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# AN ATTEMPT AT DEFORMATION TESTS OF DEEP ICE CORE SAMPLES CONTAINING CLOUDY BANDS

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***Abstract:*** We conducted detailed mechanical property investigations of deep polar ice core samples. In order to understand the effect of cloudy band structure on deformation of ice core samples, uniaxial compression tests were carried out by using the GRIP ice core containing cloudy bands. The uniaxial compression tests were performed under the conditions of constant strain rate (Type A) and constant load (Type B) at −15°C. The enhancement factor (*Es*) correlates with the schmid factor (*F*) that indicates *c*-axis orientation development with *F* less than 0.46. The *Es* of ice specimens with *F* larger than 0.46 showed large values (approximately 3 to 50) with significant data scatter. The straight lines were scratched on the surface of a few specimens and the changes of these line shapes were observed after compression tests. It is clearly shown that the specimens containing cloudy bands deform non-uniformly. Specimens with cloudy bands tend to deform easily, but there is no clear correlation between the *Es* and the number of cloudy bands.

## 1. Introduction

The mechanical properties of ice cores are dependent on the crystal size and *c*-axis orientation and impurity concentrations which vary with depth in ice cores (PATERSON, 1994). A detailed mechanical property study on the impurity softening effect of deep ice core has been performed on the Dye 3 core, Greenland (SHOJI and LANGWAY, 1988). Their results show that an obvious impurity softening effect was not observed. *C*-axis orientation is a prime parameter for shear deformation below 1786 m at Dye 3.

The GRIP deep ice core was drilled at summit (72°34.5′N, 37°38.5′W; 3230 m a.s.l), Greenland by the joint European research effort of the Greenland Ice Core Project (GRIP). The quality of this ice core is excellent through the whole length of 3029 m long from the surface to near the bedrock. The lowest 10% of the 3029 m long GRIP ice core has, however, flow disturbances that have been confirmed by stratigraphic observation (KIPFSTUHL and THORSTEINSSON, 1993). The Holocene/Wisconsin transition depth is 1623.6 m (JOHNSEN *et al*., 1992). In the Wisconsin ice (1624 m to 2790 m), the cloudy bands are observed as horizontal layers of milky-colored ice. Cloudy band structure is alternating layers of cloudy ice and clear ice with dimensions of a few millimeters to a few centimeters. The cloudy bands are identified as low $\delta^{18}O$ ice, changing small grain size and low electric conductivity. These consist of microbubbles, however, these detailed characteristics are not yet clear.

In this paper, we report the result of a uniaxial compression test of deep ice core samples containing cloudy bands. We have assumed that there is no change in the distribution of grain size, orientation or impurity concentrations in compressed test pieces. However, we must take the effect of ice structure change (ex. cloudy band) into consideration for detail study of mechanical properties of ice core.

## 2. Experiment

The sample was exposed to light from the side, so that the cloudy bands could be

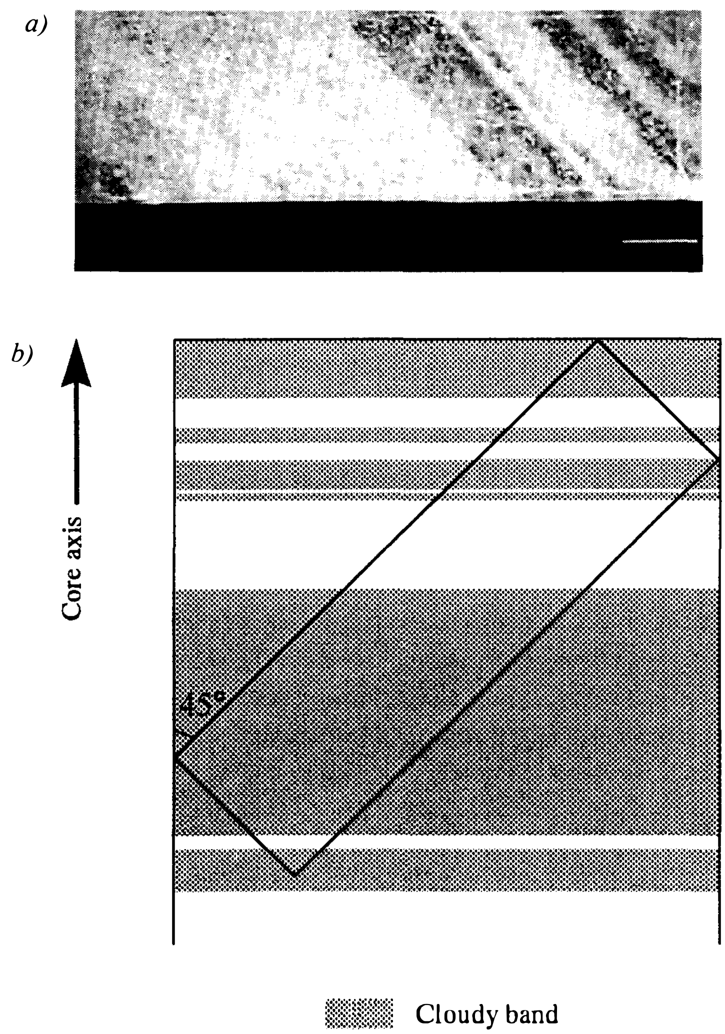


*Fig. 1. a) Cloudy band layering at 1823 m. The scale bar is 10 mm. b) Schematic diagram of cloudy band layering.*

observed. We investigated the distribution and scattered light intensity of cloudy bands by visual stratigraphic observations. Figure 1 shows the cloudy band layering at 1823 m in a uniaxial compression test specimen.

Uniaxial compression tests were conducted under both conditions of constant strain rate (Type A) and constant load (Type B). Each test specimen (approximately $2.5\times2.5\times9$ cm) was prepared from thirty-nine slab core samples (approximately $3.5\times10\times55$ cm each) except for brittle zone (650 m to 1300 m) samples with their uniaxial stress axis inclined 45° to the original long-core axis in order to obtain maximum resolution of the shear stress planes parallel to the horizontal plane of the ice sheet undergoing uniaxial compression tests. The tests were conducted with a strain rate of about $4.5\times10^{-8}\mathrm{s}^{-1}$ and the constant stress took values from 0.2 to 0.7 MPa. The experimental temperature was kept constant at $-15$°C during each test run.

Straight scratch lines were made on a few samples parallel to the core axis by microtome blade on the specimen surface. After a compression test, the change of the scratch line caused by the deformation was observed under a microscope.

## 3. Result and Discussion

The result of mechanical tests is discussed as the flow enhancement factor ($Es$). The flow enhancement factor is defined as follows:

$$Es=\frac{\dot{\varepsilon}_{\text{measured}}}{\left[A\sigma^{n}\exp\left(-\frac{Q}{RT}\right)\right]},$$

where the uniaxial strain rate $\dot{\varepsilon}_{\text{measured}}$ and $\sigma$ are given from the result of mechanical tests, and the constants $A$, $n$ and $Q$ (activation energy) are taken from BARNES *et al.* (1971). $R$ is the gas constant and $T$ is the absolute temperature. The enhancement factor is the ratio of the measured strain rate to that of isotropic ice at the same stress and temperature. The $Es$ value was calculated from the yield point on the stress-strain curve (Type A), and minimum strain rate on the creep curve (Type B).

The obtained $Es$ value points (Fig. 2) show gradual increase from a depth of 1300 m to a depth of about 2200 m. At the Holocene/Wisconsin transition boundary (1624 m), although the climatic condition changed suddenly, the $Es$ value did not change. Below about 2200 m, the points are wide by scattered with very high values. Figure 3 shows a comparison between the $Es$ value and the Schmid factor ($F$). $F$ is defined by the following equation:

$$F=\frac{(\Sigma\ \sin\theta\cos\theta)}{N},$$

where $\theta$ is the angle between the $c$-axis direction of individual crystals and the compression axis, and $N$ (approximately 200 crystals each) is the number of crystals. The Schmid factor ranges from 0.27 to 0.37. From 0.27, the relation between the $Es$ and the $F$ is known from an other ice core study (SHOJI *et al.*, 1992). While the distribution of $c$-axis orientation has a strong single maximum on the GRIP ice core with Schmid factor larger than 0.46, the $Es$ value has no correlation with the Schmid factor. In Fig. 3, relative light

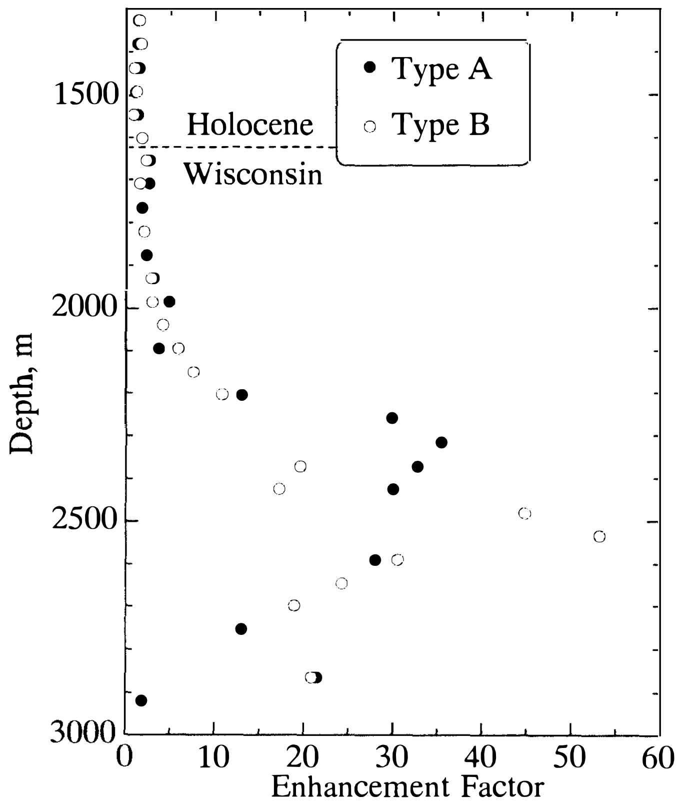


*Fig. 2. The profile of enhancement factor from the uniaxial compression tests.*

scattering intensity of cloudy band in the slab samples is classified by visible stratigraphic observations. Specimens with a large value (>0.46) of Schmid factor have cloudy bands, we examined the relation between the *Es* values and cloudy band structure.

A plot of the enhancement factor versus the number of cloudy bands in the uniaxial compression specimen is given in Fig. 4 for Schmid factors lager than 0.46. There is no relation between the *Es* value and the number of cloudy bands. Even the specimen with no cloudy bands has various *Es* values. Figure 3 suggest that the cloudy ice and/or the boundary between cloudy ice and clear ice is an easily deformed area with a large value of Schmid factor. But this tendency was not recognized from the observation of cloudy bands in the uniaxial compression test specimens (Fig. 4). In this study, cloudy bands are classified by the visible stratigraphic observation method. If we classified cloudy bands by other methods, for example the distribution of grain size in the compression test specimen may show as alternation between small grain size layers and large grain size layers, even if we observe no milky-colored ice. It is possible that these laminar type structures control the mechanical properties of the ice sample.

Under the microscope, the curve of the scratched line was observed. Figure 5 shows the curved scratch line after the uniaxial compression test near the cloudy band at 1823 m. We observed a part of straight scratch line curves and slip off on the grain boundary nearby cloudy band, however, we cannot decide whether the deformed position of scratch line correspond with the boundary between cloudy ice and clear ice. Because, the feature of the boundary between cloudy ice and clear ice is not yet apparent under the microscope

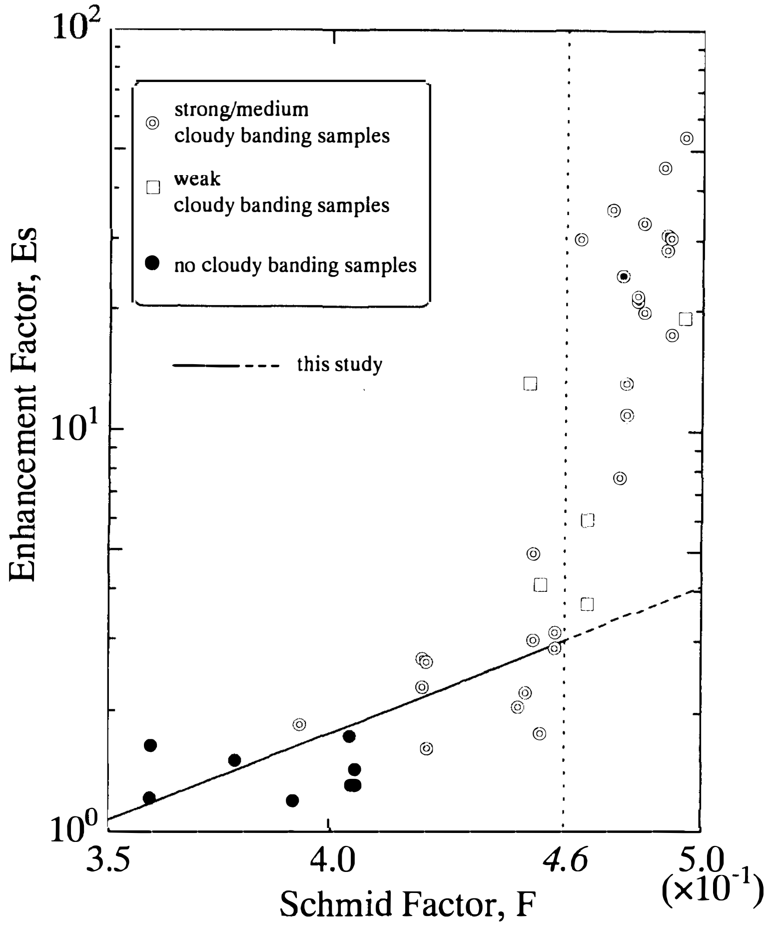


*Fig. 3. A log-log plot of Schmid factors and enhancement factors. Each data point indicates light scattering intensity of a cloudy band in the slab samples.*

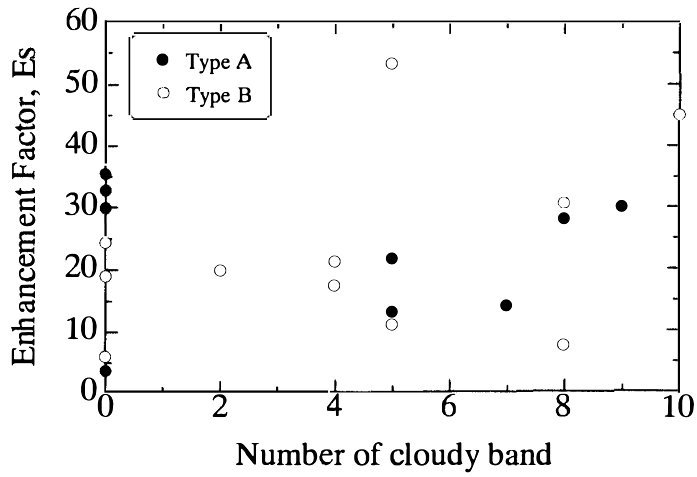


*Fig. 4. Enhancement factors versus the number of cloudy bands in the uniaxial compression test specimen for Schmid factors lager than 0.46. The solid circles and open circles are Type A and Type B uniaxial compression test conditions, respectively.*

*Fig. 5. Curved scratch line after uniaxial compression test near a cloudy band at 1823 m. The scale bar is 1 mm.*

observation. It is certain that the specimen containing cloudy bands deformed non-uniformly with scale of the cloudy band size. The reason that these deformation patterns appear is probably various changes of crystal structure (grain size, *c*-axis orientation) with thickness of a few millimeters to a few centimeters, such as cloudy bands. We had only the visible stratigraphic observation method for observing cloudy bands in the present study. In order to represent cloudy bands quantitatively, other methods and signals (ex. ECM in the detailed measurement with compression test specimen size, chemical composition) must be taken into consideration to determine the scale of cloudy bands.

The result of deformation testing shows that ice samples containing cloudy bands have high enhacement factor and non-uniform deformation on the scale of a few millimeters. It is likely that an ice core containing cloudy bands has a different deformation mechanism corresponding to each crystal texture (grain size, *c*-axis orientation) in the cloudy ice, clear ice and the boundary.

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