"Pollen and Isotope Investigations of an Ice Core from Vavilov Ice Cap, October Revolution Island, Severnaya Zemlya Archipelago, Russia"

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Géographie physique et Quaternaire, vol. 51, n° 3, 1997, p. 379-389.

Géographie physique et Quaternaire, 1997, vol. 51, n° 3, p. 379-389, 4 fig., 2 tabl.

POLLEN AND ISOTOPE INVESTIGATIONS OF AN ICE CORE FROM VAVILOV ICE CAP, OCTOBER REVOLUTION ISLAND, SEVERNAYA ZEMLYA ARCHIPELAGO, RUSSIA

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SUMMARY The Vavilov Ice Cap (79°27'N, 95° 21'E) was cored during February and March of 1988. The corer passed through 457.18 m of glacier ice, 2.15 m of moraine-containing ice, and 2.28 m of underlying rocks. Structural-stratigraphical and isotope analysis show the glacier ice is of Holocene in age; the ice layer covered by frozen deposits is Pleistocene glacier ice; and the ground (ice wedge?) ice from underlying sediments was formed during the Last Interglacial. Palynological studies of this core, carried out for the first time in the Russian Arctic demonstrate that the pollen spectra have a unique pattern. It reduces the possibility of correlation between the Vavilov Ice Cape spectra and pollen spectra from other surficial deposits, because the ice retains pollen and spores brought from enormous distances. Only the upper 65 m of the core is easily dated, to the last millennium, by the presence of cereals, *Plantago lanceolata*, *Centaurea cyanus, Cannabis* pollen. That is in good agreement with the model of age distribution based upon depth. The presence of considerable amounts of *Tilia cordifolia* pollen, a West-European species in the upper layers suggests that summer air masses have been dominantly from the southwest during the last 500 years. The pollen data do not contradict the conclusion the Vavilov ice core is composed of a section of Holocene ice, moraine-containing ice representing the Pleistocene episode, and a ground ice formed during an earlier warm period (Last Interglacial?).

RÉSUMÉ *Analyses pollinique et isotopique de la calotte glaciaire de Vavilov, Île de la Révolution d'Octobre, archipel de Severnaya Zemlya, Russie.* Une carotte de glace prélevée en 1988 au sein de la calotte glaciaire de Vavilov (79°27', 95°21'E) a fait l'objet d'analyses isotopiques et palynologiques. Le sondage comprend 457,18 m de glace « pure », suivis de 2,15 m de glace chargée de sédiments et 2,28 m de roches gelés du socle. Les résultats des analyses structurales, stratigraphiques et isotopiques sont les suivants : la glace pure datée de l'Holocène, les 2,15 de la couche chargée de sédiments datent du Pléistocène, tandis que la glace présente dans les fentes du socle s'est formée au cours du dernier interglaciaire. Les spectres polliniques de cette carotte sont caractérisés par des grains de pollen d'origine lointaine préservés dans la glace. Cette constatation réduit grandement les possibillités de corrélation avec les données sédimentaires de la région, qui reflètent la composition de la végétation locale. Un âge inférieur à 1000 ans peut être attribué aux 65 m supérieurs de la carotte en raison de la présence de pollen de céréales, de *Plantago lanceolata, Centaurea cyanus* et de *Cannabis*. Cette interprétation concorde avec le modèle du taux d'accumulation de la glace. Dans la partie supérieure de la carotte, la présence en quantité considérable de *Tilia cordifolia*, une espèce de tilleul d'Europe de l'Ouest, laisse supposer que les masses d'air en provenance du sud-ouest ont prédominé au cours des étés des 500 dernières années. En conclusion, les données palynologiques ne contredisent pas les résultats antérieurs selon lesquels la carotte glaciaire étudiée couvre une partie de l'Holocène, que la glace contenant la moraine représente l'épisode du Pléistocène et que la glace du socle se soit formée pendant une période chaude (le dernier interglaciaire?).

РЕЗЮМЕ *Палинологические и изотопные исследованя ледяного керна с Купола Вавилова, остров Октябрьской Революции, архипелаг Северная земля.* Купол Вавилова (79°27' с.ш, 95°21' в.д) был пробурен в феврале-марте 1988. Бур прошел 457.18 м “чистого” льда, 2.15 м морено-содержащего льда и 2.28 м мерзлых подстилающих пород. Стратиграфические и изотопные исследования показали голоценовый возраст чистого льда. Лед, перекрытый мерзлыми породами, датируется плейстоценом, а лед из подстилающих поржд, (ледяная жила?) сформировался в последнее межледниковье. Впервые для Российского сектора Арктики было проведено палинологическое изучение ледяного керна.Уникальный характер пыльцевых спектров существенно снижает возможности корреляции между этими спектрами и палиноспектрами из других типов отложений. Ледовые спектры накапливали пыльцу принесенную с больших дистанций. Только верхние 65 м ледяного кернд моут быть уверенно датированы последним тысячелетием благодаря присутсгвию пыльцы хлебных злаков, *Plantago lanceolata, Centaurea cyanus, Cannabis,* что хорошо согласуется с моделью распределения возраста слоев льда с глубиной. Присутствие значительного количества пыльцы западно-европейской липы, *Tilia cordifolia* в верхних слоях льда свидетельствует о доминировании юго-занадного переноса в течении последних 500 лет. В целом, результаты пыльцевого анализа не противоречат выводам стратиграфического и изотопного анализов.

Manuscrit reçu le 2 février 1996 ; manuscrit révisé accepté le 5 mai 1997.

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INTRODUCTION

Paleoenvironmental data from the high-latitude Arctic are very important for understanding patterns of past and present global climate circulation. Pollen analysis is one method that provides a view on vegetation dynamics, climate history, and sediment stratigraphy. Unfortunately, in high-latitude areas there are usually few opportunities to use palynology for investigating deposits that have continuously accumulated during more than a few millennia. Estimating the age of the deposits is often a difficult task, too. However, ice cores from the high-latitude islands provide a unique opportunity for palynological investigation of long-term records in parallel with isotope analysis, the results of which allow us to evaluate an ice core's age.

A number of papers are devoted to palynological investigations of ice cores from the Canadian Arctic and Greenland (Fredskild and Wagner, 1974; Lichti-Fedorovich, 1975a, 1975b; McAndrews, 1984; Short and Holdsworth, 1985; Bourgeois, 1985, 1986; Koerner *et al.*, 1988). These studies have demonstrated the possibility of correlation between pollen fluctuations and glaciological events in the high Arctic. Long-distance transported pollen grains generally dominate the pollen spectra, although the presence of a considerable number of pollen grains from the local vegetation is noticed by all the authors. Interpretation of the ice spectra is rather complicated, but some correlations between the pollen assemblages in the ice and the local and regional landscapes with climatic changes have been made (McAndrews, 1984; Bourgeois, 1986).

This paper presents the results of pollen analysis of the Vavilov ice core in conjunction with isotope, structural, and stratigraphic analyses. The new data have helped the understanding of environmental changes in the Arctic. The palynological investigation of an ice core were done for the first time in the Russian Arctic. These results allowed us to estimate the age of the upper part of the ice core and provide the unique possibility to infer past atmospheric circulation patterns. However, direct correlation of the Vavilov Ice Cap pollen assemblages with regional pollen diagrams is impossible.

DESCRIPTION OF THE STUDY AREA

Vavilov glacier, located in the southwestern part of the October Revolution Island (Fig. 1), was chosen as a location

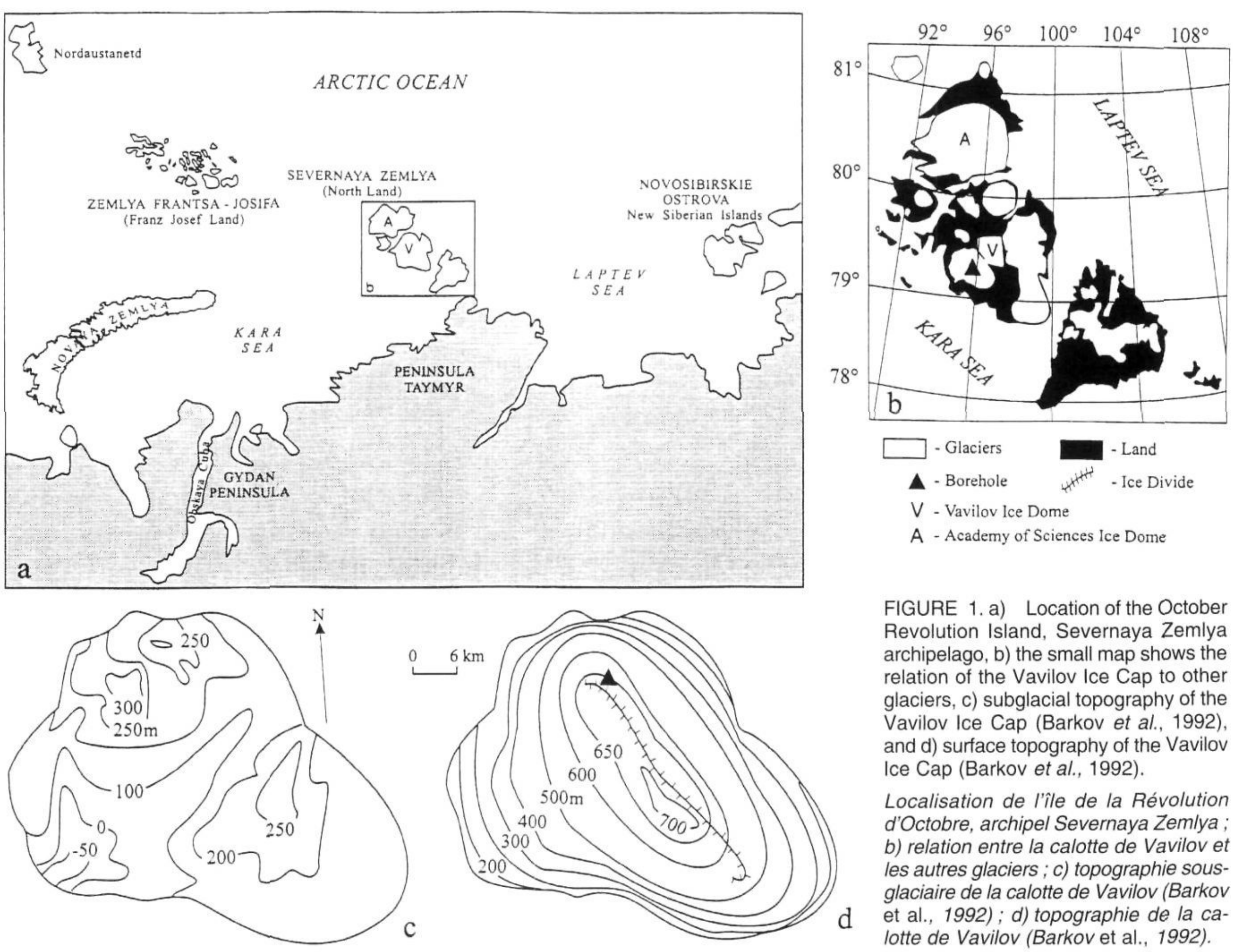

FIGURE 1. a) Location of the October Revolution Island, Severnaya Zemlya archipelago, b) the small map shows the relation of the Vavilov Ice Cap to other glaciers, c) subglacial topography of the Vavilov Ice Cap (Barkov *et al.*, 1992), and d) surface topography of the Vavilov Ice Cap (Barkov *et al.*, 1992).

Localisation de l'île de la Révolution d'Octobre, archipel Severnaya Zemlya ; b) relation entre la calotte de Vavilov et les autres glaciers ; c) topographie sous-glaciaire de la calotte de Vavilov (Barkov et al., *1992) ; d) topographie de la calotte de Vavilov (Barkov* et al., *1992).*

for a lengthy and detailed investigation of the thermal regime and inner structure of the Severnaya Zemlya archipelago glaciers. Glaciological studies on the glaciers have been carried out since 1962. Year-round continuous observations of the Vavilov Ice Cap were carried out at the glaciological station (79°27'N, 95°21'E, 665 m a.s.l.) from 1974 to 1989 (Barkov *et al.*, 1992). This study greatly increased our knowledge about glaciation of the Severnaya Zemlya archipelago and of the Russian Arctic in generally.

The Vavilov Ice Cap is about 1820 km^2 in area (Barkov *et al.*, 1992). The gypsometrical marks of the ice cap are up to 728 m and its maximum diameter is 55 km. The maximum thickness of the glacier is 610 m, based on radio-location data (Boyarsky *et al.*, 1981). The deepest borehole reached bedrock at a depth of 556.5 m (Morev *et al.*, 1988). The glacier lies on a dissected plateau that is above 200 m, with only the southwestern part of its underlying surface close to sea level. The long axis of the ice cap is oriented northwest to southeast.

October Revolution Island is covered mostly by Paleozoic highly-fractured sedimentary rocks. The Quaternary deposits of marine, deltaic, and glacial origin (Makeev *et al.*, 1992) are situated in river valleys. Watersheds are covered by a thin, fragmented cover of alluvium and till.

The climate is extremely severe. January temperatures reach –29 to –33°C. Positive air temperatures are observed only in July and August. During these two months, three local climatic zones are distinguished: glacial, periglacial, and marine. In the periglacial zone the air is warmer by 2 to 3°C than in the marine zone. The marine zone, in turn, is warmer than the glacial zone by 1.5 to 2°C (Bryazgin and Yunak, 1988). According to data from the polar station in the marine zone, July usually is the warmest month with an average temperature varying from –0.5° to +2.7°C. Average annual air temperature is –13 to –14°C. The average annual precipitation is 400 mm in the glacial zone and 240-260 mm in the marine zone. Everywhere on the archipelago, 70% or more of the precipitation falls as a snow. The maximal amount of precipitation in the marine and periglacial zones was observed in September, whereas in the glacial zone it was from September to October. The non-snowy period lasts about two months (July to August).

The combination of low air temperatures and strong winds causes considerable severe weather (Catalogue Glaciers of USSR, 1980). The glaciers also influence the local climate. For example, Vavilov Ice Cap is an orographic barrier to air masses bringing precipitation from the southwest (Barkov *et al.*, 1992; Nikolaev and Kolokolov,1993). Glaciological conditions on the Vavilov Ice Cap are variable. Periods of anomalous warmth or little snow will lead to changes in the glacial growth-rate and alimentation (from firn to superimposed ice) even on the top of the ice cap. During some years, conditions typical of the sub-cold firn subzone create considerable glacial runoff and the formation of small melt layers in the upper horizons of the snow-firn mass (Govorukha, 1988).

The vegetation cover of the island is made of herb, moss, and lichen polygonal arctic deserts (Korotkevich, 1958). A great diversity of vegetation exists on river terraces in the central part of the island, where plants such as *Artemisia borealis, Siversia glacialis,* and *Potentilla emarginata*, rare for the archipelago, are found. On the island there are about 70 species of higher vascular plants, belonging to the following families: Brassicaceae (16 species), Poaceae (15), Saxifragaceae (11), Caryophyllaceae (7), Rosaceae (5), Salicaceae (4), Juncaceae (3), Ranunculaceae (2), Papaveraceae (2), Cyperaceae (1), Polygonaceae (1), Boraginaceae (1), Scrophulariaceae (1) and Asteraceae (1). The zonal climatic group of the flora on October Revolution Island are representative of high-arctic flora. Arctic and arcto-alpine species dominate the flora (Safronova, 1981).

LOCATION OF THE BOREHOLE AND DRILLING

A borehole was made near the glaciological station in 1988 (Fig. 1). The borehole is located at the edge of the present-day accumulation zone, 20 km to the northwest of the ice cap summit (Barkov *et al.*, 1988). Present accumulation in the borehole area is 8 g/cm per year (Bryazgin, 1981). The corer passed through 457.18 m of "pure" glacier ice, 2.15 m of moraine-containing ice (including 1.35 m of large-fragmented debris), and 2.28 m of underlying frozen rocks. The description of the ice core macrostructure was made in the field. Samples for isotope and palynological analyses were taken from the "pure" ice and samples for granulometrical and mineralogical analyses were taken from the moraine-containing ice and frozen underlying rocks. Microstructural studies were performed on individual horizons in order to correlate this new ice core with previous boreholes (Barkov *et al.*, 1988; Klement'ev *et al.*, 1988, Bol'shiyanov *et al.*, 1990).

RESULTS OF STRUCTURAL, STRATIGRAPHIC, AND ISOTOPE INVESTIGATION OF ICE CORE

Direct dating of ice cores is difficult. Ice flow models are usually utilized and compared with structural and stratigraphic results from firmly dated paleodata. Our initial age model is based on a modified Nay model of steady-state glacier (Hammer *et al.*, 1978), using the present accumulation rate of 8 g/cm per year in the area of the drillhole site (Bryazgin, 1981). This calculation should be reliable for the upper two-thirds of the ice mass and yields an age of about 5400 yrs BP for the depth of 300 m (Fig. 2).

On the basis of the macroscopic description of the ice core, three genetic types of ice were distinguished: regelation, infiltration, and infiltration-congelation. The texture and structural characteristics of the ice core were described according to Korotkevich *et al.* (1985), who found that the ratio of the different genetic ice types can be an important stratigraphic and climatic indicator. The percentage of infiltration and infiltration-congelation ice in the core, at 5 m intervals, as shown in Figure 3, can be interpreted in light of summer air temperatures.

One of the main factors influencing the type of ice formed is the presence of melt water, which in turn depends upon air temperature during the ablation period. When melting is absent or not significant, regelation ice (an indicator of cold conditions) forms. Infiltration ice reflects the conditions of a

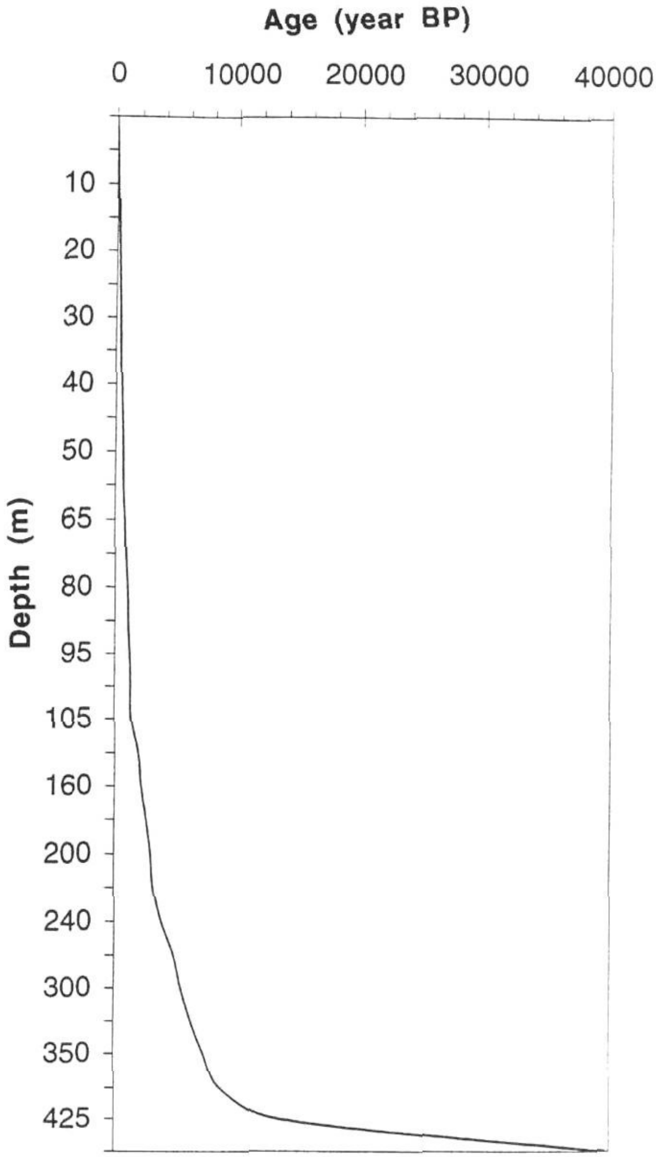

FIGURE 2. Age/depth curve, calculated by the modified model of a stationary Nay glacier (Hammer *et al.*, 1978).

Courbe âge/profondeur, calculée à partir d'un modèle fondé sur le modèle Nay d'un glacier stabilisé (Hammer et al., *1978).*

moderately warm season, when temperature conditions cause melting. The infiltration-congelation ice is formed by considerable melting in warm summers. An investigation of the Vavilov glacier (Korotkevich *et al.*, 1985) demonstrated a strong dependence of the ice layer structure upon the summer season temperature. They found that when frequent alternation of cold and warm periods takes place, the resulting macroscopic ice produced structure in an exaggerated view of the warm summer season. The absence of regelation ice in the core falsely indicates that cold summer periods lasted at least several years in succession, because water filtration into the porous firn layers during warm summers can totally mask features from previous cold years. This process is demonstrated in the upper part of the core from the Vavilov Ice Cap (Fig. 3). As the ice flowed from the summit to the present borehole, thawing and infiltration processes increased in the newly deposited snow. As a result, the apparent fluctuation between infiltration and infiltration-congelation ice decreased dramatically, although their real average values increased considerably.

The amount of infiltration ice in the core is often close to 100%, making it impossible to use warm peaks for correlation. Thus, it is better to use cold peaks for climatic-stratigraphic correlation with the Severnaya Zemlya glacier data, at least for the upper part of the cores. The most notable cold peaks in our core are situated at the following depths: 170 m (2300-2400 yrs ago), 195-225 m (2800-3400 yrs ago) and 250-310 m (4000-5700 yrs ago). These three peaks indicate time periods of decreased summer ablation on the ice cap. The younger two peaks are corroborated indirectly by ice accumulation data from the Severnaya Zemlya glaciers (Kotlyakov *et al.*, 1989). The accumulation maximum occurred about 2500-2700 yrs ago. According to the temperature distribution data in the Vavilov glacier, the age of the maximum Holocene glacial expansion on Severnaya Zemlya was 2400 yrs ago (Barkov *et al.*, 1988). Relatively cold summer conditions were also inferred for the interval of 250-310 m (4000-5700 yrs ago). This cold period was interrupted by brief rises in temperature about 4500-4600 and 5100-5300 yrs ago, at depths of 270-275 and 290-295 m, respectively. In the interval from 310-445 m (more than 5700 yrs ago), ice structural and stratigraphical data from the core suggest relatively warm summer conditions.

The oxygen isotope analysis of the ice core is presented in Figure 3. Values of $\delta^{18}O$ of the glacier ice on Severnaya Zemlya are related to the temperature of atmospheric precipitation and to the temperature during warm seasons, which determines snow thawing. This process is accompanied by meltwater runoff causing additional isotope fractionation. However, there is a statistically significant correlation between averaged ten-year values of $\delta^{18}O$ ice and air temperature, according to metereological observations (Kotlyakov and Gordienko, 1982). The oxygen isotope curve and previous data from Severnaya Zemlya (Vaikmyäe and Punning, 1982; Kotlyakov *et al.*, 1989, 1991) exhibit considerable variations in values of $\delta^{18}O$ for the upper part of the core, relatively stable conditions in the middle part, and high (warm) values in the lower part. For the lowest 25 m of the core, considerable $\delta^{18}O$ fluctuations also are observed. The average modern isotope content of atmospheric precipitation on Vavilov Ice Cap is -19‰ and the minimum value of isotope shift at the boundary between Pleistocene and Holocene ice is 5-6‰ (Nikolaev and Kolokolov, 1993). Pleistocene level of isotope values were not found in the core except in the basal stratum. Several sharp oscillations typical for the transitional period from the Late Pleistocene to Holocene were recorded in the basal layer of the ice (Fig. 3). However, it is not possible to correlate these oscillations with known climatic events because the ice layers could be formed by folding of basal ice (Boulton, 1993).

According to the oxygen isotope curve, the thermal optimum is observed at depths greater than 375 m, more than 8500 yr ago. This corroborates well the estimate of 8800-

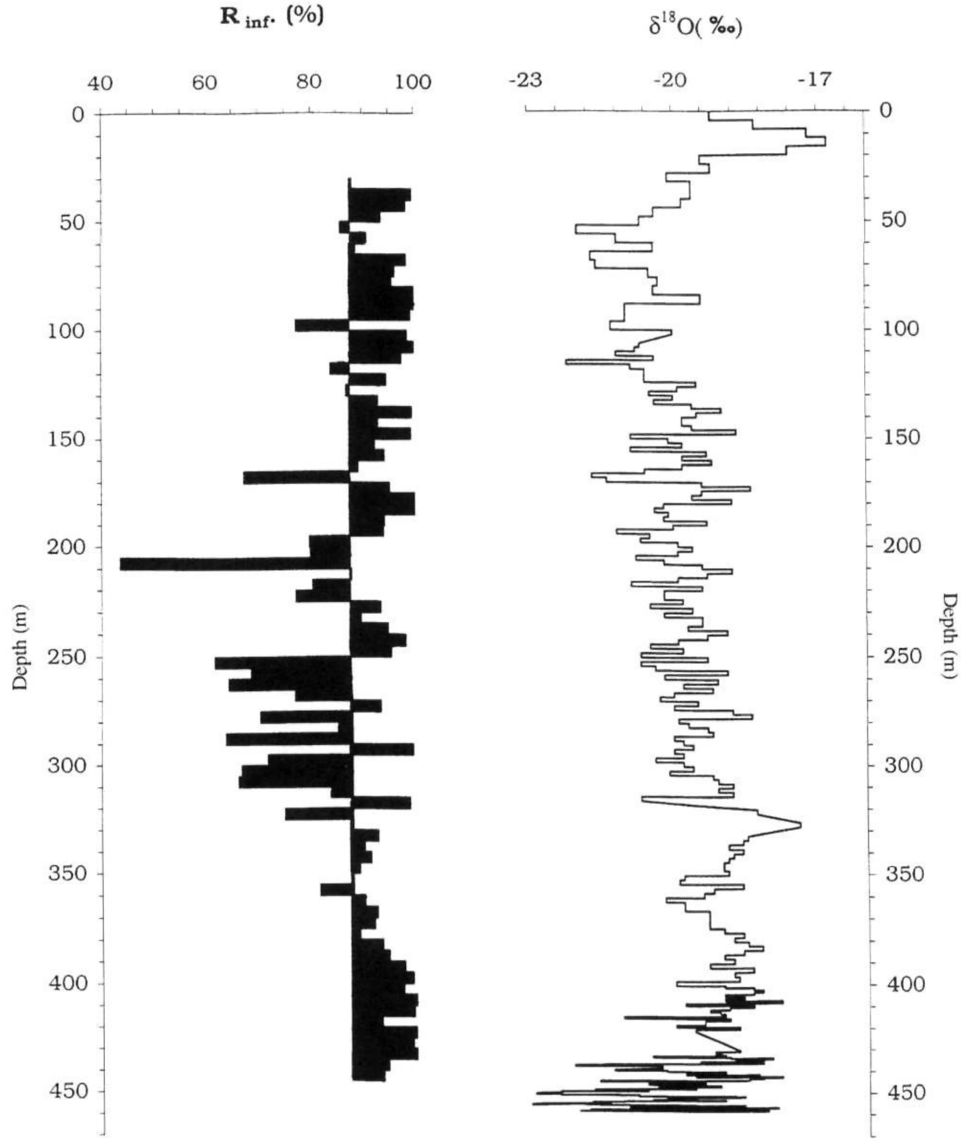

FIGURE 3. Results of structural and stratigraphical ($R_{inf.}$ - percentage of infiltration ice) and isotope (^{18}O, %) studies of the ice core from the Vavilov Ice Cap, October Revolution Island, Severnaya Zemlya archipelago.

Résultats d'études structurales et stratigraphiques ($R_{inf.}$ - pourcentage de glace d'infiltration) ainsi qu'isotopiques (^{18}O, %) de la carotte de la calotte glaciaire de Vavilov, île de la Révolution d'Octobre, archipel Severnaya Zemlya.

10800 yr BP for the climatic optimum on Severnaya Zemlya suggested by Bo'Ishiyanov and Makeev (1995) on the basis of Quaternary sedimentary deposits. A slight temperature drop took place about 7300-8500 yr BP (350-375 m depth) according to the oxygen isotope curve (Fig. 3), followed by a temperature rise that occurred about 6000-7300 yrs BP (315-350 m depth). A steady fall in temperature is recorded in the upper part of core, reaching the lowest values about 600 yrs ago (50-55 m depth). According to previous studies on Severnaya Zemlya glaciers (Kotlyakov *et al.*, 1989, 1991), the thermal optimum is estimated at about 7000-9000 yrs ago, followed by a fall in temperature from about 7000 to 6000 yrs ago, followed by a rise in temperature from about 5000 to 6000 yrs ago. This pattern also fits well with the climatostratigraphy of Eurasia suggested by the palynological data (Khotinsky, 1987). However, there is no clear correspondence between the ages of climatic events reconstructed by pollen and those of the oxygen isotope data from the Vavilov Ice cap. It should be noted that the estimation of ice age was based on an assumption of stationary conditions of Vavilov Ice Cap, although even at its summit (where the conditions are the most stable), ice accumulation during the Holocene varied within 90-150% of its modern level (Nikolaev *et al.*, in press). We believe that the trend toward a decline in temperature is caused by the patterns of the Severnaya Zemlya glacier growth during the Holocene (see also Kotlyakov *et al.*, 1991).

The results of structural and stratigraphic investigation of the ice show that the borehole passed through the pure ice, moraine containing ice, ice with large-fragmented debris, and underlying frozen unlithified rocks. Isotope studies (δD and $\delta^{18}O$) of the debris-containing ice and the ice from the underlying frozen rocks offered an opportunity to determine if the genesis of the investigated ice is the glacial or permafrost in origin. The debris containing ice was identified as Pleistocene by its isotopic composition (up to δD=–187‰ $\delta^{18}O$=–26‰)

(Stievenard *et al.*, 1996). The ice from underlying frozen unlithered sediments consists mostly of segregation ice and ice-cement. According to the oxygen isotope data, its main water source is snow-melt water (Nikolaev and Mikhalev, 1995). The oxygen isotope content of the original water in the underground ice was $\delta^{18}O=-13‰$. Using a value for the isotope to temperature ratio of 0.5–0.6‰ per °C, we then estimated that the temperatures during permafrost formation were about 10° warmer than present-day January temperatures (Nikolaev and Mikhalev, 1995). The January temperatures on Severnaya Zemlya were higher than the modern by 10 to 12°C during the Last Interglacial, 125,000 yrs ago (Atlas of Paleoclimates and Paleoenvironment of the Northern Hemisphere [Late Pleistocene - Holocene], 1991). Thus, we infer that the investigated ice core is mostly of Holocene age. There is the possibility of stratigraphical breaks in periods with high summer ablation. Debris-containing ice represents the Pleistocene episode, and ice from underlying frozen unlithified was likely formed in a warm period, probably the Last Interglacial.

METHOD OF PALYNOLOGICAL STUDY

After taking samples for oxygen-isotope and other analyses, the ice core was sampled in the field for palynological study. The average length of the core segment for palynological studies was about 2-2.5 m, and varied from 1.5 to 4 m. The core diameter was from 8 to 10 cm. To avoid pollen contamination, the surfaces of core segments were carefully rinsed with filtered water before melting the core samples. The melted water was filtered through 10 μm membrane filters, with a vacuum pump to help speed the filtering. The average volume of filtered liquid was about 22 liters per sample.

The filters were dried and dissolved in acetone under clean-hood conditions in Moscow. The samples, containing mineral particles (mostly rounded and non-rounded grains of quartz and muscovite) together with spores and pollen, were centrifuged. The sediment remaining was then subjected to acetolysis. Modern pollen rain samples were collected from snow, firn, the upper 20 cm of ice on Vavilov glacier, and also snow samples from non-glaciated parts of the island. All 17 samples from the upper 42 m of the core proved to be considerably different from pollen spectra from lower strata. Palynological analysis of the lower part of the ice core was carried out at about 10 to 15 m intervals (32 samples total). Nine samples were analyzed from the ice-containing debris and underlying sediments at the depth of 458-462 m.

The results of pollen analysis are presented in Figure 4, Tables I and II. A pollen percentage diagram was not made as many ice samples contained less than 50 pollen grains in the sample (Table I).

RESULTS OF PALYNOLOGICAL STUDIES

The total pollen sum fluctuates considerably from one sample to another (from 1,545 grains at the depth of 4.78-6.21 m, to 10 grains at 26.56-28.75 m and 9 grains at 247.5-250.02 m). Generally, the depth of the samples did not

TABLE I

Pollen sum and subdivision of pollen taxa from the Vavilov Ice Cap core to groups

Depth (cm)	Pollen sum	Local pollen sum	Long distance pollen and spores sum		
			Tundra and taiga taxa	Thermophilic plants	Antropophytes
1	2	3	4	5	6
snow 1	15	4	11		
snow 2	74	31	49	1	2
firn	254	20	234		
0.00-0.20	169	29	136	1	3
2.65-4.65	302	29	267	6	
4.78-6.21	1547	1322	69	152	2
6.51-8.45	617	469	88	59	1
8.77-10.70	180	124	3	36	2
10.70-12.31	81	43	14	24	
12.61-14.60	42	26	4	12	
14.60-16.62	111	62	37	11	1
17.00-18.79	29	22	4	3	
21.65-22.82	146	109	14	23	
24.51-25.98	49	31	12	6	
26.56-28.25	10	4	5	1	
28.68-30.38	24	10	12	2	
30.38-32.41	254	187	44	20	3
32.41-34.75	123	79	35	9	
34.75-36.30	61	41	20	2	
37.75-40.05	418	317	86	10	5
40.05-41.84	265	93	159	2	11
52.26-54.00	39	19	15	4	1
62.06-65.49	206	60	134	10	2
74.05-76.10	44	13	31		
84.01-86.00	102	41	57	2	2
92.13-93.93	39	8	27	4	
93.93-96.00	75	33	36	6	
96.00-98.02	17	9	8		
113.11-115.86	60	13	46	1	
121.89-124.01	27	11	15	1	
139.06-140.82	38	8	29	1	
154.30-157.32	34	12	21	1	
168.55-171.47	53	12	40	1	
182.04-184.23	12	4	8		
198.09-201.98	107	41	63	3	
216.08-218.95	32	8	23	1	
232.03-233.84	20	6	12	2	
247.52-250.02	9	2	7		
265.89-269.05	112	32	77	1	
283.83-286.76	53	13	40		
300.22-304.79	141	51	90	2	
318.77-322.78	64	11	43	6	
336.22-340.07	128	60	64	4	2
352.10-355.84	54	25	28	1	
368.74-372.10	48	14	3	4	
385.14-388.00	42	14	25	3	
399.29-401.94	21	8	12	1	
414.01-416.84	22	5	16	1	
426.31-428.85	17	13	4		
437.17-439.60	14	5	9		
449.33-451.92	44	12	30	2	
454.43-457.07	14	5	7	2	
458.02-458.29	55	15	39	2	
458.44-458.54	113	18	92	3	
458.59-458.70	0				
459.99-460.15	7		7		
460.15-469.24	6		6		
460.24-460.41	21	6	15		
461.03-461.35	1		1		
461.35-461.46	15	8	6	1	
461.46-461.61	14	3	11		

TABLE II

Rare pollen and spore taxa not included in the diagram from the Vavilov Ice Cap core

	total pollen grains
Local taxa	
Papaveraceae	1 at 62.06 m
Brassicaceae	1 at 458.44 m, 3 at 37.75 m
Scrophulariaceae	1 at 10.70 m
Tundra and taiga taxa	
Abies	4 at 0 m, 1 at 4.78 m and 198.09 m, 2 at 336.22 m, 6 at 458.44 m
Larix	2 at 2.65 m, 4.78 m, 1 at 30.38 m, 34.75 m, 113.71 m, 300.22 m, 458.44 m, 461.46 m
Lamiaceae	1 at 2.65 m, 4.78 m, 10.7 m and 32.41 m
Fabaceae	1 at 28.68 m
Thalictrum	1 at 40.05 m and 458.44 m
Plantago sp.	2 at 40.05 m, 52.28 m and 318.77 m
Plumboginaceae	1 at 113.71 m
Ericales	1 at 426.31 m
Polemonium	1 at 2.65 m
Valeriana	1 at 32.41 m
Myriophyllum	1 at 8.77 m and 336.22 m
Typha	1 at 4.78 m and 36.31 m
Potamogeton	1 at 32.41 m
Utricularia	1 at 37.75 m
Indeterminable pollen	3 at 10.7 m, 1 at 8.77 m, 84.01 m, 113.71 m, 182.04 m, 458.15 m, 458.44 m
Pteridium aquilinum	1 at 40.05 m and 62.06 m
Antoceros levis	1 at 40.05 m
Lycopodium sp.	1 at 12.61 m and 34.75 m
L. alpinum	1 at 2.65 m and 4.78 m,
L. clavatum	1 at 182.04 m and 300.22 m
L. annotinum	1 at 300.22 m
L. tristachium	1 at 37.75 m
Thermophilous taxa	
Carpinus betulus	2 at 2.65 m, 4.78 m; 1 at 37.75 m, 62.06 m, 92.13 m, 198.08 m, 216.08 m, 265.89 m, 318.77 m
C. orientalis	1 at 300.22 m
Fagus	1 at 336.22 m
Quercus	1 at 336.22 m, 368.74 m and 449.33 m
Juglans	2 at 2.65 m, 4.78 m, 62.06 m, 385.14 m and 461.35 m
Malaceae	1 at 52.28 m
Rhamnus catharctica	2 at 62.06 m, 1 at 168.55 m and 449.33 m
Vitis	2 at 52.28 m, 1 at 336.22 m, 368.74 m, 385.14 m and 454.43 m
Humulus	1 at 336.22 m and 368.14 m
Malvaceae	1 at 458.44 m
Impatiens noli-tangere	1 at 458.44 m

significantly influence the concentration of grains, although, the greatest concentrations are recorded in the samples from the upper 65 m of the ice core (Table I).

Pollen and spores identified from each sample are divided into two groups: 1) pollen and spores of local plants, and 2) long-distance transported (exotic) pollen and spores. Pollen grains and spores of families and genera represented in the modern local flora, include Rosaceae (reaching a maximum of 84% in some spectra), *Artemisia* (65%), Poaceae (15%), Ranunculaceae (8.6%), *Salix* (5.4%), Polygonaceae (3.6%), Caryophyllaceae (1.6%), Brassicaceae (1%), Papaveraceae (0.6%), and spores of Bryales (1.2%). The pollen of local taxa dominates only the upper 4.78 to 49.05 m of the ice core.

Long transport pollen and spores were subdivided into the following subgroups: 1) tundra and taiga plants, 2) thermophilous, and 3) anthropophytes. Pollen grains of plants requiring warm conditions, typical of areas thousands of kilometers south and southwest of the island, are considered thermophilous. This subgroup comprises pollen from *Corylus avellana, Carpinus betulus, Carpinus orientalis, Fagus, Quercus, Ulmus campestris, Tilia cordifolia, Tilia cordata, Juglans, Rhamnus catharctica, Vitis, Humulus, Impatiens noli-tangere,* and Malaceae. Many of these are rare types in the pollen spectra. The pollen of *Corylus avellana* is most common, except in the samples in the upper 65 m of the core, in which *Tilia cordifolia* (*platyphyllos*) pollen is consistently found, sometimes reaching 30% of the total pollen spectra. Generally, the number of thermophilous taxa pollen is higher in the upper 65 m.

The small group of anthropophytes includes pollen of cultivated plants and weeds, such as cereals, Malaceae, *Centaurea cyanus, Plantago lanceolata,* and *Cannabis*. Single representatives of this group are found in the ice pollen spectra, but only in the upper 85 m of the ice core. Two exemples of large Poaceae (cereals?) pollen grains at the 336.22-340.07 m depth are most likely related to wild representatives of these family, such as *Agropyrum* or *Avena*.

Tundra and taiga plants are the most numerous group encompassing pollen and spores from the families and genera widespread in the tundra and taiga zones of the Northern Hemisphere today. Pollen of the following trees is consistantly present in the ice core: *Betula* sect. Albae (26%), *Betula* sect. Nanae (13%), *Betula* sect. Fruticosae (3.6%), *Alnus fruticosa* (39%), *Alnus glutinosa* (5%), *Alnus incana* (2.6%), *Pinus* s/g Diploxylon (21%), *Pinus* s/g Haploxylon (17%), and *Picea* (4.5%). Only single pollen grains of *Larix* and *Abies* were found, perhaps due to their poor aerodynamic structure or low pollen production rates.

Among the herb taxa, in addition to the ever-present pollen of *Artemisia*, Rosaceae, Poaceae, and Ranunculaceae refering to the group of local plants, pollen grains of the following taxa are constantly present: Chenopodiaceae (25%), Asteraceae (5.2%), Apiaceae (8%), and Cichoriaceae (3.2%). In addition to these taxa, single examples of pollen grains of the following taxa were identified: *Thalictrum,* Lamiaceae, Plumbagenaceae, *Typha*, Scrophulariaceae, *Potamogeton,* Fabaceae, *Polemonium,* Ericales, *Valeriana, Myriophyllum,* and *Utricularia*. Among alien palynomorphs, *Sphagnum* (24%) and *Polypodiaceae* (16%) more commonly found. Occasionally spores of the following taxa were identified: *Equisetum, Pteridium aquilinum, Anthoceros levis, Lycopodium alpinum, Lycopodium clavatum, Lycopodium annotinum,* and *Lycopodium tristachyum*.

The following pollen zones are delineated in the core (Fig. 4). Zone I from, 0.0 to 4.7 m depth, is dominated by taiga and tundra pollen taxa, with the highest concentration of

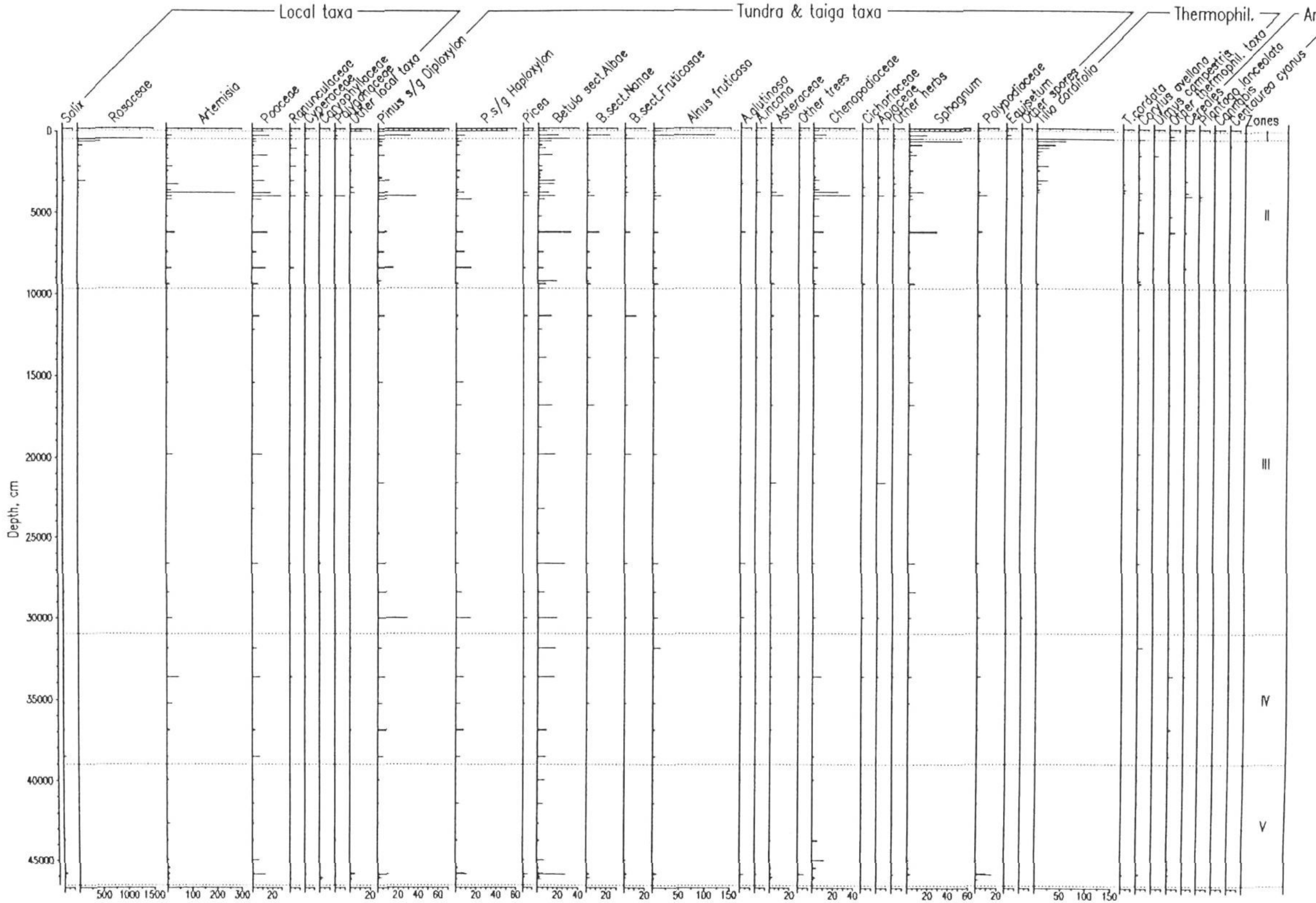

FIGURE 4. Pollen and spore diagram for Vavilov Ice Cap core. A pollen percentage diagram was not made because many samples contained less than 50 pollen grains.

Diagramme sporo-pollinique de la carotte de la calotte glaciaire Vavilov. Le diagramme de pourcentage pollinique n'a pas été fait en raison du trop grand nombre d'échantillons comprenant moins de 50 grains de pollen.

pollen. Zone II, from 4.7 to 96.0 m depth, is dominated mostly by local plant pollen with the thermophilous and anthropophytes pollen significant in the spectra. Zone III, from 96.0 to 310.0 m depth, is again dominated by taiga and tundra taxa pollen. Zone IV, from 310.0 to 388.0 m depth, is also dominated by taiga and tundra taxa pollen, although there is a small increase in thermophilous pollen. Two possible grains of anthropophytes pollen were also noticed in this zone. Zone V, from 388.0 to 461.61 m, is again dominated by taiga and tundra taxa pollen.

DISCUSSION

Parallel palynological, isotopic, structural and stratigraphic investigations were conducted on the ice core from the Vavilov Ice Cap. Since the results of the isotope, structural, and stratigraphic investigations already have been discussed (Barkov *et al.*, 1988, 1992; Bol'shiyanov *et al.*, 1990; Kotlyakov *et al.*, 1989, 1991; Nikolaev and Kolokolov, 1993; Stievenard *et al.*, 1996), we will focus here on the results of the pollen analyses.

Total pollen sum fluctuates considerably through the core (Table I). Importantly, neither the depth of the samples nor the length of the ice core segment (volume of the filtered water) significantly influence the number of grains found in a sample. The greatest concentrations of pollen (mostly local) are recorded in the samples from the upper 65 m of the ice core, which accumulated during the last 500-800 years (Fig. 2). The concentrations of pollen grains counted in the Vavilov ice core are similar to the numbers reported from the Canadian Arctic and Greenland (Fredskild and Wagner, 1974; McAndrews,1984; Bourgeois, 1986, 1990a).

Our snow and firn surface samples show large percentages of long-distance transported pollen, which agrees well with the palynological investigations of surface snow and glacial ice on Guker Island, Franz-Joseph Land (Krenke and Fedorova, 1961) and samples collected from several non-glaciated parts of October Revolution Island (Kalugina *et al.*, 1979, 1981). These studies all show relatively high amount of long-distance transported pollen. Some pollen grains of *Corylus, Tilia,* and cereals were found in samples from the Guker Island (Krenke and Fedorova, 1961). Snow from the High Arctic Canadian ice caps and Greenland studied by Lichti-Fedorovich (1974, 1975b) and Bourgeois (1990a, 1990b), also has the high contents of long-distant-transported (exotic) pollen.

The results of modern airborne sampling of pollen and spores during June-July, 1975, directly above Vavilov Ice Cap (Kalugina *et al.*, 1979, 1981) show a low concentration of pollen and spores, with most of the pollen not related to the local vegetation. Our studies show that snow and firn samples from October Revolution Island contain long-distance transported pollen as well as local taxa. Bourgeois (1990b) noticed annual and seasonal pollen variations in the snow layers from the Agassiz Ice Cap on Devon Island in the Canadian Arctic, that probably correlated with summer temperatures in the surrounding tundra and penetration of air masses from the south. The pollen data from the Vavilov Ice Cap (airborne pollen deposition obtained in June-July 1975 (Kalugina *et al.*, 1979, 1981), and our snow and firn pollen data obtained in February-March 1988) do not demonstrate significant seasonal variations.

The majority of pollen identified in the Vavilov Ice Core belong to local flora, especially in the interval from 4.71 to 40.05 m depth. Although, some of these palynomorphs result from long-distance transport, generally, we find it impossible to separate the local origin pollen from long-distance transport pollen of the same taxa. Thus, we relate all pollen grains from these taxa to the local plant pollen group. Indeed indirect evidence that the pollen grains in this group derive mostly from the local plants is the large number of small-sized, deformed pollen grains of Poaceae, Rosaceae, and *Artemisia*, suggesting that such pollen grains must have been produced in extremely unfavorable local conditions. Additional indirect evidence that most pollen from this group belongs to the local plants is the low percentage of Chenopodiaceae. Plants of the Chenopodiaceae family are absent in the modern flora of Severnaya Zemlya archipelago. As Chenopodiaceae pollen has the aerial transport characteristics about equal to that of Poaceae and *Artemisia*, the presence of Chenopodiaceae pollen (which is constantly present in the fossil pollen spectra) is a good indicator of the presence of long-distance transported pollen for these taxa. Chenopodiaceae pollen generally does not exceed 3-12%, indicating that most of the pollen from the local plants group belongs to local producers.

The presence of exotic pollen shows the possibility of long-distance transport. Some pollen grains, such as *Carpinus orientalis, Carpinus betulus, Vitis, Humulus Fagus, Quercus, Ulmus campestris, Tilia cordifolia, Corylus avellana, Tilia cordata, Juglans,* and *Rhamnus catharctica,* were transported thousands of kilometers from the south and southwest. Some of these taxa (ex. *Corylus avellana)* occur in the pollen spectra at a constant concentration. The high percentages of *Tilia cordifolia* pollen, a mainly western European species of limes (Flora USSR, 1949) that flowers in June-July, suggests dominance of air masses transported from further southwest over the archipelago during the last 500 years. As previous investigations show (Barkov *et al.*, 1992; Nikolaev and Kolokolov, 1993), the Vavilov Ice Cap serves as an orographic barrier to air masses, bringing precipitation from the southwest today. Pollen of other lime species (*Tilia cordata*), which is also growing in western Europe and is widespread in the European part of Russia and in southern Siberia, are very rare in the pollen spectra.

McAndrews(1984) shows that pollen in the ice core spectra from the Devon Ice Cap was relatively sparse during the early Holocene because of long-distance origin, when a continental ice sheet existed. After the continental glacier disappeared during the middle Holocene, plants could grow locally and frequency of air masses incursions carrying exotic pollen increased. Pollen in the Vavilov ice core accumulated in relatively stable climatic conditions. The immediately adjacent areas of Siberia and Russian Arctic were not covered by ice sheets during the Late Pleistocene and Holocene (Bol'shiyanov and Makeev, 1995, Andreev *et al.*, 1997;

Serebryanny *et al.*, in press). So, pollen influx on the Vavilov Ice Cap was not directly influenced by continental glaciers as were the ice caps on the Canadian Arctic islands. Possibly, the Scandinavian ice sheet had a strong effect on air masses over the Vavilov Ice Cap during the early Holocene.

The anthropogenic pollen indicators are found only in the upper 85 m of the ice core, which accumulated during the last thousand years according to our age-depth model (Fig. 2). Thus, the age-depth model is in good agreement with pollen data: the large increase of cereals and weedy pollen in pollen spectra is found in deposits of different origin in both Russia and western Europe, and is radiocarbon dated to the last millennium (Behre, 1981; Berglund, 1985; Khotinsky *et al.*, 1991; Kremenetski, 1995; Odgard, 1989).

The designated pollen zones do not correlate with the cold peaks and the temperature increases interpreted from isotope curves. Our pollen studies demonstrate the unique characteristics of pollen spectra from the Vavilov ice core, which essentially reduces the possibility of using palynological stratigraphy for correlating high-latitude Arctic glacial events in this region. The published pollen diagrams from adjacent areas of Siberia are completely different (Khotinsky, 1977, Andreev *et al.*, 1989, 1993, 1997; Serebryanny *et al.*, in press) and can not be used for comparison.

The pollen results from the Vavilov Ice Cap also touch upon one of the important aspects of palynology - the problem of correspondence between the pollen spectra composition and the actual vegetation. Pollen percentages can differ considerably from the ratio of pollen to source plants in the community due to a number of factors, including pollen productivity, aerodynamics, transportation and burial, and/or differential resistance to chemical and mechanical factors.

Long-distance pollen transportation normally does not significantly influence the pollen spectra, but it is usually assumed that it does not influence results when reconstructing the vegetation itself. However, our investigations indicate that when we deal with deposits formed in areas with extremely sparse vegetative cover or plants with reduced flowering activity, then long-distance pollen will considerably influence the pollen spectra. Long-distance wind-blown pollen can, and in the past could have, play a dominant role not only in the Arctic, but also in arid areas (deserts, periglacial landscapes). Thus the interpretation of palynological data from these types of deposits should be carried out with extreme caution.

CONCLUSIONS

Our results indicate that it is impossible to find a direct correlation between pollen from the Vavilov Ice Cap and regional pollen spectra from deposits of other types, because the ice accumulates pollen and spores brought from enormous distances. The upper 65-85 m of the ice core is easily dated to the last one thousand years by the presence of cereals and weedy pollen in the pollen spectra. This conclusion is in good agreement with the age-model for ice accumulation that is depth dependent. Exotic pollen, which suggests very long-distance transport, is of great interest in terms of air mass changes. For example, the presence of considerable amounts of the West-European limes species, *Tilia cordifolia* (*platyphyllos*), in the upper 65 m depth suggests that summer air mass dominance has been from the south-west during the last 500 years.

The pollen data do not contradict the following isotope date: from the surface to the depth of 457.18 m the Vavilov ice core is Holocene in age, from 457.18 to 459.33 m, debris-containing ice represents the Pleistocene epoch, and then between 459.33 and 461.61 m, frozen unlithified sediments deposited during a warm period, probably the Last Interglacial. However, there is a possibility of stratigraphical breaks during periods with high summer ablation, which created significant amounts of infiltration ice in the core.

ACNOWLEDGEMENTS

We would like to thank the members of the drilling team, for the work would not have been possible without their co-operation. We would also like to acknowledge very thorough criticism by Drs P.T. Davis, J.H. McAndrews, and P.J.H. Richard, which improved the quality of the paper. We thank Drs. D. Peteet and M. Kneller for their critical review of an early draft.

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