**Experimental Recrystallization
of Ice Under Stress**

by
B. Kamb

Experimental Recrystallization of Ice Under Stress¹

BARCLAY KAMB

California Institute of Technology, Pasadena, California 91109

Polycrystalline ice in high-temperature creep (-5° to 0°C) under deforming stresses of a few bars undergoes rapid syntectonic recrystallization and large changes in texture and fabric that have prominent effects on flow. A simple original texture of small equant polyhedral grains recrystallizes at a shear strain γ of about 0.04 to a complex texture of coarse irregular interlocking grains with sutured boundaries and abundant strain shadows. Recrystallized grain size increases as stress decreases and temperature increases. Included air bubbles cause no detectable impediment to recrystallization or grain boundary migration. In simple shear (applied in torsion) the recrystallized c -axis fabric consists of two maximums, one at the pole of the shear plane and the other about 20° away from the shear direction. Fabric perfection mainly depends on total strain rather than time and develops progressively over the strain range $\gamma \approx 0.04$ – 0.3 . At a given total strain the fabric depends only weakly on stress: the maximums become somewhat weaker, and the angle between them increases slightly as the shear stress decreases from 4.1 to 1.9 bars. Under compressive stress superimposed across the shear plane the fabric maximums elongate and join to form a small-circle girdle, whose center reorients toward the compression axis. From the form of the fabric pattern it is possible to infer the stress character (as distinct from stress level and mean stress) over the full range of possible variation for a general state of stress. Also, it is notably possible to distinguish between simple and pure shear and to distinguish the shear plane from its conjugate plane in simple shear. The recrystallization fabric developed under simple shear has monoclinic symmetry and is incompatible in symmetry and orientation with the symmetries of stress, strain rate, and total strain but compatible with the symmetry of the velocity field measured in a coordinate system in which the stress remains fixed. This conflicts with simple thermodynamic theories of crystal reorientation and also a basic assumption in the theoretical formulation of ice flow laws. A combined mechanism of thermodynamically controlled crystal reorientation modified by intracrystalline plastic flow is qualitatively compatible with the fabric. The favored crystal orientations indicated experimentally are those which would have nearly maximum elastic strain energy if the stress were homogeneous in the polycrystalline aggregate, but because of intracrystalline plastic anisotropy it is likely instead that the stress is not homogeneous and that crystals in the preferred orientations have minimum elastic strain energy. Statistical fluctuations in perfection and orientation of fabric elements suggest that the recrystallization-reorientation mechanism is cooperative in nature. The crystal reorientations cause many-fold accelerations in creep rate as the recrystallization fabric develops. The seemingly steady creep observed between initial transient creep and the onset of recrystallization does not represent steady structural conditions, which require recrystallization. Fabrics observed in glacier ice deformed in pure shear to an equivalent strain of $\gamma \approx 0.6$ are compatible with the experimentally produced fabrics, but the commonly observed multiple-maximum fabrics of glacier ice are entirely incompatible. An experimental test shows that the incompatibility is not due to a qualitative difference between crystal reorientation at and below the melting point. An orientation-controlling mechanism that becomes operative only at high strains (~ 1) and supersedes the mechanism operative in the experimental strain range appears to be indicated; this implies that truly steady structural conditions are not established at the lower strains. The complexity of the flow-induced and flow-affecting structural changes that occur in ice suggests caution in interpreting experimental creep results for other, more complicated geological materials. Nonsteady creep is probably the rule in nature, except in flow situations involving very large strains, comparable to glacier flow.

¹Contribution 2112 from the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California; contribution

#30 from the Swiss Federal Institute for Snow and Avalanche Research, Weissfluhjoch, Davos, Switzerland.

PURPOSE

The flow of ice in nature, as observed in glaciers, leads to substantial changes in structure, texture, and fabric that appear to be controlled by the conditions and the history of deformation and resemble, in a general way, changes that occur in the deformation of rocks and metals (for a summary, see *Kamb* [1964]). The strong *c*-axis fabrics developed in glacier ice show considerable detail and complexity and thus offer the possibility of a means for inferring and interpreting the history of ice deformation. Efforts to establish the relationships between natural fabrics and deformation history by studying field examples [*Rigsby*, 1960; *Allen et al.*, 1960; *Kamb*, 1959*b*, and later unpub-

lished work] make it evident that a full understanding requires, in addition, an experimental approach in which fabrics are produced under controlled laboratory conditions. In the present study, artificial ice specimens were subjected to flow conditions similar to those in rapidly flowing glaciers, and the changes in texture and fabric were followed. Syntectonic recrystallization occurs readily under these conditions, and strong well-defined fabrics are produced. The study investigates the effects of state of stress, time, and temperature on the recrystallization textures and fabrics. An extensive earlier laboratory investigation by *Steinemann* [1958] demonstrated in considerable detail the textural changes that occur in the recrystallization of ice, and information on this subject has also

Fig. 1. Ice specimen A14 after deformation. The ink line on the surface of the specimen was initially vertical, parallel to the cylinder axis.

been given by *Rigsby* [1960] and *Shumskii* [1958]. In these earlier studies, only relatively limited and partly conflicting data on fabric changes were obtained, and the present work is therefore primarily aimed at providing a suite of experimental recrystallization fabrics extensive enough to allow a study of the consistency and systematics of crystal reorientation by syntectonic recrystallization. The experimentally produced fabric patterns are compared with natural fabrics of glacier ice and also, in a general way, with theoretical predictions.

EXPERIMENTAL METHODS

The experimental work was conducted at the Swiss Federal Institute for Snow and Avalanche Research, Weissfluhjoch, Davos, Switzerland.

Material. Ice specimens, an example of which is shown in Figure 1, were prepared by filling a container with fresh snow, saturating the snow with water, and allowing the water to freeze. The polycrystalline aggregate formed consists of a fine-grained mass of equant grains 0.5–0.9 mm in diameter. Grain boundaries are

planar, grain shapes are polyhedral, and in cross section the grains appear as polygons, most of which have four to seven sides. This type of texture, shown in Figure 2, represents an approach to minimum grain boundary surface area for the given average grain size or grain packing density determined by the packing of the nucleating snow crystals. It is here called tessellate texture and resembles the grain textures of soap bubble foams and polycrystalline metals.

The white opacity of the experimental specimens (Figure 1) is due to abundant fine bubbles of air that formed in the ice from air trapped among the original snow crystals and also dissolved in the water. The bubbles are 0.1–0.3 mm in diameter and are present at an estimated concentration of about 14 mm^{-3} . Glacier ice contains air bubbles in comparable concentration, and, since the work was directed primarily toward the interpretation of natural fabrics with the help of experimental ones, air-containing artificial ice was used in preference to air-free ice. In this respect the starting material differs from that of *Steinemann* [1958].

Fig. 2. Texture of a typical ice specimen as initially prepared. The length of the frame corresponds to 2 cm.

Torsion-compression experiments. Most of the deformation experiments were conducted in simple shear or in simple shear with compression superimposed perpendicular to the shear plane. The deformation was produced by subjecting cylindrical specimens to combined torsion and axial compression. Simple shear is of interest primarily because this mode of deformation (or something approximating it) occurs commonly in glacier ice showing strong recrystallization fabrics [Kamb, 1959b; Kamb and Shreve, 1963]. The use of torsion allows arbitrarily large shear deformations to be accomplished without the complicating end effects that limit the usefulness of simple shear apparatus.

The deformation geometry is shown schematically in Figure 3. Ice specimens were machined to hollow cylinders 4–5 cm long with outside and inside diameters of 8.0 and 3.0 cm, respectively, and attached by melting to toothed grips for loading in the torsion machine (Figure 1). The torsion-compression apparatus used was the

same as that built and used by Steinemann [1958] in his extensive experiments.

Torsional and axial strains of the specimens were measured by dial gage micrometers that followed the motion of the grips. Torsional strain γ and axial longitudinal strain e could be detected at a level of about 3×10^{-5} . Because the grips showed a tendency to come loose and slide past the specimen in the later stages of most torsion experiments, ink lines were ruled parallel to the cylinder axis on the outer surface of each undeformed specimen in A8 and subsequent experiments to provide a record of the total torsional strain experienced by the specimen independently of the motion of the grips, as is shown in Figure 1.

Axial stress σ can be calculated directly from the axial dead-weight loading. Obtaining the torsional shear stress τ from the torsional loading torque requires consideration of the radial distribution of shear stress in the torsion specimen, since the shear strain varies linearly with

Fig. 3. Schematic diagram showing deformation of cylindrical specimens in torsion apparatus. The orientation of a typical thin section plane is shown, and reference axes, which define the stress orientation in relation to the thin section, are given: T is the axis of torsion and compression, R is the radial direction, and w is the shear direction. Although there is relative rotation of the top and the bottom of the specimen around axis T in the torsion process, the bulk rotation discussed in the text is what accompanies simple shear locally at any point in the specimen and is a rotation around the local axis R at that point, in the sense shown.

TABLE 1. Physical Conditions of the Recrystallization Experiments

Experiment	Duration t , days	Temperature T , °C	Shear Stress τ , bars	Normal Stress σ , bars	Shear Strain		Compressive Strain $-e_T$
					Rate $d\bar{\gamma}/dt$, 10^{-7} sec^{-1}	Total $\bar{\gamma}$	
A10	59.0	-1.2	1.9	0.0	0.2	0.13	0.13
A8	2.8	-1 to -2.5	4.1	0.0	2.8	0.12-0.24	0.00
A7	1.1	-2.5	4.1	1.3	3.1	0.05	0.003
A6	13.5	-4 $\pm$	4.1	1.3	1.1	0.40	0.01
A5	42.0	-2.5	3.0	2.5	0.7	$\sim$ 0.27	0.06
A3	5.0	-4	4.9	3.8	1.4	$\sim$ 0.16	0.05
A14	1.9	-1.2	4.1	6.3	3.4	0.15	0.082
A13	3.0	-1	3.0	11.3	8.9	0.22	0.42
C1	2.0	0	0.0	2.4	0	0	?
C4	2.3	0	0.0	6.4	0	0	0.31

radial distance r from the torsion axis. If we assume, because of the high nonlinearity normally found in the stress versus strain rate relation for ice, that τ is independent of r , then τ in kilograms per square centimeter is 7.9×10^{-2} times the applied torque in kilogram centimeters for the specimen geometry used. Shear stresses are quoted here on this basis. If, on the other hand, the nonlinearity were as low as $n = 2$ in the flow relation $\dot{\gamma} = b\tau^n$, where b is a constant, the shear stress at $r = 2.75$ cm, midway between the inner and the outer surface of the hollow cylinder, would be consistently larger by a factor 1.2. The range of possible uncertainty here is not large enough to cause concern in the present experiments. Temperature in the cold laboratory was controlled to an accuracy of about $\pm 1^\circ\text{C}$ most of the time, although larger excursions occurred occasionally.

The torsion-compression experiments for which recrystallization data are presented here are summarized in Table 1. The strain rates listed are those observed during the second stage of creep, as defined in the section on flow behavior. The total shear strain was obtained from the external ink lines where available and otherwise was estimated by extrapolating to the full duration of the experiment from the creep observed in the initial creep period, before sliding against the grips began. The shear strain rate $d\bar{\gamma}/dt$ and the total shear strain $\bar{\gamma}$ are applicable to ice midway between the inner and the outer wall of the specimens, at $r = 2.75$ cm. The sampling of different total strains was extended somewhat by using the radial dependence of the shear strain

and also, in experiment A8, by taking advantage of inhomogeneous deformation that occurred in the specimen (Figure 4). Results for the top and bottom halves of specimen A8 are labeled A8T and A8B below; the total shear strain in A8B was twice as great as that in A8T.

Compression experiments at 0°C . To compare the results of the torsion experiments, conducted at temperatures of -1° to -5°C , with natural fabrics formed in temperate glacier ice at the melting point, it is desirable to test a basic aspect of the temperature dependence of the recrystallization process, namely, whether

Fig. 4. Sketch of the surface of specimen A8 after deformation, showing distortion of ink lines that were initially vertical. Note the pattern of detachment of the ice specimen from the toothed grip at the bottom, leading to development of a sliding surface. Incipient sliding has begun at the top.

recrystallization at the melting point produces effects fundamentally different from those produced at temperatures distinctly below the melting point. Torsion tests cannot be used for this purpose, because the grips fail to hold the specimens at 0°C. A device was therefore built to subject specimens as nearly as possible to pure shear at an ambient temperature of 0°C. The device, shown schematically in Figure 5, consists of a trough of rectangular cross section into which a closely fitting platten slides, delivering a compressive load to a cube-shaped specimen confined in the trough. The specimen is a cube 5 cm on edge. The entire apparatus is submerged in an ice water bath to maintain the melting temperature. Two experiments of this type, for which recrystallization data are given below, are listed in Table 1.

Because of pressure melting on the loaded faces of the specimen, it is not possible to measure the plastic strain by following the motion of the platten. For strain markers four small brass pins were implanted in the horizontal midplane of the specimens, about 1 cm

from the center of each of the four vertical faces of the cube. Measurement of the pin separations before and after the experiment provided rough but definite values for the two longitudinal strain components transverse to the main compression axis; the third strain component, in the direction of the main compression, was obtained from the incompressibility condition. The strain for experiment C1 was not directly measured but was estimated from that for C4 by assuming a nonlinear flow law with $n = 3.5$.

At a compressive stress of 6 bars (experiment C4) the rate of pressure melting on the loaded faces is so large that the specimen is melted down to about half its initial thickness in 10 hours. To continue the recrystallization experiment for a longer time, the specimen was removed from the apparatus after about 7 hours loading and cooled to -10°C. Extra slabs of ice were frozen on to the top and the bottom of the specimen to make a cube-shaped sandwich in which the original ice formed the center. The specimen could then be returned to the

Fig. 5. Diagram of compression device used for deforming ice specimens at 0°C. Stress axes are indicated and labeled x , y , and z in conformity with those in Figure 17a.

apparatus and loaded for another 7–10 hours at 0°C. This process was repeated 7 times in experiment C4.

Reference stress axes for specimens compressed at 0°C are labeled as follows (Figure 5): axis z is the direction of main compression, perpendicular to the loading platten, axis y is the direction of lateral constraint, and axis x is the direction of free expansion along the length of the rectangular trough. The principal stress σ_z is determined directly by the loading, σ_x is 0, and σ_y is controlled by the nature of the lateral constraint, as is discussed later.

Thin sectioning. After the completion of each experiment the specimen was immediately cooled to -10°C, and thin sections were cut. For torsion specimens the sections were cut along radial planes through the cylinder axis. Such planes have the advantage that reference axes related to the loading have the same orientation in all parts of the section. The reference axes are the direction of torsion and compression T , the radial direction R , and the shear direction w , which is perpendicular to R and T and lies in the plane of simple shear wR (Figure 3). Specimen C1 was sectioned parallel to the yz plane, and C4 parallel to the xz plane. To insure independent sampling of the texture and fabric, separate sections were spaced as far apart as practical.

Each thin section was photographed under crossed polaroids shortly after preparation and stored at -20°C thereafter. Later inspection and comparison with the photographs showed that no textural changes occurred subsequent to thin sectioning. The sections thus preserve the texture and fabric as it was during deformation. Post-tectonic recrystallization was not studied.

Fabric measurement and presentation. Orientations of crystal c axes were measured under the polarizing microscope with a standard four-axis universal stage. For ease of handling, the sections were mounted on the stage without hemispheres. Measured c -axis inclinations were corrected for light refraction by the methods described by Kamb [1962]. Thin sections of torsion specimens were measured in traverses parallel to the T axis, so that all the ice in a given traverse lies at approximately the same radial distance from the torsion axis and has therefore experienced approximately the same shear strain. The approximate cross-sectional

area of each crystal measured was recorded, and for many specimens the individual crystals measured were identified by number on the thin-section photographs.

The measured c -axis orientations were plotted in equal-area projection (lower hemisphere), symbols indicating the crystal cross-sectional areas. Since it developed that all crystals, large and small, conformed well to a common overall pattern of preferred orientation, the distinctions among crystals of different areas were disregarded in reducing the plots to contoured fabric diagrams. Counting and contouring of the orientation density was done by following in a general way the method suggested by Kamb [1959b, p. 1908]. For each diagram a counter area A was chosen so that, in the regions of the diagram where significant concentrations of c axes occurred, the average number of points falling within the counter would be about 10 or somewhat larger. This procedure assures that in these regions statistical fluctuations in counted orientation density should be only about a third or less of the average density. The area A used is stated (as a fraction of the hemisphere area) below each fabric diagram given, together with the number of measured c axes (written as 626 c). In diagrams for undeformed specimens the contour interval is chosen to be twice the standard deviation expected for no preferred orientation [Kamb, 1959b, p. 1908]. For deformed specimens, solid contours are drawn at orientation densities of 2, 4, 6, ...% per 1% of hemisphere area; contours at 1 and 3% are shown by dashed lines in some diagrams. Areas of density of >2% (or >1% if the 1% contour is shown) are shaded lightly, and those of density of >4% (or >3% if the 3% contour is shown) are shaded more heavily.

The expected standard deviation of the contours varies in accordance with the number of c axes measured and the orientation density in the major fabric maximums. In general, it is about a third of the average density in the maximums, and it can be calculated in detail for each diagram from the data given. In drawing the contours, local density irregularities comparable to the expected standard deviations were smoothed somewhat, on the assumption that they are not statistically significant. The smooth appearance of the contours in comparison with the results of conventional contouring

procedures reflects the effort to avoid statistically insignificant information in the diagrams while obtaining the maximum resolution of detail consistent with adequate counting statistics.

FLOW BEHAVIOR

The deformation record for experiment A14, given in Figure 6, shows typical features that allow three creep stages to be distinguished. An initial stage of transient decelerating creep is followed by a stage in which the creep rate becomes stabilized and essentially steady. This second stage continues to a total shear strain $\bar{\gamma}$ of about 0.03 (± 0.005 in different specimens). It is followed by the third stage, in which the creep rate accelerates. For some specimens a more or less continual increase in creep rate occurs during the third stage, whereas for others a creep rate acceleration at the onset of the third stage is followed by an interval of steady creep, after which further accelerations occur. Figure 6 illustrates the latter type of behavior: a three-fold increase in creep rate near $\bar{\gamma} = 0.025$ is followed by essentially steady creep to $\bar{\gamma} \approx 0.1$, where a twofold acceleration occurs, followed again by approximately steady creep. The three creep stages were designated primary, secondary, and tertiary creep by *Steinmann* [1958, pp. 20, 30]. *Steinmann's* description does not emphasize the continual or repeated creep rate accelerations that occur in the third stage, although it recog-

nizes that some increase in creep rate does occur during this stage, after the initial acceleration.

The shear strain rates $d\bar{\gamma}/dt$ listed in Table 1 are those measured during secondary creep. The selection of measurements is not extensive enough to define the flow law of the material in detail, but some significant features are evident in the data. A strong correlation between temperature and flow rate is seen when the $d\bar{\gamma}/dt$ values for A6 and A3 (at about -4°C) are compared with the value for A8 (at about -1.5°C). Comparison of A8 and A10 shows a marked nonlinearity in the dependence of $d\bar{\gamma}/dt$ on τ ; interpreted in terms of a flow law of the type $\dot{\gamma} = b\tau^n$, where b is constant at a fixed temperature, it corresponds to $n \approx 3.5$. The increase in $d\bar{\gamma}/dt$ for A14 and especially for A13, in comparison with that for A8, demonstrates the strong effect that superposition of an independent stress component (the normal stress σ) has on the effective viscosity of ice as measured in shear. The effective shear viscosity is much less in A14 (0.3×10^{13} poises) than in A8 (1.5×10^{13} poises), even though the shear stress used is lower in A14 than in A8. This effect is an additional consequence of the nonlinear rheology and agrees quantitatively with the expected behavior of a generalized Newtonian fluid [*Nye*, 1953].

These observations and the numerical data in Table 1 agree well in general with the more extensive flow measurements of *Steinmann* [1958]. However, *Steinmann* [1958, p. 32] concluded that the generalized Newtonian fluid formulation of *Nye* [1953] is not adequate to account for the differences in flow behavior for different states of stress (different ratios of σ/τ).

In experiment A8 the ink line marked on the specimen surface revealed a markedly non-homogeneous deformation, the lower half of the specimen having undergone a shear strain twice that of the upper half (Figure 4), even though the entire specimen was subjected to the same loading for the same period of time. Observation of this type of behavior shows that caution is needed in interpreting the flow of polycrystalline ice specimens.

Grip sliding. In some of the observed creep curves a large acceleration in the apparent creep rate reflects the onset of a sliding process of the specimen past one or both of the grips. Adhesion between ice and grips tends to be

Fig. 6. Deformation history of specimen A14 showing torsional shear and axial shortening as a function of time. Note the creep rate accelerations at 14 and 31 hours.

Fig. 7. A portion of specimen A3 after deformation, showing deformed air bubbles. The length of the frame corresponds to 3.5 cm. The serrations on the upper edge are places at which the teeth of the grips engaged the specimen. The line at the base of the serrations is the sliding surface of the grip against the specimen.

lost at about the time that syntectonic recrystallization starts, and a plane of sliding frequently develops between the ice and the grips, tangent to the crests of the teeth. Such a sliding plane is visible in Figure 7, and a sliding plane at an early stage of development is shown in Figure 4. The ice remaining in the spaces between the teeth executes rotational motions, somewhat like roller bearings. Cohesion across the sliding plane is not entirely lost, and the applied torque is still transmitted to the specimen, but the sliding causes the rate of grip rotation to increase many times over that due to torsional deformation of the specimen alone. Axial compression inhibits the sliding; for example, no sliding occurred in experiment A14 (Figure 1).

This phenomenon offers a possible mechanism for basal sliding of polar glaciers, where the ice is everywhere below the melting point. Unlike other proposed mechanisms [Weertman, 1967], sliding of the type observed here does not depend on the melting of the ice. (At the ambient temperatures used, stresses of several hundred bars would be necessary to cause pressure melting.) However, the inhibiting effect of normal pressure appears to limit the applicability of this sliding mechanism to the shallower parts of polar glaciers.

Bubble deformation. In the torsion tests, ice deformation causes a well-defined flattening of air bubbles contained in the ice, as is shown in Figure 7. There is considerable variation in the amount and the direction of elongation of individual bubbles, showing that local inhomogeneities affect the bubble flattening, but there is a consistent over-all pattern. The orientation of the average elongation direction is given in Table 2 for specimens in which it could be observed; the angle given, $w \wedge E$, is the angle between the elongation direction E and the shear direction w . The estimated elongation direction corresponds approximately to the direction of the extensional principal strain axis e_1 ($w \wedge e_1$ in Table 2). The agreement is within 4° except for specimen AS, in which the elongation was not well shown. The degree of bubble flattening (axial ratio of $\sim 3:1$ in experiments A5 and A13) is somewhat larger than that expected from the bulk strains of the specimens, but a reliable evaluation of this discrepancy requires a detailed statistical study of bubble shapes.

In the deformation experiments at 0°C the air bubbles respond in a rather different way: instead of becoming flattened, they migrate through the ice. This type of behavior will be discussed in a separate paper.

TABLE 2. Orientation Information for Fabric and Deformation Features in Syntectonically Recrystallized Ice Specimens

Experiment	Figure	1 σ/τ	2 $w \wedge E$, deg	3 $w \wedge e_1$, deg	4 $T \wedge \sigma_3$, deg	5 $T \wedge$ $\frac{1}{2}(M_1 + M_2)$, deg	6 $T \wedge M_1$, deg	7 $w \wedge M_2$, deg	8 $M_2 - M_1$, deg	9 $D \perp wT$, deg
A10	15a	0			45	40	0	11	79	
AS	12	0	~ 30	40	45	38	-6	19	65	
A7	13a	0.3			40	~ 35	~ 0	~ 20	~ 70	
A6	14b	0.3	36	37	40	35	-3	24	63	
A5	16a	0.8	39	35	34	30	1	29	62	70
A3	16b	0.8	36	36	34	29	4	30	68	70
A14	16c	1.5			26	31	5	23	72	60
A13	16d	3.8	17	16	14	11	16	52	54	60
C4	17a	∞			0	0	37	53	74	75

1. Ratio of compressive stress σ to shear stress τ in simple shear.
2. Angle between shear direction w and direction of bubble elongation E .
3. Angle between w and extensional principal strain axis e_1 .
4. Angle between torsion axis T and compressive principal stress axis σ_3 .
5. Angle between T and bisector of acute angle between M_1 and M_2 .
6. Angle between pole T of shear plane and fabric maximum M_1 .
7. Angle between pole w of conjugate shear plane and fabric maximum M_2 .
8. Acute angle between maximums M_1 and M_2 .
9. Diameter of small-circle girdle, measured perpendicular to wT plane.

TEXTURAL CHANGES DURING FLOW

The texture of syntectonically recrystallized ice is illustrated in Figures 8–10. In place of the planar grain boundaries of the starting material (Figure 2), grain boundaries in the recrystallized specimens have become highly irregular. The irregularity is not simply a suturing superimposed on a pattern of boundaries inherited from the original tessellate texture but instead represents a thorough reorganization in which the original equidimensional grain shapes have been altered to highly irregular interlocking or interdigitating shapes reminiscent of the pieces of a jigsaw puzzle. Extensive grain boundary migration is indicated by the textural reorganization and also by a general coarsening of grain size from that of the starting material.

The extent of grain coarsening varies inversely with the applied stress over the range studied. Thus the texture of A10 (Figure 8), recrystallized under a shear stress of 1.9 bars, is much coarser than that of A8 (Figure 9), deformed at 4.1 bars.

Neither time nor total strain has a prominent influence on texture over the range studied in these experiments. Thus A7, A8, and A6 show similar grain sizes after deformation times of 1.1, 2.8, and 13.5 days, respectively, under the same shear stress. This finding implies that the recrystallization textures have reached an essentially steady state in the times involved. At a shear strain of 0.05 in A7 (Figure 10) some relict tessellate grains from the original texture remain, but the ice as a whole has already recrystallized to an interlocking texture.

Recrystallized grain shapes appear to show a slight elongation parallel to the shear plane, but the effect is largely obscured by the irregularity of the grains.

A pronounced effect of temperature on the recrystallization texture is seen in a comparison of C4 and A8, which were deformed under comparable effective shear stresses (3.7 and 4.1 bars, respectively) for comparable times; C4 was deformed at 0°C, and A8 at about -1.5°C. The grain size in C4 is somewhat

Fig. 8. Texture of specimen A10 after deformation for 59 days under a shear stress of 1.9 bars. The length of the frame corresponds to 2.5 cm. The torsion axis is oriented parallel to the length of the frame (left and right). The small dark circles and points are air bubbles.

Fig. 9. Texture of specimen A8, after deformation for 2.8 days under a shear stress of 4.1 bars. The torsion axis is oriented parallel to length of frame, which corresponds to 4 cm. Note strain shadows in the large grain near the bottom of the photograph.

larger (by about 50%) than that in A10 (Figure 8), which was deformed at a lower stress for a much longer time, and it is thus substantially larger than that in A8 (Figure 9). A correspondingly great sensitivity of texture to temperature is not evident in a comparison of A6 and A8, although the similarity in the grain sizes of the two samples might be interpreted as the result of the compensating effects of longer deformation time and lower temperature in A8. The marked increase in grain size in C4 suggests that the mobility of grain boundaries is greatly enhanced when the melting point is reached.

Many of the grains show strain shadowing in bands parallel to the trace of the c axis (Figure 9), which represents kinking by translation gliding on the (0001) plane. Strain shadows are abundant in ice deformed both at 0°C (C4) and below the melting point.

Similar textural features were observed in the more detailed study by Steinemann [1958]. The relationship between grain size, stress, and temperature was summarized by Rigsby [1960].

SYNTECTONIC RECRYSTALLIZATION FABRICS

Simple shear. In the ice specimens as initially prepared, c -axis orientations are nearly random, as is indicated by Figure 11. Recrystallization during deformation produces well-defined c -axis fabrics, which are shown in Figures 12–17. The type of fabric developed under simple shear is illustrated in Figure 12. There are two maximums in the c -axis orientation density, the first maximum, M_1 (Figure 12), oriented approximately normal to the shear plane (or parallel to the torsion axis T) and the second maximum, M_2 , inclined about 20° to the shear direction w (the point at the center of Figure 12). Generally, M_1 is somewhat stronger than M_2 , and the peak orientation density is higher in M_1 than in M_2 by about 2% per 1% of area. Maximum M_2 is located approximately along the great circle between w and T , and its location in relation to the sense of shear can be described by saying that it is rotated away from w in the direction corresponding to the bulk rotation experienced locally by the deform-

ing ice. This rotation, which occurs about axis R , is clarified in Figure 3. The sense of rotation is shown in Figure 12 by symbols representing the shear stress vector acting across the shear plane wR . The minus sign at the top represents the stress vector acting across the plane wR from above on the material below wR , and the plus sign at the bottom similarly represents the stress vector acting from below on the material above wR . The minus sign represents a vector directed toward w , perpendicularly down into the plane of the diagram, and the plus sign represents a vector in the opposite direction, toward $-w$, up out of the diagram.

Maximum M_2 typically shows a marked elongation perpendicular to the wT plane. In Figure 12, M_2 at the height of the 2% contour is about 28° wide in the wT plane and about 65° wide perpendicular to that plane. The elongation can be explained to some extent by the observation that in individual samples of about 100 c axes, from single thin sections, the position of the M_2 peak varies somewhat from section to section, scattering 5° – 15° on either side of the wT plane. Combination of results from several thin sections thus pro-

duces a composite M_2 peak elongated in the direction of scatter. Evidence of a tendency for the M_2 maximums in different experiments to scatter somewhat out of the wT plane can be seen in Figures 12, 14, 15, and 16. These figures suggest a tendency for M_2 to be displaced out of the wT plane preferentially toward $+R$. Such an apparent tendency might be due to a systematic orientation error in the cutting of the thin-section planes.

Maximum M_1 in Figure 12 appears elongated perpendicular to wT , but this effect, although present to some extent, is exaggerated by the peripheral distortions in the equal-area projection. At the height of the 2% contour, M_1 in Figure 12 is about 41° wide in wT and about 54° wide perpendicular to wT .

The relatively few c axes that do not fall within M_1 or M_2 tend to lie in the region spanned by the acute angle between the two maximums. When the $\frac{1}{2}\%$ contour is drawn in Figure 12, a ring-shaped area of weak orientation density is defined, forming a small circle containing M_1 and M_2 and centered over the bisector of the acute angle between them. The region around R is almost devoid of orientation

Fig. 10. Texture of specimen A7 after deformation to a shear strain $\bar{\gamma}$ of 0.05. The length of the frame, which is parallel to the torsion axis, corresponds to 4 cm. Fine crystals in the right-center part of the figure are relicts from the original texture.

Fig. 11. c -axis orientation density for ice specimens as initially prepared (in the case of C1, after slight deformation). The contour interval and shading are explained in the text.

density, as is the region in the obtuse angle between M_1 and M_2 .

The relationships between the type of c -axis fabric shown in Figure 12 and observations of previous workers are as follows. The fabric diagram of a shear experiment of Steinemann [1958, Figure 60; reproduced in Kamb, 1959b, Figure 15] was interpreted by him as showing two maximums symmetrically disposed about T in the TR plane 25° from T and a third maximum in the Tw plane 50° from T . Resolution among the three maximums is not good, and the statistical validity of the individual maximums is not certain. It appears that the first two maximums taken together may correspond to M_1 as observed here but with abnormal elongation in the TR plane. The third maximum may correspond to M_2 , but it is poorly resolved and 20° closer to T than is M_2 as found here. Its orientation in relation to the sense of shear is not known. Rigsby [1960, p. 603] produced a two-maximum fabric by subjecting an ice specimen to shear deformation with repeated reversals in the sense of shear. The maximums are oriented approximately perpendicular to the two conjugate shear planes of the specimen, and in this sense both play a role analogous to M_1 in the present experiments. (The angle between Rigsby's maximums is, in fact, 82° , so that perpendicularity to conjugate shear planes can only be approximate.) Because of the shear reversal the maximums cannot be related to a sense of shear. From the pattern in Figure 12 we would expect that repeated reversals of the sense of shear would cause M_2 to oscillate back and forth about w and to lie on the average near w , the position found by Rigsby. Shumskii [1958, Figure 3] showed a similar but somewhat more diffuse and less clearly portrayed pattern of two broad maximums from an ice specimen deformed for 20 days in shear. The two maximums appear centered at points corresponding to T and w in the present experiments. A relation of the maximums to the sense of shear was not given.

Shumskii [1958, p. 247] stated that c axes forming the maximum near T represent newly formed relatively unstressed crystals, whereas the c axes near w represent relict crystals from the original texture, which are highly deformed. In the present study no such distinction was found between crystals in M_1 and those in M_2 :

Fig. 12. c -axis fabric of specimen A8 showing typical features of fabrics produced by syntectonic recrystallization under simple shear. The stress axes T , R , and w are explained in the text and Figure 3. The symbols at top and bottom show the sense of the shear stress vector, minus down into the figure (toward w), plus up out of the figure (away from w), as is explained in the text. The number of c axes measured is designated by c ; the fractional area of the counter used in preparing the contoured density diagram, as explained in text, is designated by A . The contours are at densities of 2, 4, and 6% per 1% area of hemisphere; the dotted contour is at $\frac{1}{2}$ % per 1% area.

the latter grew to sizes comparable to the former, and strain shadows were, in fact, 4 times more abundant in M_1 than in M_2 . However, as a specific test of Shumskii's interpretation, a special ice sample (A11) was prepared in which all the c axes of the original crystals were directed approximately radially outward (toward R) in the cylindrical specimen. After 2 days under an average shear stress of 5.5 bars the specimen began to recrystallize, as was indicated by acceleration in the creep rate. The new crystals formed predominately in the grain boundary regions between remnants of the original crystals, producing a brick and mortar texture. Numerous crystals in orientations corresponding to both M_1 and M_2 were found in the newly recrystallized material.

Dependence of fabric on strain and time. Progressive development of recrystallization fabrics under simple shear is shown in Figures

13–15, obtained from experiments carried out to different total strains. Diagram ASB (Figure 14a) was obtained from the more highly sheared bottom half of specimen AS (Figure 6), and diagrams AST (Figure 13b) and AST' (Figure 15b) were obtained from the top half in traverses at radial distances of 2.6 and 3.3 cm, respectively, corresponding to $\gamma = 0.11$ and to $\gamma = 0.13$.

Experiments A7 and AST (Figure 13), at $\bar{\gamma} = 0.05$ and at $\bar{\gamma} = 0.11$, show early stages in the development of the recrystallization fabric. Although larger *c*-axis samples would be needed to define these fabrics fully, the beginning of a preferred concentration of axes around *T* and in the area between $+w$ and $-T$ is evident. The fabric in A7 is weak, but the concentration of axes near *T* and the deficiency of axes near *R* are statistically significant. In AST the disappearance of axes in the region between $+T$ and $+w$ has become significant, and the concentration near *T* has increased. By $\bar{\gamma} = 0.24$ (ASB, Figure 14a) the fabric has become much stronger, and maximum M_2 has appeared clearly. The contrast between AST (Figure 13b) and ASB (Figure 14a) is noteworthy, since these fabrics come from the same specimen but from regions of different total strain (Figure 4). Further strengthening and sharpening of the pattern is evident at $\bar{\gamma} = 0.40$ (A6, Figure 14b), the largest shear strain reached in these experiments.

The transition from the relatively weak fabric in AST to the well-developed fabric in ASB is bracketed more sharply by comparing AST (Figure 13b) and AST' (Figure 15b), which are *c*-axis samples from traverses at two different radial distances in the top part of specimen AS and therefore differ only slightly in total strain. The fabric in AST', at $\bar{\gamma} = 0.13$, is fully as well developed as that in ASB; this finding suggests that a major step in fabric reorganization occurs at a shear strain of about 0.12. Again, the fabric in A5 (Figure 16a), for which $\bar{\gamma}$ is estimated as 0.27 (Table 1), is almost as strong as that in A6, at $\bar{\gamma} = 0.40$, and it is significantly stronger than that in ASB, at $\bar{\gamma} = 0.24$. These results suggest that the fabric development proceeds in a step-wise fashion, distinct reorganizations occurring at shear strains near 0.04, 0.1, and 0.3. It is, however, alternatively possible that the fabric develops continuously but that individual regions containing several hundred crystals are subject

to large statistical fluctuations in the extent of crystal reorientation at a given total strain. Thus AST' and A5 may have sampled regions in which the fabrics became perfected more rapidly than they do on the average, and AST and ASB may represent regions in which fabric development was retarded in relation to the average. More extensive experiments are necessary to choose between these two alternative interpretations of the data in Figures 13–15.

The similarities in strength and perfection of fabrics A5 (Figure 16a) at $\bar{\gamma} \sim 0.27$ and A6 (Figure 14b) at $\bar{\gamma} = 0.40$ suggest that a steady state is reached in the development of the fabric pattern at a shear strain of about 0.3. (In A5 the equivalent shear strain, if the contribution of the longitudinal strain is taken into account, is 0.30.) Likewise, in comparing A13 with A14 there is only a modest increase of fabric strength, in spite of the much greater strain (especially e_T) for A13; this evidence suggests that a steady state is being reached.

The position of M_1 in simple shear ($\sigma = 0$) remains steady as strain increases. Maximum M_2 remains roughly steady in position from AST' to ASB, but the angle $w \wedge M_2$ increases about 8° from ASB to A6. Part of this increase (about 5°) should be due to stress reorientation in A6 ($\sigma = 1.3$ bars causes $T \wedge \sigma_3$ in Table 2 to change by 5°). In the present experiments there is thus no definite indication that $w \wedge M_2$ increases progressively with increasing strain, as would be required to explain the angle $w \wedge M_2 \sim 40^\circ$ in Steinemann's [1958, Figure 60] diagram, for which a shear strain $\bar{\gamma}$ of 0.75 was given. A progressive increase in $w \wedge M_2$ with strain would imply that a structural steady state is not reached for shear strains γ of ~ 0.5 . Further experimental study of this important point is needed.

Since shear strain and time increase together, the dependence of fabric on strain in Figures 13–15 can also be viewed as a dependence on time. In experiment AS, however, the different strains and fabrics developed under a given stress and in the same time; this experiment indicates that time alone is not the determining variable.

Dependence of fabric on shear stress. Figure 15 compares the fabrics of two samples deformed to the same total shear strain but at different shear stresses. The fabrics are similar

Fig. 13. *c*-axis fabrics of ice deformed in simple shear to shear strains γ of 0.05 and 0.11. The contours are at 0.5% (dotted), 1% (dashed), and 2 and 3% (dashed) per 1% area of hemisphere. The conventions are as in Figure 12 and explained in the text.

Fig. 14. *c*-axis fabrics of ice deformed in simple shear to strains γ of 0.29 and 0.40. The duration of the deformation for each experiment is designated by t . The conventions are as stated in the legends of Figures 12-13.

Fig. 15. c -axis fabrics of ice deformed in simple shear to the same strain ($\gamma = 0.13$) at shear stresses τ of 1.9 and 4.1 bars. The conventions are as stated in the legends of Figures 12-14 and explained in the text.

in a general way, although the one obtained at the higher stress (AST') is somewhat stronger (contrary to the conclusion of Steinemann [1958, p. 46]). The M_2 peak is about 7° closer to w in the experiment at lower stress (A10). Also, the weak small-circle girdle between M_1 and M_2 is more strongly developed at the lower stress.

Since the time duration was some twentyfold longer in experiment A10 than in experiment A8, the comparison in Figure 15 might alternatively be interpreted as a test of the effect of time on the recrystallization process for fixed total strain. If stress and strain rate are related functionally by a flow law, so that time and stress are not independent variables at fixed total strain, the distinction between alternative interpretations of Figure 15 emphasizing time or stress is, in fact, academic. In any case the relatively slight differences between A10 and AST' in Figure 15, in spite of the very different times used to produce the two fabrics, show that any effects of time alone, as distinct from effects tied to total shear strain, must be rather small.

Although strain shadows were observed microscopically with about equal over-all frequency

(10%) in the grains of specimens A8 and A10, the fraction observed in grains of M_2 was much lower in A10 (5%) than in A8 (28%). This difference may be related to the detected difference in fabric.

Effect of stress state. Figure 16 shows the effect of progressively increasing the normal stress σ superimposed on a shear stress τ in the torsion experiment. Two changes occur in the resulting c -axis fabrics. (1) The small-circle girdle connecting M_1 and M_2 becomes enhanced at the expense of the maximums, which weaken and elongate perpendicular to the wT plane, following the girdle. (2) The pattern as a whole rotates around R so as to bring the center of the girdle toward coincidence with T . The first effect is faintly recognizable when $\sigma/\tau = 0.8$ (A3) and becomes definite at $\sigma/\tau = 1.5$ (A14). A clear indication of the rotation effect, maximum M_1 definitely moving away from T , is seen for $\sigma/\tau = 3.8$ (A13). At $\sigma/\tau = 1.5$ (A14), maximums M_1 and M_2 have moved about 5° away from their average positions for $\sigma = 0$, but the amount of rotation appears somewhat less than that for A3, in spite of the larger ratio of σ/τ .

Quantitative information on the orientations

of the maximums in relation to axes T and w , as a function of σ/τ , is given in Table 2. The angles listed as $T \wedge M_1$ and $w \wedge M_2$ are the directly measured angles if the maximums lie in the wT plane; otherwise they represent the

component obtained by projecting the positions of the maximums into the wT plane, along great circles through R . The bisector of the angle between M_1 and M_2 , called $\frac{1}{2}(M_1 + M_2)$ in Table 2, shows a general correlation with the

Fig. 16. The effect on c -axis fabrics of the superposition of compressive stress σ on shear stress τ . Stresses are indicated at the top of each diagram. The contours and conventions are as stated in the legend of Figure 13 and explained in the text. The longitudinal strain parallel to the torsion axis is indicated by e_T .

maximum compressive principal stress axis σ_3 , whose orientation is given in terms of the angle $T \wedge \sigma_3$ between it and T . However, at $\sigma = 0$ there is a definite discrepancy between the two orientations, which reflects the fact that M_2 is not located at w while M_1 is located at T . The angular separation between M_1 and M_2 (designated $M_2 - M_1$ in Table 2) and the diameter of the small-circle girdle measured perpendicular to the wT plane (designated $D \perp wT$ in Table 2) do not show any clear dependence on stress state, but a small dependence could be masked by the rather large and seemingly random fluctuations in these angles.

The limiting case $\sigma/\tau \rightarrow \infty$, toward which the sequence in Figure 16 tends, represents simple uniaxial compression, which was studied by Steinemann [1958, Figures 62-65], who gives syntectonic recrystallization fabric data for five stress levels from $\sigma = 3.4$ -16.0 bars. Although the fabrics are rather irregular, particularly for the higher stresses, the general pattern is that of a small-circle girdle centered about the pole of compression, in agreement with what is expected from the trend shown in Figure 16. At a stress of $\sigma = 11.0$ bars the diameter of the small-circle girdle in the fabric of Steinemann [1958, Figure 65] is about 80° , rather larger than that indicated here in experiment A13 (Table 2). The considerable irregularity in Steinemann's fabrics may reflect poor counting statistics, and the tendency for increased apparent orientation densities toward the center of the diagrams may reflect the fact that the orientations were plotted in stereographic projection. Difficulties with the counting procedure are indicated by the fact that the diagrams show large departures from the required centrosymmetry at the margins.

Compression at 0°C . The c -axis orientation density produced in experiment C1 shows no significant preferred orientation and is given in Figure 11. The specimen showed no visible change from the tessellate texture of the starting material. Specimen C4, deformed slightly longer at a stress about 3 times greater than that for C1, gives a fabric showing substantial crystal reorientation (Figure 17a). There is an incomplete small-circle girdle about z with broad maximums located around the two points where it crosses the xz plane. (The separate closures of the 3% contour in the upper-right and lower-

left quadrants of Figure 17a are not statistically significant enough to imply resolution into two maximums there.)

To interpret this fabric in relation to those of the torsion experiments, it is necessary to estimate the state of stress in C4. If the lateral constraint along the y axis (Figure 5) were such as to produce plane strain, the stress state would be pure shear, with $\sigma_y = \frac{1}{2}\sigma_z$. However, pressure melting on the y faces of the specimen lowers the compressive stress σ_y substantially. From the roughly measured strains, $e_{zz} = +0.18$ and $e_{yy} = +0.13$, the stress σ_y is estimated as $0.1\sigma_z$ on the assumption that the ice deforms as a generalized Newtonian fluid. If the fabric pattern does not depend on the mean stress, the 0°C compression experiment with $\sigma_y = 0.1\sigma_z$ and $\sigma_x = 0$ corresponds to a torsion experiment having $\sigma/\tau = 2.7$, a stress state intermediate between that in experiments A13 and A14. The fabric of C4 is, in fact, compatible with one intermediate between A13 and A14, as can be seen by comparing Figures 16 and 17a, with due regard for the different orientations of the principal stress axes in the different figures (Table 2). The angle between the two maximums in the fabric of C4 is nearly the same as that in the fabric of A14, whereas that in the fabric of A13 is distinctly smaller (Table 2). The strength of the pattern for C4 is distinctly weaker than that for A13 and A14.

It thus appears that syntectonic recrystallization at the melting point produces a fabric pattern that is qualitatively, if not quantitatively, similar to that produced at temperatures a few degrees below the melting point. A full evaluation of the suggested quantitative differences between fabrics produced at the melting point and below requires more extensive experimental material to cope with statistical fluctuations in the fabric data.

The longitudinal strain $-e_x$ required for recrystallization and fabric reorientation is bracketed between the limits 0.009 and 0.31 by experiments C1 and C4. It is thus compatible with the shear strains $\bar{\gamma}$ of 0.04-0.1 required for comparable effects in experiments below the melting point.

EFFECTS OF RECRYSTALLIZATION ON FLOW

The extensive changes in texture and fabric accompanying syntectonic recrystallization of

Fig. 17. (a) Fabric of ice syntectonically recrystallized at 0°C . Contours of c -axis orientation density are at 1% (dashed), 2% (solid), and 3% (dashed) per 1% area of hemisphere. Stress axes are labeled to correspond with Figure 5. The arrows represent the principal strains designated e_x and e_z . (b) Fabric of glacier ice from the base of an icefall in Blue glacier, Washington, core-sampled at a depth of 10.6 meters. Contours of c -axis density are at 1% (dashed), 2, 4, 6, and 8% (solid) per 1% area of hemisphere. The core axis is U . Compression and extension axes (inward-directed and outward-directed arrows, respectively) represent pure shear, compression being perpendicular to macroscopic foliation and sub-parallel to ice flow direction.

ice contribute in an important way to the flow process and are responsible for some of the complexities in the flow curves discussed earlier (Figure 6). Since the textural and fabric changes are only partly developed at a shear strain $\bar{\gamma}$ of 0.05 (experiment A7), there is a general correlation between the onset of recrystallization as recognized texturally and the acceleration in creep rate that occurs at the end of the second creep stage ($\bar{\gamma} \sim 0.03$). This acceleration can be attributed to the crystal reorientations produced by recrystallization: the newly formed crystals are in orientations that are relatively favorable for intracrystalline plastic flow, and the orientations preferentially eliminated are those for which intracrystalline plastic flow is most difficult. Single crystals of ice deform readily by translation gliding parallel to the basal plane (0001), whereas other types of intracrystalline deformation, if they occur at all, are very difficult [Griggs and Coles, 1954; Glen and Perutz, 1954; Nakaya, 1958]. Under simple shear, crystals having c axes centered in maximum M_1 (at T) are oriented with their glide plane parallel to the

shear plane wR of the specimen and are thus in the orientation for 'easy glide' [Butkovich and Landauer, 1958]; intracrystalline plastic flow in these crystals contributes directly to the over-all shear deformation of the specimen. The same statement would be true for crystals with c axes at w . Because of the approximately 20° displacement of M_2 away from w , somewhat more resistance to the shear deformation of the specimen is offered by crystals in this maximum than by crystals with c axes at T or w : for a given resolved shear stress on the crystal glide plane the required shear stress across the specimen shear plane is greater by a factor of $1/\cos 40^\circ = 1.3$. Nevertheless, crystals in M_2 are favorably oriented in comparison with the orientations eliminated in recrystallization, those with c axes near R and midway between w and $\pm T$. The orientation at R is the orientation for 'hard glide' [Butkovich and Landauer, 1958], and the orientation midway between $+w$ and $-T$ with the c axis aligned with the maximum compressive principal stress axis is one for which single crystals of ice show no measurable plastic flow

and remarkably high strength, ~ 1 kb (W. F. Brace and B. Kamb, unpublished manuscript, 1968). Crystals with c axis midway between $+w$ and $+T$ could fail in tension by basal cleavage, but, in fact, there was no microscopic evidence of such failure in the specimens listed in Table 1.

As a compressive stress σ is superimposed on the shear stress τ , the changes in the fabric pattern (Figure 16) are such as to promote intracrystalline plastic flow under the altered stress state. The crystal orientations would be maximally effective if, as the stress state approaches uniaxial compression, the diameter of the small-circle girdle in the fabric pattern were 90° . The actual angle is somewhat less, but, again, the orientations eliminated (c axes nearly parallel and perpendicular to the compression axis) are those offering the greatest resistance to intracrystalline plastic flow.

A threefold acceleration in shear-strain rate is achieved with an extent of crystal reorientation indicated in the relatively weak fabric of experiment A7 (Figure 13a). A large scatter remains in crystal orientations away from the easy glide orientations at T and w . The further accelerations in creep rate that occur later during the third creep stage are attributable to the additional steps in sharpening and strengthening the fabric pattern that occur at higher strains (Figure 14). The abrupt transitions to higher creep rates seen in some flow curves (such as those in Figure 6 at a strain $\bar{\gamma} = 0.10$) have an explanation in the seemingly stepwise fabric reorganization implied by the measured fabric diagrams.

Textural and structural changes other than fabric reorientation doubtless also contribute to the complexities in the flow curve of polycrystalline ice, but their effects are less easily assessed. It is not known in detail how the change from tessellate to interlocking grain shapes should affect the flow of the aggregate, although it seems clear that irregularities in the grain boundaries should interfere with grain boundary sliding and thus inhibit one possible deformation mechanism in the flow of the polycrystalline aggregate. A general coarsening of grain size during recrystallization should tend to increase the creep rates. An inverse relationship between grain size and creep resistance has been suggested from experimental indications by Steinemann [1958, pp. 24, 34] and is also recognizable in field observations [Kamb and Shreve,

1963]. This effect could appear in the present experiments as a correlation between increase of grain size on recrystallization and increase in creep rate. Comparison between experiments A14 and A10 should reveal such a correlation if it exists, because the recrystallized grain size in A10 (Figure 8) is several times that in A14 (similar to A8, Figure 9). However, the creep rate acceleration in A14 (sixfold at a shear strain of about 0.12) is comparable to the creep rate acceleration in A10 (fivefold). It appears that any effect of smaller grain size in A14 is compensated for by the somewhat stronger and sharper fabric pattern that developed at the higher stress level. Steinemann [1958, Figure 14] reported a somewhat increased creep rate acceleration at larger stresses and hence smaller recrystallized grain sizes.

The strain-softening property of ice single crystals [Griggs and Coles, 1954; Steinemann, 1958, p. 13] should contribute to creep rate acceleration in the flow of polycrystalline ice. Since strain softening is due to the accumulation of dislocations in the process of intracrystalline plastic flow, its contribution to the flow of the polycrystal tends to be eliminated by recrystallization.

The development of strain shadows in the individual crystals is direct evidence that the creep process in polycrystalline ice involves intracrystalline plastic flow and results in the accumulation of crystalline defects. The attainment of a true steady state in the creep process therefore requires the operation of a recrystallization mechanism, which generates undistorted crystalline material at a rate that keeps pace with the generation of defects by intracrystalline flow. The process that leads to the fabrics in Figure 14 is thus essential to the attainment of a steady state. The abundance of strain shadows in the specimens shows erratic fluctuations but no systematic increase as total strain increases (A10, shadows observed in 11% of the grains; A8, in 10%; A14, in 23%; A6, in 4%); these data indicate that continual recrystallization keeps pace on the average with the generation of bending distortions by plastic flow. The fabrics developed under simple shear appear to become steady near $\gamma = 0.3$, but some uncertainty about the final steady state remains, as was explained earlier. The available flow data do not extend to high enough strains to show

whether a final steady state is reached in the creep rate near $\gamma = 0.3$.

The appearance of a temporarily steady creep rate during the second stage of creep is in a sense deceptive, because conditions cannot in reality be steady: there is progressive accumulation of defects that will ultimately initiate recrystallization. The steady creep rate in this stage may reflect merely a temporary balance between processes tending to harden the aggregate (evidenced by the initial stage of decelerating creep) and processes tending to soften it (in particular, intracrystalline strain softening).

PHYSICAL FACTORS GOVERNING RECRYSTALLIZATION

Comparative behavior of texture and fabric changes. The experimental results show that, although in a general way the changes in texture and fabric produced by syntectonic recrystallization occur synchronously, in detail they follow a distinctly different course and respond rather differently to the controlling physical variables. The transformation from tessellate to interlocking texture is completed early in the recrystallization process at a shear strain γ near 0.05 well before a strong recrystallization fabric has developed. Beyond $\gamma \sim 0.05$, relatively little further change in the textural pattern and grain size takes place, whereas the fabric pattern continues to develop and strengthen up to a strain of about 0.3. Grain size is strongly dependent on shear stress, whereas fabric shows only a slight dependence when observed at fixed total strain. Grain shapes show only slight anisotropy, if any, in response to anisotropic stress and are not affected appreciably by changes in stress state attainable by variation in the ratio of σ/τ , whereas the fabrics become highly anisotropic as recrystallization proceeds and respond sensitively in orientation and pattern to the stress state. Texture is sensitive to temperature, whereas fabric is not: recrystallization gives a distinctly coarser texture at the melting point than at temperatures only a few degrees below, whereas the fabrics developed under the two conditions are nearly the same.

Control of fabric strength. The perfection of the experimentally produced syntectonic recrystallization fabrics depends primarily on the total specimen strain and only secondarily on temperature, time, or stress level. The experi-

ments indicate that the fabrics become somewhat weaker at lower stress levels and at higher temperatures very near or at the melting point, but more extensive experimental material is necessary to establish these effects with certainty. Peak orientation density depends to some extent on the state of stress simply because the favored orientations, confined into discrete maximums under simple shear, become necessarily spread out over girdles under uniaxial compression, owing to the rotational symmetry.

Statistical nature of the process. In comparing the fabric data for experiments of the same or similar strains and stress states, or even from within individual specimens, marked differences in strength, perfection, or orientation of fabric maximums suggest that the course of recrystallization is subject to statistical fluctuations that are substantially larger than those that could be caused by sampling statistics alone. The fluctuations presumably occur in response to random local variations in the texture or fabric of the initial material, and they suggest that the recrystallization process is cooperative in nature, so that original fluctuations become amplified. Evidence for a phenomenon of this kind is found in the inhomogeneous deformation that occurred in specimen A8 (Figure 4). Stepwise development of fabric strength as a function of strain can explain some of the anomalous features in the measured fabric diagrams without recourse to statistical fluctuations, but, even if this explanation is valid, it appears probable from experiment A8 that the implied abrupt fabric reorganizations occur on a statistical basis rather than at rigidly fixed total strains or times.

Effect of air bubbles. Since the changes in texture and fabric that took place here in specimens containing abundant air bubbles were comparable to the changes observed by Steinemann [1958] in air-free samples, it follows that the air bubbles do not substantially inhibit the processes of recrystallization and grain growth. Rigsby [1960, p. 601] reported a seemingly contrary field observation indicating that air bubbles strongly inhibit grain growth at the melting point. In the present experiments at the melting point, extensive grain growth occurred in 2.3 days in a sample initially containing abundant air bubbles (experiment C4).

If air bubbles acted to inhibit recrystallization

and grain growth by pinning the grain boundaries locally and interfering with their lateral migration, one would expect to find that grain boundaries in the experimental specimens had moved into positions such that a large fraction of the bubbles are located along them. This is not the case, as is shown in Figure 8: most of the bubbles are intracrystalline. A pinning mechanism of this type could not be effective in preventing grain boundary migration in the experiments at 0°C because of the high mobility shown by the bubbles in these experiments.

It seems likely that the stress level in the glacier ice observed by Rigsby was much lower than that in the present experiments, and it therefore remains possible that an inhibitory effect of air bubbles on recrystallization could operate at low stresses. However, Rigsby [1960, Figure 16] showed an example of recrystallization and grain growth occurring in bubbly ice in an unstressed state.

Fabric symmetry and orientation. In the fabrics developed under simple shear (Figures 12–15), maximums M_1 and M_2 are of unequal strength and do not lie at 90°. With due allowance for statistically expectable fluctuations of orientation density in the measured diagrams, the indicated fabric pattern has monoclinic symmetry; a single twofold symmetry axis lies to a good approximation along the radial direction R , and a single mirror plane lies along wT . The pattern does not conform to the orthorhombic symmetry required if the crystal reorientations occurred in response to either the stress tensor, the strain tensor, or the strain rate tensor. Even if M_1 and M_2 were of equal strength, their relative orientations are not compatible with the symmetry axes (principal axes) of these tensors. The pattern does conform to the 'movement picture' (velocity field) as this concept is used in structural petrology, but some clarification is required to make this concept meaningful because of the possibility that arbitrary rotations can be added to the velocity field without affecting phenomena based on specimen deformation. Rational choice of a reference coordinate system in which the velocity field should be described can be made when conditions allow a steady-state fabric to develop, namely, when the deforming stresses remain constant; this coordinate system is the one in which the fabric, and hence also the

stresses and velocity field, remains constant. For this choice of coordinate system under simple shear the velocity field has monoclinic symmetry, conforming with the observed fabrics. The agreement here signifies that crystal reorientation in syntectonic recrystallization is controlled by the time progression of deformations experienced by the material rather than by the stress or corresponding momentary deformation increment alone or by the fully integrated deformation (total strain).

In considering theoretically the flow law of ice Glen [1958, p. 180] assumed that fabric anisotropy in deforming ice has the same symmetry as the applied stress. The present experiments show that this assumption is not rigorously valid, but they do not indicate the extent to which the observed departures from Glen's assumption should have measurable consequences for the flow law.

The fabric symmetry and geometry make it possible in principle to distinguish a deformation history of pure shear from simple shear, and, in the latter case, to identify the 'shear plane' and sense of shear across it. Simple shear is recognized when nonequivalent maximums M_1 and M_2 are distinguished: M_2 is weaker and shows a greater tendency to elongate perpendicular to the M_1M_2 plane. Identification of the flow pattern within the continuous range of transitional possibilities between simple shear and pure shear requires a quantitative measure of the relative strengths of M_1 and M_2 , which is dependent on adequate sampling statistics. When simple shear is recognized, the shear plane is perpendicular to M_1 , and the sense of shear across it is the same as the sense of rotation of M_2 away from the shear direction w . In pure shear the maximum principal compressive stress bisects the acute angle between the two equivalent fabric maximums, and the minimum principal compressive stress bisects the obtuse angle (Figure 18).

The possibility of using the fabric pattern to distinguish between the shear plane wR and its conjugate plane TR is noteworthy, because other methods of inferring deformation history, such as fault plane solutions, do not have this capability. The physical distinction between the two planes, which makes it possible in principle to distinguish between them, is the fact that, under simple shear, material particles located

in a plane parallel to the shear plane wR remain in this plane as deformation proceeds, whereas particles originally in a plane parallel to the conjugate plane TR rotate out of this plane as deformation proceeds.

Fabric geometry in relation to stress state. As the stress state is modified from simple shear toward uniaxial compression, the c -axis fabric evolves progressively from the two-maximum pattern toward a small-circle girdle via intermediate patterns consisting of two maxima linked by a small-circle girdle. From the geometry of this pattern, and specifically from the ratio of orientation densities at minimum and maximum around the girdle, it is possible in principle to infer the stress character in terms of the ratio of σ/τ . Figure 16 provides data for this purpose but makes it evident that more experimental material would be needed to develop the method on a statistically sound quantitative basis.

At the high value of $\sigma/\tau = 3.8$ (A13, Figure 16d) clear maximums still appear in the small-circle girdle where it crosses the wT plane. The corresponding feature is also visible in the fabric of C4 (Figure 17). These observations show that the fabric pattern is sensitive to small departures from rotational symmetry in the applied stress.

In considering the general dependence of fabric pattern on stress state it is useful to describe a general state of stress in terms of three parameters: (1) mean stress, (2) maximum principal stress difference $\sigma_3 - \sigma_1$, which we can call 'stress level,' and (3) relative value of the intermediate principal stress, expressed as $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$, which we can call 'stress character.' There is only a weak dependence of fabric on stress level, as was discussed previously. The present experiments are not suited to testing for a dependence on mean stress, but a strong dependence is ruled out by the similarity of the C4 fabric (Figure 17a) to a pattern intermediate between A14 and A13 (Figure 16c, d): the C4 experiment has a mean stress higher than that of the corresponding torsion-compression experiment (with $\sigma/\tau = 2.7$) by 0.6 bars. If we assume that any dependence of fabric pattern on stress level and mean stress can be neglected, the fabric geometry can be described as a function of a single stress parameter, the stress character, which can be expressed either in terms of the principal

stresses or, in the torsion experiment, in terms of σ/τ . The experiments explore σ/τ for stresses σ that are compressive or 0. Experimental fabrics for tensile stresses σ (corresponding to $\sigma/\tau < 0$ with the convention used in Tables 1 and 2) are not available, but from the consistent behavior seen in the available experiments we can predict the fabric patterns expected. They are given in Figure 18 (upper-right) together with diagrams schematically summarizing the experimental results for $\sigma/\tau \geq 0$. Also given in Figure 18 (lower half) is a series of diagrams that predict fabrics expected for triaxial tests in which normal stresses σ_1 , σ_2 , and σ_3 are applied to the surfaces of a rectangular specimen. The stress character is in this case best expressed in terms of $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$, which equals $1/2$ for the central diagram, representing pure shear. The different orientations of adjacent fabric patterns in the upper and lower halves of Figure 18 reflect the different orientations of the principal stress axes, but the patterns are otherwise closely similar. The remaining differences are due to the effects discussed in the previous section, which cause the fabric symmetry to depart from the symmetry of the stress tensor.

CAUSES OF CRYSTAL REORIENTATION

The disparity between fabric and stress symmetry shows that theoretical models of crystal reorientation based on crystal elastic strain energy and related thermodynamic variables are not rigorously applicable, since the strain energies depend only on the state of stress.

It may, however, be possible to explain the reorientation process as one in which the orientations selected in recrystallization are determined originally by thermodynamic conditions, and then become modified by mechanical rotation in the course of subsequent plastic flow of the polycrystalline aggregate. This explanation accounts qualitatively for the discrepancy between fabric and stress symmetries in simple shear: crystals in maximum M_1 have no tendency to rotate mechanically, because their slip plane is parallel to the shear plane wR , whereas crystals originating with orientation at w , which is the point equivalent to M_1 by the stress symmetry, will rotate from w toward M_2 during plastic flow in simple shear. Rotation away from w removes the crystals in M_2 from the

Fig. 18. Dependence of *c*-axis fabric on stress character, shown in schematic fabric diagrams. The upper sequence of diagrams is for simple shear τ with superimposed normal stress σ , and the lower sequence for triaxial loading (principal stresses σ_1 , σ_2 , and σ_3). The stress character is indicated by values of σ/τ or $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$ and by arrows in the diagrams. The upper middle diagram represents simple shear, and the lower middle, pure shear. Diagrams to the left of the center represent stresses of essentially compressive character, and those to the right of the center, stresses of essentially extensional character. The diagrams for $\sigma/\tau \geq 0$ and for $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1) < \frac{1}{2}$ summarize experimental data schematically. The remaining diagrams are proposed by generalization, and the angle values given are hypothetical.

TABLE 3. Comparison between Rotation Angle θ_R and Departure Angle of M_2 from w

Fabric	Figure	γ	θ_R , deg	$w \wedge M_2$	
				Peak, deg	Average, deg
AST'	15b	0.13	7.5	18	15
A10	15a	0.13	7.5	12	12
A8B	14a	0.24	13.5	14	18
A6	14b	0.40	22	24	25

supposed orientation of maximum stability equivalent to M_1 , and hence the maximum should be weakened in relation to M_1 . (The nature of this rotation is explained in Figure 3.)

To test this explanation quantitatively, note that the rotation angle for each crystal is the same as that of its slip plane, so that, if crystals in M_2 undergo a shear strain equal to that of the bulk specimen, the crystal rotation angle θ_R is given by $\theta_R = \tan^{-1}\gamma$, where γ is the bulk shear strain. Table 3 compares the angle between w and M_2 with rotation angles θ_R on this basis for four fabrics. Angles $w \wedge M_2$ are listed both for the position of the summit of the orientation-density peak and for a visually estimated orientation average over the peak to provide a measure of the uncertainty in estimating the peak position; as in Table 2, the angles are measured as projected from R into the wT plane. At the higher strains the rotation θ_R is adequate to reorient crystals from w to M_2 , but at lower strains it is inadequate, notably for the fabric in AST'. The inadequacy is increased when we consider that most of the crystals forming maximum M_2 probably did not originate or become selected by recrystallization at the very beginning of specimen deformation but instead formed later, either during the initial recrystallization marking the transition from the second to the third creep stage or even later. If they originated at a shear strain $\gamma = 0.05$, when the recrystallization fabric was still poorly developed (Figure 13), the available rotation angles are 3° less than the θ_R values in Table 3. The increase in $w \wedge M_2$ from A8B to A6 is consistent with mechanical rotation of M_2 , but the lack of increase from AST' to A8B is not. Part (5°) of the increase from A8B to A6 should be due to stress reorientation ($T \wedge \sigma_s$ values in Table 2). If crystals originated at w and rotated toward M_2 in a

subsequent history of growth to maximum crystal size followed by disappearance, there should be a correlation between size and orientation along the arc from w to M_2 and beyond, but no such correlation is found. The statistical nature of the fabric reorientation process interferes with an unambiguous decision here, but, in balance, the data in Table 3, and especially the fabric of AST', do not support the idea that maximum M_2 represents crystals that originated at w and were rotated into their observed orientation by plastic flow. Some rotation of this type is, however, required in any case, the amount depending on the lifetime of the crystals in M_2 , under the recrystallization process.

If the departure of M_2 from w is ignored, the preferred orientations developed experimentally by recrystallization in pure shear are the ones that would make the shear stress across the basal plane of the ice crystal a maximum, if the stress were homogeneous in the polycrystalline specimen. By the methods of Brace [1960] it is readily shown that for pure shear these orientations maximize the elastic strain energy of the ice crystal. Under uniaxial compression the elastic energy is maximized for c inclined 50° to the compression axis [Brace, 1960]. The small-circle girdle produced experimentally has a radius of about 30° (Table 2), but, as with the departure of M_2 from w , a collapse of the radius from 50° to 30° might be explained as the result of mechanical rotation by plastic flow subsequent to crystallization in the energetically favored orientation. Although there is thus an approximate correlation between the observed orientations and those which would maximize the elastic strain energy under homogeneous stress, it cannot be taken as unqualified support for theories of crystal reorientation based on maximum elastic strain energy.

The plastic anisotropy of the ice crystal is much greater than the elastic anisotropy and has the same general form—greatest weakness in shear across the basal plane (the slip plane). Through basal gliding, stresses applied externally to crystals with c axes at T and w in the shear experiments will tend to be relaxed rapidly, whereas crystals with c axes at R and midway between w and $\pm T$ cannot relax the over-all applied stresses by plastic flow and will thus bear a higher proportion of the applied stress than crystals at T and w . If the more highly stressed crystals are less stable, as general thermodynamic considerations indicate, the favored orientations are the ones at T and w . These orientations have minimum stress and minimum elastic strain energy in the nonhomogeneous stress field that results from stress relaxation by plastic flow.

By this reasoning, theories of crystal reorientation that assume homogeneous stress and omit the effects of plastic flow should not be applicable to the recrystallization phenomena in the present experiments. Orientations predicted from Gibbsian thermodynamics [Kamb, 1959a] by assuming intergranular material transfer under homogeneous stress, without intracrystalline plastic flow, differ greatly from the observed orientations; crystals in the predicted orientations would have elastic strain energies near minimum under the assumed homogeneous stress. Although there are theories that predict orientations giving maximum elastic strain energy under the assumption of homogeneous stress, the approximate agreement between these predictions and the present experiments is of doubtful significance if the actual stress state is highly inhomogeneous and especially if the fundamental basis of the theories is unsound [Kamb, 1961a]. The validity of maximum strain energy as the criterion for preferred crystal orientation in twinning transformations of Dauphiné type under fixed stress, although a useful conclusion in its own right, does not provide a basis for its application to recrystallization, in which the special coherence features of the twinning transformations do not operate.

COMPARISON WITH GLACIER ICE

The interlocking grain texture produced by recrystallization in these experiments is qualitatively similar to the texture of typical glacier ice, although on a finer scale, and the starting

material texturally resembles firn, although lacking the permeability of firn. The experiments thus reproduce in miniature the textural metamorphism of firn to glacier ice that occurs in nature. Whether the geometry of the experimental recrystallization texture is fully comparable quantitatively to that of glacier ice, particularly its extreme degree of interdigitation [Bader, 1951], is not established here.

The typical c -axis fabric of glacier ice that has undergone substantial strain is well developed in the marginal zones of valley glaciers, where the ice deformation consists primarily of simple shear across nearly vertical planes parallel to the margin. The fabric consists typically of four sharp maximums clustered around the pole of the shear plane [Rigsby, 1960; Kamb, 1959b]. Most observed examples of this fabric type have come from surface samples in which, either because of the approach of the free surface or because of crevassing, the original flow stresses have been relaxed or modified before sampling, so that the fabrics may have been affected by post-tectonic recrystallization. However, fabrics from core and tunnel samples obtained near the bottom of a flowing glacier [Kamb and Shreve, 1963; Kamb and LaChapelle, 1968], where there was no previous stress relaxation and the ongoing strain rates were high ($\sim 1 \text{ year}^{-1}$) show the same type of fabric and establish that it is the pattern characteristic of glacier ice undergoing rapid deformation. A typical example, from core sampling [Kamb and Shreve, 1963], is shown in Figure 19a. According to measurements of borehole tilting, the ice deformation occurring in the part of the glacier sampled in Figure 19a is approximately simple shear, the pole of the shear plane being at T and the direction of shear across it being at w in Figure 19a. Except for a rotation of 13° around R , the orientation and state of stress, including the sense of shear, are the same in Figure 19a and in the experimental diagrams in Figures 12–15, and corresponding axes are therefore labeled with the same letters. The pattern in Figure 19a has fairly good mirror symmetry about the plane Um indicated on the diagram. The 20° discrepancy between this plane and wT , about which mirror symmetry is expected on the basis of the measured ice deformation, is a fairly typical complication, but for simplicity it will be ignored here, since it

Fig. 19. (a) The c -axis fabric of ice from near the base of Blue glacier, Washington, in core-hole J , at a depth of 136 meters. The core axis is U , the pole of shear plane parallel to the glacier bed is at T , and the direction of shear is at w , approximately parallel to the ice flow direction. Plane Um is a plane of approximate mirror symmetry in the fabric. Contours are at $1\frac{1}{2}$, 3, 6, 9, ... % per 1% area of hemisphere. (b) The relationship between positions of c -axis maximums in experimental and natural recrystallization fabrics under simple shear, shown in equal-area projection. Maximums in experimental fabrics are dotted, and maximums in natural fabrics are crosshatched. The pole of the shear plane is T , the shear direction is w , and the sense of shear is indicated by arrows.

could result from a 20° error in orientation angle around the core axis U .

The complete contrast between the multiple-maximum type of natural fabric in Figure 19a and the experimental type of fabric in Figures 12–15 is emphasized by plotting the positions of the two sets of maximums on a single diagram, Figure 19b. The only feature common to the two fabrics is monoclinic symmetry. The cause of this great discrepancy is not due to a difference in stress character, because in the full range of experimental fabric types in Figure 18 there is no near equivalent of the natural fabric. Nor is it due to a difference between recrystallization at and below the melting point; this finding is established by the results of experiment C4 and by the observation of multiple-maximum fabrics in the subfreezing ice of polar-type glaciers [Gow, 1963; Vallon, 1963]. Shear stresses in the torsion experiments are higher than the in situ shear stress of 1.4 bars estimated for the ice of Figure 19a, which is near the maximum of about 1.5 bars generally reached in glacier ice; but the relatively slight change in fabric over the experimental stress range

from $\tau = 4.1$ bars (A8) to 1.9 bars (A10) reasonably precludes a major change in fabric type between 1.9 and 1.4 bars. The grain size of glacier ice showing multiple-maximum fabrics is usually much coarser than that achieved by recrystallization in the experimental specimens, and admittedly the fabric of fine-grained glacier ice is very different [Kamb, 1959b, p. 1896], but it is difficult to imagine that macroscopic grain size alone can itself be the cause of these major differences in crystal fabric.

The largest difference in physical conditions between the experiments and the natural situation is in the length of time available for the recrystallization process and correspondingly in the total strain accumulated. The 59-day length of experiment A10 is to be compared with many tens or hundreds of years available in typical rapidly flowing glaciers. To explain the difference in fabrics on this account, we must surmise that a second mechanism exists that is capable of controlling crystal orientations but that requires long-continued recrystallization for its realization. The nature of such a second mechanism will be considered more closely in a sepa-

rate paper dealing fully with the natural fabrics. Here it is important to note that the existence of a process whereby the second mechanism takes over from the first as deformation continues, and as the proper textural and fabric architecture becomes established, implies that a true steady state has not been reached in the recrystallization process even at the largest strains attained in the present experiments. It also implies that at an early stage in their deformation history the natural fabrics would resemble the experimental ones and that at a later stage the second mechanism is able to generate, select, and amplify crystals in orientations not included in the fabric generated by the first mechanism.

Support for these ideas comes from the type of natural fabric shown in Figure 17*b*, which has been found repeatedly in core sampling of ice subjected to deformation in approximately pure shear at the base of an icefall in Blue glacier, Washington [Kamb and Shreve, 1963; B. Kamb, E. R. LaChapelle, and C. F. Raymond, unpublished manuscript, 1971]. A somewhat similar fabric is reported by Gow [1963, Figure 7] from a depth of 140 meters in the Ross ice shelf. The example shown in Figure 17*b* comes from coarse bubbly ice in which there is textural evidence that recrystallization from a finer-grained starting material has recently occurred, and for which a total logarithmic strain in pure shear of about 0.3 (corresponding to $\gamma \approx 0.6$) accumulated in a period of about 1 year. The compression and extension axes judged from the orientation of macroscopic foliation are marked in Figure 17*b*. As in Figure 19*a*, there is some incompatibility between the fabric orientation and the independently inferred strain symmetry; it corresponds to a rotation error of 25° around the core axis U and will again be passed over here. The fabric consists of two moderately broad maximums linked by a weak small-circle girdle and is thus similar to the experimental fabrics of specimens A10 (Figure 15*a*), A14 (Figure 16*c*), and C4 (Figure 17*a*). The angle between the two maximums in Figure 17*b* (57°) is smaller than that in the experimental fabrics cited (79° , 72° , 74°) and is instead comparable to A13 (54°). The maximums in Figure 17*b* are subequal in strength and stronger than those in A10, A14, or C4, although comparable to those in A13.

Although there are thus some detailed differences between the natural and experimental fabrics, Figure 17*b* is approximately what is expected experimentally for a stress character deviating somewhat from pure shear in the direction of uniaxial compression. Extensive sampling of situations in other glaciers (Austerdal in Norway and Trift and Great Aletsch in Switzerland) where the deformation pattern is similar but the total strain, time of deformation, and extent of recrystallization are greater, consistently reveals fabrics of four-maximum type (B. Kamb, unpublished manuscript, 1961). In Austerdal glacier, multiple-maximum fabrics are found in ice only 8 years old, deformed to a logarithmic strain of 2.2 in approximately pure shear. It thus appears that the development from the two-maximum fabric of Figure 17*b* to a multiple-maximum fabric like Figure 19*a* takes place over a time scale of 1–8 years in natural ice deformation at high strain rates ($\sim 1 \text{ year}^{-1}$).

Another important class of glacier ice fabrics consists of single-maximum types: in temperate glaciers the broad single maximum of fine ice [Kamb, 1959*b*, Figures 5–7] and rare coarse ice samples [Allen *et al.*, 1960, Figure 10] and in polar glaciers the sharp single maximum reported at depth in the Antarctic ice sheet by Gow *et al.* [1968, p. 1013] and in a sample from Greenland by Rigsby [1960, Figure 8]. The present experiments and discussion do not provide direct evidence for the origin of these fabrics, although they raise the possibility that progressive rotation of the M_2 maximum in simple shear to large strains could produce a single maximum by merging M_2 and M_1 in the experimental fabric.

IMPLICATIONS FOR TECTONOPHYSICS

The panoply of structural and textural phenomena that unfolds in the high-temperature creep of such a compositionally and structurally simple material as ice and that has major effects on the flow behavior of the material should probably serve as a warning against overly simplistic interpretations of creep experiments on other, more complicated geological materials. If other materials behave with a complexity similar to that of ice, results of creep experiments should not be extrapolated much beyond the range of strains explored with regard to either the flow behavior (strain versus time and stress) or

the textural and fabric effects of flow. In particular, apparently steady creep behavior observed at early stages in the deformation (strains of a few per cent or less) should not be assumed to continue to strains larger than those observed. This restriction is seriously at odds with the need to carry out the experiments at tectonically appropriate low strain rates: it is obviously not possible in the laboratory to reproduce or approach simultaneously both the strain rates and the total strains that occur in flow processes on geological time scales. If test materials having a structural and textural state preserved by quenching from conditions of deformation in nature are available, a deformation increment beyond the total strain already achieved in nature can be experimentally explored, but, to apply this increment reliably, information on the previous history of deformation and proof of the quenching are needed. The difficulty would be ameliorated if it were empirically true that, in spite of the possible effects of time-dependent processes such as recovery and recrystallization, the structural architecture of materials deforming in creep is determined mainly by the total strain, without regard to the time scale. It would be possible to satisfy both the strain and the strain rate restriction by rapidly prestraining the material to the needed total strain and then reducing the strain rates toward tectonically pertinent values for the actual experimental tests. To some extent the experiments on ice give support to this approach, because the fabric, which greatly affects the flow properties, shows at most a modest dependence on stress or strain rate for given total strain. As far as existing evidence goes, this stress-

independent behavior appears to hold even in comparing the experimentally produced fabrics with the very different natural fabrics typical of glacier ice. However, the well-defined inverse relation between stress level and steady-state grain size in syntectonically recrystallizing ice negates the idea of time scale independence for the texture. It would be dangerous to ignore this finding in extrapolating experimental results to geological time scales, because grain size generally affects both the relative contributions of different creep mechanisms (such as diffusion versus dislocation creep) and the creep behavior under a given mechanism. In fact, the recognized effects of grain size on creep are rather modest for ice, but a similar situation cannot be assumed to hold for other geological materials, without experimental confirmation.

Experience with ice suggests that significantly nonsteady creep effects extend to high strains, of the order of 1. If other geological materials behave similarly, only at strains comparable to those in flowing glaciers can we expect a reasonably steady state to be reached in the creep process.

Acknowledgments. I am grateful to Dr. Marcel de Quervain, Director of the Swiss Federal Institute for Snow and Avalanche Research, and to other members of the Institute staff for help in many ways. Field work was made possible by cooperation of the National Park Service, Olympic National Park.

The field work and the preparation of the paper were supported by grants from the U.S. National Science Foundation. The experimental part of the work was made possible by a John Simon Guggenheim Memorial fellowship and by the hospitality and support provided by the Swiss Federal Institute for Snow and Avalanche Research, Weissfluhjoch, Davos, Switzerland.