Folds in Firn

A structural glaciology study on the Vaughan Lewis Glacier
Juneau Icefield, Alaska

by
Charles J. Waag
Juneau Icefield Research Program
Foundation for Glacier and Environmental Research
Seattle, WA. 98109

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CHARLES J. WAAG *Department of Geology, Georgia State University, University Plaza, Atlanta, Georgia 30303;* and *Foundation for Glacier and Environmental Research, and Juneau Icefield Research Program, Seattle, Washington 98109*

ABSTRACT

Folds in firn on glaciers of the Gilkey Trench, Alaska, have been observed during years of heavy snowfall and reduced ablation. The firn folds were formed by upbuckling and decollement resulting from intense lateral shortening within the underlying glacier ice. Trends of the firn fold axes were normal to the shortening direction (σ_1), and subparallel to foliations in the glacier ice and the ice-flow direction (σ_3). Extension crevasses normal to the fold trends were also common in the area of the firn folds. Peculiar parallelogram patterns formed by recrystallization of the lowermost centimetre of firn were exposed in the ablated cores of some folds. The patterns were consistently oriented with respect to the firn fold axes and englacial structures, and they seem to reflect the same stress field.

INTRODUCTION

Although a wide variety of structures in glacier ice have long been recognized and described (Cloos, 1929; Balk, 1937; Carey, 1962; Ragan, 1969; Waag, 1972; Hudleston, 1977), descriptions of folds within firn are rare (Gould, 1935; Reid, 1964; Pinchak, 1973; Waag, 1974). During the summer of 1973 and again in 1978 (1978 observation, written commun. from M. M. Miller) a large number of folds in firn were observed on glaciers of the Gilkey Trench, Juneau Icefield, Alaska.

The setting in which the folds in the firn developed is one of intense lateral shortening as is indicated by abrupt convergence of the lateral moraines of the glaciers of the Gilkey system. The glaciers have their origins in the high ice and firn plateaus of the Juneau Icefield in the vicinity of Mount Ogilvie (2367.6 m) where they cascade into the broad, deeply glaciated Gilkey Trench. In its upper portion, the Trench trends southward; then it makes an abrupt right-angle turn westward toward Berners Bay on the Alaskan Coast (Fig. 1). The Vaughan Lewis Glacier enters the Trench at the point where the glaciers of the Gilkey System swing through the right-angle bend. At this juncture, large quantities of firn and glacier ice cascade ~ 500 m down the trench wall, forming the spectacular Vaughan Lewis Ice Fall (Fig. 2). Wave bulges or wave ogives 30 m in height and 125 m in wavelength are generated at the base of the fall. (Wavelength here indicates the map distance between adjacent wave crests or troughs, and height indicates the difference in elevation between adjacent wave crests and troughs).

Crowding induced by the massive accumulation of firn and ice in the wave bulges, and the effects of the swing in the flow of Gilkey ice contribute to a marked decrease in the width of the glaciers of the Gilkey Complex just below the turn. Convergence of the lateral moraines of one of the glaciers, the Ogilvie-Gilkey Glacier, indicates a decrease in width of about 40% in a flow distance of 100 m. Apparently as a result of unusually heavy snowfall and reduced ablation in 1972–1973 and again 1977–1978, the firn limit extended down

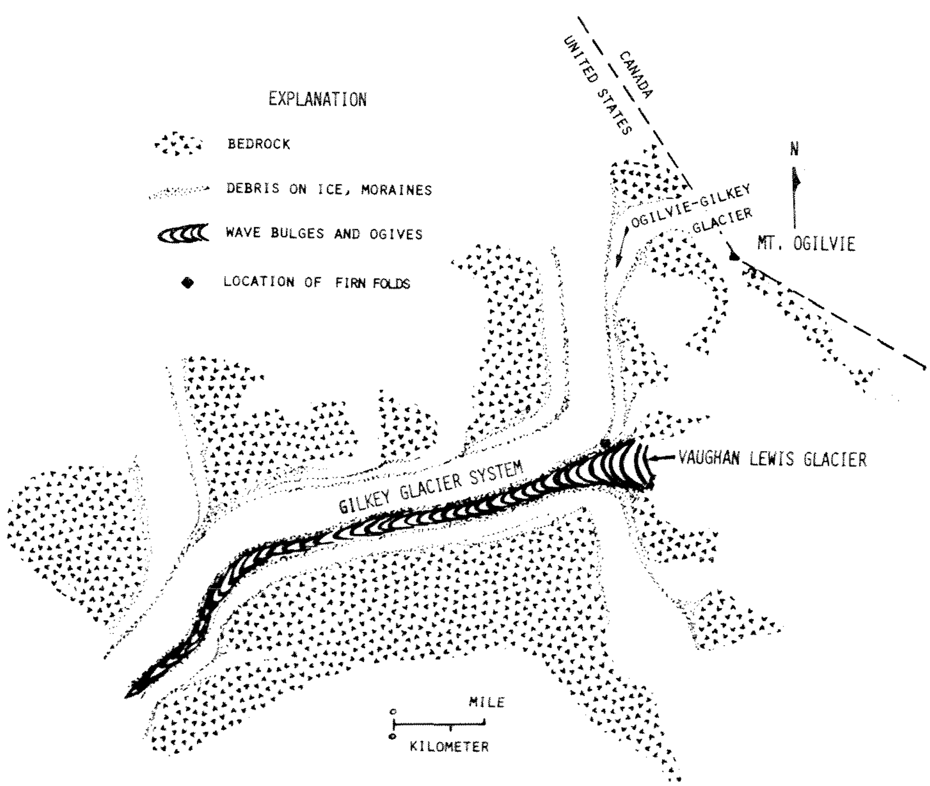

Figure 1. Map of the Gilkey Trench showing the location of the firn folds on the Ogilvie-Gilkey Glacier of the Gilkey Glacier System.

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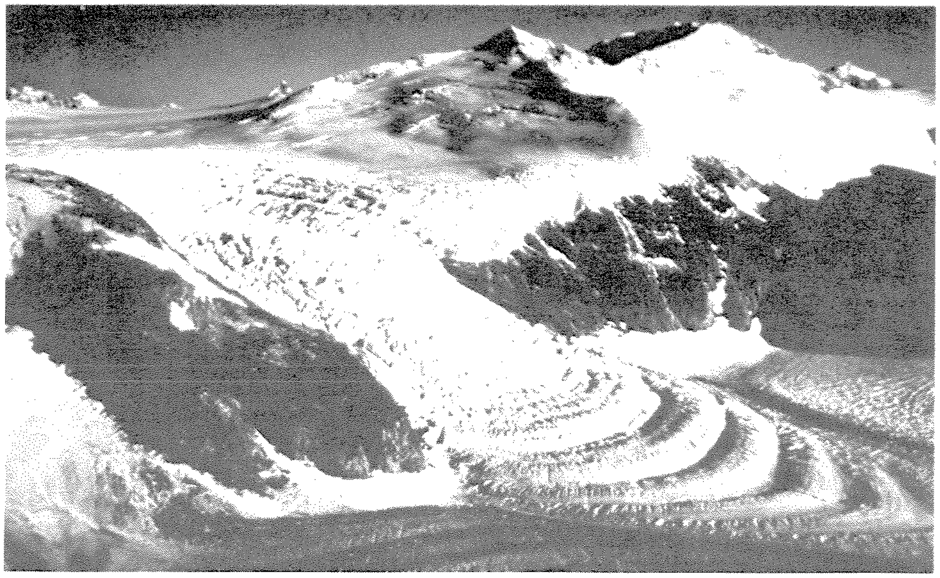

Figure 2. Photograph of the Vaughan Lewis Icefall and glaciers of the Gilkey System. Firn folds formed between the rapidly converging moraines in the lower foreground. Impinging flow from wave bulges contributes to compression of the Gilkey Glaciers.

glacier into this zone of abrupt reduction in width. As a consequence of intense lateral shortening within the ice, the overlying firn was buckled upward, and the greatest abundance of folds was formed in this zone (Fig. 3).

STRUCTURES WITHIN THE GLACIAL ICE

The glacial ice beneath the firn folds had a strongly developed metamorphic tectonite fabric but did not appear to be significantly different from ice elsewhere in the glaciers. Relatively clear, coarsely crystalline, well-foliated ice was most abundant; however, intercalations of finer-grained, poorly foliated white bubbly ice were common. At least two and locally three directions of subparallel foliation were recognizable within the clear ice. These foliations were manifestations of differential concentrations of entrained debris and bubbles

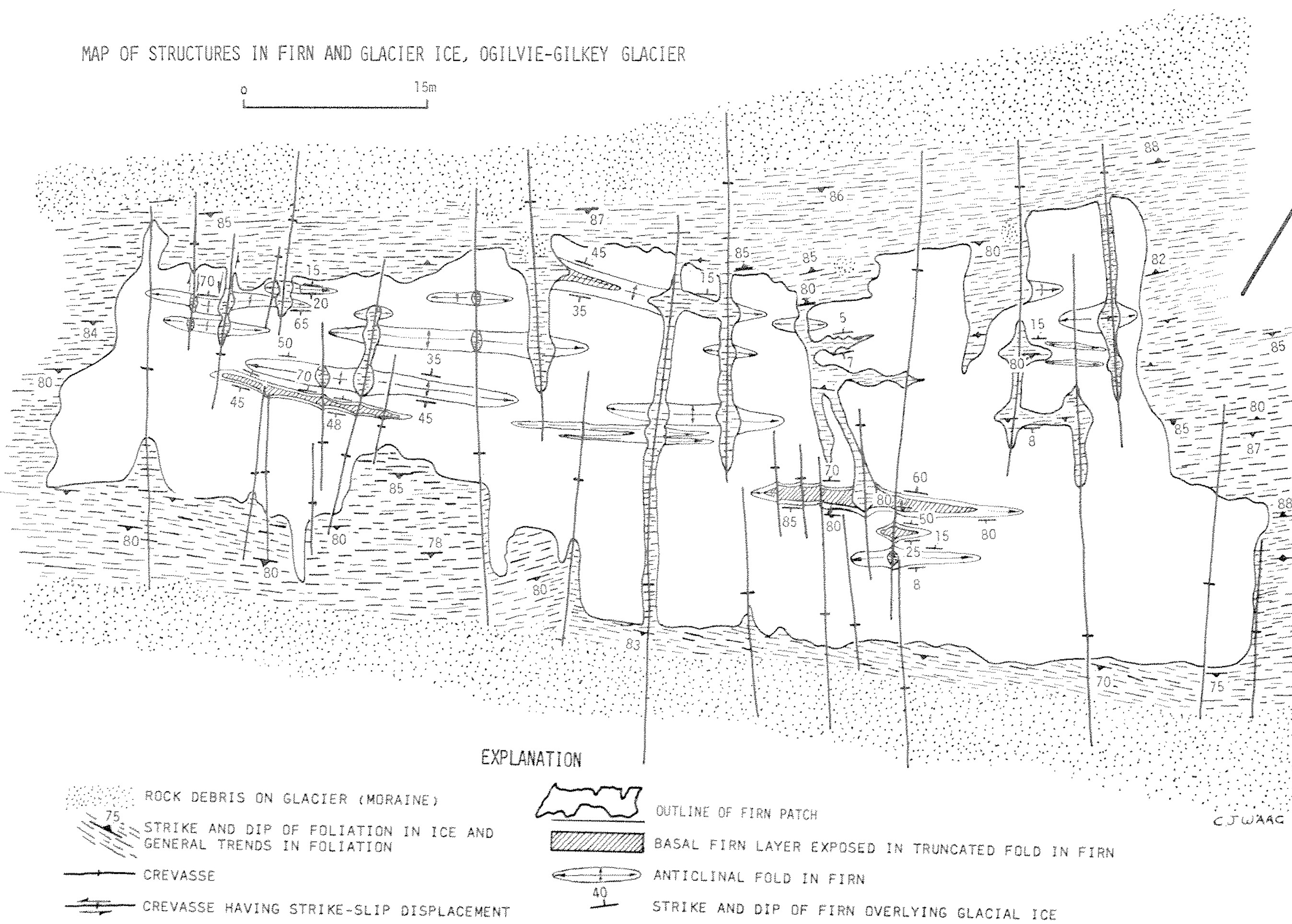

Figure 3. Map of a portion of the Ogilvie-Gilkey Glacier showing structures within the firn patch and the glacier ice.

flattened within the plane of the array. The foliations were also subparallel to the intercalated white bubbly ice bands, and all four planar elements commonly had angles of intersection of less than 15°.

Above the right-angle bend, strikes of foliations in the Ogilvie-Gilkey Glacier were subparallel to the flow direction and dipped steeply toward the longitudinal axis of the glacier. Below the right-angle bend, in the area where firn folds were formed, the strikes of foliations were likewise subparallel to the flow direction; however, dips were isoclinal and dipped toward the Vaughan Lewis Glacier. Reversal of dip direction in ice adjacent to the Vaughan Lewis Glacier is attributed to overturning caused by compression and overriding of the topographically higher wave bulges.

Folds within the ice were common, particularly along the margins of the glacier, in and near the morainal septa. Fold styles were predominantly Class 2 folds of Ramsay (p. 365) having tightly appressed limbs and poorly developed axial plane cleavage. Folds were small, measuring 0.5 to 1 m in wavelength and 2 to 3 m in amplitude. Plunges were consistently up glacier and ranged from 45° to 80°.

En echelon and through-going fractures which could be traced the width of the trench were abundant in the vicinity of the firn folds. Strikes of the fractures were essentially perpendicular to foliation and ice-flow direction. Some of the fractures were merely incipient rents; however, most were open crevasses as wide as 2 m.

STRUCTURES WITHIN THE FIRN

The firn was generally even bedded and ranged from less than 1 cm to 1.5 m thick. Grain sizes ranged from 2 to 5 mm and averaged approximately 2.5 mm. Coarser textures were most common at the base, and locally vague foliation could be traced from the underlying glacier ice into the lowest few centimetres of firn. The contact, however, was unconformable and represented a major structural discontinuity (Fig. 4).

The unconformity was especially well exposed where the crevasses within the glacier ice extended upward through the firn. Owing to higher rates of ablation along the crevasses and beneath the upbuckles, the firn was selectively removed where the crevasses intersected the firn folds. In places the upbuckled firn was completely ablated, and the glacier ice was exposed as inliers in the firn cover (Fig. 3).

Upbuckles or anticlines within the firn were numerous and ranged from 1.5 to 25 m long, from 35 cm to 5.9 m wide and from 12 cm to 1.5 m high. The axes of folds were doubly plunging, having trends subparallel to the foliations in the glacier ice, the longitudinal axis of the glacier, and the ice-flow direction. The total area of folds was much less than the nonfolded area, but the distribution of folds was asymmetrical. As shown in Figure 3, a greater concentration of folds was present in the downstream (convergent) portion of the firn compared to the upstream (divergent) portion. The distribution of folds was also asymmetrical with respect to the longitudinal axis of the glacier. A greater portion of the firn between the longitudinal axis and the moraine to the northwest was folded compared to that between the axis and the moraine to the southwest. This asymmetrical distribution of folds with respect to the longitudinal axis reflects the asymmetry of the convergence. The moraine to the northwest has greater concavity away from the glacier axis and indicates greater lateral shortening in that portion.

Broad, open folds with gently dipping limbs were the most common, but tightly appressed structures with steeply dipping limbs were also present (Fig. 5). Tight folds ranged from upright to overturned; however, the directions of overturning were not consistent. Unlike folds within other rock types, most of the firn folds had open spaces between the deformed layers or between the firn and the glacier ice (Fig. 5). Decollement between the firn layers allowed considerable freedom during deformation; disharmonic and concentric folds were most

Figure 4. Photograph of a firn fold and the unconformable contact between the firn and glacier ice exposed in a crevasse. Note the vertical foliation within the glacier ice, and the change in style and tightness of folding within the firn layers. The gently folded basal firn layers are more coarsely crystalline than the upper tightly folded layers. Pencil for scale.

common (Figs. 4, 6). Fold styles, however, were variable not only in cross-sectional profile but also longitudinally along the fold axis (Fig. 5).

MECHANISMS AND CAUSES OF FIRN DEFORMATION

The base of upbuckling for many of the concentric and disharmonic folds was at or near the unconformity, but the firn-glacial ice interface was probably not an important decollement. The unconformity was generally irregular, having linear highs and lows several centimetres to tens of centimetres in relief. The relief, a reflection of pre-firn differential ablation along compositional layering within the glacier ice, was essentially perpendicular to the direction of shortening and probably did not allow significant decollement. In most disharmonic folds, however, decollement along the bedding was evident. In some folds, the upper layers were tightly appressed, whereas the lower layers deformed into broad open buckles (Fig. 4). In these particular folds, the lower firn layers were especially coarsely crystalline, and a nearly vertical foliation could be traced from the glacier ice across the unconformity into the lowermost few centimetres of firn. By contrast, in a few disharmonic folds, the lower firn layers were more tightly folded, and the upper layers were deformed in broad sine-like curves (Fig. 6). In these folds, the lower layers may have deformed gradually by lateral compression, by gravitational collapse as the upbuckle was being generated, or by gravitational collapse after the larger wavelength folds in the upper layers were formed.

Although gravity may have played a minor role in the collapse of some layers, the principal cause of folding in the firn was clearly lateral compression. The 40% reduction in width of the Ogilvie-Gilkey Glacier in a flow distance of 100 m indicates intense lateral shortening in the glacier ice. In the firn, the obvious manifestations of that lateral shortening were folding and decollement, and interpretations of the stress conditions reflected by the structures within the firn and glacial ice are generally consistent. Judging from the physical setting and the englacial structures, the direction of greatest shortening (cross-glacier) is interpreted as the approximate orientation of the axis of maximum principal stress (σ_1). Thus, σ_1 would be parallel to the strike of the extension crevasses, perpendicular to the foliation and ice-flow direction. Owing

Figure 5. Photograph up-glacier looking along the axes of the firn folds. Note the change in fold style along the fold axis in the left foreground and middle-ground, and the crevasses approximately normal to the fold axes.

Figure 6. Photograph of a disharmonic fold in which the lower layers are more intensely deformed than the upper layers.

to the large amount of shortening, σ_1 was probably strongly compressive. The minimum principal stress (σ_3) is interpreted as oriented approximately perpendicular to the extension crevasses and parallel to the foliation and ice-flow direction. The openness of most extension crevasses indicates that σ_3 was probably tensional. The intermediate principal stress (σ_2) is interpreted as essentially perpendicular to the glacier surface.

Relative to the firn folds, σ_1, therefore, would be oriented perpendicular to the fold axes as expected. It is likely that extension in the glacier ice prompted elongation parallel to the fold axes and σ_3. σ_2, again,

Figure 7. Photograph of rhombus and rhomboid parallelogram patterns in basal firn. Zones of more coarsely crystalline firn outline lighter, less coarsely crystalline parallelograms. Note the crevasses approximately parallel to the short axes of rhombi and obtuse angle bisectors of rhomboids. Such patterns were common in the ablated cores of the firn folds. Pencil for scale.

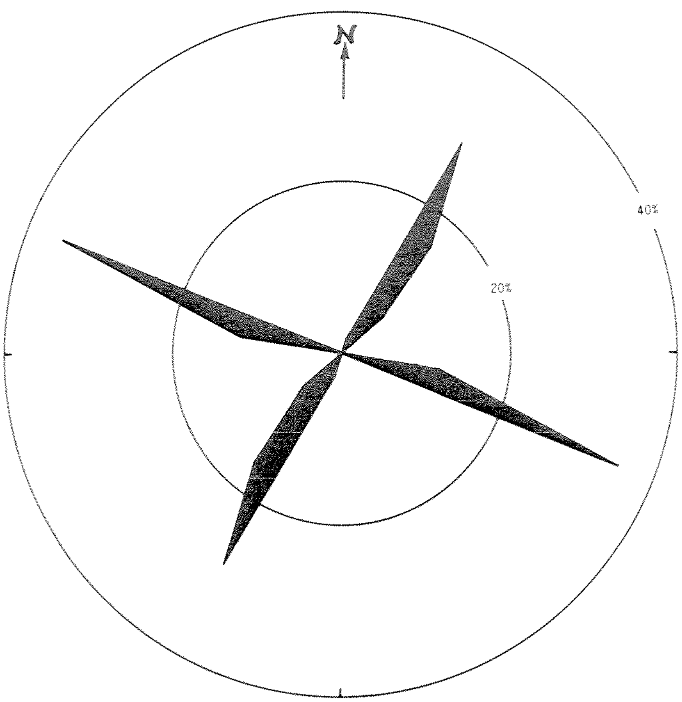

Figure 8A. Rose diagram of the orientations of the sides of the parallelogram patterns (68 readings).

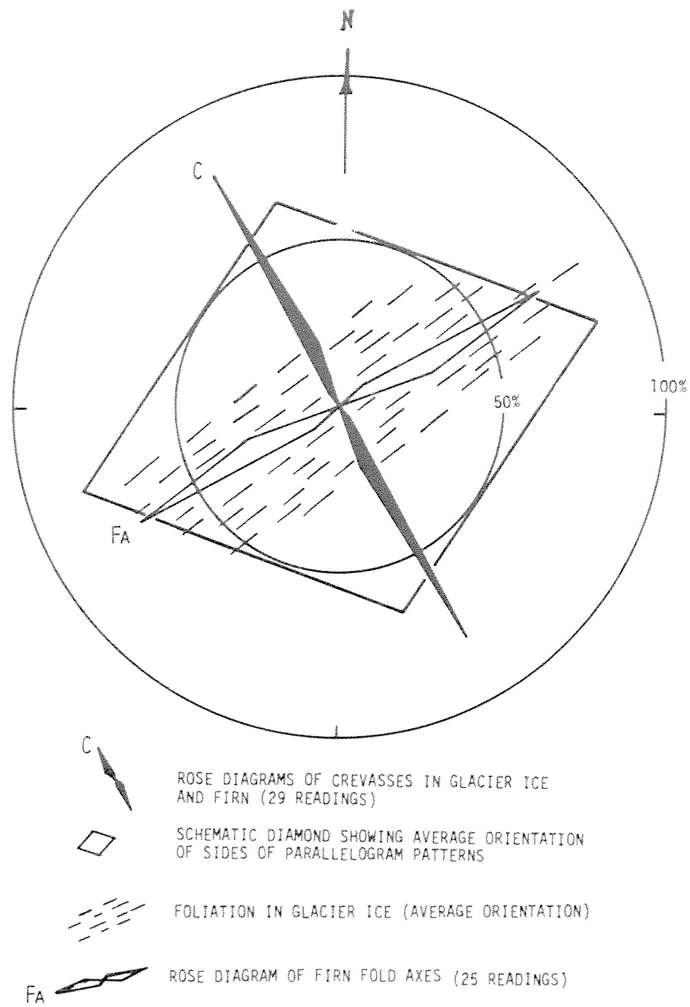

Figure 8B. Rose diagram of the firn fold axes and crevasses plotted with the average foliation in the glacier ice. The schematic diamond shows the average orientations of the parellogram patterns from Figure 8A. Note that the long and short axes of the diamond are nearly parallel to the firn fold axes and the crevasses, respectively.

would be perpendicular to the glacier surface, and in the direction of the upbuckling.

The mechanism or mechanisms by which stresses were passed from the glacier ice upward into the firn are not fully understood. However, that the stresses were, indeed, transmitted into the firn is evidenced not only by the folds and decollement, but also by the vague foliation in the basal firn. The fact that the foliation in the basal firn could be traced upward from similarly oriented foliation in the glacier ice suggests that the basal firn recrystallized under stress conditions similar to those present in the glacier ice.

Further evidence of stress transmittal into the firn seems to be present in the distribution of grain transformation in the firn. Obviously, some transformation in firn grain size must be attributed to lithostatic load, heat transfer, and refreezing of melt water which percolated downward to the less permeable unconformity. Under these conditions, the distribution of grain transformation would be influenced by the configuration of the unconformity, and the structures within the firn controlling the permeability, including bedding, fractures, and folds, and so on.

However, peculiar parallelogram patterns found in the firn seem to indicate that lateral stresses played an important role in the distribution of the recrystallization. Where the firn was ablated to a veneer one centimetre or less thick, subtle rhombus and rhomboid parallelogram patterns formed by concentrations of different grain sizes were present in the firn at the firn-glacier ice interface (Fig. 7). In plan, the parallelograms ranged from a few centimetres to greater than a metre on a side. Firn crystals within narrow zones outlining the patterns were coarser grained and averaged approximately 5 mm in diameter, whereas grain sizes within the parallelograms averaged only 2.5 mm. The patterns occurred in scattered localities throughout the Gilkey Trench but were most common where intense shortening was evident and abundant in the ablated cores of the firn folds (Waag and Echelmeyer, 1979).

Orientations of 68 sides of rhombi and rhomboids were measured using a pocket transit. A rose diagram of the data and a schematic rhombus or diamond having the average orientation of the patterns are shown with the average orientations of the firn-fold axes, the foliations, and the extension crevasses (Fig. 8). It is evident that the average trend of the firn fold axes is subparallel to the foliation and approximately perpendicular to the extension crevasses. It is also evident that the long and short axes of the schematic diamond are subparallel to the fold axes and the extension crevasses, respectively. These consistent geometric relationships suggest that the patterns and folds in the firn, as well as the englacial structures, are all manifestations of the same stress field.

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