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Pleistocene ice at the bottom of the Vavilov ice cap, Severnaya Zemlya, Russian Arctic

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ABSTRACT. The Vavilov ice cap was perforated in 1988 by a drilling which reached the underlying frozen sediments. In contrast to the overlying glacier ice, the basal ice is composed of different ice layers with a variable debris load. The stable-isotope composition of these layers shows δ values much lower than everywhere else in the core or in the Vavilov ice cap. This is most probably the signature of a remnant of Pleistocene ice which, for the first time, is shown to occur in the Russian Arctic.

INTRODUCTION

Severnaya Zemlya is located in high latitudes (78–81° N), not far from the Eurasian continent. Its ice cover is thus interesting to study, as it could shed some light on the glacial history of the Russian Arctic.

The Vavilov ice cap, on October Revolution Island, is located between 79° and 79°30′ N, and between 94°30′ and 97° E (Fig. 1), and has a size of about 1817 km^2. In spring 1988, it was perforated by an electromechanical drill, developed by the St Petersburg Mining Institute. This borehole was located near the present-day firn line at an altitude of 665 m, northwest of the highest point on the ice cap (Fig. 1). It reached a depth of 461.61 m.

The core was examined for ice texture and structure. Debris content and grain-size distribution of the included particles were determined, and organic matter, spores and pollens were collected for laboratory studies. The first

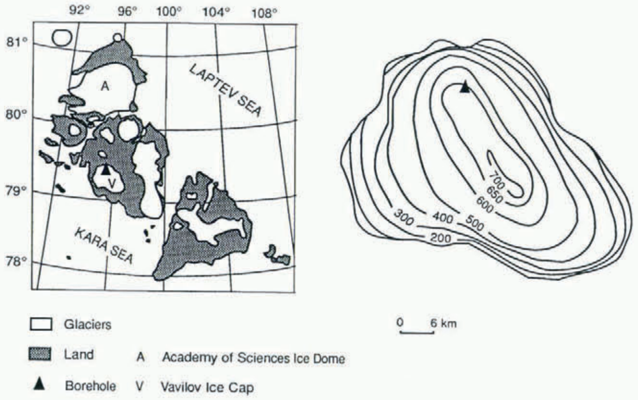

Fig. 1. Location of the Vavilov ice cap and of the borehole studied in the present paper. (a) Location map. (b) Surface topography of the Vavilov ice cap with position of the borehole.

results were recently published by Bol'shiyanov and others (1990). The present study deals with the stable-isotopic composition of the ice.

The samples of basal ice were analyzed at the Centre d'Etudes Nucléaires de Saclay, France, for δD and at the Institute of Geography, Russian Academy of Sciences, Moscow, for δ^{18}O. The δD and δ^{18}O obtained are expressed in per mil changes relative to SMOW (standard mean ocean water with D/H and $^{18}O/^{16}O$, respectively, equal to 155.76 and 2005.2 ppm). Precision of the measurements is ± 0.5‰ in δD and ± 0.1 to 0.15‰ in δ^{18}O.

THE δ^{18}O PROFILE IN GLACIER ICE

Figure 2 gives a comparison between the δ^{18}O profiles obtained on the Vavilov ice cap, in the Academy of Sciences ice dome, north of the Vavilov ice cap on the same archipelago, and in the Camp Century ice core. The ages given on the y axis for the two Russian profiles (Klement'yev and others, 1991) are the result of a combined approach of ice stratigraphy, δ-seasonal variations and ice-flow modelling. A remarkable feature of this figure is the presence of the Younger Dryas (YD) and Alleröd climatic oscillations in the Academy of Sciences ice dome, while the Vavilov ice cap profile seems to start just after these events. A Holocene climatic optimum can be clearly seen on the Academy of Sciences ice dome profile and seems also to be present, although less developed, on the Vavilov ice cap profile. No Pleistocene ice is displayed and this raises the question of the existence of these glaciers on Severnaya Zemlya during this period.

BASAL ICE

Coarse-grained ice with a mean grain area of 58.8 mm^2 characterises glacier ice down to a depth of 457.39 m. Between 457.39 and 457.46 m, fine-grained ice is developed with a mean grain area of about 4.6 mm^2. Shear deformation occurs at this level. Then, between 457.85 and 457.90 m depth, the ice contains more fine particles and consists of very small crystals, probably resulting from fragmentation by shear. Their mean area is about 0.8 mm^2.

Basal ice beneath the glacier ice comprises three units. The upper unit is developed between 457.90 and 458.70 m and is characterised by blocks of frozen sediments similar to those of the third unit. Debris-contaianing ice with a relatively high ice/debris ratio (more than 70%) constitutes the second unit. Some of the mineral particles suspended in the ice reach the size of rock fragments. An isoclinal fold plunging at 35–40° to the horizontal plane can be detected at a depth of 458.77–458.90 m. The contact between this debris-containing ice and the underlying frozen sediments can be located at a depth of 459.07–459.30 m. The third unit is in fact subglacial frozen sediments with an ice/debris ratio of less than 50%. These sediments are red-brown aleurites and argilites with a large amount of rock debris from the red-coloured Devonian Sandstone. The loam covering wide areas on the western part of October Revolution Island, which is presently unglaciated, is very similar to these sediments. No deformation can be identified at the contact between the debris-containing ice and the subglacial frozen sediments. Sliding at the interface, which is below the pressure-melting point, seems to be absent.

ISOTOPIC COMPOSITION OF BASAL ICE

Results of the isotopic analyses performed on the basal ice are displayed in Figure 3. The δ^{18}O values exhibit a range of about 13‰, between –26.0‰ and –13.2‰, the δD values, a range of about 90‰, between –187‰ and –96‰. The most negative δD values (–187‰) and δ^{18}O values (–26‰) are located at the level of the previously described isoclinal fold.

Let us compare the δ values of the basal ice with δ values of glacier ice from different ice cores of the Severnaya Zemlya archipelago. The range in $\delta\delta^{18}$O values for glacier ice in the borehole on top of the Vavilov ice cap is –21.5‰ to –17.5‰ (Kotlyakov and others, 1989).

In the borehole on top of the Academy of Sciences ice dome (for location, see Fig. 1) the range of δ^{18}O values is between –23.5‰ and –18.0‰ (Klement'yev and others, 1991). All these values seem to correspond to Holocene ice, with the exception of the ice from the base of the Academy of Sciences ice dome ($\delta^{18}O = -23.5$‰) which is considered by Klement'yev and others (1991) to be about

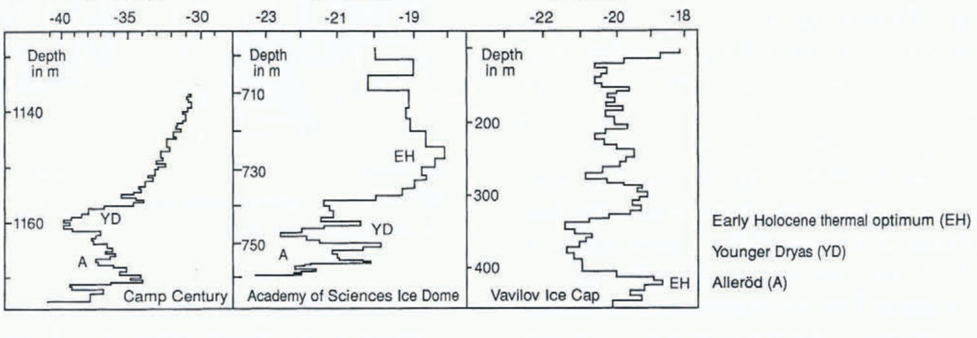

Fig. 2. Comparison of δ^{18}O profiles from the Vavilov ice cap, the Academy of Sciences ice dome and the Camp Century ice core.

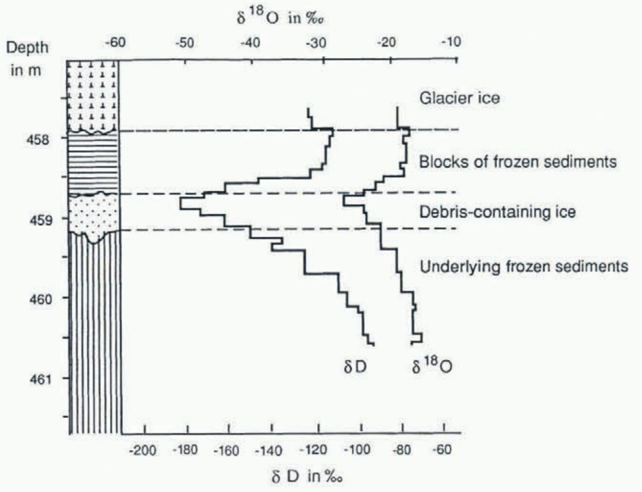

Fig. 3. $\delta^{18}O$ and δD profiles in the basal ice from the Vavilov ice cap.

12 000 years old, from the last glacial transition. The differences in δ^{18}O values between these boreholes are due to the altitude effect and to the position of the Academy of Sciences ice dome, about 120 km north of the Vavilov ice cap. The δ values of the debris-containing ice are more negative (δ^{18}O = –26‰) than all these values (Fig. 3). This could represent Pleistocene ice, but the question arises whether glaciological processes occurring at the ice–substratum interface could be responsible. The distribution of the points representing the samples in a δD–δ^{18}O diagram can give some information on this problem. δD–δ^{18}O relationships can reveal whether phase changes have occurred in the basal ice (Jouzel and Souchez, 1982; Souchez and Jouzel, 1984; Gordon and others, 1988). The samples of the debris-containing ice are well aligned on a straight line with a slope $S = 7.88$ in a δD–δ^{18}O diagram. The line has the equation

$$\delta D = (7.88 \pm 0.44)\, \delta^{18}O + (10.8 \pm 1.4);\; r^2 = 0.97;\; n = 12. \tag{1}$$

This line can be considered as a meteoric water line (MWL; Dansgaard, 1964; Merlivat and Jouzel, 1979). Rozanski and others (1993) recently proposed for the equation of the MWL

$$\delta D = (8.17 \pm 0.06)\delta^{18}O + (10.35 \pm 0.65);\; r^2 = 0.99;\; n = 206. \tag{2}$$

This relationship is generally true for fresh precipitation. Since samples from the debris-containing ice are aligned on a MWL, it can be considered that this ice has not undergone isotopic changes during its transfer from the accumulation area to its present position at the base of the Vavilov ice cap.

The samples from the frozen underlying sediments also lie on a straight line but with a different slope as defined by the least-squares regression line:

$$\delta D = (6.54 \pm 0.71)\, \delta^{18}O - (6.5 \pm 1.7);\; r^2 = 0.92;\; n = 10. \tag{3}$$

A t test indicates that there is a probability $p = 0.95$ that the slopes of Equations (1) and (3) are indeed different. However, the small number of samples and the relatively low value for r^2 must be taken into account since this reduces the level of significance and makes the fit very sensitive to the loss of a few points. Nevertheless, the slope of Equation (3) is typical of that arising from a freezing or melting–refreezing process (Souchez and Jouzel, 1984). If the values of the ice–water equilibrium fractionation coefficients at 0°C are taken as 1.0208 for deuterium (Arnason, 1969) and 1.003 for ^{18}O (O'Neil, 1968), the theoretical freezing slope can be calculated. Its value is 6.39 which is in excellent agreement with the observed value. There is no evidence for an influence of OH-bearing minerals on the isotopic composition (Souchez and others, 1990).

Some of the δ values from the debris-containing ice at the base of the Vavilov ice cap are much lower than normal Holocene values for the area. They possibly represent the first Pleistocene ice discovered in the Eurasian sector of the Arctic. In the Academy of Sciences ice dome, the δ^{18}O value for the YD reaches –22.5‰, while Holocene values are less negative than at the Vavilov ice cap. Therefore, δ^{18}O values of –26‰ in debris-containing ice from the base of the Vavilov ice cap cannot be considered as YD ice since the impoverishment in heavy isotopes is too large. This supposed Pleistocene ice layer is covered by blocks of frozen sediments. All previous boreholes were drilled by a thermal drill, and therefore have not been able to penetrate through them. The process by which particles have been included in the debris-containing ice is not known. Freezing-on is precluded in the absence of stratified facies and of a freezing slope in a δD–δ^{18}O diagram. Melting and regelation is a possibility, but there is no evidence that the pressure-melting point was reached at the base. Shearing and folding can also be responsible for inclusion of particles in the ice and is likely given the presence of an isoclinal fold. The transitional δ values between those of the debris-containing ice and those from the frozen sediments most probably indicate the role of diffusion along water veins at the surface of the ice crystals and along grain boundaries, even at a temperature below the melting point.

PALAEOCLIMATIC IMPLICATIONS

Two hypotheses can be formulated for the development of the Severnaya Zemlya glaciation in the past. The first one considers a continuous ice cover throughout the Pleistocene and the Holocene. According to the second one, the present-day glaciers of Severnaya Zemlya came into existence only during the Holocene (Govorukha, 1988).

In favour of the first hypothesis, recent palaeoglaciological reconstructions (Lindstrom and MacAyeal, 1989; Grosswald and Glebova, 1991) consider a 2500 m thick ice cover for Severnaya Zemlya in the Late Glacial Maximum. However, no Pleistocene ice has yet been found on the archipelago. Did the Pleistocene ice melt during the Holocene thermal optimum? But there is some ice underneath the ice from the Holocene thermal optimum (Vaikmäe and Punning, 1984; Klement'yev and others, 1991). In the Academy of Sciences ice dome, it is possible to recognize such climatic events as YD and

Alleröd (Fig. 2). Moreover, the isotopic data presented here seem to confirm the second hypothesis, with only buried Pleistocene ice locally preserved. The following evidence also indicates the small extent of Severnaya Zemlya glaciers during the Pleistocene/Holocene transition. ^{14}C dating of vegetation remnants at the edges of the Vavilov ice cap and of the Academy of Sciences ice dome gives the following ages: 9950 ± 110 BP and 9620 ± 110 BP (Leningrad University, Nos 665 and 1160) and 6990 ± 170 BP (Institute of Geography, U.S.S.R. Academy of Sciences, No. 879) (Makeyev and others, 1979; Kotlyakov and others, 1991; Barkov and others, 1992).

All these arguments indicate that large glaciers did not exist in Severnaya Zemlya during the late Pleistocene. Either the local glaciers were relatively small during the Last Glacial Maximum (18 000 BP; Faustova and Velichko, 1992) because of dry climate during this period, or the ice caps were relatively thin (Bol'shiyanov and Nikolayev, 1992).

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