ICE CORE ANALYTICAL SYSTEMS

V. S. Zagorodnov[1]
J. J. Kelley[2]

[1]Institute of Geography
Russian Academy of Sciences
29 Staromonetny per.
Moscow, 109017, Russia

[2]Polar Ice Coring Office
University of Alaska Fairbanks
Fairbanks, Alaska 99775-1710

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V. S. Zagorodnov[3]
Institute of Geography, the Russian Academy of Sciences
29 Staromonetny per., Moscow, 109017, Russia

J. J. Kelley
Polar Ice Coring Office, University of Alaska Fairbanks
Fairbanks, Alaska 99775-1710, USA

[3]V. S. Zagorodnov is presently a visiting research professor at PICO, University of Alaska Fairbanks.

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ABSTRACT

Methods for the continuous study of ice core structure and impurities have been examined. Laser sensors have a high spatial resolution and can be used for quantitative investigation of ice crystals, air bubbles, brine cells and insoluble inclusions. Electrical conductivity measurements can be used to obtain pilot data for further detailed chemical composition studies of ice cores. A continuous sampling system offers the opportunity to make continuous analyses of meltwater. Multi-parametric investigations of an ice core can be done as quickly as 1 cm/min.

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INTRODUCTION

After an ice core is extracted from a borehole in glacier ice, particularly from a great depth, its structural parameters change. Ice density diminishes and the form of air inclusions changes; the dimensions and the form of the ice crystals also change. Detailed studies of ice core structural elements using traditional methods take a considerable amount of time and cannot ensure continuous analyses. Sampling and studying ice core isotopes and their chemical composition also take a considerable amount of time.

Through continuous automated studies of optical, electrical and acoustical parameters of ice cores and water melting from them, significant data can be derived. The main advantages of automatic analysis are as follows:

- Ice cores can be examined continuously.
- Analysis is performed *in situ*.
- Various parameters of ice core can be measured rapidly.
- Fresh ice (non-metamorphosed by storage) can be investigated.
- A small part (about 10%) of ice core volume is spent.
- The continuous sampling procedure does not contaminate the meltwater.

CONTINUOUS SAMPLING AND ANALYSIS OF ICE CORE – WHAT HAS BEEN DONE?

Electrical Conductivity Measurements (ECM) (Figs. 1 and 2)

Electrical DC current between two electrodes moving on the ice core surface in most cases, depends on the acidity of the ice. The method allows for the identification of annual layers in polar glaciers. Cross correlating between $\delta^{18}O$, microparticle concentration, and ECM profiles leads to improvement in dating accuracy. Simplicity and the high speed (1-10 cm/s) of measurements are the main advantages

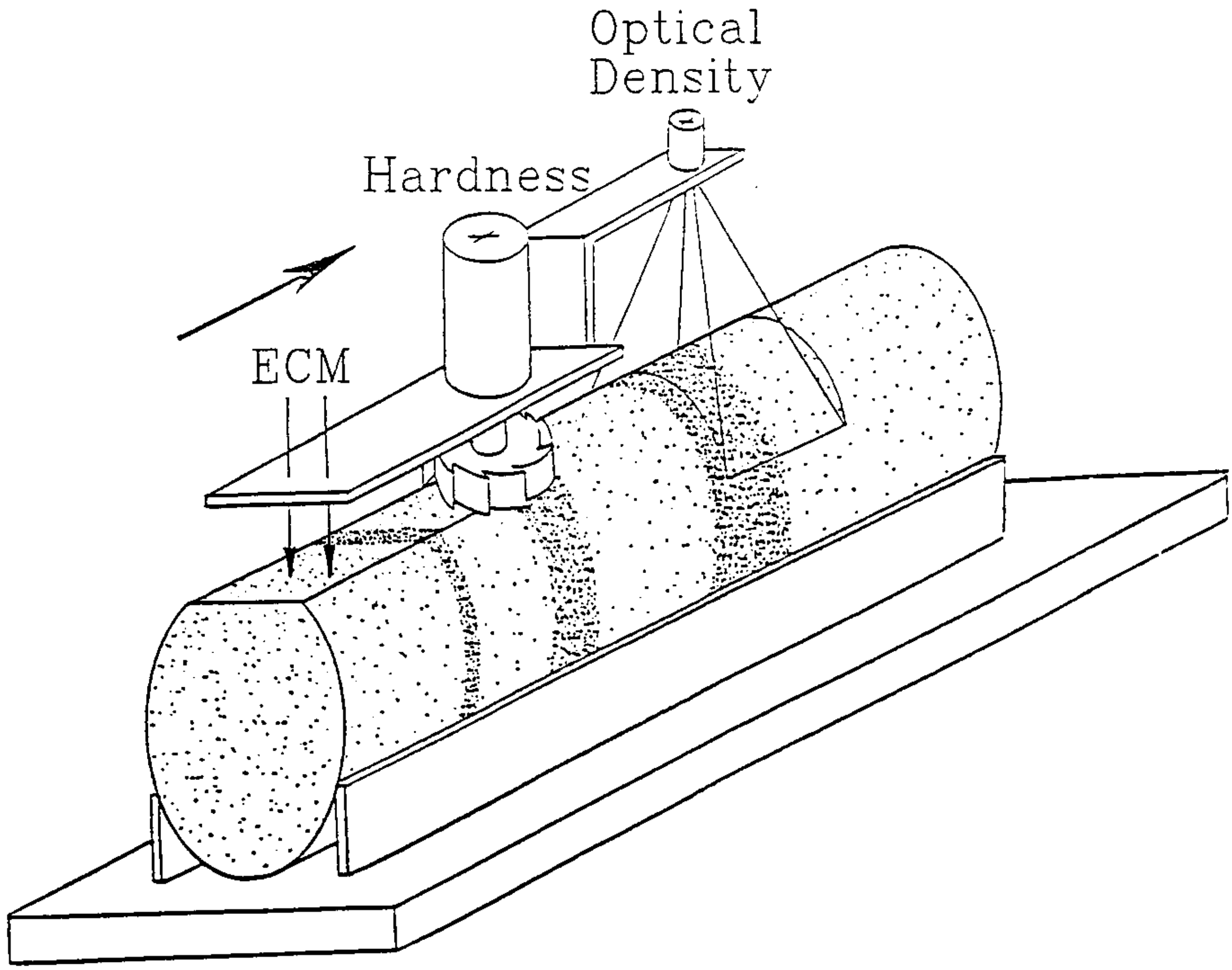

Figure 1. Scheme of apparatus for continuous multi-parameter analysis of ice core; sensors installed on carriage moving along the ice core.

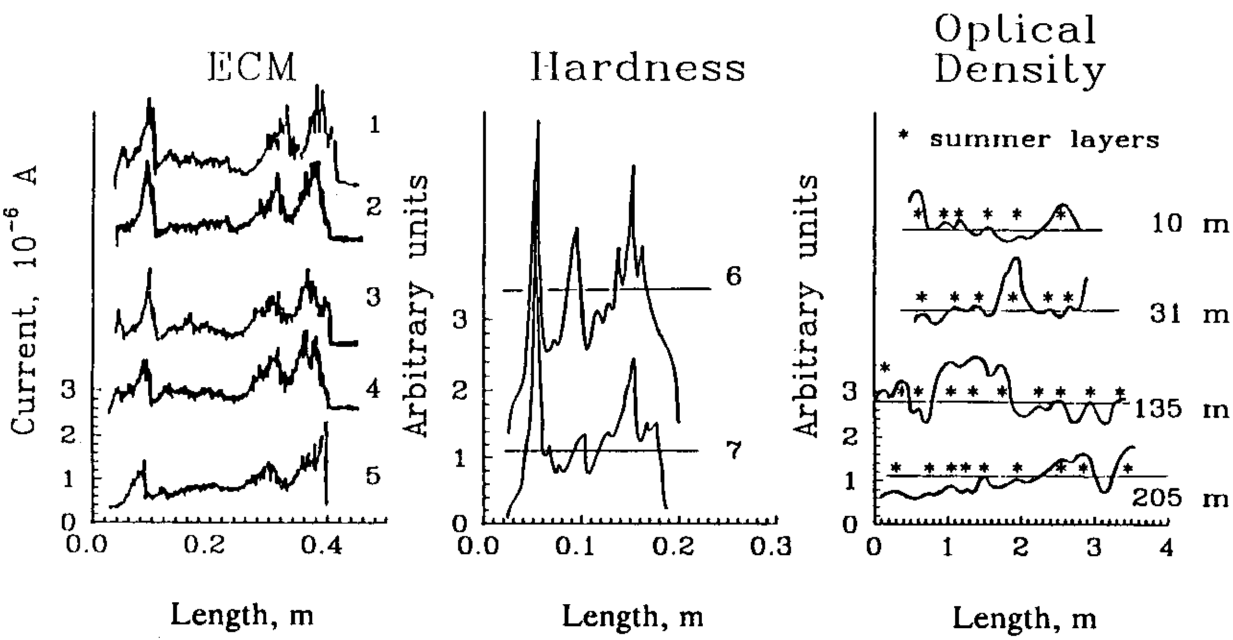

Figure 2. Examples of continuous profiles: Electrical Conductivity Measurements (ECM), Hardness (H), Optical Density (OD); 1 to 5 – Electrical Conductivity Measurements profiles from different sides of Lomonosovfonna (Svalbard) ice core segment; 6 to 7 – Hardness profiles from different sides of Lomonosovfonna snow core segment; Optical Density profiles obtained from Austfonna (Svalbard) ice core.

of the method (Hammer *et al.*, 1978; Hammer, 1989). Today, this method is in widespread use with several modifications.

Optical Density (OD) (Fig. 1)

The intensity of light reflected by air bubbles in an ice core was measured with the aid of a photodiode sensor which moved along the ice core. Longitudinal variations of the photodiode output signal correlated with the concentration of air bubbles in ice cores and in the density of ice. The speed of measurement was about 5 cm/s. This method has been used for measuring seasonal variations in the concentration of air bubbles in an ice core (Fig. 2) (Zagorodnov and Arkhipov, 1990).

Hardness (H) of Snow and Firn (Fig. 1)

Milling of snow, firn and ice cores is accompanied with different resistance. The correlation of mill torsion resistance (electrical output) with the position of the cutting instruments relative to the ice core's longitudinal axis allows detection of small variations in its hardness (Fig. 3). The latter is mostly related to concentrations and pore volume in snow-firn cores. This method has been tested with snow cores.

Ice Fabrics (IF)

Ice fabrics studies are especially important for investigation of various phenomena in an ice cover or a glacier. Measurements of the c-axes orientation usually have been carried out by a Rigsby type universal stage. This method requires laborious preparatory work and has rather low accuracy. Recently, an automatic ice fabric analyser was developed which determines c- and a-axes of the individual ice grains. An analysis of 100 grains takes approximately three hours (Mori *et al.*, 1985).

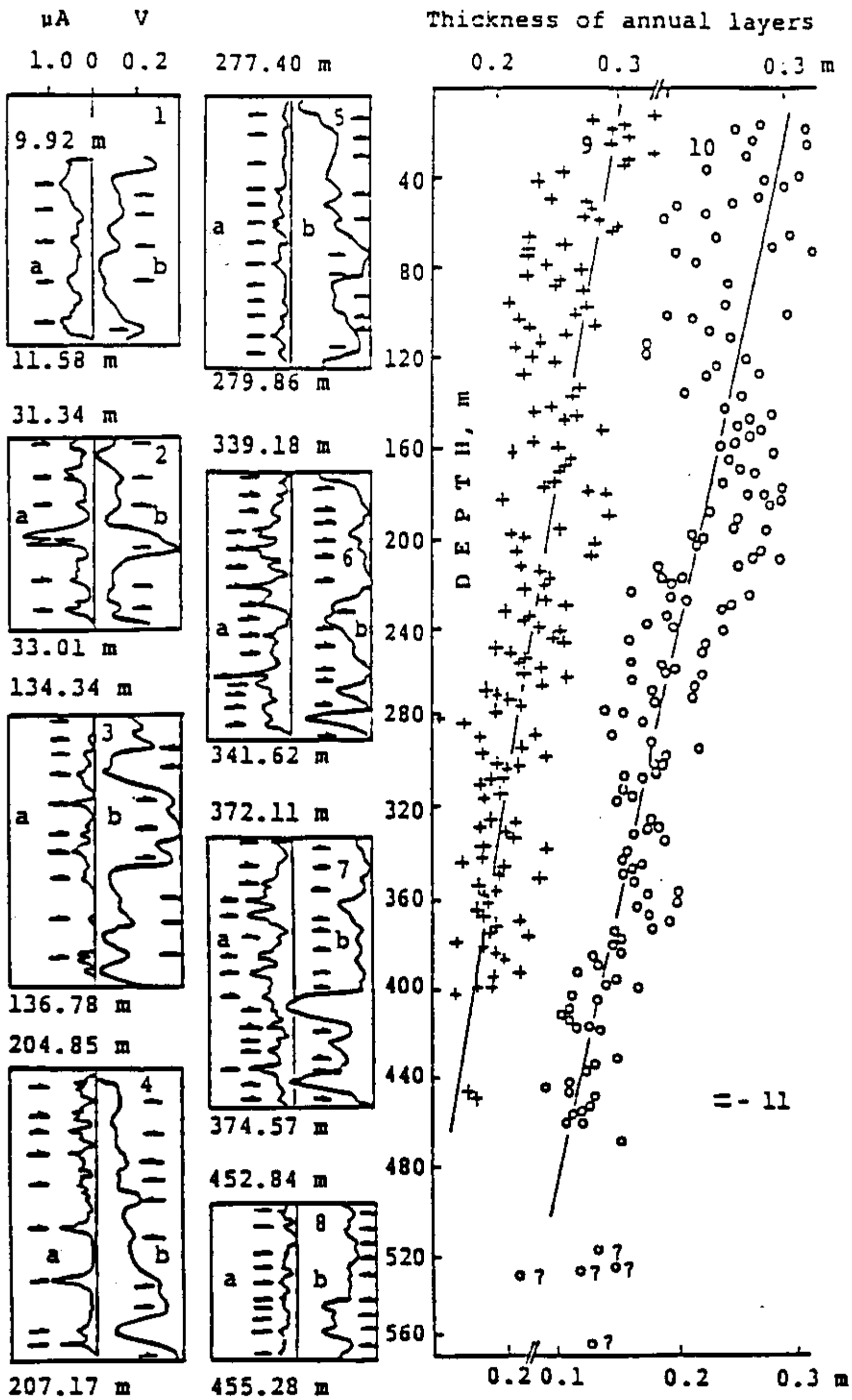

Figure 3. Profiles of Electrical Conductivity Measurements (a) and Optical Density (b) of Austfonna ice core segments (1 to 8), and thickness of annual layers identified by seasonal variations of optical density (9) and electrical conductivity (10) of ice core. Arrows mean summer layers.

Crystal Dimensions (CD) and Air Bubble Concentration (ABC) (Figs. 4 and 5)

Initially, the ice core is milled and polished to create a suitable thin section along the ice core. Polarized laser light is passed through the thin section. Its intensity depends on the c-axis position in the ice crystal. Movement of laser sensors along an ice core allows for the detection of ice crystals with different positions of the c-axis, air bubbles and opaque particles. The method was tested on an antarctic ice core. Maximum rate of thin-section preparation and laser-based measurements is 6 mm/s (Zagorodnov *et al.*, 1991).

Measurements of Impurity Concentrations (MIC)

This method includes the cutting, the continuous melting of subcores and the measurements of certain impurity concentrations (e.g., H_2O_2) continuously along the ice core in the field. The method has been applied during the deep drilling at Dye 3 (1979-1981) Greenland and at the South Pole (1983 and 1984) (Stauffer *et al.*, 1988). Now it is used at GRIP, Greenland. The rate of analysis is about 1 mm/s.

Meltwater Sampling System (MS) (Fig. 6)

The sampling head is heated by steam or hot water. Meltwater has no contact with the water circulated inside the head. The meltwater from the head is conducted to the beaker without coming into contact with the pump. The device (Fig. 6) for the continuous meltwater sampling has been tested with artificial and natural ice. With ultra-pure artificial ice, it was shown that the continuous sampling procedure does not contaminate water; microparticle concentrations in continuous water flow (1-200 ml/min) are lower than in Antarctic ice cores. Simultaneously with water sampling, gas extraction has also been accomplished. The maximum sampling rate is 5 mm/s.

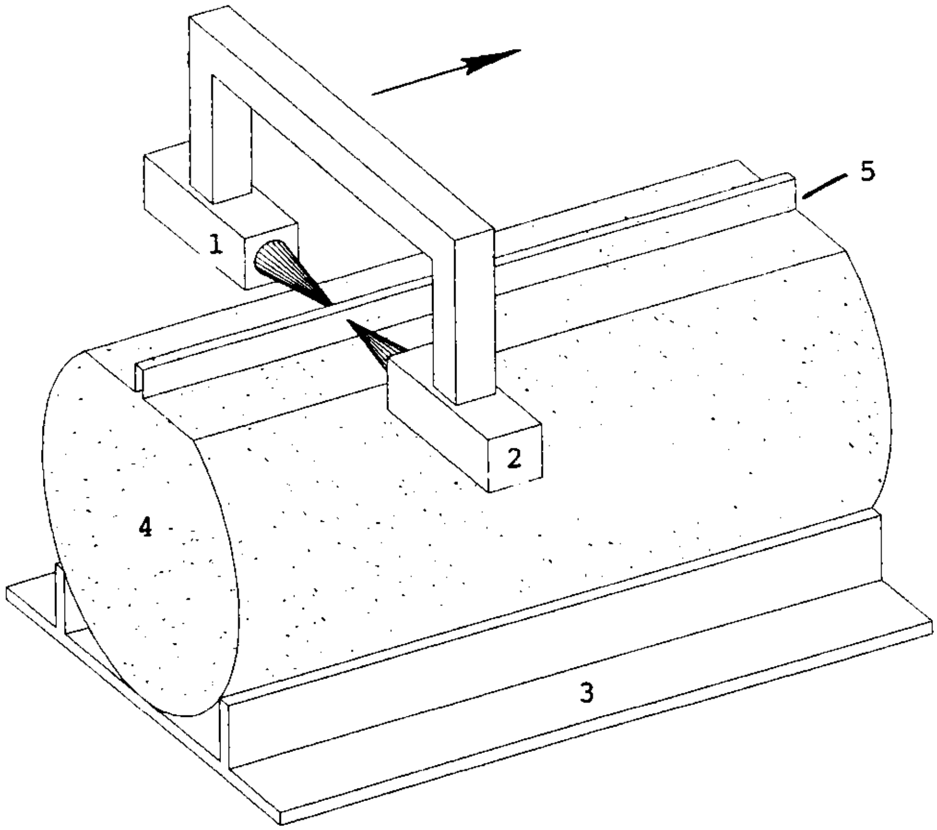

Figure 4. Scheme of apparatus for optical investigations of thin section; 1 – laser light source, 2 – light receiver, 3 – foundation, 4 – ice core, 5 – thin section.

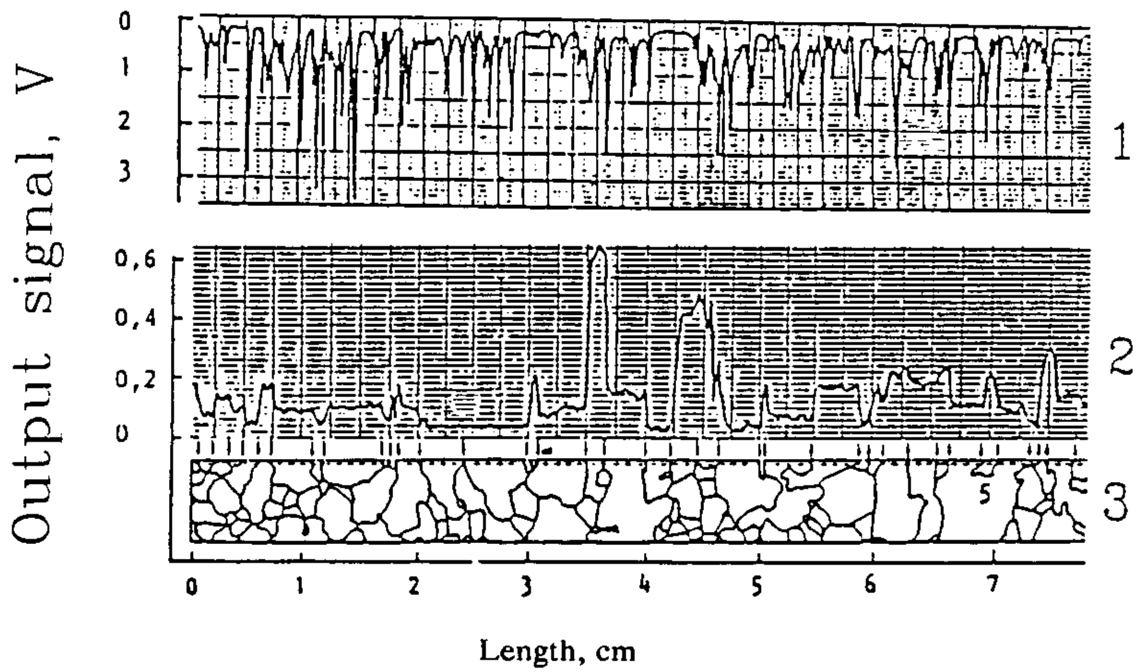

Figure 5. Continuous profiles are obtained with the aid of laser sensors moving along the thin section; 1 – output signal depends on concentration of inclusions in ice core, 2 – output signal depends on c-axis position of ice crystals; 3 – grain boundaries taken from photo of thin section taken under crossed polarized light.

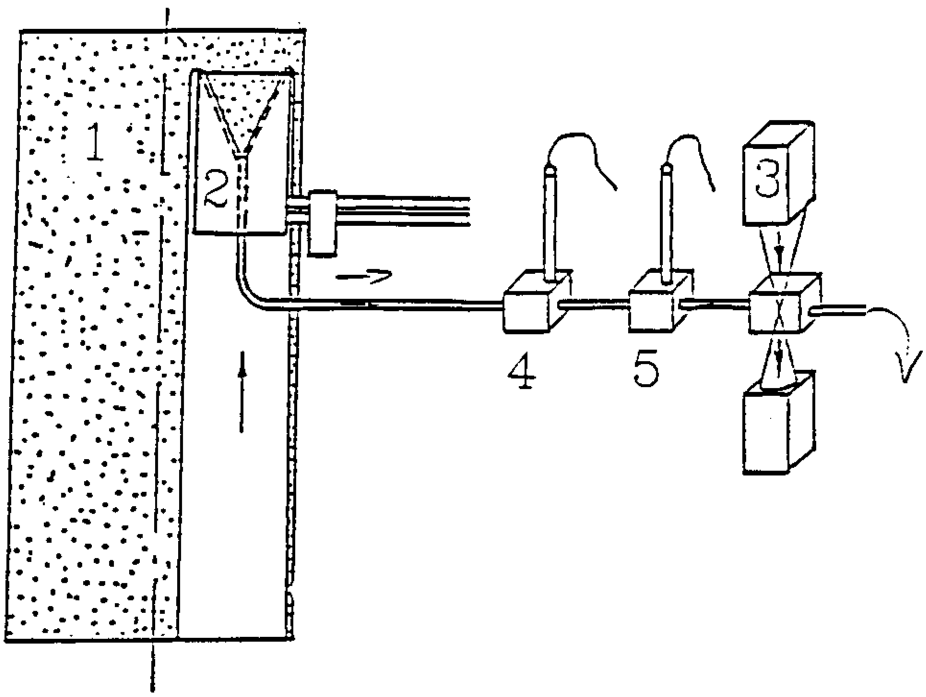

Figure 6. Melt water sampling – analytical system. 1 – ice core; 2 – sampling head; 3 – laser particles detector; 4-5 – pH and ion-selective cells.

γ-Absorbtion (γ-A)

This method has been successfully tested with snow, firn and ice cores for measuring longitudinal density. The speed of measurements is about 1 cm/min (personal communication from O. Watanabe and M. Lange).

Ultrasonic Speed Measurements (USM)

Experiments with sea ice showed that the c-axis fabrics correlate with the ultrasound speed distribution along the ice core. Continuous USM requires a complex instrument which can carry out specific ice core surface treatments. Speed of USM is less than 10 cm/min (personal communication from M. Lange).

PERSPECTIVES

The combination of methods mentioned above on one computer-driven machine, allows for the construction of powerful instruments for multiparameter studies of ice. Such analytical systems can be operated in the field or in cold laboratory conditions.

At present, only γ-A, USM and ECM sensors are combined on the analytical system (personal communication from M. Lange). This system was used for studying glacier ice cores on the GRIP project on the Greenland ice cap.

Most natural processes that have an effect on ice crystallization have seasonal variations. Structural and physical parameters and impurity distribution in an ice core have vertical variations. In the bottom part of a glacier sequence, the thickness of the annual layers are a few millimeters or less. The diameter of the brine inclusions in sea ice is 1-5 mm. The diameter of ice grains in all types of ice is often about 1 mm. Hence, to measure some parameters of an ice core with high spatial resolution or for quantitative analysis of small sections of ice core structure, it is necessary to use a sensor with a small zone of interaction. It would also be expedient to sample the meltwater for isotope and chemical composition of glacier or sea ice from thin layers.

Laser sensors have a high spatial resolution (about 0.1 mm) (Zagorodnov *et al.*, 1991). This allows for a continuous analysis of geometrical parameters (dimensions, form, concentration and axis orientation) of ice crystals, air, dust, biorganic and brine cell inclusions in an ice core. Also, such sensors can be employed for determining the insoluble impurities in meltwater taken from an ice core (Hammer, 1989).

ECM methods have comparatively high spatial resolution, and they can be used for measuring some chemical parameters along the ice core. In sea ice, the concentration of impurities (in brine cells) is high. Ion-selective electrodes can be employed for chemical composition studies on the continuous flow of meltwater taken from an ice core (Fig. 6). For glacier ice this method can be used for sampling and analyzing the concentration and size distribution of micro particles.

At present, the portable analytical system shown in Figure 6 can be used for further improvement of continuous structural and melting water analysis methods.

In sea ice structural parameters, such as temperature and concentration of impurities, vary with depth. The compact sensors can be used for studies of their sequence. A portable thermal probe allows for the placement and movement of several sensors inside the ice sequence.

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