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Palaeoclimate Reconstruction on Big Lyakhovsky Island, North Siberia—Hydrogen and Oxygen Isotopes in Ice Wedges

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ABSTRACT

Late Quaternary permafrost deposits on Big Lyakhovsky Island (New Siberian Islands, Russian Arctic) were studied with the aim of reconstructing the palaeoclimatic and palaeoenvironmental conditions of northern Siberia. Hydrogen and oxygen stable isotope analyses are presented for six different generations of ice wedges as well as for recent ice wedges and precipitation. An age of about 200 ka BP was determined for an autochtonous peat layer in ice-rich deposits by U/Th method, containing the oldest ice wedges ever analysed for hydrogen and oxygen isotopes. The palaeoclimatic reconstruction revealed a period of severe winter temperatures at that time. After a gap in the sedimentation history of several tens of thousands of years, ice-wedge growth was re-initiated around 50 ka BP by a short period of extremely cold winters and rapid sedimentation leading to ice-wedge burial and characteristic ice-soil wedges ('polosatics'). This corresponds to the initial stage for the Late Weichselian Ice Complex, a peculiar cryolithogenic periglacial formation typical of the lowlands of northern Siberia. The Ice Complex ice wedges reflect cold winters and similar climatic conditions as around 200 ka BP. With a sharp rise in $\delta^{18}O$ of 6‰ and δD of 40‰, the warming trend between Pleistocene and Holocene ice wedges is documented. Stable isotope data of recent ice wedges show that Big Lyakhovsky Island has never been as warm in winter as today.

KEY WORDS: Big Lyakhovsky Island; ground ice; ice wedges; Late Quaternary; northern Siberia; palaeoclimate; stable isotopes

INTRODUCTION

For palaeoclimatic studies in the continental areas of northern Siberia, relatively few archives are available which cover periods of more than 10,000 years. These are mainly ice caps occurring in a few limited areas such as on Severnaya Zemlya (Vaikmäe and Punning, 1984) or lake deposits such as in Lake Baikal (Colman *et al.*, 1995).

On Big Lyakhovsky Island as well as in other lowland areas in northeast Siberia, deep lakes with long records are also rare and glacier ice is not available. Therefore, we selected different generations of ice wedges embedded in mostly ice-rich deposits of different ages as archives for palaeoclimatic reconstruction. For palaeotemperature reconstruction (Petit *et al.*, 1999) and the identification of moisture sources (Merlivat and Jouzel, 1979), stable water isotopes are widely used in palaeoclimatology. The early pioneer works, using ice wedges for palaeoclimatic studies were performed by Michel (1982), Mackay (1983), Vaikmäe (1989) and Vasil'chuk

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(1991), who considered oxygen isotope variations in ice wedges as indicators for winter temperature changes. Ice wedges are excellent objects for palaeoclimatic research, especially when ice wedges of different generations covering a long time span are available. Ice wedges, as strictly periglacial features, are indicative of permafrost conditions. The source of wedge ice is mainly snowmelt water, which penetrates into frost cracks. Melt water freezes rapidly enough to prevent fractionation (Michel, 1982), and an ice vein is formed containing the isotope signal of one discrete winter. Frost cracks are formed preferentially between mid-January and mid-March (Mackay, 1974). In general, frost cracking occurs in a zone of weakness preformed by the ice vein of the previous cracking event (Mackay, 1974). Therefore, stable isotope composition of ice wedges can be correlated with mean annual winter and January temperatures (Vasil'chuk, 1992; Nikolayev and Mikhalev, 1995; Vasil'chuk and Vasil'chuk, 1998). Wedge ice may also serve for stratigraphical distinctions (Vasil'chuk and Trofimov, 1988; Vaikmäe, 1989). A detailed work of palaeoclimatic studies, by means of oxygen and hydrogen isotopes on ice wedges, based on precise age determinations, has recently been presented for the Bykovsky Peninsula, near the Lena Delta, by Meyer *et al*. (2002). In order to understand which factors may influence the isotopic composition of an ice wedge, we used recent snow and ice veins as a base for the palaeoclimatic interpretation (Lauriol *et al*., 1995; Meyer *et al*., 2002). The influence of moisture exchange between ice wedges and adjacent segregated ice in the sediment is demonstrated by Meyer *et al*. (2002). Segregated ice is mainly formed by the freezing of suprapermafrost pore water at the bottom of the active layer (International Permafrost Association, 1998) and is thus fed by water sources other than ice wedges. Therefore, samples taken near the boundary between ice wedge and ice-rich sediment were discarded from our palaeoclimatic interpretation.

Our stable isotope studies are embedded in the German-Russian research project ''System Laptev Sea 2000'', being part of a multidisciplinary approach dedicated to a better understanding of palaeoclimatic and palaeoenvironmental change during the Late Quaternary.

WORKING AREA AND CLIMATIC BACKGROUND

The working area is situated on the south coast of Big Lyakhovsky Island in the eastern Laptev Sea region. Big Lyakhovsky Island is the most southern of the New Siberian Islands, separated from the continent by the Dimitri Laptev Strait. A NE-SW striking coastal outcrop with a length of about 6 km was studied at both sides of the Zimov'e River mouth (Figure 1). The study area belongs to the Arctic Tundra (*Atlas Arktiki*, 1985). A first description of the Quaternary sequences of Big Lyakhovsky Island was performed by Romanovsky (1958). The closest meteorological station is located at Cape Shalaurova, SE coast of Big Lyakhovsky Island (73°11'N, 143°56'E). The present climatic situation is characterized by a low mean precipitation and temperature of 184 mm/year and −13.6 °C, respectively, calculated for a seven year period between April 1994 and September 2000 (National Oceanic and Atmospheric Administration (NOAA) data archive). The main period of precipitation is between June and September, when about two thirds of the annual volume occurs. The coldest month is January (mean temperature −31.0 °C), the warmest month August (mean temperature 2.4 °C). Mean daily temperatures as low as −40.5 °C and as high as 9.4 °C point to a highly continental climate despite the proximity of the Laptev Sea.

METHODS

Several generations of ice wedges were studied on Big Lyakhovsky Island. According to new datings, these span the last 200 ka (Schirrmeister *et al*., 2002). Sampling of ice wedges was performed at 10 cm intervals in the horizontal direction. Sampling was carried out for horizontal transects of all ice wedges, at different height levels of the outcrop corresponding to discrete time intervals. The mean stable isotopic composition of one horizontal sampling transect is supposed to be characteristic for the winter temperature of the time this transect was formed. Samples were taken by means of a chain saw (in vertical slices 1.5 cm thick) and an ice screw (ø 14 mm), then thawed and poured into plastic bottles, which were sealed tightly. The widths of single veinlets vary between 1 and 6 mm. Thus, one sample represents an integral signal of several (up to 15) ice veins. 'Heads' of ice wedges were sampled separately from the lower ice wedge and are not included into the statistics (Table 1). Hydrogen and oxygen isotope ratios were measured with a Finnigan MAT Delta-*S* mass spectrometer, at the Alfred Wegener Institute Potsdam, using equilibration techniques. They are given as permil difference to V-SMOW, with internal 1σ errors

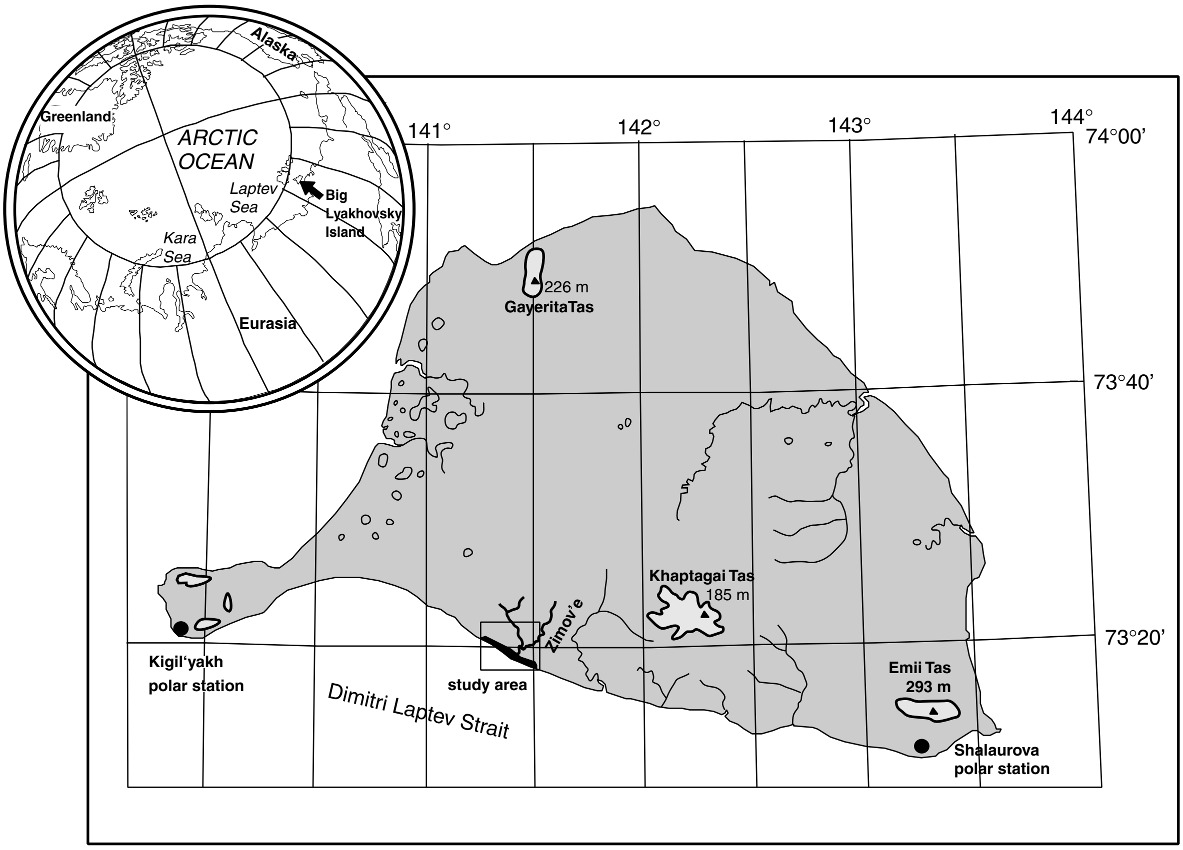

Figure 1 Location of the working area on Big Lyakhovsky Island.

of better than 0.8‰ and 0.1‰ for δD and δ^{18}O, respectively (Meyer *et al.*, 2000). The results are presented in δ^{18}O-δD diagrams with respect to the Global Meteoric Water Line (GMWL), in which fresh surface waters are correlated on a global scale (Craig, 1961). In general, the most negative δ^{18}O and δD values reflect the coldest temperatures. Slope and intercept in the δ^{18}O-δD diagram are valuable indicators for the identification of (1) precipitation deriving from the evaporation of ocean water in different regions and (2) participation of secondary evaporation processes (Dansgaard, 1964). The deuterium excess ($d = \delta D - 8\delta^{18}O$) introduced by Dansgaard (1964) is an indicator for non-equilibrium fractionation processes.

The ages of the sediments in the outcrop were estimated by accelerator mass spectrometry (AMS) ^{14}C dating of plant remains (mainly small roots, leaves or twigs). The measurements were carried out in the Leibniz Laboratory in Kiel, Germany. Details of the AMS facility in Kiel are given in Nadeau *et al.* (1997, 1998). In order to eliminate contamination by younger organic acids, only the leached tissue was used for dating. For a better comparability of Pleistocene and Holocene samples, uncalibrated AMS ^{14}C ages were used.

RESULTS OF THE FIELD STUDIES

At least 11 different geocryological units can be distinguished in the section (Kunitsky and Schirrmeister, 2000). Seven units contain different generations of ice wedges, six of which were sampled for stable isotope analyses (Figure 2). In all sampled units, ice wedges of different size, colour and genesis enclose mostly ice-rich sediment with finely-dispersed segregated ice. The oldest stratigraphic unit is a horizon composed of weathered Permian sandstone, which outcrops in parts of the working

Table 1 Stable isotope ($\delta^{18}O$, δD and d excess) minimum, mean and maximum values, standard deviations as well as slopes and intercepts in the $\delta^{18}O$-δD diagram for all sampled ice wedges and for recent precipitation samples of Big Lyakhovsky Island.

ICE WEDGE TYPE	N	height a.s.l. (m)	width (m)	$\delta^{18}O$ (‰) min.	$\delta^{18}O$ (‰) mean	$\delta^{18}O$ (‰) max.	$\delta^{18}O$ (‰) std. dev.	δD (‰) min.	δD (‰) mean	δD (‰) max.	δD (‰) std. dev.	d (‰) min.	d (‰) mean	d (‰) max.	d (‰) std. dev.	slope	intercept	R^2
RECENT ICE WEDGES																		
	8	varying	<0.05	−22.48	−20.42	−19.21	1.27	−175.5	−158.9	−149.2	9.6	3.3	4.5	6.6	1.1	7.56	−4.58	0.99
FLUVIAL DEPOSITS																		
L2-1	14	3.0	1.5	−23.74	−23.12	−21.55	0.53	−183.1	−178.3	−166.7	4.1	5.7	6.6	7.2	0.4	7.71	−0.01	0.99
THERMO-EROSIONAL VALLEY DEPOSITS																		
R19-1	5	16.0	1.5	−27.83	−27.04	−26.38	0.58	−211.0	−205.9	−201.2	3.9	9.4	10.3	11.6	0.9	6.64	−26.52	0.99
TZ2-3	4	19.0	0.5	−28.61	−27.89	−26.76	0.81	−216.6	−211.1	−202.4	6.3	11.6	12.0	12.4	0.4	7.75	5.12	1.00
ALAS																		
L21-1	32	9.0	2.4	−26.52	−24.42	−23.03	0.76	−203.5	−187.7	−177.9	5.5	5.3	7.7	8.8	0.9	7.23	−11.21	0.99
R32-2	33	14.0	2.9	−26.27	−24.56	−21.05	1.27	−200.0	−189.0	−164.1	9.1	2.9	7.4	10.2	1.7	7.06	−15.61	0.98
ICE COMPLEX																		
TZ3-1	28	27.5	2.5	−32.62	−31.35	−26.10	1.15	−257.5	−246.2	−204.1	9.4	3.2	4.7	5.7	0.7	8.12	8.38	1.00
R10-2	6	23.0	0.5	−32.57	−32.40	−32.10	0.18	−251.9	−247.9	−241.5	4.4	8.4	11.3	15.4	3.1	23.27	505.76	0.87
R10-1	57	22.0	4.7	−32.87	−31.56	−24.47	1.54	−258.1	−247.4	−192.4	12.2	2.7	5.1	8.5	1.1	7.90	2.00	0.99
TZ2-2	24	19.0	2.1	−31.07	−30.39	−28.32	0.77	−244.0	−235.0	−219.7	7.2	4.6	8.1	12.2	1.7	9.23	45.44	0.96
TZ2-4	19	19.0	1.2	−30.91	−28.68	−27.18	0.94	−239.1	−220.1	−207.6	7.9	8.0	9.3	11.3	0.9	8.33	18.77	0.99
TZ2-5	4	16.8	0.9	−30.91	−30.48	−29.95	0.48	−239.7	−235.4	−231.3	4.3	7.5	8.5	10.3	1.3	8.60	26.67	0.91
R8-1	10	15.4	0.8	−32.74	−32.05	−30.32	0.70	−251.6	−246.1	−232.8	5.2	8.6	10.3	15.1	1.9	7.04	−20.46	0.89
R9-1	26	9.0	2.2	−30.64	−30.09	−28.71	0.44	−237.1	−232.3	−221.0	3.5	7.7	8.4	10.2	0.5	7.85	3.86	0.98
UNIT B																		
R6-1	14	6.5	0.7	−37.34	−35.96	−34.82	0.88	−289.3	−281.0	−274.6	5.0	3.0	6.7	9.4	2.1	5.63	−78.40	0.99
R7-1	24	6.5	2.2	−36.23	−35.55	−34.61	0.46	−284.1	−278.2	−261.2	4.9	4.7	6.2	15.7	2.1	9.87	72.85	0.85
UNIT A																		
R17-1	30	7.0	3.2	−34.77	−31.98	−29.90	1.65	−273.2	−250.0	−232.2	14.2	2.7	5.9	8.3	1.6	8.60	25.21	0.99
R17-2	23	3.0	2.6	−32.31	−31.56	−30.81	0.40	−255.5	−247.4	−240.4	3.9	2.4	5.1	7.1	1.3	9.55	53.98	0.92
SEGREGATED ICE																		
segregated ice	100	varying		−32.30	−24.50	−14.07	4.66	−235.2	−188.0	−118.4	30.2	−12.0	7.9	33.5	9.8	6.35	−32.48	0.96
RECENT PRECIPITATION																		
rain water	13			−20.69	−12.09	−8.27	3.24	−161.3	−101.1	−76.6	22.5	−10.9	−4.4	5.1	6.0	6.80	−18.92	0.96
snow patches	10			−31.43	−26.29	−16.13	5.78	−239.0	−198.7	−125.6	41.1	3.5	11.6	23.4	6.8	7.08	−12.44	0.99

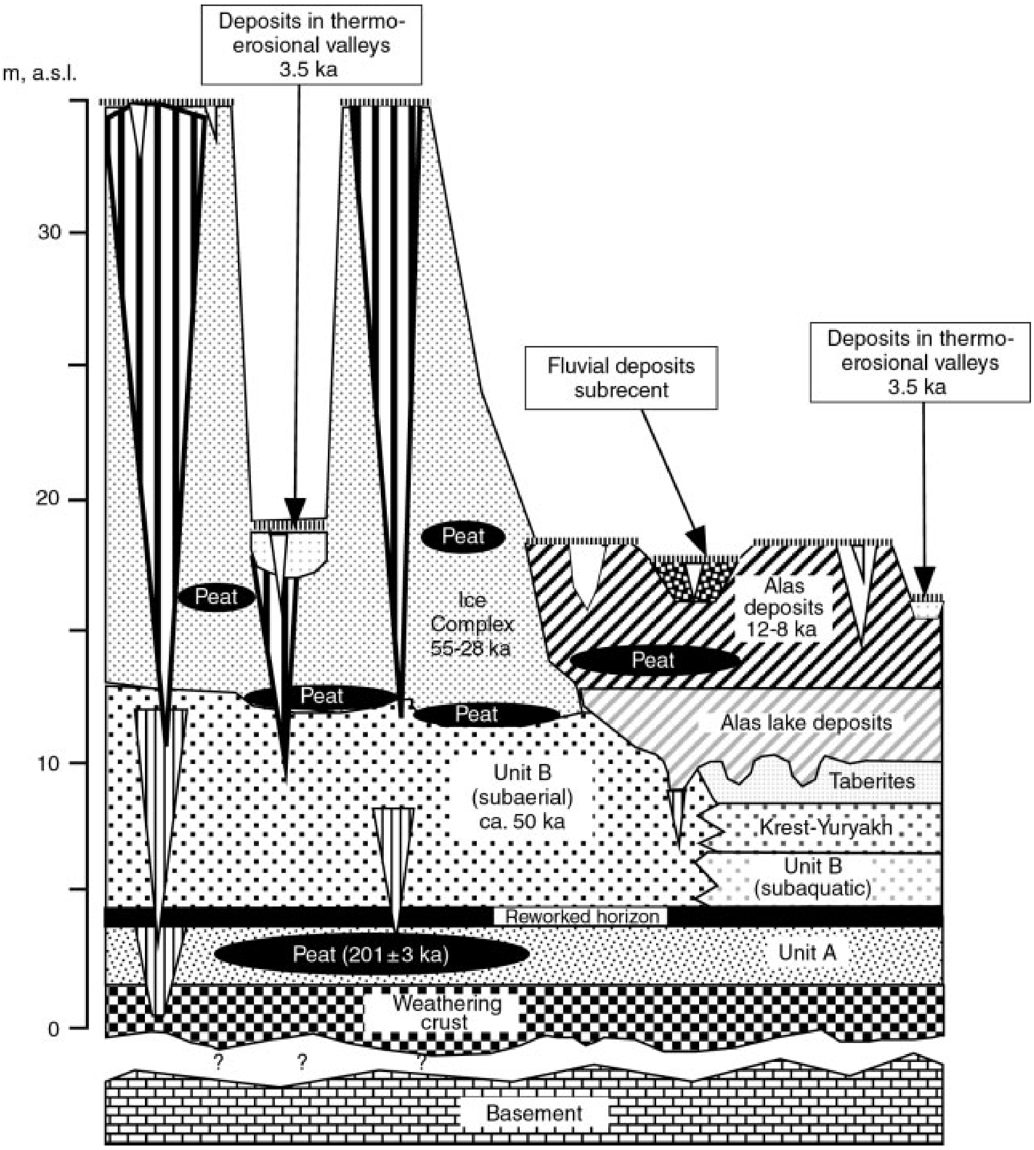

Figure 2 Schematic profile of the study site at the south coast of Big Lyakhovsky Island with cryolithogenetic units (modified after Grosse, 2000). The peat ovals represent organic layers, which can be followed for several tens of metres in horizontal extension.

area near sea level. This weathering crust consists of eluvial clay and silt with poorly-rounded rock fragments and is characterized by basal and cellular cryostructures. The oldest generation of ice wedges, being in general narrower than 0.5 m, penetrates from the next younger unit A into the weathering crust.

Unit A is composed of greyish-brown silt to fine-grained sand with some peat inclusions and cryoturbated palaeosols. A peculiarity of unit A is the inclusion of the underlying weathering crust of yellowish rock debris in the sediment and in ice wedges. Ice wedges in unit A sediments reach widths of 3.5 m. Two types of wedges occurring side-by-side can be distinguished: (1) with light grey transparent ice, gas bubbles ≥ 1 mm and low sediment content and (2) ice-soil wedges, called 'polosatic' in the Russian literature (Kunitsky, 1998). 'Polosatics' are related presumably to the next youngest unit B and are explained later. Horizontal ice belts of up to 15 mm thickness characterize the cryolithogenic structure of unit A. Ice-wedge growth was probably both syngenetic, as shown by ice belts bound upward near ice wedges, and epigenetic (the 'polosatic' part).

Unit B consists of yellowish to greyish-brown, 'loess-like', fine-grained sands with many subvertically oriented *in situ* grass roots. Unit B has a relatively low ice content of 30–40 wt% (relative to the dry-weight) in a sediment of mostly massive cryostructure. Ice wedges are rather rare compared to other units, and some soil wedges occur. The ice wedges in unit B are between 1 m and 2.5 m wide and contain in most cases ice-soil wedges or 'polosatics'. 'Polosatics' (Figure 3) are phenomena where very sediment-rich vertical bands are interrupted by single ice veins. The ice veins are in general turbid and yellowish, about 1 to 3 mm thick, but may attain up to 1 cm. The thickness of mineral strips is normally about of 1 to 2 mm, but may be higher. Vertical zebra-striped 'polosatic' structures can be found at different height levels from 1–17 m a.s.l., both in contact with the Ice Complex and the unit A ice wedges. Similar structures were described as ice-sand wedges by Romanovsky (1976). In general, we observed an uneven upper part of unit B ice wedges with several vertical extensions. The width of these 'heads' may reach up to 20 cm and in some cases, they are buried under unit B sediments, and are therefore considered to be of unit B age. The phenomenon of buried ice-wedge heads may be explained by a reduced thaw depth in the active layer or, most likely, by a sudden rise in the sedimentation rate. Melting processes may have caused a degradation of the ice wedge from above prior to the growth of ice-wedge heads. The contact between unit B and the Late Pleistocene Ice Complex is not clearly defined and not uniformly at the same height above sea level. Some parts of the permafrost profile of unit B sediments have visible marks of thawed ice wedges. These ice-wedge pseudomorphs belong to a subaquatic facies of unit B and are usually associated with lake depressions.

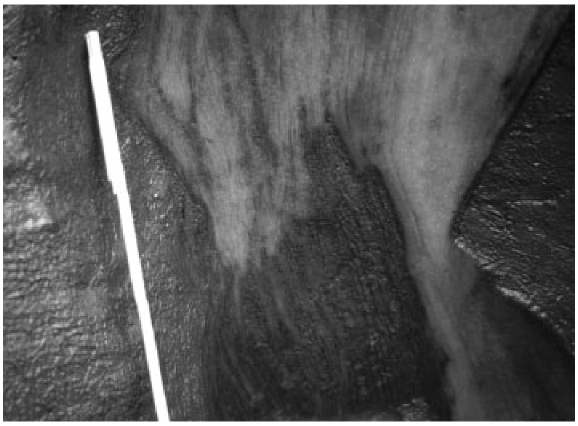

Figure 3 Subvertical oriented ice-soil wedges ('polosatics') of unit B. Interfingering of single ice veinlets with the sediment is observed.

The next younger unit is the Ice Complex with typical geomorphological forms such as steep ice cliffs reaching 35 m a.s.l. and thermo-erosional cirques extending some 100 m in length. They are characterized by a 50–100 m wide 'thermo-terrace' with numerous thermokarst mounds (baydzherakhii). The sediments are composed of silty to fine-grained sand of greyish-brown colour, some cryoturbated peaty palaeosols and peat inclusions especially in the lower part of the unit. Yellowish-grey coloured ice wedges are up to 6 m wide and more than 20 m high. Well-defined subvertical structures such as elementary ice veins of about 1–4 mm thickness, oval gas bubbles and thin mineral layers are common. Massive subhorizontal, 2–4 cm thick ice belts in the sediment, always bound upward in contact with the ice wedges, point to the syngenetic formation of the ice wedges.

Three younger facies overlie the Ice Complex and older deposits. The formation of these younger facies, such as deposits in thermokarst depressions (alasses) and in thermo-erosional valleys as well as fluvial deposits, is linked with the destruction of the older units. Ice wedges of two alas depressions of different depth were sampled. Alas deposits are determined by polygonal ice-wedge systems attaining 10–15 m in diameter and by alternating horizontal layers of thin ice belts and reticulate cryostructures. The layers are observed to be incliented upwards near their contacts with the ice wedges. Typically, the alas sediments are composed of grey fine-grained sands with layered bedding, high organic contents and some peaty palaeosol horizons. Alas ice wedges may reach widths of about 3.5 m and contain subvertical structures such as up to 3 mm thick elementary ice veins and small orientated gas bubbles. The ice wedges are white and milky and contain datable organic material. In alas deposits, recent ice-wedge growth with single 1–4 cm wide ice veins in the lowermost part of the active layer are very common.

Thermo-erosional channels are typical features in the whole working area. They are mainly associated with the Ice Complex, and their sediments consist of grey and silty fine-grained sand, partly organic-rich and dissected by roots. Ice wedges are up to 1.5 m wide and characterized by white to grey, milky ice with subvertically elongated gas bubbles resembling a string of beads. Single ice veins are between 1 and 4 mm thick. Low-centred ice-wedge polygons with diameters of 8 to 12 m are found in the Holocene fluvial terrace at the mouth of the Zimov'e River. The maximum thickness of these deposits is about 5 m, being composed of light brown fine- to medium-grained sand with ripple and cross-bedding structures. The width of ice wedges may reach 1.5 m. The ice wedges are still active and show subvertically orientated, 2 to 6 mm thick, ice veins, very thin sediment layers and elongated gas bubbles. The ice is relatively clear and colourless. Enclosing sediments are characterized by a layered cryostructure that bounds upward near ice wedges.

One to 4 cm wide recent ice veins have been observed in various parts of the outcrop, especially in alas depressions, thermo-erosional valleys, and fluvial deposits. Recent ice wedges were identified by tritium analyses and sampled as a base for the climatic interpretation of the older ice wedges. In some units, no ice wedges were available. Unit B and alas deposits are both characterized by subaquatic facies, which consist of sediments with relatively low ice content and the presence of lacustrine shells (bivalves and gastropods). These deposits were formed when the heat capacity of overlying water bodies was high enough to cause thaw of underlying deposits. Subsequently, they refroze after the lake dried out. In all these units, ice-wedge pseudomorphs document the melting of ice wedges caused by temporary open water bodies (Figure 2). The upper part of subaquatic unit B is considered separately by some authors (Gavrilov *et al*., 2000) and interpreted as the Krest-Yuryakh suite, which corresponds to the Eemian. Further information about those units where no ice wedges are available for stable isotope analyses is found in Kunitsky and Schirrmeister (2000) and Grosse (2000).

GEOCHRONOLOGY

Thermoluminescence (TL) dating carried out on silty sands close to the Zimov'e River point to ages around 1 Mio a for unit A (Arkhangelov *et al*., 1996). Palaeomagnetic investigations in the upper part of unit A sediments show the Jaramillo magnetic reversal (Arkhangelov *et al*., 1996). Schirrmeister *et al*. (2002) showed that a pre-Eemian ^{230}Th/U age of a sample taken near the top of unit A deposits from a frozen peat layer several tens of metres long revealed a younger age of 201 ± 3 ka. This requires attribution to another magnetic reverse such as Biwa I or II. We have assumed that this U/Th age is highly reliable because (1) frozen peat in permafrost behaves like a closed system for uranium and thorium (Schirrmeister *et al*., 2002), and (2) it is within the dating range of the method (which is questionable for TL ages of 1 Mio a). Unit B sediments were also TL dated by Arkhangelov *et al*. (1996) to 360 ± 90 ka and by Kunitsky *et al*. (1996, 1998) to ages between 94 ± 26 and 35 ± 10 ka. Our AMS ^{14}C ages derived from the unit B sediments are 50.1 ± 3.0 ka BP and 49.8 ± 3.2 ka BP, thus close to the limit of AMS dating range. Nevertheless, these two ages are reliable, because we dated *in situ* grass roots. Consequently, we assume a hiatus of 150 ka or more (possibly including the Eemian) between the deposition of unit A and unit B. The deposition of the Krest-Yuryakh suite was attributed to the Eemian (Gavrilov *et al*., 2000) based on the TL dating by Arkhangelov *et al*. (1996). In earlier studies, units A and B were classified as Olyor and Kuchchuguy sediments (Arkhangelov *et al*., 1996). Since the new geochronology for these two units differs considerably from ancient TL dates on which the stratigraphical classification was based, we decided to use the terms unit A (for the Olyor) and unit B (for the Kuchchuguy). But the controversial age of these two units is still insufficiently understood and requires further research and dating.

Conventional ^{14}C dates published by Japanese scientists (Nagaoka *et al*., 1995) show that the Ice Complex on Big Lyakhovsky Island was deposited between >42.2 ka and 28.7 ± 0.4 ka BP and covered by Holocene deposits of 7.4 ± 0.8 ka BP. According to our age determinations the Ice Complex on Big Lyakhovsky Island started forming around 50 ka BP as indicated by several AMS ^{14}C ages (54.1 ± 3.1 ka BP, 52.9 ± 4.6 ka BP, 51.2 ± 4.7 ka BP, 50.3 ± 2.6 ka BP). These ages are in the same range or slightly older than those of the underlying unit B. In the Ice Complex, a small *salix* leaf found in an ice wedge at 15.8 m a.s.l. was dated by AMS to 35.0 ± 2.1 ka BP. A lemming coprolith in an Ice Complex ice wedge at 8.2 m a.s.l. revealed an AMS age of 49.2 ± 2.1 ka BP, and at 9 m a.s.l. an AMS ^{14}C age of 39.7 ± 1.3 ka BP was derived. According to available data, the age of the Ice Complex formation is now proved for the time interval between around 55 ka and 28.7 ka BP. It must be mentioned that we were unable to sample the uppermost part of the Ice Complex. Consequently, younger ages are to be expected for the Ice Complex.

According to AMS ^{14}C dated organic material, formation of the two thermokarst depressions started at 12.4 ka BP and 11.3 ka BP, respectively, proceeding at least until 8 ka BP. Alas ice wedges formed in the last 1 ka epigenetically, as shown by two AMS ^{14}C datings of organic matter in ice wedges (135 ± 30 a BP and 835 ± 50 a BP). Tritium analyses prove the occurrence of recent ice-wedge growth in alas and fluvial deposits (Dereviagin *et al.*, 2002). The Holocene development of thermo-erosional valley deposits was confirmed by an AMS ^{14}C age of 3.43 ± 0.03 ka BP. However, whether the thermo-erosional valley or alas ice wedges are younger cannot be solved yet. Uncertain age estimates and large differences obtained from different methods, particularly from the Pleistocene deposits, reveal the necessity for more detailed age determinations on Big Lyakhovsky Island. Nevertheless, it is concluded that: (1) there is a gap in the sedimentation history between unit A and unit B, (2) unit B was deposited rapidly before formation of the Late Pleistocene Ice Complex started, and (3) mostly Holocene deposits are linked with the destruction of the older units.

RECENT PRECIPITATION

The range of stable isotopes in precipitation reflects seasonal variations of condensation temperatures. Recent precipitation is displayed in the δ^{18}O-δD diagram for rain water and snow patches of Big Lyakhovsky Island (Figure 4). The isotopic composition for rain, snow and recent ice wedges can be drawn from Table 1.

Rain water (N = 13) was collected for all precipitation events in July and August 1999. The mean isotopic composition is $\delta^{18}O = -12.1‰$ and $\delta D = -101‰$. The samples are characterized by a low mean *d* excess of −4.4‰ and a slope of 6.8 in the δ^{18}O-δD diagram. The deviation from the GMWL points to the participation of kinetic fractionation processes. We assume that this enrichment in heavy isotopes is due to evaporation processes, probably originating either from surface waters or from the open Laptev Sea.

During the field season in summer 1999, remains of snow patches (N = 10) were sampled on Big Lyakhovsky Island. The mean isotopic composition of snow patches is −26.3‰ for δ^{18}O and −199‰ for δD. The *d* excess of snow is highly variable between 23‰ and 3.5‰, with a mean *d* of 11.6‰. In the δ^{18}O-δD diagram (Figure 4), snow samples have a slope of 7.1 and an intercept of −12. The isotopically heavier snow samples are located below the GMWL, whereas 'colder' snow is located above the GMWL. This shift in *d* excess may be explained by percolation of rain water or melt water through the snow cover or by evaporation or sublimation processes of snow. The notable influence on *d* excess is possibly also due to the low amount of winter precipitation on Big Lyakhovsky Island. Another possibility for the shift of *d* excess in snow is the participation of a local isotopically-depleted moisture source. Since

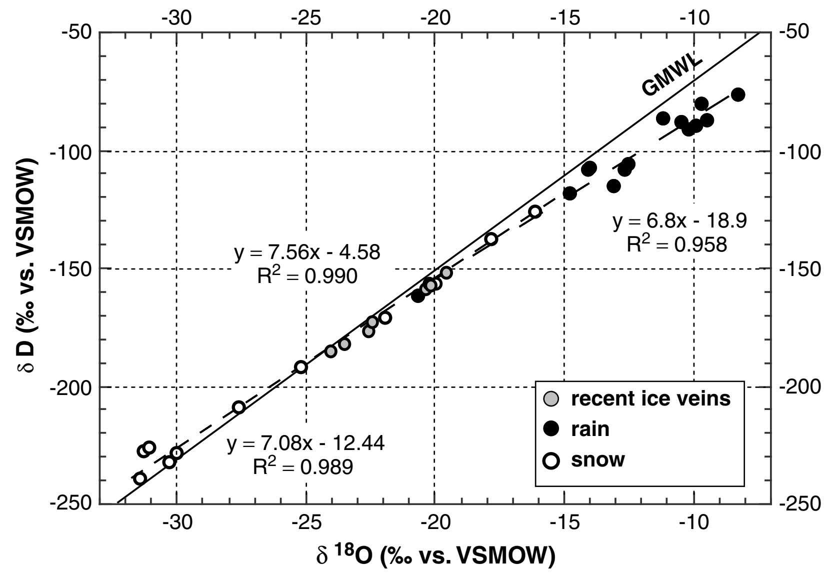

Figure 4 δ^{18}O-δD diagram for snow patch and rain water samples collected in summer 1999 on Big Lyakhovsky Island. GMWL is the Global Meteoric Water Line.

the Laptev Sea and lakes are frozen in winter, a polynya, a belt of open water conditions in the sea, would be the only possible local source.

On Big Lyakhovsky Island, the isotopic composition of snow differs significantly from that of recent ice wedges (Figure 4, Table 1, Dereviagin *et al.*, 2002), with mean $\delta^{18}O = -20.5‰$, $\delta D = -152‰$ and $d = 4.5‰$. In the $\delta^{18}O$-δD diagram, recent ice wedges have a slope of 7.6 and an intercept of −4.6, and correspond isotopically to relatively heavy snow samples, but also to light rain (Figure 4). This leads to two possible scenarios: (1) the recent ice wedges on Big Lyakhovsky Island are fed by a mixture of snow-melt water and rain, e.g. by percolation of rain through the snow cover; (2) ice wedges are fed by snow-melt water, which was changed isotopically before entering the frost crack. This contrasts with results from Taymyr (Dereviagin *et al.*, 2002) and the Bykovsky Peninsula (Meyer *et al.*, 2002), where fractionation and mixing did not change the *d* excess in snow melt before trickling into the frost crack.

Melting of the annual snow cover leads to the formation of one single elementary ice vein. Consequently, a meteoric water line of snow is transferred into one point in the $\delta^{18}O$-δD diagram. If we consider isotope fractionation for snow melting, the first melt water will be characterized by lighter $\delta^{18}O$ and δD and lower *d* excess than the last (Lauriol *et al.*, 1995). This means that the recent ice wedges on Big Lyakhovsky Island with their heavier mean isotopic compositions compared to the remains of snow patches, are most likely fed during the later stages of snow melt. According to Lauriol *et al.* (1995), the same process is observed for Holocene ice wedges along the Yukon River in Canada.

Another possible process for the isotope fractionation between snow and recent ice wedges is evaporation or sublimation of the snow cover, which would also result in lower *d* excess. This could be due to the relatively low amount of winter precipitation on Big Lyakhovsky Island (and thus a thin snow cover, the isotopic composition of which could be changed relatively easily). Flooding of frost cracks can be ruled out, because of the position of recent ice veins, which were sampled 10–15 m above sea (and river) level.

Additionally, the seasonality of precipitation events and frost cracking within one year has to be taken into account. Two climatically identical years might give different $\delta^{18}O$ in ice veins, e. g. when in one year, the frost crack is mainly fed by colder January snow and in the next year by warmer March snow. Since we do not know the precise time of frost-cracking events and the formation of ice veins, we refer to winter temperatures when considering the isotope composition of ice wedges.

STABLE ISOTOPES IN ICE WEDGES AND THEIR PALAEOCLIMATIC INTERPRETATION

For Big Lyakhovsky Island, stable isotope compositions for different generations of ice wedges were analysed for a reconstruction of the palaeoclimatic evolution. In Table 1, hydrogen and oxygen isotope minimum, mean, and maximum values, standard deviations, slopes and intercepts in the $\delta^{18}O$-δD diagram are given for 17 ice wedges of six geocryological units. For comparison, stable isotopic composition of recent ice wedges and precipitation as well as for segregated ice are presented. The isotopic composition of ice wedges on Big Lyakhovsky Island is highly variable throughout time, ranging between −37.3‰ and −19.2‰ for $\delta^{18}O$ and from −290‰ to −150‰ for δD. Within one ice wedge, we observed relatively constant stable isotopic composition with variations, in general, less than 4‰ and 30‰ for $\delta^{18}O$ and δD. For all ice wedges on Big Lyakhovsky Island including recent ice wedges, the mean *d* excess varies between 4.5‰ and 12‰.

The isotopic composition of ice wedges is valuable for stratigraphic subdivision of the outcrop (Meyer *et al.*, 2002). The three Pleistocene units can be differentiated by means of stable isotopes, despite light isotopic composition in all of them. The ice wedges of the oldest unit A show a mean isotopic composition around −32‰ for $\delta^{18}O$ and −250‰ for δD (Figure 5a). For ice wedges of unit B, much lighter $\delta^{18}O$ as low as −37.3‰ and $\delta D = -290‰$ are observed, with a respective mean isotopic composition of −35.5‰ and −280‰ (Figure 5b). Unit A and B ice wedges are characterized by a relatively low mean *d* excess of 5 to 7‰. The mean $\delta^{18}O$ and δD values of the Ice Complex ice wedges range from −32.5‰ to −28.5‰ and from −250‰ to −220‰ (Figure 5c), and are thus similar to those of unit A. In the lower part of the Ice Complex, the mean *d* excess is between 8 and 10.3‰. In the upper part a *d* excess around 5‰ is observed (an exception is R10-2). For ice wedges in two alasses, $\delta^{18}O$ and δD values range from −26.5‰ to −21‰ and −200‰ to −160‰ (Figure 5d), reflecting much heavier isotopic composition than in all older units. The mean $\delta^{18}O$ and δD in alas ice wedges are −24.5‰ and −190‰, with a mean *d* excess around 7.5‰. The sampled ice wedges in thermo-erosional valley deposits (Figure 5e) are of Holocene

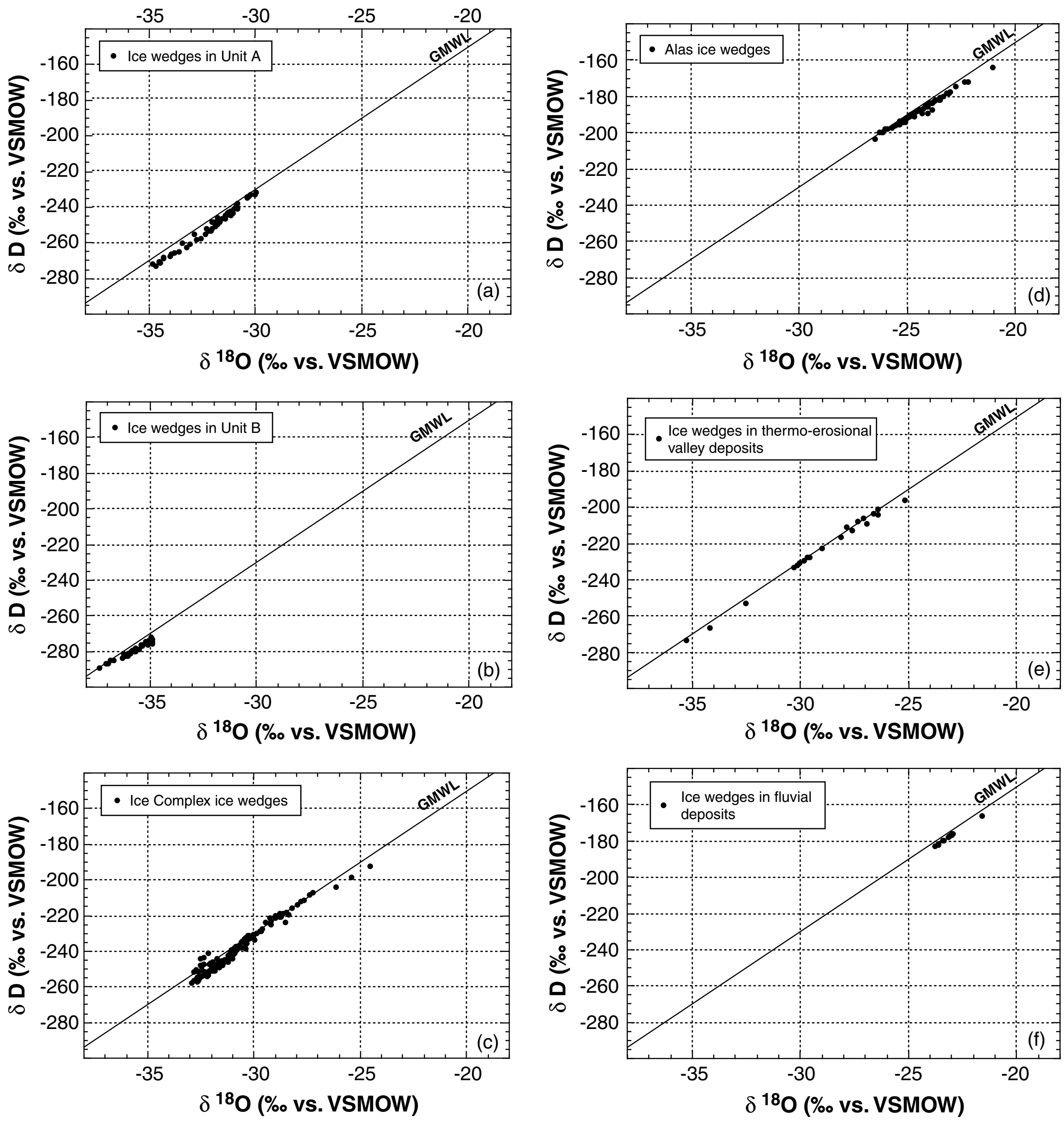

Figure 5 δ^{18}O-δD diagrams for ice wedges in all geocryological units: (a) unit A; (b) unit B; (c) Ice Complex; (d) thermokarst depression (alas); (e) thermo-erosional valley; (f) fluvial deposits of the Zimov'e River. GMWL is the Global Meteoric Water Line.

age with mean δ^{18}O and δD values of −27.5‰ and −200‰, respectively. The ice wedge sampled in fluvial deposits of Zimov'e River exhibits sub-recent to modern ice-wedge growth and the heaviest mean isotopic composition with mean δ^{18}O of −23‰ and δD of −178‰ compared to all other units (Figure 5f). Only recent ice wedges, sampled in the active layer above thermo-erosional valley, alas and fluvial deposits, have heavier isotopic compositions.

The temporal development of stable isotopic composition in ice wedges is depicted in Figure 6 for the different units in chronological order. Severe winter conditions are reflected in stable isotopes of the oldest unit A. The ice wedges sampled here may

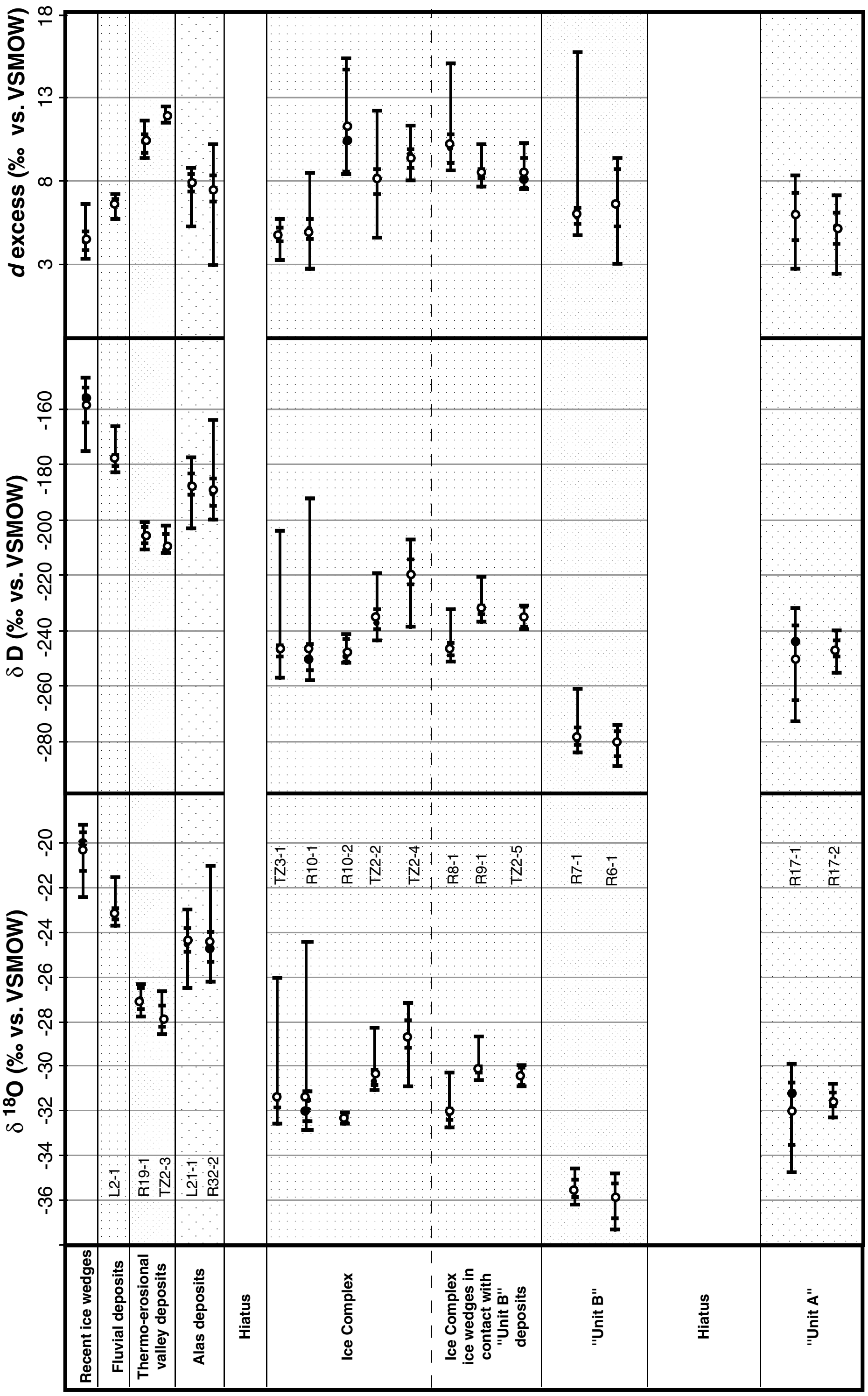

Figure 6 Development of δ^{18}O, δD and *d* excess of all ice wedges (without samples influenced by exchange processes) in 'logical' stratigraphic order. White dots represent the mean isotopic composition of every ice wedge, the median (black dots) is given when different to the mean value. The respective ranges (outer bars) and the quartiles Q1 and Q3 (inner bars) are held out.

be as old as 200 ka, and thus, are the oldest ice wedges ever analysed for hydrogen and oxygen isotopes. The pollen spectra of enclosing deposits (Andreev *et al.*, 2001) are dominated by taxa of grass-sedge tundra, which indicate a relatively warm and wet (summer) climate for this unit. The combination of stable isotope and pollen data leads to the assumption that the annual temperature amplitude of Big Lyakhovsky Island must have been high at that time.

In the period of ice-wedge growth in unit B, about 50 ka ago, the winter temperatures are assumed to have been extremely cold as indicated by unit B stable isotope data. The presence of cryoxerophytic taxa in the pollen spectrum also indicate cold and dry climatic conditions (Andreev *et al.*, 2001) for the time when unit B was formed. This is in good agreement with ice-wedge morphology and stable isotope data. Interfingering of various ice veinlets and subvertical structures in the sediment ('polosatics') are related only to unit B ice-wedge growth, which is also observed in contact with the upper part of unit A and the lower part of the Ice Complex. A high number of buried and multiple ice wedges in unit B suggests a rapid deposition of the sediments. Other explanations for the burial of ice-wedge 'heads' may be linked with changes in the thermal or hydrological regime, i.e. a reduced thaw depth of the active layer. There is no evidence in the sediment structures near the buried ice-wedge 'heads' pointing to one of these hypotheses. But the hypothesis of a high sedimentation rate is also supported by similar AMS ^{14}C dates of *in situ* grass roots around 50 ka in the 5 to 8 m thick unit B sediments. With high sedimentation rates, not only ice wedges, but also the vertical structures of frost cracks (these being zones of weakness) can be buried. This leads to interfingering of ice veins (Mackay, 1974), because frost cracking could not originate in the same place. This is a possible explanation for the 'polosatic' phenomenon, which consists of numerous single ice veinlets interrupted by vertical sediment-rich bands.

Another possibility to explain 'polosatics', as well as the relatively low water content and the small number of ice wedges in unit B sediments, may be linked to either a low amount of winter precipitation or a well-drained accumulation surface. A relatively dry climate with a thin snow cover would result in low heat insulation and less melt water entering frost cracks, possibly without forming an ice vein at every frost cracking event. A consequence would be frequent and deep frost cracking, which could also explain the interfingering ice-soil wedges entering sediments of unit A.

In summary, the numerous phenomena found in unit B are certainly linked with the competition between sedimentation and winter precipitation. Nevertheless, the existing data do not allow us to decide whether a higher sedimentation rate or a relatively lower precipitation is the responsible process. Since 'polosatics' are also found near the lower boundary to the Ice Complex with heavier isotopic composition, we interpret 'polosatics' as being indicative of the initial stage of ice-wedge growth and perhaps represent the beginning of the Late Pleistocene Ice Complex formation on Big Lyakhovsky Island. This is supported by the occurrence of relatively small ice wedges in the lower part of the Ice Complex.

For the Ice Complex, winter temperatures were assumed as relatively cold for the investigated time interval between about 50 ka BP and 28.7 ka BP. Low total pollen concentration dominated by typical tundra species also reflects cold climatic conditions, more humid than before (A. Andreev, personal communication). However, compared to unit B a climate warming of both winter and summer temperatures has to be assumed. Winter temperatures were slightly warmer but comparable to ice wedges from unit A. Due to the similar stable isotopic composition, we consider unit A as an older equivalent of the Ice Complex. This is supported by a similar sediment matrix, a high gravimetric ice content (60 to 170 wt%), the similar type of ice wedges and the presence of palaeosols and ice belts interrupted by lens-like reticulate cryostructures in both units.

The Holocene ice wedges reflect much warmer winter temperatures compared to the Pleistocene ice wedges. The rise in $\delta^{18}O$ of about 6‰ and in δD of 40‰ reflects the amelioration of the global climate at the Pleistocene-Holocene boundary. This is known from several climate archives worldwide such as glaciers and ground ice (e. g. Cuffey *et al.*, 1995; Meyer *et al.*, 2002). An increase in the total pollen content and the occurrence of shrub pollen confirms this climate warming trend, with most favourable climatic conditions between 9 ka BP and 4.5 ka BP and subsequent cooling of the climate after 4.2 ka BP (Andreev *et al.*, 2001). Ice-wedge growth in alas and thermo-erosional valleys probably started after this climatic deterioration. In alas ice wedges, slightly warmer winter conditions are seen, as compared to ice wedges in thermo-erosional valleys. A sub-recent ice wedge in fluvial deposits of the Zimov'e River indicates even warmer winter temperatures in the Holocene. Only recent ice wedges identified by high tritium concentrations (Dereviagin *et al.*, 2002) show heavier isotopic composition. Hence, Big Lyakhovsky Island has never been as warm in winter than at the present time. For ice wedges of the Holocene fluvial and thermo-erosional valley deposits and recent ice wedges, slopes in the δ^{18}O-δD diagram vary around 7.5. Alas ice wedges with relatively low slopes of 7.1 may be influenced by further evaporation, possibly due to the participation of melt water running down slopes (Meyer *et al*., 2002).

Evidently, the recent synoptic situation for the winter precipitation on Big Lyakhovsky Island is different compared to Bykovsky Peninsula (Meyer *et al*., 2002), which is fed by Atlantic moisture. This can be seen in the slope of 7.1 in the δ^{18}O-δD diagram for snow samples of Big Lyakhovsky Island, pointing to either moisture from a source region enriched in heavy isotopes, or to a change in the low amount of snow by mixing, melting or evaporation/sublimation. Kuznetsova (1998) reports that in winter, the influence of moisture originating from the Pacific easterlies and Atlantic Ocean westerlies meet between 130° and 150 °E. Precipitation in Canada originating in the Pacific Ocean is characterized by a low *d* excess (Clark and Fritz, 1997). Consequently, the Pacific Ocean is a possible winter precipitation source for Big Lyakhovsky Island. Recent ice wedges on Big Lyakhovsky Island show an isotopic composition different to that of snow. Therefore, variations in the isotopic composition (especially in the *d* excess) of ice wedges through time cannot simply be related to the moisture source of the precipitation. Other local processes such as fractionation in the snow cover, i.e. by melting or sublimation/evaporation, have to be taken into account for the temporal variations in the *d* excess of ice wedges.

On the Bykovsky Peninsula, 50 km SE of the Lena Delta, a shift towards a high *d* excess was found around 20 ka BP. This was interpreted as a change of the moisture source (Meyer *et al*., 2002). If a similar change of the main winter precipitation source took place, we should expect a sharp increase in *d* excess between the youngest Ice Complex and Holocene ice wedges. On Big Lyakhovsky Island, a slight increase from 5‰ (in the Ice Complex) to 7‰ (in alas and in fluvial deposits) is observed. Despite the lack of ^{14}C dated samples for the time interval between 28 ka BP and 12 ka BP, the slight increase in *d* excess indicates no significant change of the main precipitation source at that time.

CONCLUSIONS

The study of ice wedges on Big Lyakhovsky Island in the eastern Laptev Sea, northern Siberia, reveals permafrost conditions for periods during the last 200 ka. By means of stable isotope analyses, six generations of ice wedges are distinguished and used for the reconstruction of palaeoclimatic variations. This palaeoreconstruction is based on the comparison between the stable isotope composition of recent precipitation (both snow and rain) with recent ice wedges, which were identified by means of tritium analyses. On Big Lyakhovsky Island, recent ice wedges are most likely fed by melt water of the later stages of snow melt, and consequently winter temperatures are derived from ice wedges.

The variations of the oxygen and hydrogen isotopic composition reveal distinct changes in the winter climate history on Big Lyakhovsky Island. A period of cold winter temperatures was determined for an old equivalent of the Late Pleistocene 'Ice Complex' at about 200 ka. According to radiocarbon data, a hiatus of more than 100 ka in the sedimentation history including the Eemian was followed by a short period of extremely cold winters around 50 ka BP characterized by high sediment accumulation rates sometimes exceeding vertical ice-wedge growth rates. Peculiar ice-soil wedges ('polosatics') initiate ice-wedge growth for the classical Late Weichselian Ice Complex. During Ice Complex formation, winters must have been cold. A warming trend between Pleistocene and Holocene ice wedges is found in sharply increasing δ^{18}O and δD values. The warmest winter temperatures were derived from recent ice wedges on Big Lyakhovsky Island.

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