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Review

Physical properties of the Dome Fuji deep ice core

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***Abstract*:** Recent results of physical analyses of the Dome Fuji ice core are summarized with special attention to new methods introduced in the present studies. Microphysical processes which affect the ice core records are reviewed to better understand the paleoclimatic and paleoenvironmental signals stored.

key words: ice core, physical property, fabrics, paleoclimate, hydrate

1. Introduction

The climatic and environmental signals recorded in the ice core are not unvarying, but change slowly as a consequence of a variety of physical processes. Understanding on a microscopic level is indispensable to clarify the reliability of the signals. In addition, it is known that physical processes in the shallow layer create new signals. It has become clear that highly reliable core analyses can be obtained by interpreting the physical analysis data as well as chemical analysis data.

To obtain new information from the Dome Fuji core and to clarify various microphysical processes that affect formation and modification of the ice-core records, we have introduced several new physical analysis methods: (1) AC-ECM for impurity distributions (Sugiyama *et al.*, 1995, 2000; Fujita *et al.*, 2002a, b); (2) X-ray transmission method for bulk

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density (Hori *et al.*, 1999); (3) Raman spectral method for local distribution of gas molecules (Ikeda *et al.*, 1999); (4) Automatic fabric analyzer for rapid analyses (Wang and Azuma, 1999); (5) Laser scattering tomography for distribution of inclusions (Narita *et al.*, 1999); (6) Neutron scattering method and x-ray diffraction method for crystal structures (Fukazawa *et al.*, 1998a).

Using the above new methods as well as conventional ones, physical analyses of the Dome Fuji ice core have been carried out to reveal fundamental properties of the core: (1) Stratigraphy (Watanabe *et al.*, 1997a; Narita *et al.*, 1999) (2) Bulk density by a volumetric method (Watanabe *et al.*, 1997a; Hondoh *et al.*, 1999), (3) Bulk density by an x-ray transmission method (Hori *et al.*, 1999), (4) Total gas content (Hondoh *et al.*, 1999), (5) Permeability and bubble volume (Watanabe *et al.*, 1997a; Hondoh *et al.*, 1999), (6) Distribution of air-bubbles (Narita *et al.*, 1999), (7) Distribution of clathrate hydrates (Narita *et al.*, 1999) (8) Raman spectral N_2/O_2 ratios of air-bubbles and clathrate hydrates (Ikeda *et al.*, 1999; Ikeda-Fukazawa *et al.*, 2001b), (9) Ice fabrics (Azuma *et al.*, 1999, 2000), (10) Ice grain size (Azuma *et al.*, 1999, 2000), (11) Laser scattering tomography, (12) DC-ECM and AC-ECM (Sugiyama *et al.*, 2000; Fujita *et al.*, 2002c), (13) Mechanical test, and (14) Crystalline structures of ice and clathrate hydrate (Fukazawa and Mae, 2000; Fukazawa *et al.*, 2000).

The principal results for each of the above topics are summarized in the following sections.

2. Formation processes of clathrate hydrates and fractionation of gas molecules

Among the physical processes that take place in the ice sheet, our research has emphasized clathrate hydrate formation (Shoji *et al.*, 2000). The microscopic Raman scattering method is used for detailed measurements to clarify the reliability of the reproduced atmospheric composition. In the case of the Antarctic Dome Fuji core, as shown in Fig. 1, the

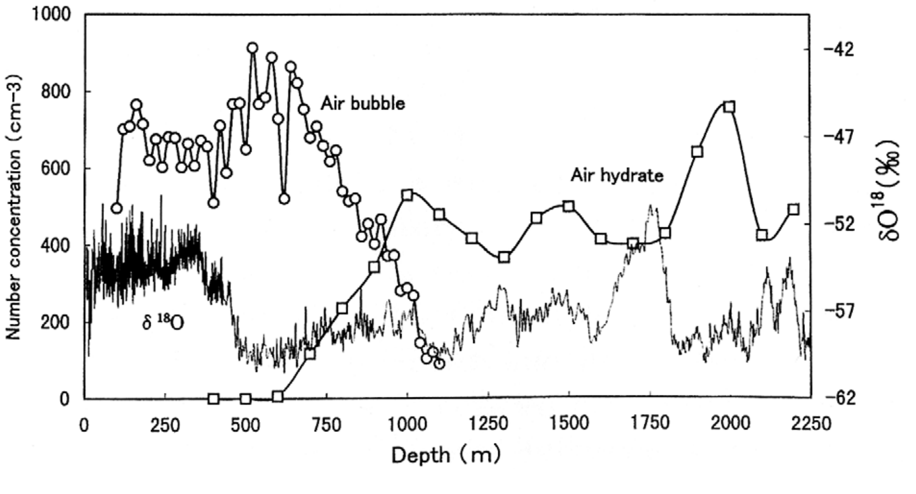

Fig. 1. Number concentrations of air-bubbles and air-hydrates. The $\delta^{18}O$ profile is also shown for reference (Narita et al., 1999).

transition from air-bubbles to clathrate hydrates takes place from 525 m to 1200 m (Narita *et al.*, 1999; Ohno *et al.*, in preparation). It is clear that, accompanying this transition, a major separation of the two major atmospheric constituent gases, nitrogen and oxygen, takes place (see Fig. 2 of the article by Ikeda-Fukazawa and Hondoh, 2003). This transition takes place in the transition zone where air-bubbles coexist with clathrate hydrates (Uchida and Hondoh, 2000), and is well explained as the result of molecular diffusion from air-bubbles to clathrate hydrates (Ikeda *et al.*, 2000a, b). A model which incorporates the difference in diffusion coefficients among different types of molecules is nearly completed (Salamatin *et al.*, 1998, 1999, 2001; Ikeda-Fukazawa *et al.*, 2001b). The fractionation process is described in detail in a separate paper in this volume (Ikeda-Fukazawa and Hondoh, 2003). The quantitative effect of this process on analysis of atmospheric composition remains to be studied.

3. Development of ice crystal textures and ice sheet flow

Crystal *c*-axis orientations, and sizes and aspect ratios of crystal grains, were measured by the use of an automatic fabric analyzer developed by Wang and Azuma (1999). Using this powerful new tool, a large number of samples have been analyzed in a rather short period without laborious work in a cold room. As depth increases, mean crystal size increases and median inclination decreases. This change in orientation distribution of *c*-axes means that crystals rotate toward vertical orientation by vertical compressive stresses to form typical single-maximum fabrics. Differences from the average in both crystal size and median inclination correlate with the $\delta^{18}O$ profile (Azuma *et al.*, 1999). These correlations were well explained in terms of impurity contents and contribution of diffusional creep (Azuma *et al.*, 2000).

Flow characteristics of ice sheets are strongly affected by the ice crystal texture, partic-

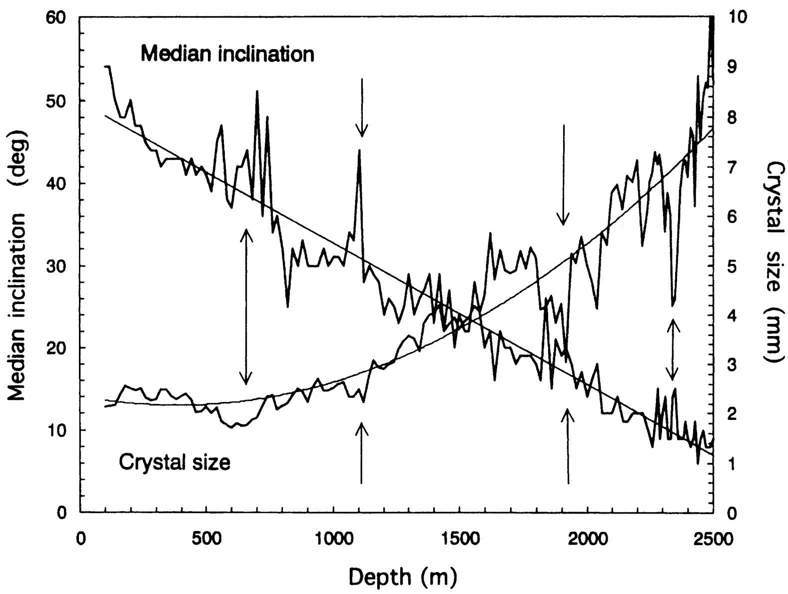

Fig. 2. Texture development of the Dome Fuji ice core (Azuma et al., 2000).

ularly the distribution of *c*-axis orientations. In the Antarctic Dome Fuji core, as shown in Fig. 2, the *c*-axes gradually become oriented in the vertical direction, clearly becoming large single crystals at great depth (Azuma *et al.*, 1999, 2000). This is a consequence of rotation of crystals by compressional deformation in the vertical direction; it has been discovered that, reflecting the characteristics of the dome, the width of the distribution of orientations decreases linearly with increasing depth. Deviations from linearity observed in places are caused by the effect of impurities, of which there were many during cold periods. A similar trend occurs in the distribution of ice crystal sizes. Crystal grain diameters gradually increase with increasing depth, but, as in the case of the *c*-axis orientations, there are large deviations from the average trend during cold periods. Various factors that can alter the rate of grain growth have been studied in terms of correlations between the grain diameters and impurity contents (Azuma *et al.*, in preparation)

Flow calculations and simulations done thus far have created the ice as an isotropic deforming body, but in some cases ice behaves as a strongly plastic anisotropic substance that deforms several tens of times faster (for example, Miyamoto *et al.*, 1999). As deformation progresses, the ice crystals rotate and their *c*-axes align along the direction of the compression axis. As a result, deformation of the ice sheet shows a strong directional dependence with respect to stress. It is not easy to do a 3-dimensional flow simulation that incorporates all of these processes, but if simplified flow laws that have been discovered in a series of research studies (Azuma *et al.*, 1999) are used, it becomes possible. We are improving the model in order to do more realistic flow calculations. Meanwhile, we are using the distribution of crystal orientations and grain diameters to establish a new method to accurately reproduce the flow at the dome location (Azuma *et al.*, 2000). It is expected that this will also be a new method to estimate the age of the ice although the Dome Fuji core has already been dated by several different methods (Watanabe *et al.*, 1997b; Hondoh *et al.*, 2002). This result also illustrates the importance of understanding the physical processes involved in interpreting related data.

4. Stratigraphical analysis

By careful observations of the Dome Fuji core, a characteristic layer structure was found in the shallow part of the cores, and the thickness or periodicity of the structure was measured. The average water-equivalent-thickness of the layer is 28 mm, which is close to the present accumulation rate (32 mm determined by using 1966 Tritium reference, and 25 mm by snow stake measurements). This variation of layer thickness probably suggests changes in accumulation rates in the last 5000 years (Narita *et al.*, 2003). Similar layer structure was also found by an x-ray transmission method to measure a detailed density profile with a spatial resolution down to 1 mm (Hori *et al.*, 1999), for example as shown in Fig. 3. To understand the layering in firn densification, these data obtained by core analyses are compared with the layer structure observed in surface snow at Dome Fuji (Shiraiwa *et al.*, 1996) and surface mass balance data (Kameda *et al.*, 1997).

Numbers and sizes of air-bubbles and clathrate hydrates were measured by optical microscope observations and laser scattering tomography (Narita *et al.*, 1999; Ohno *et al.*, in preparation). As transition from bubbles to hydrates, the number concentration of air-bubbles gradually decreased and finally disappeared at 1200 m. The first hydrate crystal was

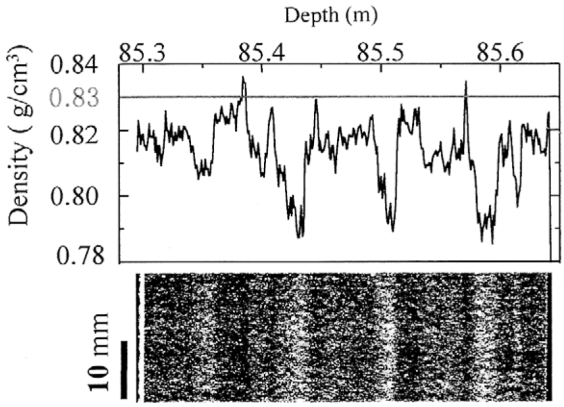

Fig. 3. X-ray density profile and x-ray stratigraphy (Hori et al., 1999).

found at 525 m, and the number concentrations of the hydrates increased with depth. The transition zone at Dome Fuji is therefore from 525 m to 1200 m. Above and below the transition zone, the fluctuation of the number concentrations seems to correlate with $\delta^{18}O$ although more data at shorter intervals are required for further discussion of the phenomenon (Narita *et al.*, 1999).

To observe the distribution of inclusions such as air-bubbles, air-hydrates and other particles, laser scattering tomography was used. A layer structure was found in the distribution of air-bubbles and air-hydrates. From the detailed profile of the number densities of air-hydrates, we found a periodic fluctuation in the number densities of which period decreases with depth. Since such a non-uniform distribution of air-hydrates is attributed to non-uniform distribution of air-bubbles, the period probably corresponds to stratigraphical period found in the shallow part. This fact offers us a new method to deduce accumulation rates along the whole length of the Dome Fuji core (Narita *et al.*, 2003).

It is known that many physical analysis data are correlated in some way with the concentration of the isotope $\delta^{18}O$ or δD, but unless the cause of the correlation is made clear, the data concerned do not constitute a useful signal. Here let us explain the indices which are believed to be useful. In Greenland ice cores, the seasonal variation of the isotope $\delta^{18}O$ is used to estimate age and precipitation, but in deep layers in Greenland and in Antarctica, formed from a small annual amount of snowfall, the seasonal variation of isotopic composition cannot be observed (Watanabe *et al.*, 1999a, b). As an alternate method, we are analyzing the physical layer structure. In shallow layers, the layer structure reflects seasonal variations in the deposition process. We have discovered that in the deeper part these variations remain as variations in the number density of air-bubbles and clathrate hydrates. Deformational compression in the vertical direction causes the annual layer thickness to decrease with depth, but it is still possible to see the effect of deposition processes (Narita *et al.*, 2003). To determine annual precipitation from layer thickness at depth a correction for glacier flow would be necessary. Being able to estimate annual precipitation through all layers and to determine ages along the time axis has very great significance. Measurements are being continued in order to obtain detailed data.

5. Electrical properties of ice cores and radar echo sounding

The ECM technique (DC-ECM) developed by Hammer (1983) is one of the standard methods for ice core analyses to observe the distribution of acidity along the whole length of ice cores. In this method, a continuous profile of DC currents is recorded by scanning two electrodes on the ice surface. In contrast, the AC current profile is recorded by a new AC-ECM technique. This new method permits us to observe the distributions of both basic and acid impurities (Sugiyama *et al.*, 1995). Although similar changes can be seen in the DC-ECM and AC-ECM profiles below 800 m depth, a significant difference was also found. Comparisons of the two profiles offer a new tool to find unknown paleoenvironmental events.

New events have been discovered from the AC conductivity profile. Whereas DC conductivity reveals the distribution of acidic impurities, the AC conductivity profile, newly introduced in this research, is also sensitive to alkaline impurities, and previously unknown characteristic changes are being discovered (Fujita *et al.*, 2000, 2002a,b,c; Sugiyama *et al.*, 2000). We are also continuing detailed analysis to observe the local distribution of impurities that may affect the electrical properties of ice (Fukazawa *et al.*, 1998b).

The dual wavelength ice radar which we are using for the first time in our on-site observations is attracting attention as a powerful method to clarify the internal structure of the ice sheet (Fujita *et al.*, 1999, 2002d; Matsuoka *et al.*, 2002; Siegert and Fujita, 2001). The ice radar used in the past was only able to detect the layer structure inside the ice sheet; the present method is able to detect variations in such physical characteristics as the distribution of crystal orientations as shown in Fig. 4. This is a new technology that uses the capability to separate reflection effects due to the real and imaginary parts of the permittivity by compar-

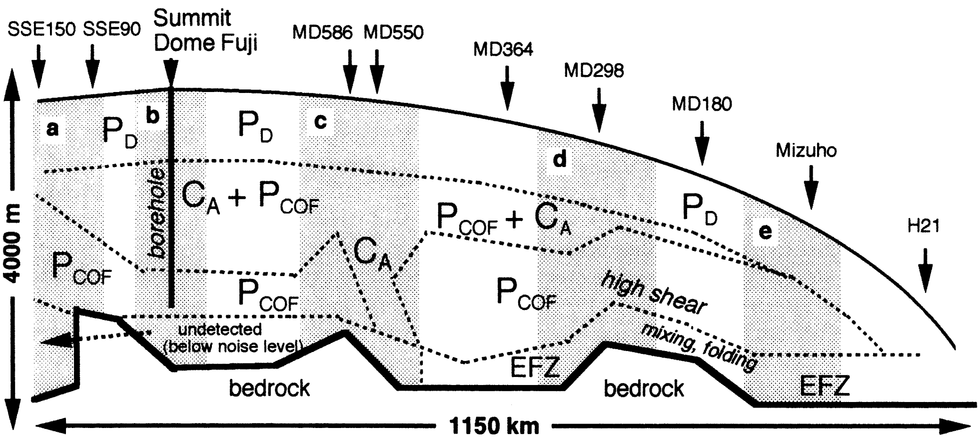

Fig. 4. Schematic map interpretation of the dominant radio echo reflection mechanisms from the Dome Fuji area to the coast. EFZ: echo free zone. In a P_D zone, reflection is dominantly caused by local fluctuations in dielectric permittivity depending on density; in a P_{COF} zone, by local fluctuations in dielectric permittivity depending on crystal orientation fabrics; and in a C_A zone, by local fluctuations in electrical conductivity depending on acidity. These dominant mechanisms were deduced from the detailed local measurements at the ten sites indicated by the downward arrows and the cross section analyses at the five shaded-areas denoted by a, b, c, d and e (Fujita et al., 1999).

ing data obtained at 2 wavelengths. We have succeeded in determining the variations of crystal structure that accompany flow, which not only provides ice core data over 2 dimensions but also provides important data for ice sheet flow calculations.

An important physical characteristic of the crystals is disorder in the proton arrangement; it is known that there is a phase transition to the ordered phase at and below 72K. However, the characteristics of the ordered phase have been discovered in measurement of Raman scattering and neutron scattering in the ice core even though the temperature is much higher than 72K (Fukazawa *et al.*, 1998a, 1999a, b, 2000; Fukazawa and Mae, 2000; Ikeda-Fukazawa *et al.*, 2001a). There is a strong possibility that, as a result of aging for a very long time in the ice sheet, a condition exists that cannot be produced in the laboratory. As a result of molecular dynamic simulation, it has become clear that even in the absence of the ordered phase, if there is change in the hydrogen bond combination a similar spectral variation will be obtained (Horikawa *et al.*, in preparation). However, why this kind of ice exists in the ice sheets and what kind of effect it has on core analysis data remain as subjects for future research.

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