# REPEATED COMPRESSION-ANNEALING EXPERIMENTS ON ANISOTROPIC CORE ICE*

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**Abstract** Three runs (6 samples) of repeated uniaxial compressionannealing experiments were conducted on a creep testing machine with a loading accuracy of 1% at $-2\pm0.2°C$. The tested samples were cut from BHQ ice core. Compression axes were parallel, at an angle of 45° and normal to the vertical of the core respectively. The initial orientation fabrics of samples were single-maximum pattern or approximate single-maximum pattern with different mean grain size. The sample was compressed with an initial axial stress of 0.8 MPa, until 10% axial strain was obtained, and then annealed for 72 hours. Such compression-annealing procedure was repeated 6 times for a run.

The experimental result shows that under a warm temperature and large load, the initial features of structure and fabric disappear finally, and n small circle girdle fabric with fine equigranular grains appears, and a multi maxima fabric developes to some extent. Analysis of structure and fabric shows that the formation mechanism of new fabrics in these experiments is principally recrystallization. With the repetition of compression-annealing, the difference in the fabric of the six samples is reducing, their rheological behavior tends to be uniform, and their grain size decreases towards a steaty state value.
**Key words** strain rate, c-axis orientation, grain size, recrystallization.

## 1. Introduction

A obvious behaviour of ice mass is that its multi–maxima c-axis fabrics may form near the base of an ice sheet or a glacier, particularly when the basal ice temperature is warmer, as well as at surface locations in ablation area of temperate glacies. To reveal the formation mechanisms of multi–maxima fabrics, recently many experiments have been carried out on artificial ice (e. g. Wilson & Russell–Head, 1982; Jacka & Maccagnan, 1984; Huang et al., 1982, ; Gao, 1989), on core ice (e. g. Pimienta et al., 1987) or on both ices (e.g. Duval, 1981; Azuma & Higashi, 1985). Most of the experiments began with randomly orientated fabric at relatively high temperature. Recently we have sucessfully developed a preferred orientation fabric into another one in laboratory to verify the previous theory.

The experiment is a repeated uniaxial compression–annealing at $-2°C$ and an axial compression stress of 0.8 MPa (i. e. octahedral shear stress of 0.38 MPa). A compression was terminated when 10% axial strain (i. e. 7.1% of octahedral shear strain) was obtained, and then annealed for 72 hours. Such compression-annealing procedure was repeated 6 times for a run. Three runs (6 samples) were performed. The samples were cut from BHQ ice core, Law Dome, Antarctica. Compression axes were parallel, at an angle of 45° and normal to the vertical of the core respectively. As a result, the post–experimental fabrics and grain size

are nearly the same, a preferred fabric pattern with fine grains, irrespective of the variety of pre-experimental fabrics and grain sizes. It basically coincides with the results of uniaxial compression experiments by Wilson and Russell-Head (1982) and Jacka and Maccagnan (1984) and of compression-annealing by Huang and others (1985) and Gao (1989). It is clear that the initial structure can be eliminated entirely by repeated recrystallization.

## 2. Experimental Methods

### 1. Apparatus

The compressions on samples were performed on a creep testing machine for snow and ice, Model WZ-5, which was described by Huang and others (1988). It is an uniaxial compression creep testing machine with constant load, ranging from 0.3 to 50 kN and a loading accuracy of 1%.

The displacement between two plates which clamped the sample was measured by a dial indicator in order to determine the strain value and strain rate.

The machine was kept in a heat-insulating box in which the temperature was maintained at $-2\pm0.2°C$ by a temperature control system, connected with heater and fans. All apparatus were installed in the cold room, where the temperature was below $-15°C$, in Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences.

### 2. Ice sample

Two ice samples were coupled for a run. Six samples was tested. They were rectangular, cut from BHQ ice core at different depths. Their depths, sizes, directions and grain sizes before experiment are listed in Table 1. The pre-experimental c-axis orientation fabrics are shown in Figure 1. Before experiment, the grain sizes of samples are coarse and variegatted, the crystal shapes complicated with interlocking texture of some large crystals, and the c-axis fabrics of single-maximum oryapproximate single-maximum. The maximum strengths of c-axis orientation are rather high, ranging from 16 to 27 %.

### 3. Experimental procedure

Before experiment, thin sections were cut out for measuring grain sizes and c-axis orientations and investigating structural features.

A couple of samples was stacked up and frozen together, and then put into a plastic bag to avoid evaporation. The couple was compressed, beginning at an axial stress of 0.8 MPa, until 10% axial strain was obtained, and then unloaded and annealed in the same heat-insulating box at same temperature for 72 hours. In the process of compression, the displacement was regularly measured. The deformed couple was restored to its rectangular shape after annealing. Such compression-annealing procedure was repeated 6 times for a run. After the last annealing, thin sections were cut out for same measurements as before experiment. The post-experimental grain sizes are also listed in Table 1, and the c-axis orientation fabrics shown in Figure 2.
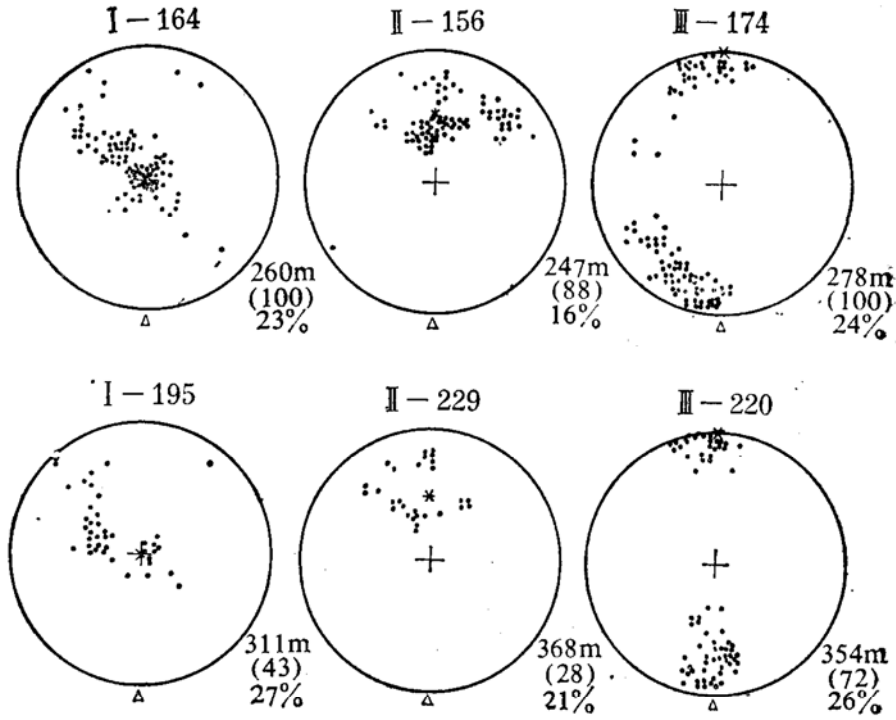
**Fig. 1.** Pre-experimental fabric patterns of c-axis orientation. The figure above the circle indicates the number of sample, at the bottom right the sampling depth, the number of c-axes measured and the maximum strength of c-axis orientation, respectively. The centre of circle is compression direction and * vertical of the core.
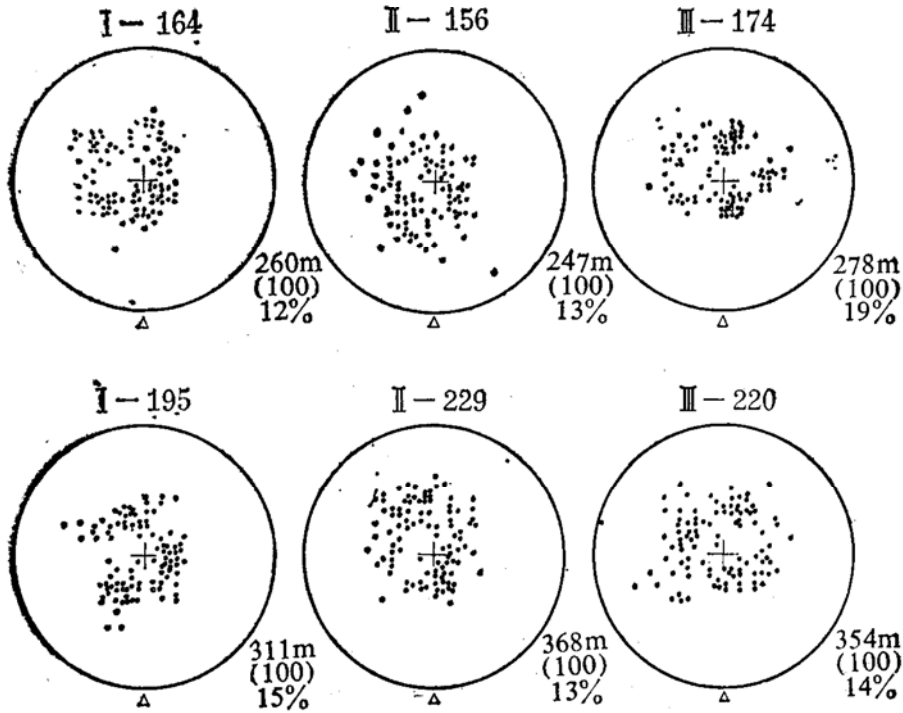


**Fig. 2.** Post-experimental fabric patterns of c-axis orientation. The symbols are same to those in Figure. 1.

Table 1. Dimensions, compression directions to the vertical of the core ($\alpha$), mean grain sizes before ($D_1$) and after experiment ($D_2$) of samples.

| Run | No. | Sampling depth (m) | Dimension of sample (mm) | $\alpha$ (degree) | $D_1$ (mm) | $D_2$ (mm) |
|-----|-----|-----|-----|-----|-----|-----|
| I | I-164 | 260 | $70 \times 65 \times 80$ | 0 | 8.96 | 4.66 |
|   | I-195 | 311 | $70 \times 65 \times 80$ | 0 | 19.00 | 7.14 |
| II | II-156 | 247 | $64 \times 74 \times 65$ | 45 | 14.03 | 5.21 |
|   | II-229 | 368 | $64 \times 74 \times 65$ | 45 | 36.26 | 5.37 |
| III | III-174 | 278 | $70 \times 70 \times 105$ | 90 | 7.15 | 6.85 |
|   | III-220 | 354 | $70 \times 70 \times 105$ | 90 | 14.75 | 6.04 |

## 4. Measurement and data processing

Thin sections were used to measure the c–axis orientstions by a standard procedure Langway, 1958) on Rigsby universal stage. The c–axis orientation fabrics were plotted on a Schmidt equal–area net by computer as shown in Figures 1 and 2.

The grain sizes in Table 1 were determined by linear intercept method. Since the grains were equidimensional, the relationship

$$D = 1.75 \, L / N$$

was used, where L is the length of a linear traverse, N the number of grains intercepted by the traverse, D the mean grain diameters, and a coeficient of maximum section transformation 1.75 (Jacka & Maccagnan, 1984). D was averaged over nine traverses on the photograph of each thin section, whose scale is taken into account.

## 3. Results

### 1. Strain value and strain rate

The compression creep process indicated that as the loading starts, there is a work harding for a few hours, ending with a minimum strain rate when 1—2% axiai strain was reached, and then transforming to tertiary creep stage with a maximum strain rate, through an acceleaiting stage. The strain rate is considerable high for the aplied axial stress is as high as 0.8MPa.

At the first compression the difference in the minimum strain rate among the 3 runs was great because the angle of the compression axis to the vertical of the core were quite different, so did the difference in the maximum strain rate. These differences reduced gradually with repetition of compression–annealing. At last they were comparable. The minimum and maximum strain rates at the last compression range from 23 to 68 and from 26 to $100 \times 10^{-6}$ $s^{-1}$ respectively. The ratios of the maximum strain rate to the minimum strain rate at the last compression are 1.6, 1.5 and 1.2 for Run I, II and III respectively. The minimum and maxi-

mum axial strain rates and their ratios in Table 2 are typical of the 3 runs.  We can see that the minimum strain rate increases and the ratio of maximum strain rate to the minimum strain rate decreases with the repetition of compression–annealing.

The creep curves are continuous in general.  No macro–crack was found.  It is possible, however, that some microfractures have been developed within the samples.

Table 2. Minimum and maximum axial strain rates ($\times 10^{-6} \text{s}^{-1}$) for run III.

| Repetition | Min | Max | Max / Min |
|:---:|:---:|:---:|:---:|
| 1 | 6 | 72 | 12 |
| 2 | 13 | 78 | 6 |
| 3 | 15 | 73 | 4.9 |
| 4 | 24 | 70 | 2.9 |
| 5 | 31 | 55 | 1.8 |
| 6 | 40 | 48 | 1.2 |

### 2. Grain size

As shown in Table 1, the mean post–experimental grain sizes range from 4.64 to 7.14 mm, close to each other.

### 3. Crystal shape

After experiment, new structures in all thin sections look very similar to each other, different from their structures before experiment.  Two crystal shapes can be distinguished, one is equiaxial with polygonal boundary, the other irregular with smooth boundary.

### 4. C-axis orientation

From Figure 2 we can see that a preferred fabric pattern was formed independently of the initial fabric pattern.  After compression–annealing repeated 6 times  the pre–experimental fabric features disappeared.  The newly formed fabrics for all six samples are similar to each other.  Some exhibits small circle pattern, some develops into mult–maxima  pattern with several clusters of c–axis orientation around the compression axis.  The angle of cluster to the compression axis varies between 30 and 45°. The maximum strengths  of c–axis orientation, ranging from 12 to 19%, are usually not so high as that before experiments.

## 4. Discussion

For the limitation of experimental conditions,  we applied large load to the sample.  Thus the strain  rate  is  considerable large.  The characteristics of our experiment are high temperature, high stress and high strain rate.

### 1. Annealing period

Gao (1989) has conducted an experiment to test the influence of annealing period on de-

velopment of ice structure.  He found the free energy within a sample is quickly exhausted. His observation on crystal growth during the annealing stage, extended over 70 days, has indicated that it was almost completed only a few days after removal of the stress.  Therefore that we keep annealing for 72 hours is reasonable.

## 2.  Strain rate

On polycrystalline ice with initial randomly–oriented fabric, Jacka and Maccagnan(1984) came to his conclusion after uniaxial compression test that a minimum strain rate was attained at about 0.8% octahedral shear strain. Beyond this, at about 8% octahedral shear strain, a maximum strain rate was attained, followed by a near constant tertiary flow.  This tertiary flow persisted till at least 32% octahedral strain.  At a test temperature of -3.0 ℃ and octahedral stress of 0.2 MPa, they found that the minimum strain rate was approximately $2 \times 10^{-8}$ $s^{-1}$, a factor of 3 less than the tertiary strain rate.  Typical results for simple shear and compression show that the factor is about 3 for compression and about 8 for shear (cf. Budd and Jacka, 1989).

The creep curves we obtained are analogous to that Jacka and Maccagnan (1984) described.  However, the absolute value of strain rate is larger than that of Jacka and Maccagnan by about 3 orders of magnitude.  The ratios of maximum strain rate to minimum strain rate scatter and decrease with repetition of compression–annealing, as mentioned above.  Note that in our experiments the minimum strain rate dose not correspond to an isotropic ice but to anisotropic ice, and the crystallographic anisotropy was going to be, but had not been, compatible with the stress configuration. Therefore changing minimum strain rates and decreasing ratios of maximum strain rate to minimum strain rate appeared.  The phenomena that the minimum strain rate increases and the ratio of maximum strain rate to the minimum strain rate decreases with repetition of comrpession–annealing (Table 2) are in agreement with the considernation of Budd and Jacka (1989).

## 3.  Formation mechanism of multi-maxima fabric

After compression–annealing repeated 6 times a new preferred fabric pattern has developed on the ice sample.  All initial structural features, such as interlocking texture, undulatory extinction and slip band disappeared.  This result is coincident with that by Wilson and Russeall–Head (1982) and Huang and others (1985).  In general the new fabric exhibits small circle pattern and mult-maxima pattern.  Based on the repeated compression–annealing experiments on laboratorially prepared polycrystalline ice for 12—14 times (Huang et al., 1982), we believe that a perfect mult-maxima pattern will take place if our experiments repeated enough times. The formation mechanism is principally recrystallization. Owing to repeated recrystallization, new recrystallised crystals continuously developed, which are compatible with new experimental stress configulation and replaced the initial crystals.

## 4. Grain size

### 4.1 Possibility of decrease in grain size

It is found in field that multi–maxima pattern is usually accompanied with rather coarse grains.  Some laboratory experiments, e.g. by Gao (1989), showed that the development of a multi–maxima fabric is accompanied by the growth of large crystals, but other

experiments, e. g. by Huang and others (1985), did not provide this results.

The experiment carried out by Wilson and Russeall–Head (1982) at –1.0°C under initial axial compression stress of 0.65 MPa has shown that a nucleation of new grains took place between shortening of 2 and 9% in the fine grain (0.7mm) and between shortening of 7 and 19% in the medium grain (1.2cm) samples.    During the nucleation stage the total number of grains increased and hence the mean grain diameter decreased.    With shortenings of $\geqslant 9\%$ and $\geqslant$ 20% in the fine and medium grain samples respectively, there were marked increase in grain size with no evidence for the development of additional recrystallisation nuclei.    Besides they pointed out that annealing resulted in a substantial grain size coarsening.    We believe that the mean post–experimental grain sizes in Table 1 would be finer immediately before annealing because they have been annealed and coarsened.    It is clear that the nucleation considerably took place and recrystallization was dominant for the new fabric formation during repeated compression–annealing. resulting in decrease in grain size.    This agrees with Wilson and Russeall–Head (1982) and Huang and others (1985).    Thus the development of a multi–maxima fabric is not always accompanied with the development of coarse grains.

## 4.2 Steady–state grain size

Based on three sets of uniaxial compression experiments on polycrystalline ice, Jacka (1984)has demonstrated irrespective of the initial grain size in a wide range(1—10mm), the tertiary creep rates become the same  and produce grain size distribution that are all the same. He suggested an idea of steady–state size (or equilibrium size).    The steady–state size obtained from laboratory experiments appear to be a function of  stress and temperature (Budd & Jacka, 1989).    The post–experimental grain sizes are approximately the same for the three runs (Table 1), supporting this idea.    It seems to exist a steady–state grain size in our experiments.

## 5.  Conclusions

Multi–maxiam fabric pattern can be developed by repeated compression–annealing experiment at the temperature higher than recrystallisation temperature. It is no matter whether the initial material is artificial or natural, isotropic or anisotropic ices.    Its principal formation mechanism is recrystallization.

The recrystallized ice developed under large load may be exhibited fine grains. As in our experiment, the strain rate is very high, which increases the number of recrystallized  grains rather than grain growth. Therefore it is not alway true that the multi–maxima fabric is accompanied  by  coarse  grains.

For the anisotropic ice sample the minimum strain rate increases and the ratio of tertiary strain rate to the minimum strain rate decreases with the repetition of compression–annealing.

It seems that a steady–state grain size exist in the experiment when tertiary creep stage is reached.

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