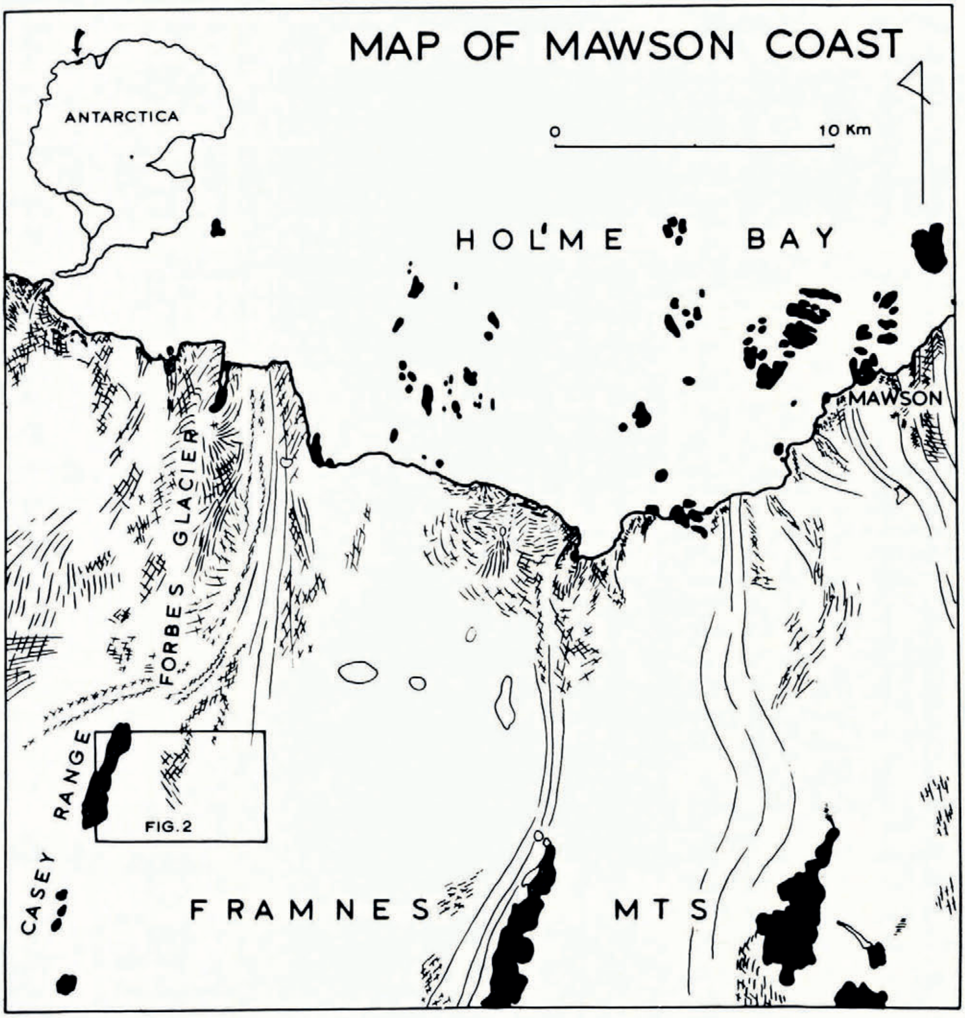

Fig. 1. Map of the coast of Antarctica in the vicinity of Mawson station.

Physical Setting

Forbes Glacier, one of the outlet ice streams from the continental ice sheet of Antarctica, is located 20 km west of Mawson station. The glacier originates on the east of the Casey Range, 25 km south of the coast and it is fed by tributaries which, after flowing east and north through the nunataks, unite to form an ice stream about 5 km wide (Fig. 1).

The present study concerns only the uppermost part of the glacier, just below the firn line, where the surface has a shallow gully at the centre of the stream and a crevasse swarm in the western part of the area (Fig. 2).

It is striking that in this area none of the foliation which has consistently been found in long ice streams such as those in the Mawson area or the valley glaciers in temperate zones can be seen. Clear bands have been sometimes described as the product of shearing movement (Taylor, 1963) but this is not so here. The clear bands always run parallel to the direction of the cleavages as well as the crevasses. It therefore seems reasonable that the origin of the clear bands is the same as that of the crevasses but they could have formed at a much earlier stage

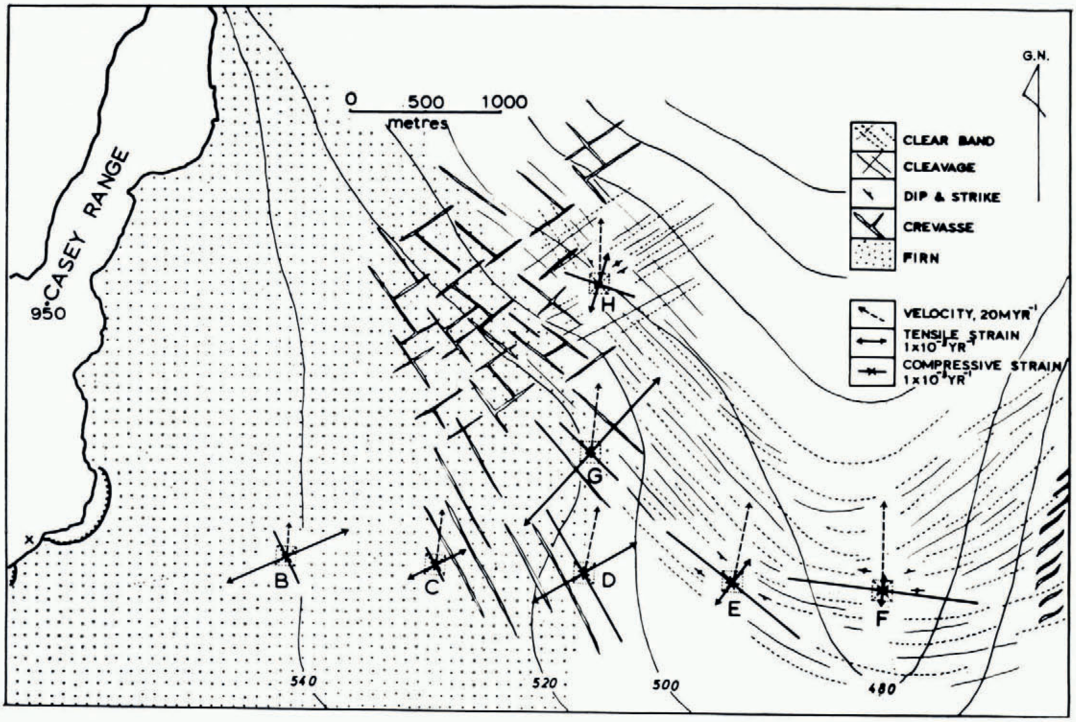

Fig. 2. Glaciological map of the Casey Range area.

than the cleavages and crevasses. Crevasses are abundantly developed to the west of the centre of the stream though they become obscured by deep snow accumulation towards the extreme western part near the nunatak.

Accumulation values from February 1966 to January 1967 are as follows:

Grid	B	C	D	E	F	G	H
Accumulation (cm)	+20	−5	−10	−5	−7	−8	−7

Surface Velocity and Strain-rate

Seven grids for measuring the strain-rates on the ice surface were set up and designated as B, C, D, E, F, G and H. Grids B, C, D, E and F were along an east–west base line, but grids G and H were established along a north line from grid D. Each grid had 200 m diagonals and was re-measured in August 1966 and January 1967. The velocities of the centre stakes of each grid were measured relative to a theodolite point fixed on the rock of the nunatak. The results are shown in Figure 2 and Table I.

Table I. Movements of Strain Grids

	B	C	D	E	F	G	H
Bearing	0° 00′	5° 00′	7° 10′	7° 45′	357° 00′	10° 35′	357° 30′
Velocity (m year^{-1})	23.4	35.3	45.9	55.1	59.0	44.5	41.1

The strain-rates were calculated following the procedure outlined by Nye (1959).

The principal strain-rates so obtained are listed in Table II and the directions of the principal strain-rates at each grid are shown by the plotted vectors in Figure 2. ϕ is the angle between the north-west–south-east diagonal of each grid and the principal axis nearest to it.

Table II. Principal Strain-rates ($\times 10^{-3}$ year^{-1})

Grid	$\dot{\epsilon}_1$	$\dot{\epsilon}_2$	$\dot{\epsilon}_3$	ϕ
B	−2.22	−2.3	+4.51	−16° 51′
C	−1.38	−0.79	+2.17	−12° 40′
D	−5.17	+0.94	+4.23	−11° 25′
E	−5.69	+3.71	+1.98	+ 9° 25′
F	−6.7	+5.78	+0.92	−40° 05′
G	−2.82	−3.91	+6.73	+ 3° 12′
H	−2.56	+0.57	+1.99	−31° 00′

Directions of principal axes:
- $\dot{\epsilon}_1$ Maximum compressional strain-rate in the horizontal plane.
- $\dot{\epsilon}_2$ Vertical strain-rate.
- $\dot{\epsilon}_3$ Maximum tensile strain-rate in the horizontal plane.

The general strike of the crevasses is parallel to the direction of the maximum compressive axes at grids C, D and G, whereas the directions of the crevasses around grid H are parallel to the maximum shear directions, suggesting that the crevasses are produced by shear stresses. That crevasses should strike perpendicular to the direction of the maximum tensile stress has been demonstrated by Nye (1952, 1959), Ward (1955), Wu and Christensen (1964) and Kizaki (1969). On the other hand, Taylor (1963) showed that crevasses due to shear stress are orientated at 45° to the direction of the maximum compressive stress. Examples of both are found in this area.

Figure 2 shows that the clear bands and cleavages strike nearly parallel to the direction of maximum compression at grids E and F, whereas at grid H they are roughly parallel to the direction of maximum shear as are the crevasses there. It is therefore clear that both the clear bands and the cleavages originated under similar conditions as the crevasses, although there are some variations in the relation between their orientations.

Fabric Analysis

Six specimens were cut from the three grids H, E and F. The procedures of the fabric analysis have already been described (Kizaki, 1969). The fabric data from the Casey Range area are summarized in Table III.

Single-maximum fabric

The ice at grid H is fine and semi-polygonal in texture resulting from recrystallization of firn. Its fabric patterns are clear single-maximum fabrics of which *c*-axes are normal to the surface (Fig. 3). It is unlikely that the stress field of the grid has caused the fabric pattern. The latter might have resulted from the mimetic recrystallization of a depositional fabric,

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because the ice has not completely recrystallized thus preserving a texture of granular snow of low density compared with solid glacier ice. The flow stress, therefore, would not have become sufficiently effective to produce a preferred orientation of crystals for such ice.

Single-maximum fabrics with a dense concentration of *c*-axes at the pole of the foliation plane are generally found at shear zones in ice streams of polar regions such as the Thule area (Rigsby, 1960) and the Mawson area (Kizaki, 1969), whereas broad single-maximum fabrics

TABLE III. FABRIC DATA FROM THE CASEY RANGE AREA

Locality	*Number of specimen*	*Ice type*	*Number of axes*	*Fabric type*	*Grain-size* number/cm	
H	1	Fine, semi-polygonal	330	1 maximum	18.8	
	2	Fine, semi-polygonal	230	1 maximum	24.3	
E	1	Fine, semi-polygonal	210	1 maximum with great-circle girdle	15.0	
	2	Fine, semi-polygonal	237	1 maximum with great-circle girdle	17.0	
J	1	Coarse with fine	211	2 maxima with small girdle	0.9	Elongate
	2	Coarse with fine	224	2 maxima with small girdle	1.1	Porphyritic

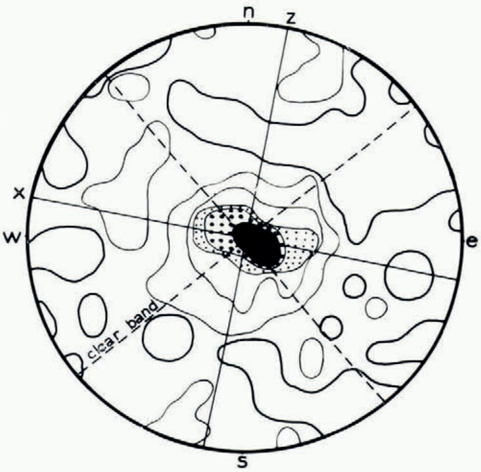


Fig. 3. 330 c-axes of ice (CH1) from grid H. Contours 1–2–3–4–5–6<%; maximum 7% per 1% area. Grain-size: 19 grains/cm².*

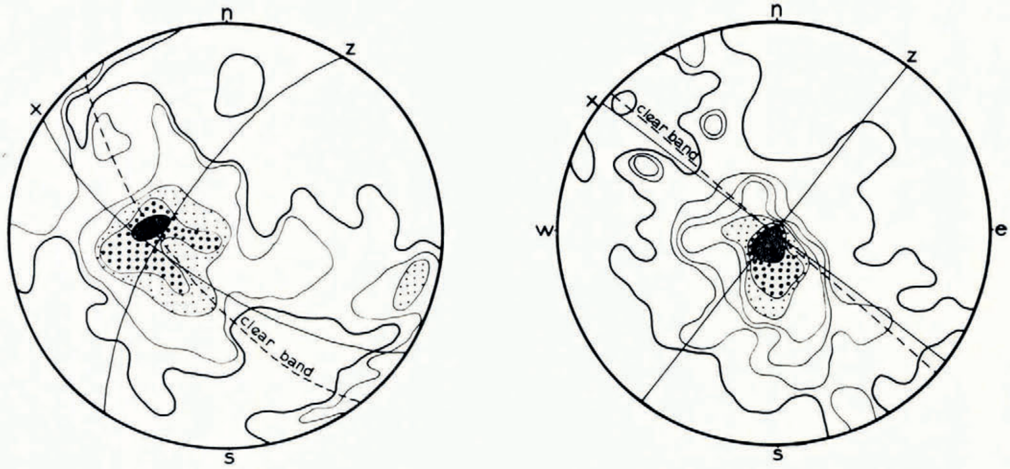
have been reported in a temperate glacier by Kamb (1959). These fabric patterns appear to be characteristic of fine-grained ice. It is assumed that, if ice has only one active glide plane, such as the basal plane, and undergoes strong shearing, the *c*-axes should orientate themselves normal to the plane of shear.

Another single-maximum fabric of a different origin has been known as a depositional fabric. Such a fabric has not yet been fully investigated because of the difficulty of preparing thin sections of snow and firn. However, Fuchs (1956) noticed that the *c*-axes of slightly

* *X* is the direction of the maximum compressive axis. The direction of the maximum tensile axis is *Z* at grid H but *Y* at grids E and F.

metamorphosed snow (firn) at depths greater than 8 m were preferentially orientated normal to the surface. Studies by Schytt (1958) of highly metamorphosed firn in Dronning Maud Land, Antarctica, revealed a similar pattern. It has been considered that the preferred orientation in firn is a result of the mimetic recrystallization of snow after the deposition of stellate snowflakes parallel to the ground surface, although this is very hypothetical.

The present author has reported a single-maximum fabric with the maximum nearly normal to the ice surface just below the firn area of the coast of Lützow-Holmbukta, east Antarctica (Kizaki, 1962). The texture of the ice is fine and polygonal, resembling those of CE and CH. Therefore, it can be expected that a single-maximum fabric of this kind would commonly occur just below the firn area of the continental ice sheet in Antarctica whatever its origin.



a b

Fig. 4. a. 210 c-axes of ice (CE1) from grid E. Contours 1–2–3–4–5 < %; maximum 6% per 1% area. Grain-size: 15 grains/cm².
b. 237 c-axes of ice (CE2) from grid E. Contours 1–2–3–4–5–6–7 < %; maximum 9% per 1% area. Grain-size: 17 grains/cm².

Great-circle girdle

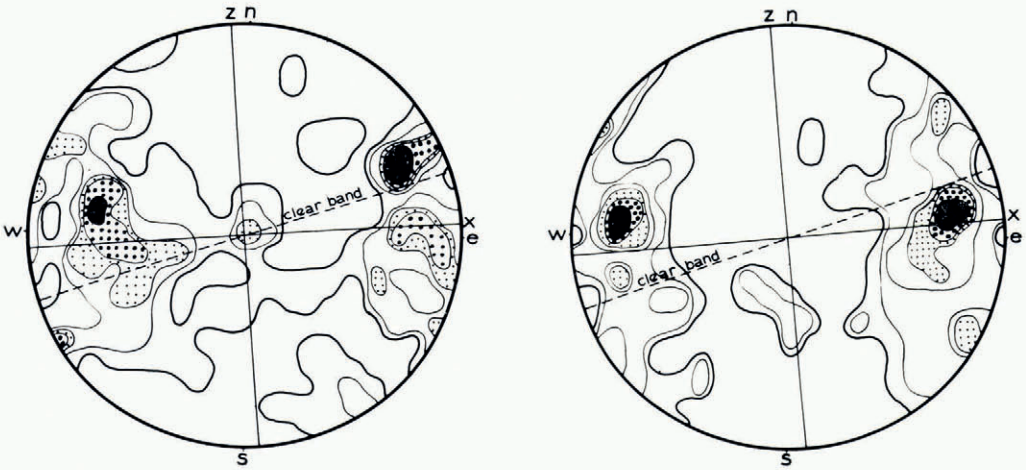
At grid E the ice is still fine-grained and also semi-polygonal in texture, although the grains are a little larger than at grid H. A great-circle girdle is parallel to the direction of cleavages, i.e. the direction of the maximum compressive axis *X*, whereas the maximum at the centre shows a strong concentration of *c*-axes which indicates the relic of the single-maximum fabric described for grid H. A tendency for a small girdle around *X* is also present (Fig. 4a and b).

The great-circle girdle through the maximum compressive axis *X* and the maximum tensile axis *Y* conflicts with the theoretical suggestion by Brace (1960), according to which the girdle should be through the maximum compressive axis and the intermediate compressive axis if each of their stress deviations is identical. However, this is not a case of a great-circle girdle due to the stress effect, but a transitional pattern from the single-maximum fabric to the small-circle girdle fabric (CF), as demonstrated by the indistinct small circle emerging about *X* in CE2 of Figure 4b.

Small girdle

A small girdle is characteristic of the fabric from grid F, although the relic of the great-circle girdle and the single-maximum fabric of the grid H type are still apparent in CF2

(Fig. 5a). The texture of the ice is porphyroblastic, showing a mixture of large grains (>4 cm) with small grains (<1 cm). It is clear that the texture indicates a differential growth of ice crystals from an even-grained fine polygonal ice such as those of CE and CH. The *c*-axis distribution analysis is shown in Figure 6, revealing that the larger crystals have orientated



a b

Fig. 5. a. 224 c-axes of ice (CF2) from grid F. Contours 1–2–3–4–5<% ; maximum 5% per 1% area. Grain-size: 1.1 grains/cm².
b. 221 c-axes of ice (CF1) from grid F. Contours 1–2–3–4–5–6<% ; maximum 8% per 1% area. Grain-size: 0.9 grains/cm².

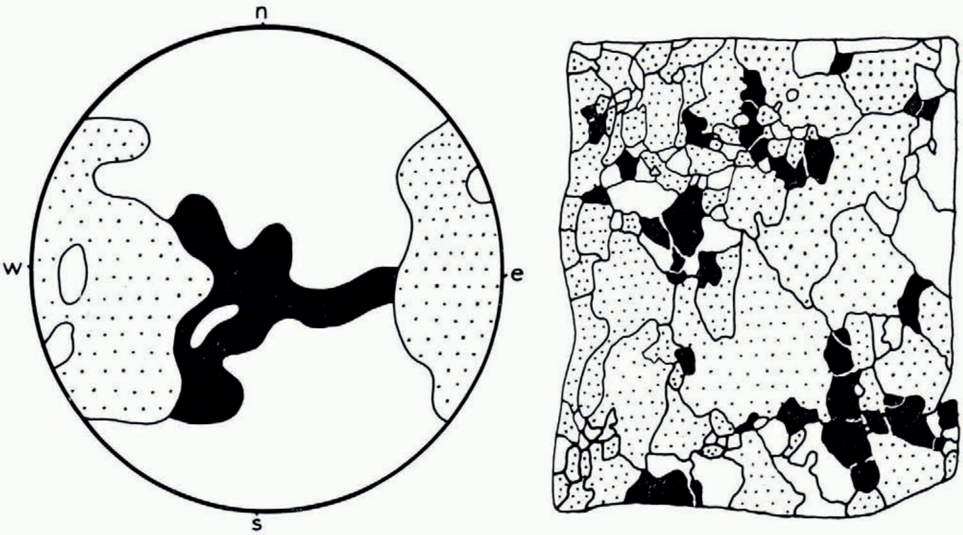


Fig. 6. Axis-distribution diagram of CF2. Thin section of the ice is 12 × 10 cm.

themselves to form the small girdle around *X*, whereas the smaller crystals have preserved the earlier great-circle girdle fabric. Thus those crystals with a favourable orientation relative to the stress distribution grow more rapidly than others, developing the porphyroblastic texture. The smaller crystals, despite having lost the polygonal texture, are inherited from the fine polygonal ice seen in sections from grids H and E.

The crystals are also elongated roughly in the flow direction to the north. This is seen to be due to the strong compression normal to the flow direction as revealed by the strain-rates calculated for CF1. The fabric of CF1 shows a much clearer pattern with a small girdle about X as a stable fabric (Fig. 5b). Brace (1960) predicted three fabric patterns in simple stress distribution. Two of these are shown in Figure 7. The orientation pattern of CF1 (Fig. 5b) is a mixture of the patterns of case I and case III predicted by Brace; also the strain distribution of grid F is neither in accord with case I ($X, Y, Z = -\sigma', +\sigma'/2, +\sigma'/2$) nor case III ($X, Y, Z = -\sigma', +\sigma', 0$), but it indicates some intermediate figures ($X, Y, Z = -\sigma', +\lambda\sigma', +(1-\lambda)\sigma'$). It seems reasonable that Brace's prediction on the orientation pattern of ice should apply to this extent, since the newly formed ice has been well deformed as well as recrystallized.

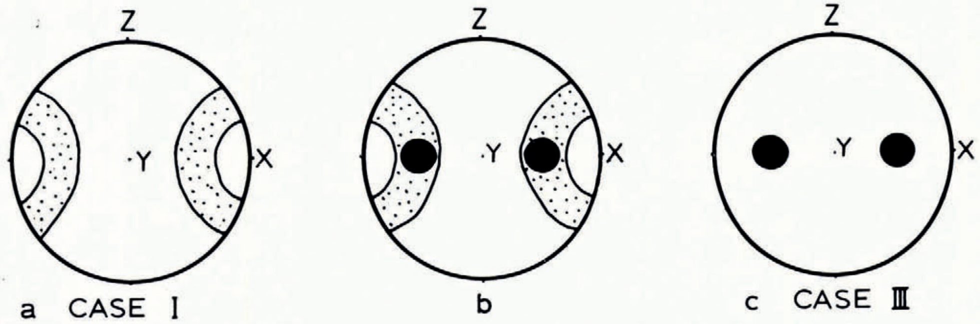


Fig. 7. a. Case I of the fabrics predicted by Brace; $X : Y : Z = -\sigma' : +\sigma'/2 : +\sigma'/2$.
b. The actual fabric simplified from CF1; $X : Y : Z = -\sigma' : +\lambda\sigma' : +(1-\lambda)\sigma'$.
c. Case III of the fabrics predicted by Brace; $X : Y : Z = -\sigma' : +\sigma' : 0$.

Concluding Remarks

It is evident that the fabric pattern changes gradually from the single maximum of an original fabric to a small-girdle fabric around the maximum compressive axis X. The patterns of great-circle girdle from grid E (CE1 and CE2) can be regarded as transitional fabrics from the single-maximum fabric to the small-girdle fabric. The strain-rate distribution of grid E is a mixture of Brace's cases I and III, which should produce a small girdle with two maxima similar to the fabric of CF. Therefore, the orientation fabrics of CE1 and CE2 may not represent equilibrium patterns. It is of interest that the changing process of the pattern is accompanied by grain growth from CE to CF. The fabric patterns at grid F (CF1 and CF2) are much clearer than those of CE and the strain-rate distributions have a similar tendency. The clear patterns of CF arise from recrystallization as revealed by grain-size (Table III).

This makes it clear that grain growth has an important role in producing the fabric patterns of ice, and that the strain–fabric relationship involves the condition of an identical grain-size.

On the basis of the single-maximum fabric from grid H as an original pattern, the fabrics develop successively to a small girdle around the maximum compressive axis. The controlling element of those patterns is consistently the maximum compressive axis X, and later on this changes to the maximum shear plane which parallels foliations or clear bands in some planes as ice streams and glaciers flow down towards the ice edge. Such patterns controlled by shear planes have been found in the ice cliffs at the snout of Forbes Glacier as a three-maxima fabric, and also in surface ice which had been subjected to long-continued strain in simple shear in the Mawson area (Kizaki, 1969), and in other temperate glaciers. A small girdle connecting these maxima parallel to a shear plane has been frequently observed (e.g. Reid, 1964). Ice which has been subjected to strong shear stress or long-continued strain commonly reveals its shear-plane control of fabrics, whether the fabric is a single maximum or small girdle, with or without maxima in association with recrystallization and grain growth. Therefore, the patterns predicted by Brace, which are in harmony with the orientation patterns from grid F, apply only to newly formed ice which is deformed to a certain extent and grows substantially in grain-size not far from the firn line.

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