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Article

Stratigraphical structure analysis of the NGRIP shallow ice core using laser tomograph technique

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Abstract

Stratigraphic features of ice core reflect past seasonal scale conditions of surface snow layers. To detect detailed stratigraphic features of ice core, we developed a new laser tomography method and applied it to NGRIP shallow ice cores for a depth range from 54 to 98 m. By examining the two-dimensional pore distribution, pore ratio and/or pore number obtained with the laser tomograph measurement images, we identified various kinds of layers that were transformed from well-developed depth hoar layers, compacted snow layers and ice crusts. Spectrum analysis of pore ratio fluctuation showed a maximum peak around 0.17 m in water equivalent, which agrees well with the recent annual accumulation rate at the NGRIP site. The present study shows that the laser tomography method has a potential to detect seasonality of stratigraphic features.

1. Introduction

Physical properties in snow and firn are different in each layer because the grain size of snow deposition and metamorphosis of deposited snow vary in accordance with meteorological conditions. For example, in central Greenland, depth hoar layers that contain large, cup-shaped crystals are formed in autumn (e.g. Benson, 1962) and summer-autumn (Alley *et al.*, 1990) by sublimation and condensation of surface snow when the vertical temperature gradient in the snow becomes large; ice crusts, which are thin ice layers, are formed in spring in Antarctica and remain if the sublimation from an ice crust surface is less than the condensation at the ice crust bottom (Fujii and Kusunoki, 1982); thick ice layers, ice lenses and ice glands are formed by the melting and refreezing of deposited snow when the air temperature is high, when solar radiation is strong, or when both occur; finally, compacted snow layers, which have high density and fine grains, are formed when the surface is exposed to strong wind (e.g. Benson, 1962). A unit layer is the snow layer that is deposited upon a previous snow surface during a single snowstorm and resided following a snowstorm (Watanabe, 1978a). Therefore, because it experiences the same meteorological conditions for deposition and metamorphosis, each unit layer has homogeneous physical properties such as snow grain size and shape. Therefore in the firn section of cores, unit layers can be identified in the difference of the physical properties. In other words, unit layers can also be identified by a difference in size, shape and distribution of pores. Pores in the firn will be closed off and changed to air bubbles in the ice due to the load of the upper firn layers. Therefore in section of ice cores, the unit layers can be identified as a difference in size and distribution of air bubble.

Visual stratigraphical structure studies have been carried out for Greenland ice cores (e.g., Benson, 1962; Langway, 1967; Alley *et al.*, 1997) and Antarctic ice cores (e.g. Watanabe *et al.*, 1978b). Continuous density measurements with millimeter-sized resolution for shallow ice cores are carried out using techniques of gamma-ray (Greland et al., 1999) and x-ray (Hori *et al.*, 1999). Takata and Fujii (2000) has developed a laser tomograph measurement system that can continuously measure the two-dimensional air bubble distribution in an ice sample at a speed of 5 mm second^{-1} and in a spatial resolution below the millimeter order without preparation of thin section samples.

We have applied the laser tomograph measure-

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ment technique on the NGRIP shallow ice core (S1 core) drilled in 1997, 400 m east of the NGRIP drill site at 75.12°N 42.30°E and 2919 m a.s.l. in north central Greenland (Dahl-Jensen *et al.*, 1997). The NGRIP site, shown in Fig. 1, is located in a dry snow zone with a mean annual air temperature of −32 °C, and a recent accumulation rate of 0.17 m in water equivalent year^{-1} (Dahl-Jensen *et al.*, 1997). To determine the physical properties of recent snow accumulation, we made 2.1 m deep snow pit observations at the NGRIP site in July 2000.

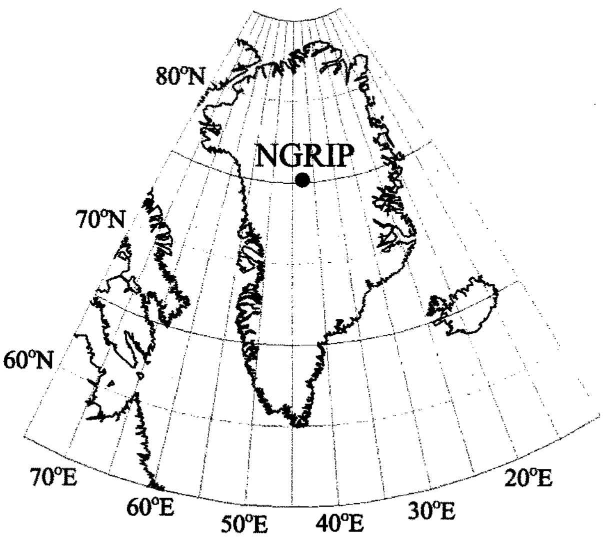

Fig. 1. Location of the NGRIP site, north central Greenland.

In this paper, we describe the results of the pit study at the NGRIP site and the stratigraphical structure analysis of the S1 core using a laser tomograph measurement system to obtain past seasonal and meteorological information from the stratigraphical structure at the site.

2. Pit work

In July 2000, we carried out snow pit observations 4 km south of the NGRIP site. Measurements of stratigraphic structure, grain size, and density were carried out using a pit wall 2.1 m deep. The density was measured continuously with 3 cm intervals using a sampler of 100 cm^3 volume and an electronic balance. Grain shapes of each unit layer were classified according to the JSSI classification for snow cover (Japanese Society of Snow and Ice, 1998). The classification of compacted snow layers is subdivided by the degree of compactness, and that of depth hoar layers is also subdivided by the degree of snow grain coarseness.

The stratigraphic structure of the pit is shown in Fig. 2. Well-developed depth hoar layers, which are low-density layers, are located near the 0.48, 1.05, 1.64 and 2.08 m depth levels. These layers are associated

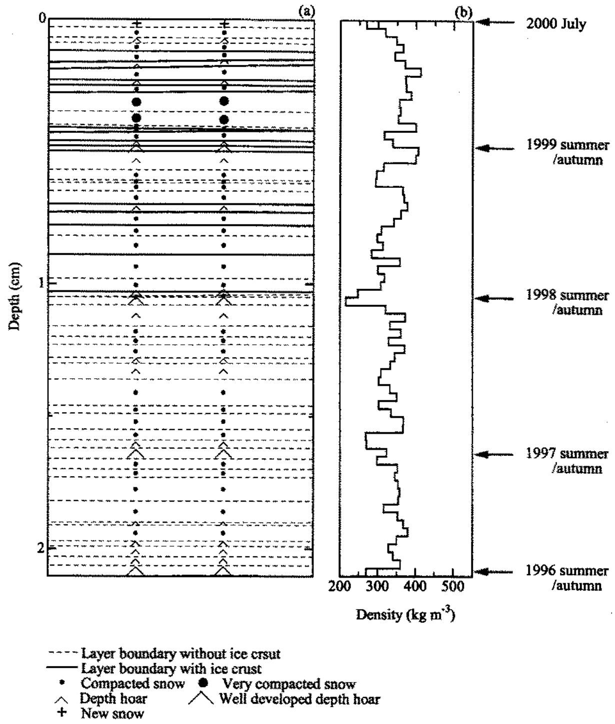

Fig. 2. Stratigraphic structure of a pit at 4 km south of the NGRIP site, July 2000. (a) Layer structure and snow classification (b) Density profile. The annual layer boundaries based on well-developed depth hoar layers are marked on the right side.

with the summer seasons of 1999, 1998, 1997 and 1996, respectively. Well-developed depth hoar layers are formed in autumn (Benson, 1962) and summer-autumn (Alley *et al.*, 1990). We use the term "summer/autumn" for the season of depth hoar formation.

Recent accumulation rates are calculated using the density profile as shown in Fig. 2b. The well-developed depth hoar layers are used as the annual boundary for the snow stratification. Accumulation rates from 1996, 1997, 1998 summer/autumn to the next summer/autumns are 0.16, 0.19 and 0.19 m in water equivalent year^{-1}, respectively. And averaged accumulation rate of the recent three years, 1996 to 1999, is 0.18 m in water equivalent year^{-1}.

3. Stratigraphic structure measurement of ice core

3.1. Laser tomography measurement

Figure 3 shows a schematic of the laser tomograph equipment. Both the He-Ne laser and CCD camera are installed on a moving stage. A He-Ne laser beam irradiates the side of the ice core sample at 1 mm depth and the scattered image is taken with a CCD camera. Scattering occurs at surfaces of air bubbles and snow grains. A two-dimensional image of the air bubble distribution is obtained by using a special image analysis program on the scattering images. The image shows the two-dimensional pore distribution of an ice core sample. Further details of

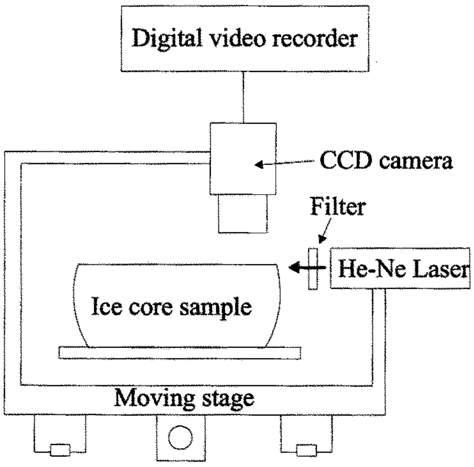

Fig. 3. Schematic figure of the laser tomography equipment.

this system and the image analysis technique are described in Takata and Fujii (2000). In this paper, we will use the term "LT image" for the two-dimensional pore distribution images obtained with laser tomograph measurement. In the LT images, the pixels are plotted using black as ice and white as pore.

We use slab-section samples 25 mm thick and 78 mm wide, made by cutting two sides of an ice core, which has been stored for 2 years prior to our measurements. Observation and laser beam irradiation surfaces of the slab section samples are shaved with a microtome knife. The irradiation depth of the laser beam is about 1 mm from the observation surface. The measurements are done in a cold room of -20 °C; measurements on one 0.55 m long sample take about 100 seconds. We measure the S1 core of a depth range between 54 and 98 m where the bulk density changes from about 750 to 870 kg m^{-3} as determined by volume and weight measurement. The age interval of the depth range corresponds to the period AD 1594 to 1810 (H. B. Clausen, personal communication). To evaluate the laser tomography results, we also perform visual stratigraphic observation on several ice cores. The spatial error for determining layer boundaries by visual stratigraphic observation is on the order of a millimeter.

3.2. Detection of depth hoar, compacted snow, and ice crust

Using the laser tomography and visual stratigraphic observations for the ice core samples, we find characteristic layers that were well-developed depth hoar layers, compacted snow layers and ice crusts near the surface and buried into the ice sheet. In this paper, we call these layers as densified well-developed depth hoar layers, densified compacted snow layers and buried ice crusts, respectively.

An example of the detection of a densified well -developed depth hoar layer is shown in Fig. 4. Figure 4a shows the visual stratigraphy observation result.

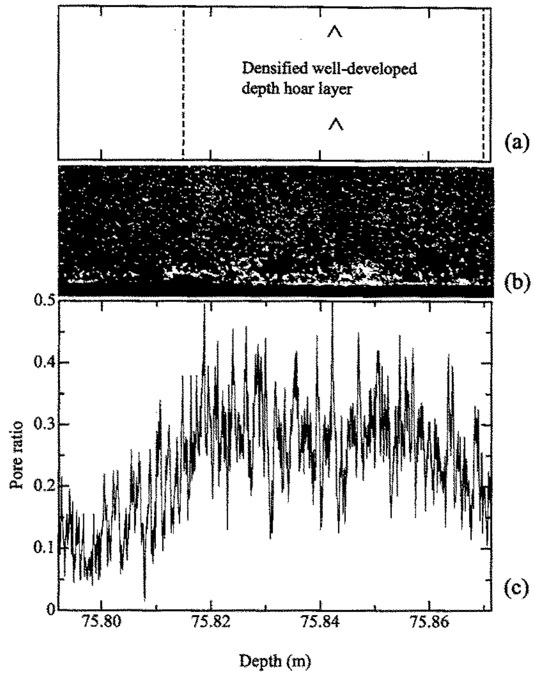

Fig. 4. Visual stratigraphic description and laser tomography image of a densified well-developed depth hoar layer. (a) Visual stratigraphic description. (b) Two-dimensional image of the pore distribution. (c) Pore ratio profile.

Visual stratigraphic observation shows a well-developed depth hoar layer located at the depth level between 75.815 and 75.870 m. Figure 4b shows the LT image. In this figure, white and black indicate pore and ice, respectively, as described before. In the densified well-developed depth hoar layer, the pore size is relatively large and the pores are elongated along the vertical direction. The pore ratio profile is shown in Fig. 4c. The pore ratio is the ratio of number of pixels judged as pore to total pixel number of an effective width of the LT image in each depth. The effective width for the LT image is in the range of 2 to 12 mm from the laser beam incident point (Takata and Fujii, 2000). In the densified well-developed depth hoar layer, the pore ratio indicates large values compared with the adjacent layers (Fig. 4c). These results suggest that the densified well-developed depth hoar layers can be identified using a LT image and a pore ratio profile.

We also investigated the densified well-developed depth hoar layers obtained with visible stratigraphy in the depth ranges of 86.35 - 87.44 m where density is about 850 kg m^{-3} (Fig. 5) and 95.70 - 96.25 m where density is about 870 kg m^{-3}. The visually identified densified well-developed depth hoar layers well correspond to large values of the pore ratio as shown in Fig. 5 (solid arrows). As well-developed depth hoar layers are formed summer/autumn season in the central part of the Greenland as mentioned previous chapter and shown in Fig. 2, it can be said that we could detect seasonality of stratigraphic features in

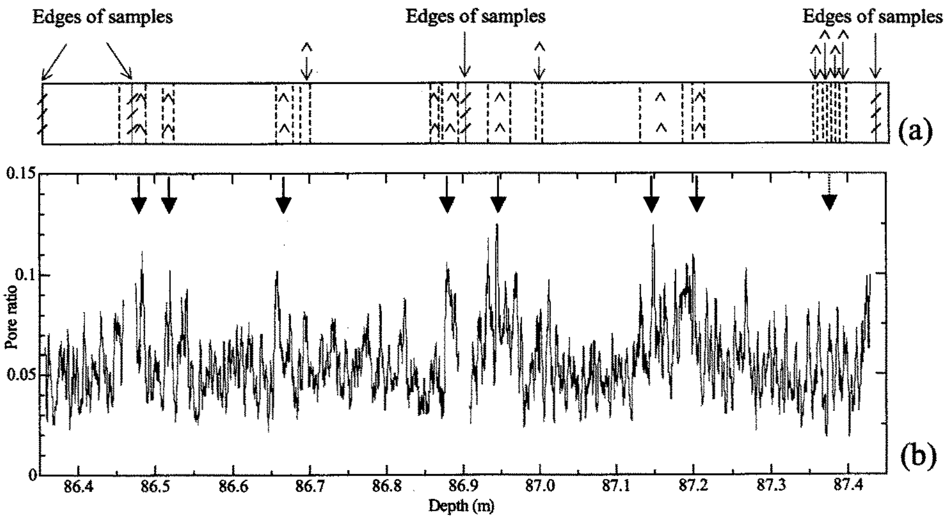

Fig. 5. Relation between locations of densified well-developed depth hoar layers and pore ratio profile. (a) Visual stratigraphic description. (b) Pore ratio profile. Each value is averaged over 0.5 mm in depth. As the pore ratio takes erroneously large values at the longitudinal edges of the samples, we omit the values at these edges. Solid arrows show pore ratio peaks which correspond to densified well-developed depth hoar layers. Dashed arrow shows location of densified well-developed depth hoar layers where large peaks of pore ratio do not appear.

the core using the laser tomograph technique. Some densified well-developed depth hoar layers, however, were not identified as large peaks of pore ratio (dashed arrows at 83.75 m depth) because they are thin and pore distribution in the layers might be affected by neighboring layers.

Figure 6 shows an example of identification of a densified compacted snow layer, which is rare in the S1 core. A densified compacted snow layer is found between 77.600 and 77.613 m by visual stratigraphic observation (Fig. 6a). In the densified compacted snow layer, many small bubbles are recognized in the LT image as shown in Fig. 6b. The pore ratio is not so different in the adjacent layers, however the pore number indicates a large value compared with the adjacent depths (Fig. 6c). The pore number profile was calculated using an image analysis program (IDL software by Research Systems). This program does the followings: (1) it identifies the individual pore objects excluding those with a size of one pixel, (2) it counts the number of individual pores in an area 1 mm deep and with an effective width given by the LT image in Fig. 6b. The reasons that the objects of one pixel are eliminated from the calculation are (1) air bubbles of the size, 0.05 mm, are rare at this depth, (2) not all pores in LT image agree completely with a real two-dimensional pore distribution, and (3) scattering with laser beam irradiation also occurs at other small objects such as dust. Hence, densified packed layers can be identified by the LT image and pore number.

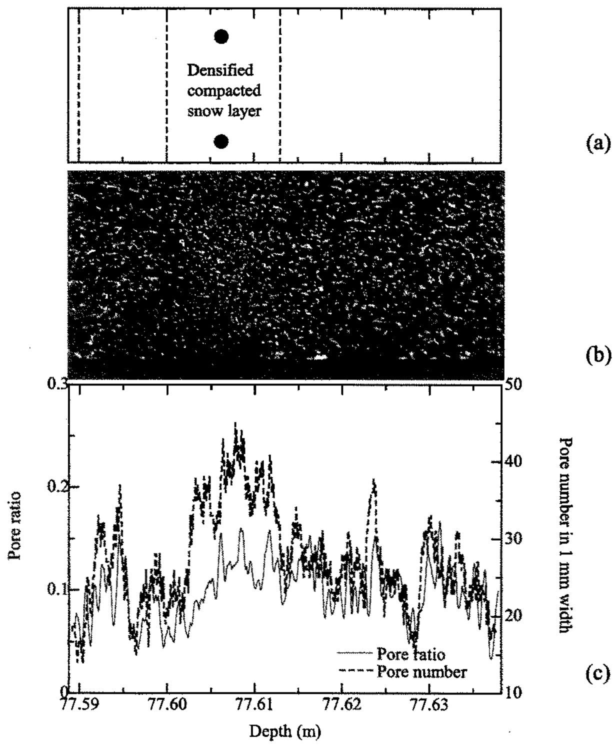

Fig. 6. Visual stratigraphic description and laser tomography image of a densified compacted snow layer. (a) Visual stratigraphic description. (b) Two-dimensional image of the pore distribution. (c) Pore ratio profile.

Figure 7 shows the result of an ice crust located at the 97.457 m depth by visual stratigraphical obser-

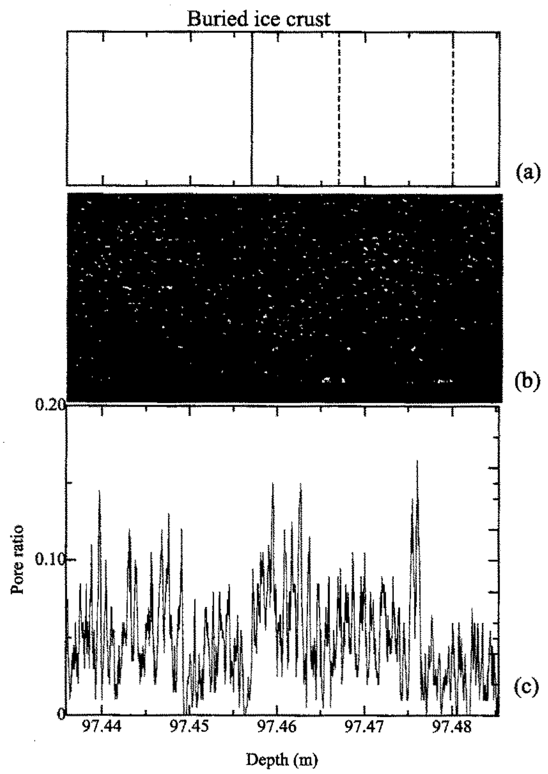

Fig. 7. Visual stratigraphic image and laser tomography image of a buried ice crust. (a) Visual stratigraphic description. (b) Two-dimensional image of the pore distribution. (c) Pore ratio profile.

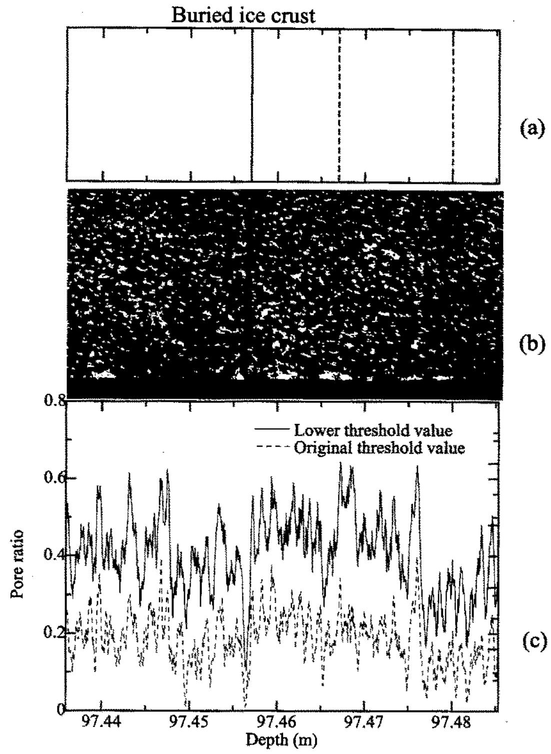

Fig. 8. Identification of a buried ice crust using improved algorithm of image analysis. (a) Visual stratigraphic description. (b) Two-dimensional image of the pore distribution. (c) Pore ratio profile.

vation (Fig. 7a). Even though this ice crust is only about 0.5 mm thick, it is identified as a black thin layer in the LT image (Fig. 7b) and the pore ratio is zero or considerably low (Fig. 7c). We have developed an algorithm of image analysis to detect ice crusts. The improvement is done by taking a lower threshold value, which uses for judging pixels to be ice or pore in an image obtained image by laser tomography. This is done in the way that a pixel of less scattering number is judged as a pore. Using the improved algorithm, an ice crust is identified clearly as shown in Fig. 8, where the distribution of the pore and the pore ratio are enhanced (Fig. 8b, c). These results suggest that an ice crust can be detected easily by using the low threshold value.

4. Periodicity of pore ratio

As mentioned in previous section, the fluctuation of pore ratio mainly depends on densitified well-developed depth hoar layers which were formed in summer/autumn season. To detect the dominant periodicity of the pore ratio fluctuation, we perform the spectral analysis for the data with water equivalent depth using a fast fourier transform, FFT. Prior to the spectral analysis, the pore ratio values are normalized for each core sample using their average value and standard deviation because the pore ratio and the amplitude of the pore ratio decrease with depth due to densification. Within 1 cm of the longitudinal edges of the ice core samples, the pore ratios measured with laser tomography are usually erroneously large. Therefore, we replaced the pore ratio values in these parts with the neighboring values.

Figure 9 shows a result of the spectral analysis of the pore ratio fluctuation at the depth range between 54 and 98 m. The maximum peak appears around 0.17

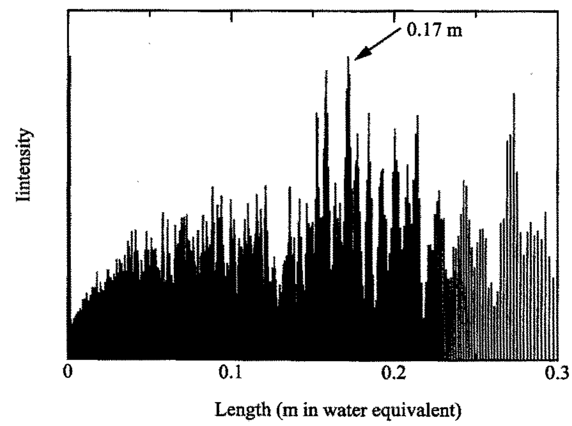

Fig. 9. Spectrum analysis of the pore ratio obtained with laser tomography measurement for the NGRIP S1 core. The maximum peak appears at 0.17 m in water equivalent, which well agrees with recent accumulation rate at NGRIP site.

m in water equivalent, which well agrees with our pit work result of an average accumulation rate of 0.18 m in water equivalent year^{-1} during the recent three years, and the estimated accumulation rate of 0.17 m in water equivalent year^{-1} at the NGRIP site which was based on data from shallow ice cores and internal radio-echo sounding in the north central region of Greenland (Dahl-Jensen *et al.*, 1997). Dominant periodicity of the fluctuation of pore ratio, 0.17 m in water equivalent, obtained by this study correspond to seasonality of depth hoar development in summer/autumn season and means that the annual snow accumulation rate has not much changed during past some hundred years.

5. Conclusions

We performed laser tomograph measurement for the shallow core drilled at the NGRIP site in the depth range from 54 to 98 m. In the firn and ice core, densified well-developed depth hoar layers, densified compacted snow layers and buried ice crusts are identified using the two-dimensional pore distribution, the pore ratio, and the pore number. Also we performed spectral analysis of the pore ratio fluctuations where the maximum peak appears around 0.17 m in water equivalent, which agrees well with the recent accumulation rate of 0.18 m in water equivalent year^{-1} obtained from our pit work and 0.17 m in water equivalent year^{-1} from published data (Dahl-Jensen, 1997). This suggests that the pore ratio fluctuates seasonally and that the accumulation rate in 17th and 18th centuries was relatively constant at the NGRIP site. Further interpretations the seasonality and long-term fluctuation of pore ratio will be determined by comparing our results to ECM, DEP, chemical composition and delta ^{18}O results.

Using the present equipment and image analysis techniques, air bubble distributions can be measured for several hundred meters depth where air bubble size is at the millimeter scale. In order to apply the laser tomograph technique for shallower or deeper depths, further development and improvement of the equipment and image analysis algorithms are required because laser scattering occurs at not air bubble but at ice crystal grain at shallwer depth and the scattering is weaker at deeper depth.

Acknowledgments

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