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Studies of structure, composition and temperature regime of sheet glaciers of Svalbard and Severnaya Zemlya: methods and outcomes

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Abstract

Exploration of bore holes and ice cores are the most efficient ways to produce information on the structure, hydrothermal regime and isotope-chemical composition of glaciers. In the recent years, techniques of express-analysis are being used in the Institute of Geography of the USSR Academy of Sciences for analysis of ice cores in field conditions. Development of this technique was stimulated by the need to rapidly explore ice cores and get statistically significant values of its parameters. This paper describes the succession of operations and techniques of analysis of ice cores and bore holes. Outcomes of analysis of ice cores from Svalbard and Severnaya Zemlya are given.

1. Introduction

Transportation of ice cores to cold laboratories from polar regions requires special equipment and considerable material investments. Absence of these items persuades one to carry out of ice core explorations in the field. Operations in the Arctic glaciers often take place in the spring-summer season with air temperatures above zero, therefore, ice cores have to be studied simultaneously with drilling process.

At the Arctic glaciers ice is formed partially by re-crystallization of snow and firn, and also by freezing of melt water in firn. Thus formed firn and ice have heterogeneous parameters. Sizes of ice crystals in the neighboring layers differ tens and hundreds times, and also concentrations and sizes of air caverns differ several times. To find out the laws of metamorphism of snow and to identify the climatic and dynamic factors, it is necessary to have a vast massif of data.

Due to the thermic impact of meltwater, the temperature inside the Arctic glaciers is 5-12°C higher than the mean annual air temperature at the level of their surface. Because of that, response of such glaciers to air temperature changes is expressed by fluctuations of temperature of their inner layers characterized by higher amplitude than that of climatic changes.

Meltwater is the main agent of heat and mass circulation in the Arctic glaciers, its migration in the inner strata influences structure, thermal regime, and isotope-chemical composition of glaciers. With freezing of meltwater inside the firn strata, infiltration ice is predominantly formed. As compared to the infiltration-recrystallization ice formed mostly through recrystallization of snow and firn, this ice contains 2-3 times less air inclusions. Exploration of firn layers of the Svalbard glaciers explicated, that at the boundary of annual layers, represented by ablation surface, concentration of infiltration ice is, as a rule, higher. Therefore, one can see in the ice cores, seasonal variations of concentrations of infiltration ice, that are pronounced on the profiles of optical density and electric conductivity. Concentration of infiltration ice in a core correlates with intensity of melting in the past, and represents a paleoclimatic parameter of an ice core.

Meltwater redistributes admixtures in inner layers down to 24 m, in some cases ; horizontal migration of water in the firn strata is also observed. These processes complicate the isotope-chemical stratification of ice core for annual layers. In less degree these processes are pronounced in ice divide areas of glaciers, that can be studied by simulation methods of ice core dating. This paper analyzes ice cores from ice divide of sheet glaciers and discusses the technique of multiparametrical analysis of ice cores showing some profiles of the Austfonna ice core, Svalbard.

2. Studies of ice core

Most comprehensively the express methods were employed to study ice cores at Austfonna, Svalbard in 1985 and 1987, and Akademiya Nauk glacier, Severnaya Zemlya in 1986 (Zagorodnov *et al.*,1988 ; Savatiugin and Zagorodnov, 1988). Figure 1 gives a general view of the drilling-laboratory construction on Austfonna. Its main elements are : a residential place for 4 persons (6 m^2), operational place with a drilling construction and with facilities for structural studies of ice cores (15 m^2), a room for isotope-chemical sampling and analysis (6 m^2), cold laboratory - ice core warehouse (13 m^2) located below snow surface. The cold laboratory has shelves to keep 80 m of ice core, the devices to measure optical density and electrical conductivity, and also a balance for measuring of ice core density. Drilling and analysis of ice core are done by 5-6 persons. The main operations, their succession, intervals of ice core analysis are given in Fig. 2 and in Table 1.

Description, photography, and measuring of optical density and electrical conductivity are carried out with a special installation. Side lightening of ice core located on a black surface emphasizes contrast of layers with different concentration and size of air inclusions ; fractures in ice also become well seen. The installation has an electric motor to move a carriage with sensors along ice core at a speed of 35.7 mm/sec. The carriage has a photoelectrical sensor

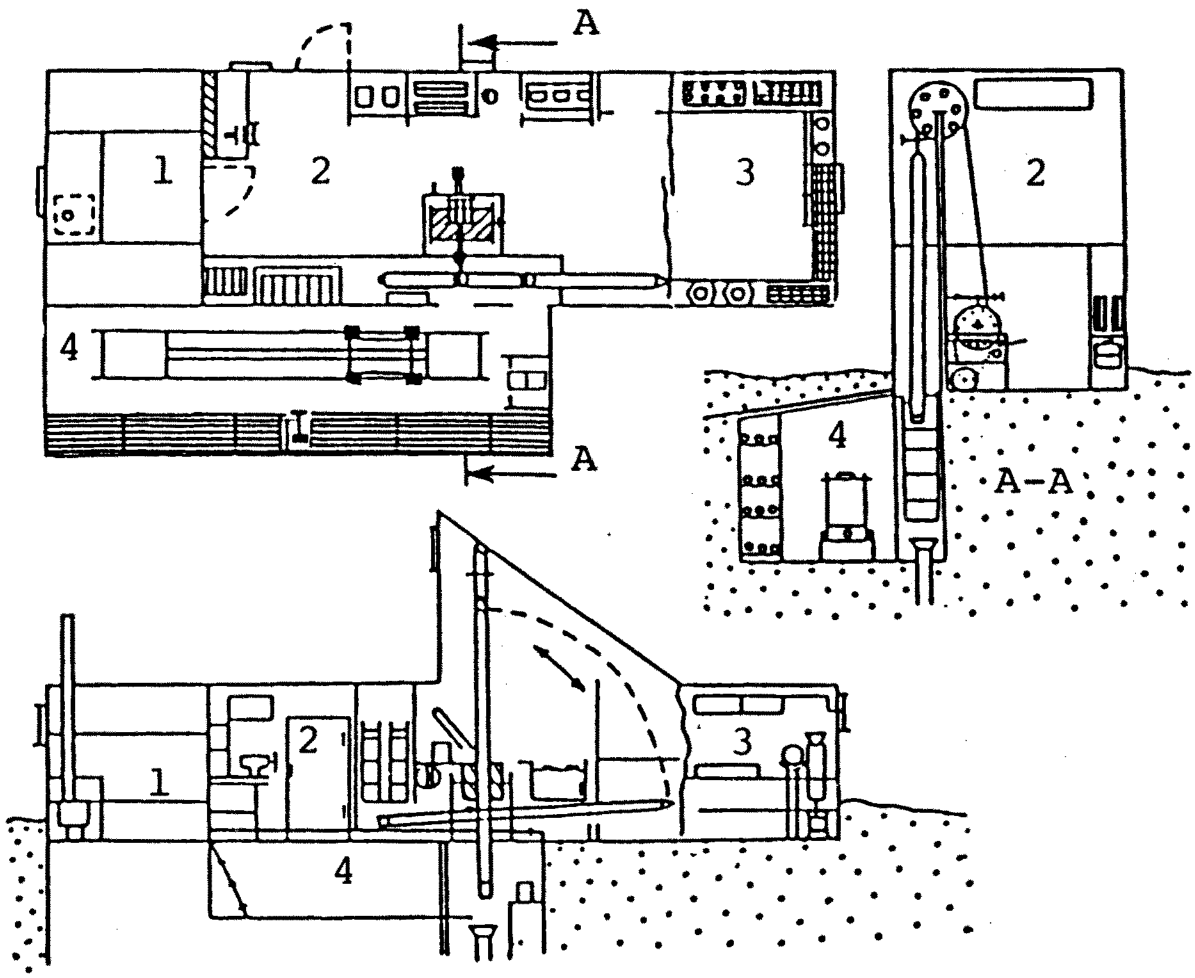

Fig. 1. Drilling complex. 1 : residential block, 2 : drilling chamber and laboratory for structural studies of ice core, 3 : geochemical laboratory, 4 : cold laboratory / ice core warehouse.

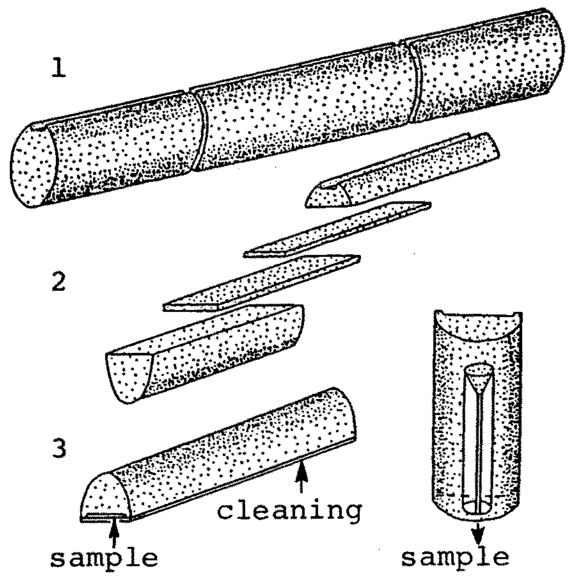

Fig. 2. Succession of ice core studies. 1 : stratigraphic studies, 2 : structural studies, 3 : isotope-geochemical sampling.

(photodiode), electrodes to measure electric conductivity of ice core (DC 300 V) and a cutter installed on axis of the electric motor that abraded the surface of ice core moving in front of electrodes. Besides, the installation has an automatic camera operating in a manual or automatic regime.

The field of observation of photodiode sensor which moves along ice cores is about 25 cm, therefore, the measured parameter - optical density is averaged. Intensity of light reflected by air inclusions is measured. Measurements are done in relative units, although the available data on the body density of samples makes it possible to calculate the dependence of optical density from bulk density for different intervals of depth.

Measurements of electrical conductivity of ice core were done with technique suggested by C. Hammer (Hammer *et al.*, 1978 ; Hammer, 1980). It was supposed that seasonal character of transportation of acidic aerosols to glaciers would be reflected in electrical conductivity of ice core. Measurements were done at temperature $-2.5°C$, before measurements, the ice core was kept in such conditions for 4-12 hours. Depth of abrasion of ice core was 4-6 mm ; the repeated measurements in most of cases reproduced the identical profiles of electrical conductivity.

The major objective of measuring of optical density and electrical conductivity of ice core was to

Table 1. Succession of operations, intervals, technology used for analysis of ice cores

Kind of analysis	Length of a sample/ interval of analysis (m)	Technology
1. Stratigraphic description	continuously	visual
2. Photography	continuously	automatic camera
3. Measurements :		
a) optical density	continuously	special
b) electrical conductivity	continuously	device
4. Structural analysis (photo) : from, size a) ice crystals b) air bubbles	0.1-5.0/0.5-2	electrothermal cutter, photo-table
5. Density	0.1/0.5-2	hydrostatic method
6. Sampling for isotope and chemical analysis	continuously 0.05-2	mechanical and hydrothermal samplers

identify seasonal variations of these parameters to calculate a dating scale.

To speed up cross-cutting of ice core a cutter was used with a disk 250 mm in diameter and 1 mm thick, and teeth 4 to 6 mm with about 100 rps. Application of such cutter allows to preserve ice core. A cut of ice core taken from depths below 300 m done by hand saw has a wedge-shape, its width in the upper portion is 3-10 cm, and new fractures can appear. A disk saw makes a cut 1.5 mm thick and seldom produces fracturing. Minimum thickness of samples produced by cross-cutting of an ice core by a disk saw is 8-10 mm. One cross-cutting is done in 6-10 sec.

For structural analysis thin plates of ice were cut along axis of an ice core by an electric thermal cutter. A piece of ice core pushed by its own weight moves along an inclined shoot ; perpendicular to the long axis of this shoot a nickel-chrome wire is stretched and heated by electric current (30-40 A, 4-6 V). Rate of ice melting is 10-13 cm/min, thickness of plates is 1 -1.5 and 2-3 mm. The surface of samples 8-30 cm long and 7-8 cm wide, as a rule, uniformly smooth. Pictures of ice plates are taken by 3 cameras : one for photography of ice crystals and, one for air bubbles in scales about the same as of ice core pictures, and one more in macroscale.

Measurements of ice density are done with the hydrostatic method by quadrant type of balance adjusted for weighting of ice samples in kerosene. This kind of balance is convenient because weighting with accuracy up to 0.01 g is done without set of weights in short time. A series of 40-50 samples can be weighed in kerosene and in air in about 3 hours.

A mechanical sampler for isotope and chemical samples consists of a shoot equal in width to diameter of an ice core and of two knives of stainless steel. The cylindrical segment of ice core is moved manually on its flat side along shoot. The first knife takes off a 1-2 mm thick layer of ice in the whole width of an ice core, and the second narrow knife installed behind the first one, takes off tips in the center of an ice segment. Thus, the first knife cleans the surface of an ice core, and the second one serves to sample ice crumb into a polyethylene bag.

A thermal sampler melts the kernel of ice core, and the sample goes into a polyethylene bottle that is used for keeping and transportation of water sample. The operational unit of the sampler is copper heat -exchanger in the form of a funnel covered by polyethylene. Water vapor of 60-85°C is transported by an electrical pump. Maximum rate of melting by this device is 2.5 cm/min. Polyethylene cover of the working surface decreases the rate of melting 5 times.

The other construction of a thermal sampler has a titanium circular crown that allows to melt ice columns 20-40 mm in diameter from the center of an ice core ; rate of melting was 5-6 cm/min. An ice sample 30-130 cm long was put into polyethylene bags where it was stored and melted.

All polyethylene bottles, bags, filtering installations and filters were washed with 10-20% solution of HNO_3 and 3-4 times by distilled water. In the field laboratory under normal conditions the melted sample was filtered through membranes with pores 0.5 micron in diameter. Filters were weighed before and after filtering in a dry state. Potentialometric measurements of pH of filtered water were carried out by the device EV-74. Concentration of the chlorine ions in this water were measured by turbometric titration.

The latter method of sampling turned out the most convenient for operations on a glacier. Besides, the ice samples produced with this method can be stored in the unmelted form, and measurements can be done any convenient time. According to the first assessments the samples produced with this method had the least amount of technological admixtures.

3. Measurements in bore holes

In the process and after drilling of the above mentioned bore holes was completed, their thermal sounding was performed. Results of measurements are shown in Fig. 3. Measurements were done by a semiconductor sensor and a digital ohmmeter. Thermometer was descended into a bore hole on one-vein cable. Error of temperature measurements is 0.2°C.

The profiles (Fig. 3) demonstrate that during 3 days after drilling the temperature in the bore hole was by 1.5-2.5°C higher than its stable values, and afterwards it does not change. Probably, 3 days is the time needed to establish an equipoise concentration of antifreeze liquid in bore hole. In the upper parts of the bore holes the measurements were done in antifreeze liquid and some time later on the same depth without it. Also at same depth temperatures were measured in the other bore hole, drilled by a

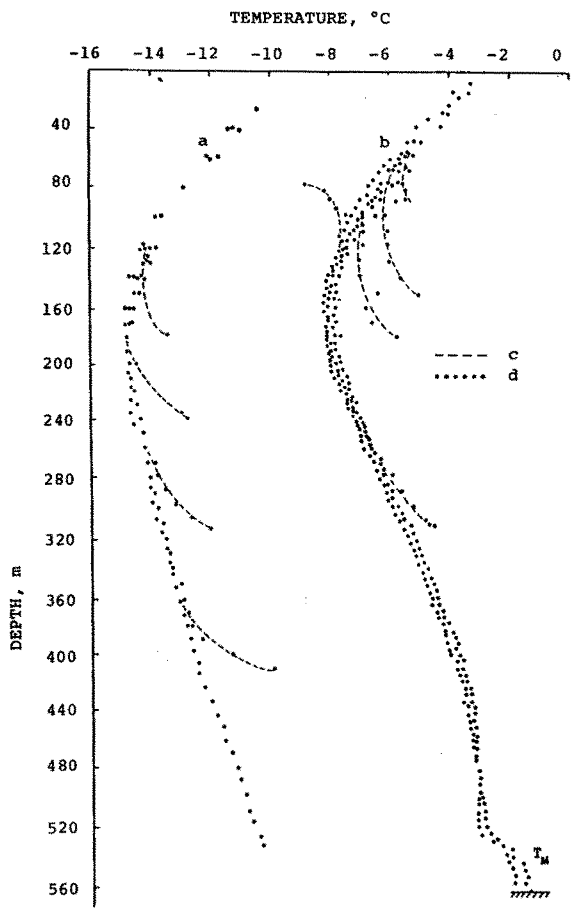

Fig. 3. Temperature profiles in bore holes in Akademiya Nauk Glacier (a) and Austfonna (b) ; c : temperature measurements carried out immediately after stopping of drilling on some depth, d : temperature measurements carreid out immediately after input of spirit to the bore hole, and Tm : ice-melting temperature at bottom depth 566.7 m (0.42°C).

mechanical drill without use of any liquids. The temperature differences in all cases were within the limit of error of measuring method.

The profile measured in Austfonna immediately after input of spirit to the bore hole to dissolve a block of slush has disclosed that for 3 days temperature in the bore hole was by 2.5°C lower than its stable values. The experiments carried out earlier explicate that 1 year after, the temperatures in bore holes without any liquid and those in bore holes with spirit-water antifreeze don't differ (Morev and Pukhov, 1981).

Measurement of inclination of bore hole was done by a standard electromechanical device MI-30 ; error of measurement of inclination angle is 30', azimuth 5° (inclination angle of a bore hole more than 3°).

Observation on the level of liquid in bore holes were done by a float and by reduction of the rate of descent of the drill in a bore hole ; the error of level measurement was not over 1 m.

4. Results of studies of ice core and bore holes

Fig. 4 shows the results of annual stratification of Austfonna ice core. As annual boundaries the peak values of electrical conductivity (a) and optical density (b) of ice core were selected. Profiles 9 and 10 of Fig. 4 represent mean values of thicknesses of annual layers in individual ice core pieces 1.5-2.5 m long. Mean deviation of these values from the linear interpolation is about 8%. Both profiles explicate a close to linear dependence of the thickness of annual layers from depth. The profile 10 of Fig. 4 shows long periodical fluctuations of the thickness of annual layers, probably linked with fluctuations in the rates of sediment accumulation. Low quality of ice core from the bottom part of the glacier prevented from getting reliable data on thickness of annual layers. Measurements were complicated by large fractures and splits in ice cores. At the same time, mean regularity - electrical conductivity of infiltration ice is higher. The same profiles, taken by electrical conductivity measurements, with linear reduction of the thickness of annual layers with depth were produced of ice cores taken in the Akademiya Nauk glacier on Severnaya Zemlya where mean accumulation rate is about 300 kg/m^2 per year.

An age scale for ice core (Fig. 5 B) was calculated by dividing 40-meter intervals of depths by mean arithmetical thickness of annual layers in this interval. For comparison another age scale was calculated with a stationary model of Nye (Hammer *et al.*, 1978) (Fig. 5 A). Down to one half of the glacier's depth, ice core datings produced by the above methods differ not more than 10% ; further down to the glacier's bottom the model by Nye gives higher age values for ice.

The parameters of core and bore holes produced in the field during drilling time are shown by Fig. 5. The profile of ice core density (a) explicates that the major genetic varieties of ice have different rates of consolidation, and at depth about 500 m density of infiltration ice is higher than that of infiltration-recrystallization ice. Much more detailed profiles of ice core densities of the Akademiya Nauk glacier demonstrated long-period variations in density resulting, probably by different conditions of melting and repeated freezing water. Repeated measurements of densities of the same samples have shown that in 6 days density of ice core taken from 350 m depth decreases from 908 to 902 kg/m^3, in the core taken from 400 m depth density changes of such magnitude take place in 1-2 days.

Electrical conductivity of the upper part of ice core (Fig. 5 (b)) is much higher than that of its main part. This is accounted for by permeation of drilling liquid to the firn layers. Below 32 m such layers were not found in the ice core. But electrical conductivity of ice core within depth interval 32-58 m is high. This portion of ice core has high concentration of infiltration ice. High values of the parameters under discussion are also found in ice core starting from depth 300 m and practically down to the glacier's bottom. Near-bottom part of ice core 2.5 m long built of remetamorphosed ice that underwent revelation has the lowest electrical conductivity as compared to the whole of ice core.

Parts of ice core with high values of electrical conductivity have high concentrations of infiltration ice. This correlation of parameters can results from intensive transportation to the glacier of marine and continental particles and aerosols, their prolonged contact with meltwater and partial dissolvent, migration of soluble admixtures and their accumulation in the infiltration ice strata in the process of their formation. All these processes or predominance of one of them are a result of warming of climate and more intensive melting of ice in summer. Thus, the marine and continental material is transported to the glacier from less distances or from larger area. Over the background of varied electrical conductivity of ice

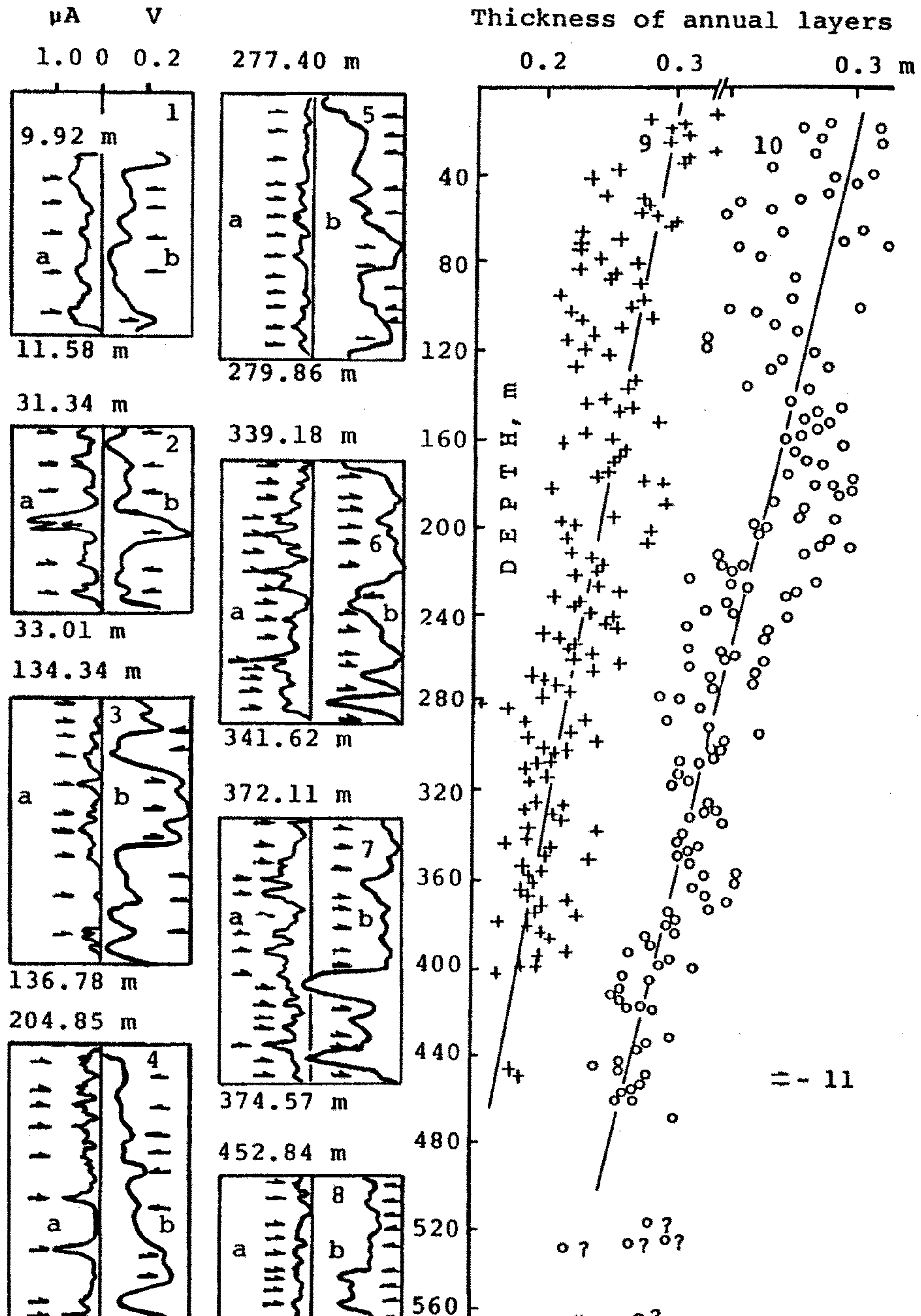

Fig. 4. Profiles of electrical conductivity (a) and optical density (b) of Austfonna ice core fragments at some depths (1-8), and thickness of annual layers identified by seasonal variations of optical density (9) and electrical conductivity (10) of ice core. Arrows mean summer layers.

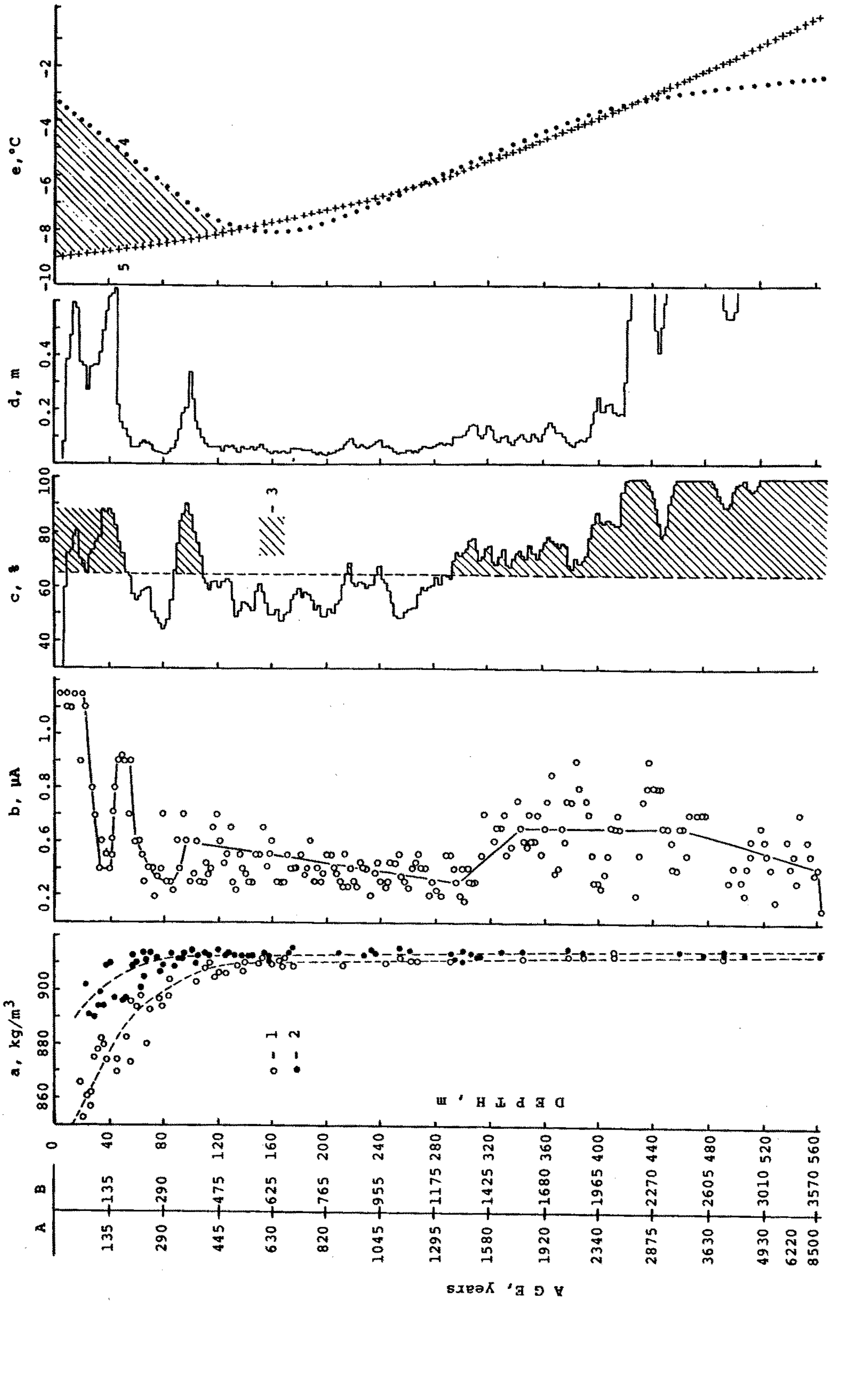

Fig. 5. Profiles of density (a), electrical conductivity (b), concentration (c) and thickness (d) of infiltration ice layers, and temperatures (e) in Austfonna. 1,2 : density of infiltration-recrystallization and infiltration ice respectively, 3; periods of warming, 4 : measured temperature distribution, 5 : stationary distribution of temperature, A : dating of ice core by stationary model of Nye, B : dating of ice core calculated with the profile of annual layer's thickness in ice core.

core due to these processes it is rather difficult to differentiate in ice individual "acid" volcanogenic admixtures.

The profiles of concentrations and thickness of interlayers of infiltration ice, Fig. 5 (c) and (d), respectively, reflect the climatic changes of the recent millennium :(in the age scale Fig. 5 B) modern warming that started from about 1820, Little Ice Age - 690 -1820, warming in 1560-1645, and Medieval climatic optimum that finished in 690. The lower third of the glacier's body is composed mostly of infiltration ice, denoting intensive ice melting on the glacier's surface. This could take place in warm climatic conditions on a glacier of modern dimensions, or in cold climatic conditions on ice cap that is smaller, as compared to the modern one. In this part of the section one can observe higher concentration of infiltration ice with depth, this obviously denoting a cooling that started about 3000 years ago. Cooling was probably associated with growth of the ice cap. These data agree to the outcomes of drilling of an ice cap on the Devon island. Changes of the isotope-oxygen composition of ice core from the Devon ice cap explicate lowering of temperatures in the Arctic by about 2°C during the recent 4500 years. For this period thickness of the Devon ice cap increased by about 125 m (Paterson *et al.*, 1977).

Figure 5 (e) gives the temperature profile measured in the bore hole, as well as the profile produced with a stationary equation of heat and mass exchange in flat glacier with negligible small horizontal temperature gradient, without inner heating (Zotikov, 1982). The calculations were done for the following marginal conditions: thickness of glacier - 560 m, mass budget 0.31 m/year, geothermal flow 5.02×10^2 W/m^2, surface temperature -9°C. This set of parameters provides the best approximation of the calculated temperature values to the measured ones at the deep part of glacier lower than 165 m. However, at the shallow part from surface to 165 m in depth, the measured temperature is higher than the calculated one. This phenomenon was due to increase of the mean summer air temperatures by about 1°C, that produced nearly 2 times higher rates of melting. Repeated freezing of meltwater inside the glacier resulted in temperature increase by 6 -7°C. Similar profiles were registered in the Akademiya Nauk Glacier(Fig. 3) and White Glacier (Blatter, 1987). In the Akademiya Nauk Glacier recent climatic warming, that started about 130 years ago, is also marked by higher concentrations of infiltration ice in the near-surface strata. More distant climatic history of ice caps is weakly pronounced in the temperature profiles.

Changes of the chemical composition of the glacial ice with depth (Fig. 6) are due to time variations of the composition of atmospheric precipitation and space-time variability of the conditions for ice formation. The most probable reasons for higher concentrations of insoluble particles (Fig. 6 (a)) in ice core within depth intervals 0-40 and below 360 m are : climatic warming, lower rates of ice accumulation, longer frostless period in the periglacial zone, smaller area of the ice cap. Depth intervals with increased concentrations insoluble particles generally correspond to the ice core intervals with high concentrations of infiltration ice, thus pointing at comparatively warmer conditions of ice formation.

Regular increase of pH down to 50 m, as shown by Fig. 6 (b), has no analogies in the section, and is probably due to higher acidity of atmospheric precipitation in the recent century produced by higher pressure of man-induced atmospheric pollution. Increased pH values below 420 m is, apparently, due to higher concentration of insoluble particles : our laboratory experiments have shown that higher concentrations of fine-dispersed particles in water produces increase of pH.

A specific feature of Cl^- profile on Fig. 6 (c) is absence of intervals with high concentrations of chlorine ions below 400 m, i.e. in ice formed in the conditions of intensive melting on the glacier's surface. Below 520 m reduction of Cl^- concentration is observed, that can be explained by washing of soluble admixtures of snow and firn by meltwater under comparably warm regimes on the glacier's surface. The lowest 50 m of ice core are, probably, built of ice formed in the warmest conditions, when meltwater was running off the ice divide areas of the ice cap ; at present this phenomenon is practically not observed. In bottom part of ice core pH increases, suggesting a prolonged contact of melt water with insoluble admixtures in snow. Probably, acute growth of pH values and lower concentrations of Cl^- in the near-bottom, remetamorphosed 2.5-meter layer of ice is explained by presence of water channels and apparently of liquid water on facets of crystals. High concentration of fine particles in this part of ice core is probably a result of upwelling of bottom material in the process of ice run-off or of accumulation of insoluble admixtures in ice in the process of bulk melting of the

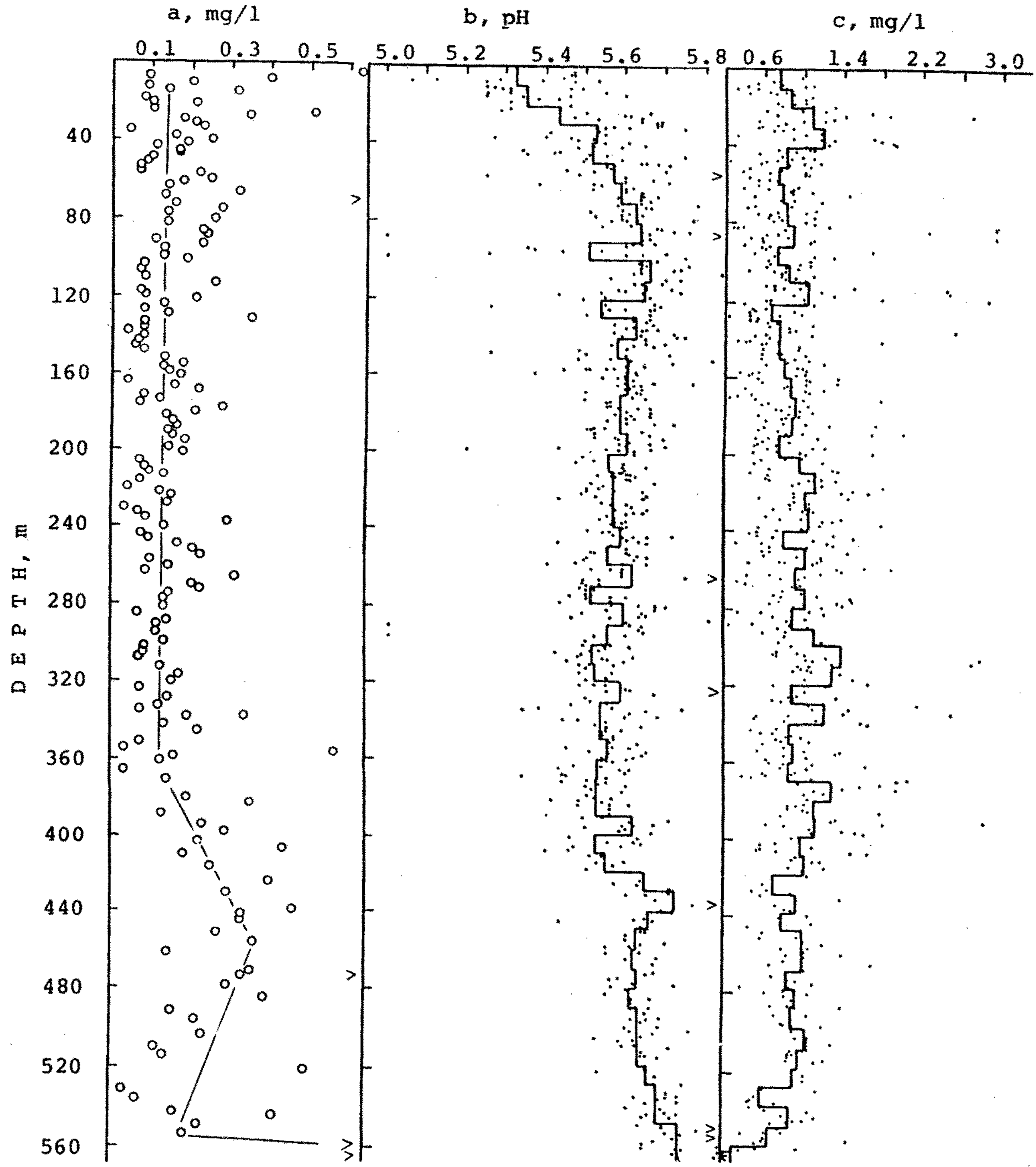

Fig. 6. Profiles of concentration insoluble particles (a), pH (b) and chlorine ions (c) in Austfonna ice core. Arrows mean extrascale values of parameters.

bottom ice stratum.

In the nearest future it is planned to carry out analysis of the ice isotope composition, of mineralogy and morphology of insoluble admixtures, sizes, form, concentration of ice crystals and air inclusions in Austfonna ice core; close to completion is quantitative simulation of the processes of heat and mass exchange in the central part of this ice cap.

5. Conclusion

Express-analysis of ice core in the field allows to obtain the basic parameters of ice strata simultaneously with drilling of bore hole. Automatic installations for continuous measurements of optical density and electrical conductivity of ice core make it possible to carry out its year-wise stratification and to identify ice developed in the special climatic conditions that differ from modern ones.

Meltwater on glaciers of Svalbard and Severnaya Zemlya is the principal agent forming the structure and chemical characteristics of ice, it is decisive for temperature regime of their strata.

On Austfonna for at least 3000 years decreasing of surface snow melting was due a possible combined following reasons: climatic cooling and the resulted growth of the ice cap.

Increase of the June-August air temperature by 1 ℃ in the recent 130-160 years produced doubling of the rates of melting, and the surface temperature of Austfonna and Akademiya Nauk Glaciers increased in their ice divide area by 6-7℃ as compared to the previous quasi-stationary state.

The most probable reason for higher acidity of the upper part of Austfonna ice core is man-induced pollution of atmosphere in the recent century.

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