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Palaeoclimate Signals as Inferred from Stable-isotope Composition of Ground Ice in the Verkhoyansk Foreland, Central Yakutia

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ABSTRACT

Ice-rich permafrost deposits and their isotopic composition were studied at four sites in the western foreland of the Verkhoyansk Mountains, Central Yakutia. The isotopic composition of ice wedges formed in alluvial and loess-like sediments generally reflects the palaeoclimate of winter conditions. The middle Weichselian Ice Complex developed around 41 ka ^{14}C BP during a period with colder winters than today. Similarly severe conditions are reflected in the late Weichselian Ice Complex from around 20 ka to 13 ka ^{14}C BP. The transition to the Holocene is characterised by increases of 5‰ and 35‰ in δ^{18}O and δD, respectively. This warming is documented in wedge ice, which grew between 8.5 and 4.5 ka BP. Towards the late Holocene and sub-recent times, a climatic deterioration is recorded, reflected by lighter isotopic composition of ice wedges, which developed between 1.2 ka and 0.7 ka ^{14}C BP. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: Central Yakutia; ice wedges; stable isotopes; late Quaternary; palaeoclimate; permafrost

INTRODUCTION

The landscape of Yakutia in northeast Siberia is strongly influenced by the existence of permafrost (Soloviev, 1973; Katasonov, 1975). The region's extreme continental periglacial setting gave rise to the development of permafrost that attains a thickness of 400 m or more. Continuous permafrost has existed since at least the beginning of the middle Pleistocene with reliable ages for old permafrost conditions between 366 and 267 ka obtained from deposits at the archaeological site Diring-Yuryakh south of Yakutsk (Waters *et al.*, 1997). The oldest dated permafrost horizon at this site contains large primary infill sand wedges that provide evidence of an extremely cold continental climate during the period of their formation.

During the last glacial period, the so-called Ice Complex was formed, composed of polygonal ice-wedge systems hosted in ice-rich soils and sediments, which had been syngenetically transformed into permafrost (Soloviev, 1959). Deposits of the Ice Complex are widespread in the coastal lowlands of Yakutia (e.g. Schirrmeister *et al.*, 2002) and in the non-glaciated lowlands of Central Yakutia (Katasonov, 1975; Romanovsky, 1985).

In contrast to the lowlands, the Verkhoyansk Mountain Range (see Figure 1) was affected by regional glaciations during the late Pleistocene (Kind *et al.*, 1971; Kind, 1975). Several glacial advances reached the western foreland, as documented by morainic arcs

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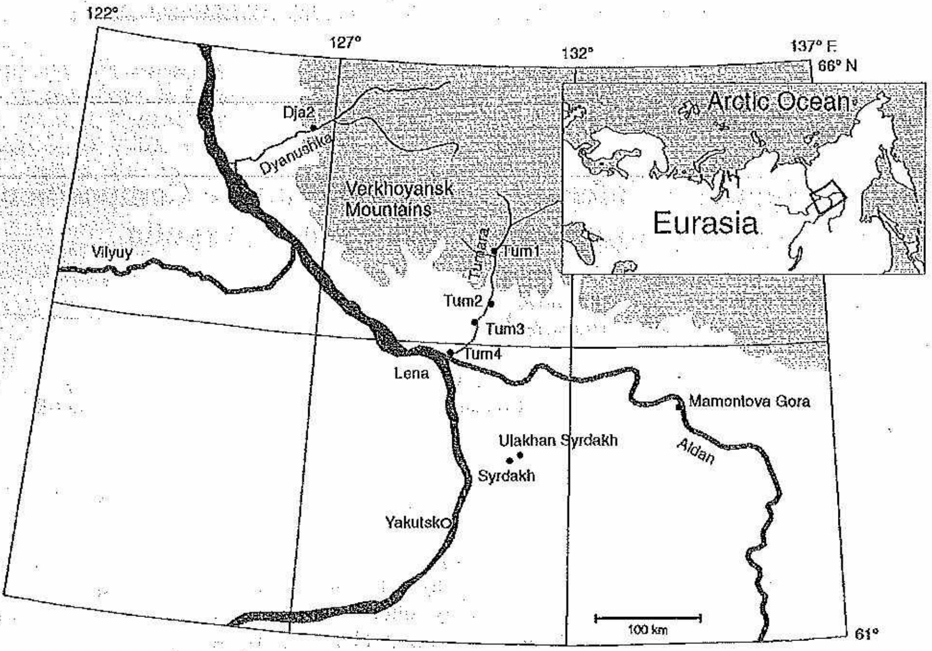

Figure 1 Map of the study area in Central Yakutia. The black dots mark the locations of the studied ice-wedge sections.

and associated glaciofluvial deposits. These prevented continuous ground-ice development and Ice Complex formation (Kolpakov, 1979). Ice-wedge growth took place in periglacial areas during those periods when glaciers were restricted to high elevations or had completely disappeared. The spatial and temporal distribution of ice-rich permafrost documents distinct episodes of ice-wedge formation between the stages of major glacial recession. At present, only small remnants of glacial ice exist at elevations above 1800 m a.s.l. in the northern Verkhoyansk Mountains and in the Suntar-Khayata Ridge (Koreysha, 1989), while ice wedges are actively developing on the plains.

Ice wedges mainly form during spring, when meteoric waters released by snowmelt enter thermal-contraction cracks that opened during late winter (Mackay, 1983; Romanovsky, 1985). Repeated cracking leads to lateral ice-wedge growth in epigenetic wedges and the resultant ground ice is younger than the host sediment. Where prolonged sediment accumulation occurs, ice wedges tend to grow vertically. In this mode, vertical ice accretion and enrichment of dispersed ice in the adjacent sediments proceed more or less syngenetically with the accumulation of fine-grained loess-like material (clayey silts and fine sand) deposited by aeolian, fluvial, lacustrine and slope processes (Mackay, 1990; French, 1996).

Previous work has demonstrated the potential for ice wedges to archive palaeoclimatic information within their stable-isotope signatures. For example, stable-oxygen isotope signals in ice wedges have been used as indicators of changes in palaeo-winter temperature (e.g. F.A. Michel, unpublished PhD thesis, 1982; Mackay, 1983; Vaikmäe, 1989; Vasil'chuk, 1991). However, studies by Meyer *et al.* (2002a, 2002b) dealing with the palaeoclimatic development of the coastal region of northeast Siberia during the late Pleistocene, have shown that palaeoenvironmental reconstruction requires knowledge of site-specific characteristics, such as slope aspect, surface relief, vegetation cover and regional climate conditions to enable full understanding of the variations in hydrogen and oxygen isotope signals in ice wedges. In this study, we present stable-isotope data from ice wedges of Weichselian and Holocene ages from the foreland of the Verkhoyansk Mountains, as well as from Central Yakutia, and discuss their palaeoclimatic implications.

STUDY AREA AND SITES

The study area in Central Yakutia stretches along the Lena and Aldan Rivers in the southwestern foreland of the Verkhoyansk Mountains (see Figure 1). Fieldwork was conducted at *Mamontova Gora* (63°N/134°E), a key location for Quaternary stratigraphy in Central Yakutia on the left bank of Aldan River, 325 km upstream of the Aldan-Lena confluence. The Ice Complex, which is exposed at this location, is distributed across the entire Lena-Amga interfluve area, developed on terrace plains of various elevations and ages (Péwé and Journaux, 1983). On the so-called Tyungyulyu terrace of late Weichselian age (equivalent to MIS 2), large ice wedges of the Ice Complex were sampled in the upper part of steep banks adjacent to two thermokarst lakes, the *Ulakhan Syrdakh Alas* and the *Syrdakh Alas* (62°30′N/131°E). Other sections were studied along the Tumara River (64°N/130°E), a tributary of the Aldan, and the Dyanushka River (65°N/126°E), a tributary of the Lena. At least four glacial advances shaped the basins of the Tumara and Dyanushka Rivers and left distinct morainal belts in front of the mountains (Kolpakov, 1979).

The study area is characterised by a strong continental climate. Data from the meteorological station in Yakutsk reveal low mean annual precipitation (222 mm) and a mean annual air temperature from 1985–93 of −8.7°C (RIHMI-World Data Centre: http://www.meteo.ru/index_e.html). Mean January temperature and precipitation are −37.6°C and 10 mm, respectively, while corresponding July values are 19.3°C and 33 mm, pointing to long severe winters and short warm summers. The distribution of annual precipitation, with its main period in summer between June and September, means that thick insulating snow cover does not form in winter and its absence promotes permafrost and ice-wedge formation.

MATERIAL AND METHODS

Single ice-wedge exposures were examined at four sites in peat and sand along the Tumara River and at one site in sandy sediments at Dyanushka River (see Figure 1). The ice wedges examined at the Ice Complex at *Mamontova Gora* and on the Tyungyulyu terrace are hosted in loess-like sediments.

Host sediments were described, sampled and the gravimetric ice contents were determined. Sampling of ice was performed along horizontal and vertical transects across the wedges, using an ice screw or chain saw, depending on the size of the wedge, according to the method of Meyer *et al.* (2002a). Samples for stable oxygen and hydrogen isotopes were collected at 10-cm intervals, thawed in sample bags, and then stored in 30-ml polyethylene bottles.

The isotopic composition of ground ice was measured with a Finnigan MAT Delta-S mass spectrometer in the laboratory of the Alfred Wegener Institute for Polar and Marine Research in Potsdam, following the equilibration technique developed for ^{18}O by Epstein and Mayeda (1953). The data are presented as permil difference relative to the standard V-SMOW (Vienna Standard Mean Ocean Water) with an internal 1-σ error of better than 0.8‰ and 0.1‰ for δD and δ^{18}O, respectively (Meyer *et al.*, 2000). Results are displayed in δ^{18}O-δD scatter diagrams, relative to the Global Meteoric Water Line (GMWL), which delineates the temperature-dependent isotopic composition of fresh natural waters, defined as $\delta D = 8\,\delta^{18}O + 10‰$ SMOW (Craig, 1961). The linear regression of precipitation data for a particular sampling site is known as Local Meteoric Water Line (LMWL). Slope and intercept of the LMWL are parameters that characterise the δ^{18}O-δD relationship and give information on the evolution of precipitation and the influence of secondary evaporation processes (Dansgaard, 1964). The deuterium excess value (defined as d excess $= \delta D - 8\delta^{18}O$) is an indicator for non-equilibrium fractionation processes (Dansgaard, 1964) and gives information on the origin of vapour masses, since the *d* excess is controlled by humidity in the source region (Merlivat and Jouzel, 1979). Thus, the winter precipitation resulting from an air mass yields a site-specific signature of its history, which is stored within glacier ice (Johnsen and White, 1989), and may also account for variations in the isotopic composition of ground ice as discussed later.

DATING OF ICE WEDGES

With one exception, the ages of the sampled ice wedges were estimated by accelerator mass spectrometry (AMS) ^{14}C dating of plant remains found within the ground ice and in the surrounding sediments (Table 1). Wood macrofossils at the *Mamontova Gora* site were dated by conventional radiocarbon method. The measurements were carried out at the Leibniz Laboratory in Kiel, Germany. In order to get reliable ages by AMS, only the leached tissue of the organic material was dated, with the exception of plant remains found within the ice wedges that contained few organic materials. The organic remnants of reed, roots and wood in bulk sediments were picked out under a microscope.

Dating ice wedges is difficult because of the diachronic growth of the ice body within a sediment sequence, and possible sources of error due to the presence of redeposited slope material as well as infiltration, migration and storage of young water containing modern ^{14}C. Dating of the host sediments

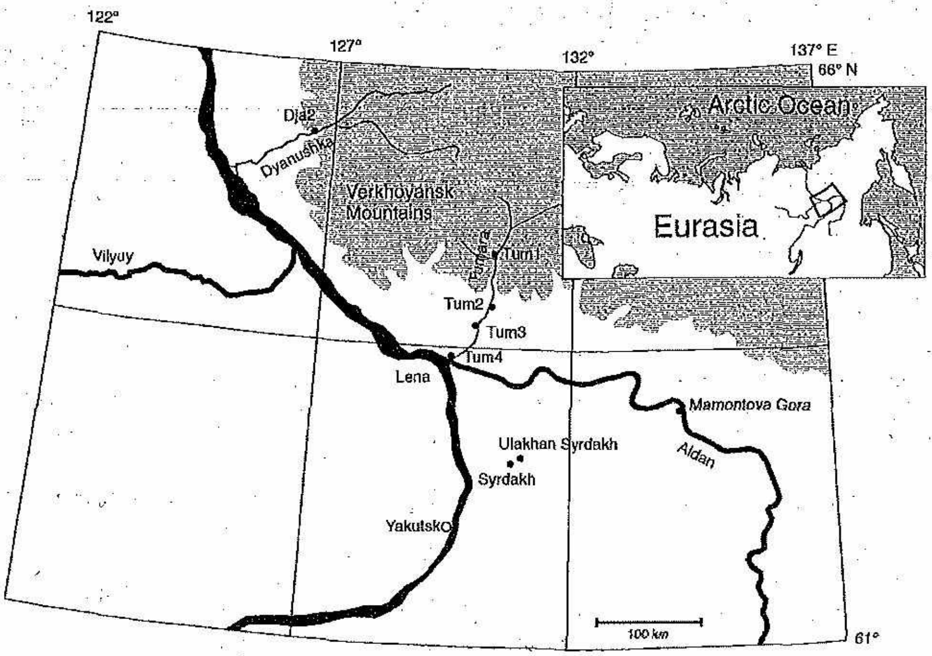

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Table 1 AMS radiocarbon ages of organic remains from host sediments and ground ice. The sample from Mamontova Gora was dated by the conventional radiocarbon method. Data without calibrated ages are out of the range of calibration data sets or contain uncertainties, preventing calibration.

Site	Lab. Number	^{14}C yr BP	cal. yr BP 2-σ range	Organic matter source	Material
Mam. G.	KI-5183	41230	Not available	Host sediments	Wood
Ulakh. Syr.	KIA 26364	13110 ± 285	16466–4410	Ground ice	Plant remains
	KIA 26365	3755 ± 30	4184–4072	Ground ice	Plant remains
Syrdakh	KIA 26367	21710 ± 680	Not available	Ground ice	Plant remains
Tum1	KIA 19144	8539 ± 44	9557–9469	Host sediments	Plant/wood remains
Tum2	KIA 19724	770 ± 22	715–666	Host sediments	Piece of wood
Tum3a	KIA 19727	2340 ± 25	2362–2314	Ground ice	Plant remains
	KIA 25983	16420 ± 400	20661–18522	Ground ice	Plant remains
Tum3	KIA 20724	40420 ± 1440	Not available	Host sediments	Plant/wood remains
Tum3	KIA 20725	39710 ± 1185	Not available	Host sediments	Plant/wood remains
Tum4	KIA 19725	1200 ± 23	1179–1057	Host sediments	Plant remains
	KIA 25984	475 ± 60	565–428	Ground ice	Plant remains
Dja2	KIA 24041	13980 ± 60	17267–16295	Ground ice	Plant remains
	KIA 24042	14620 ± 150	18125–16936	Host sediments	Plant remains

mostly provides a maximum age for the enclosed ground ice, that is the ground ice is no older than the host sediments and, more likely, is younger than them. Organic matter obtained from the ice gives an age marker of one moment in time during the entire wedge development, if redeposition and contamination of the material transported into the thermal contraction crack can be excluded. The best age constraint, however, is given when both the host sediments and the ice wedge are dated or at least the age of the sediments is known from other studies.

RESULTS

In this section, the ground-ice exposures studied are described in terms of their field appearance, their depositional environments, the datable material that constrains their ages (Figure 2) and the stable-isotope values for the ice wedges.

Mamontova Gora

This exposure extends about 12 km along the Aldan River bank and is situated about 325 km upstream of the Aldan-Lena confluence (see Figure 1). It consists of two main geomorphologic units, marked by an 80 m high and a 50 m high terrace level, respectively (Baranova, 1979). The upper part of both terrace sections is composed of greyish and brownish silt of middle and late Weichselian age (equivalent to MIS 3 and 2), respectively (Péwé and Journaux, 1983). Ice wedges up to 5 m wide were sampled within the silts of the lower terrace. Their syngenetic origin is indicated by layered cryostructures in the host sediments that turn upward adjacent to the wedge owing to the ice growth (Figure 2a). A piece of wood from the sediments somewhat above the ice samples yielded a radiocarbon age of 41230 a BP. This age fits in well to with previous published results from this site, suggesting that ice-wedge growth took place roughly between 46700 ± 1500 ^{14}C a BP and 34020 ± 1500 ^{14}C a BP (Péwé and Journaux, 1983). The isotopic composition of the ice averages −30.5‰ for δ^{18}O and −237‰ for δD. The mean *d* excess value amounts to 7.6‰. There is particularly low variability in the stable isotope composition, less than 2‰ for δ^{18}O and 16‰ for δD.

Lake Syrdakh and Ulakhan Syrdakh

These two sites are very similar and thus are described together. Both sampled ice wedges grew in loess-like deposits that cover the Tyungyulyu terrace. These sediments were dated to around 19 ka BP close to the permafrost table at *Lake Syrdakh* (Katasonov, 1979). The results of dating organic matter enclosed in the ground ice suggest a late Weichselian age for the sediments. The sampled material in the ground ice at *Lake Syrdakh* provides an age of 21710 ± 680 ^{14}C a BP (Figure 2b). At site *Ulakhan Syrdakh*, organic material in the ice dates to 13110 ± 680 ^{14}C a BP at the margin and to 3755 ± 30 ^{14}C a BP in the middle (Figure 2c). Non-parallel, lenticular cryostructures, a moderate gravimetric ice content (30%) and

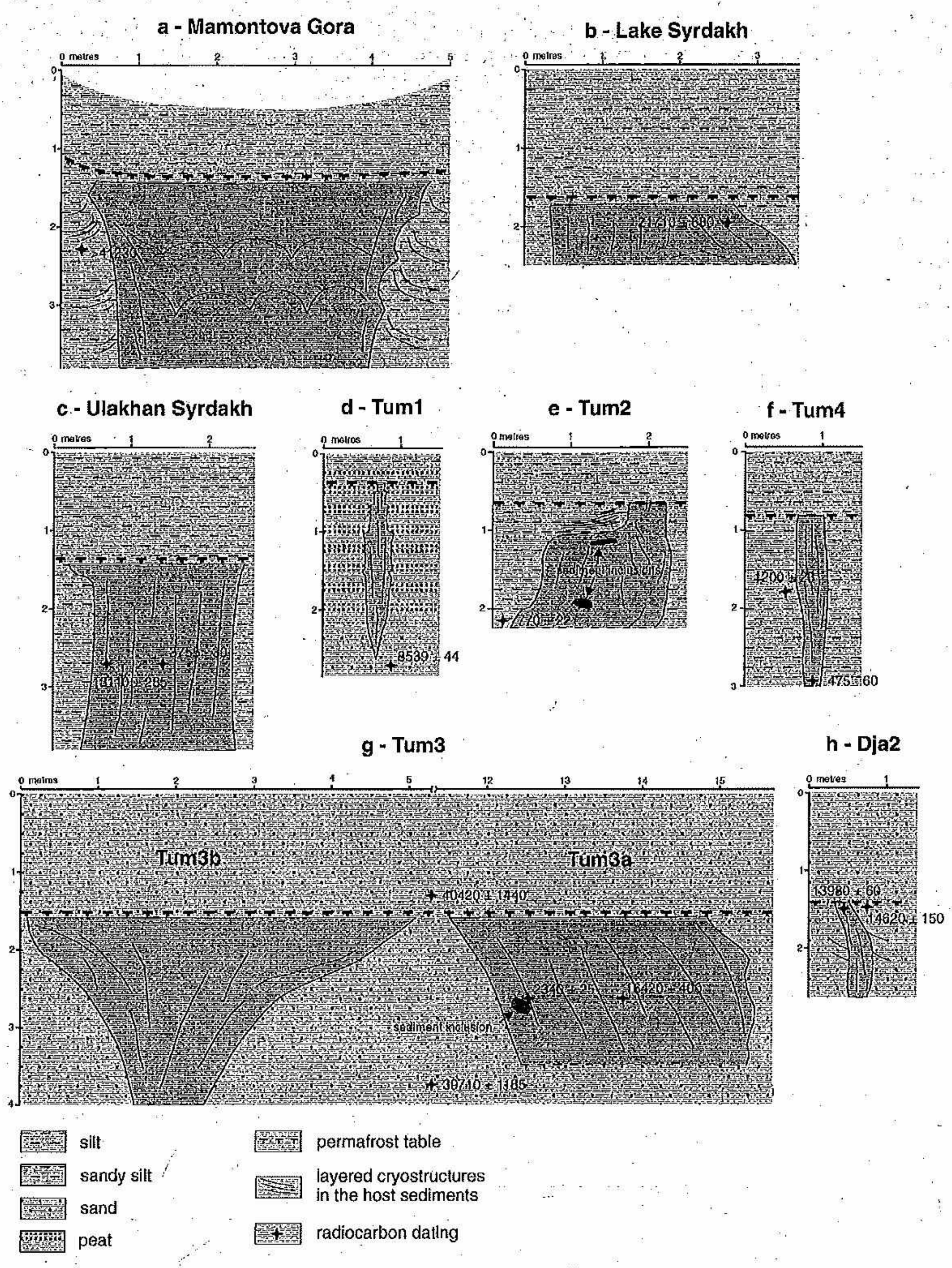
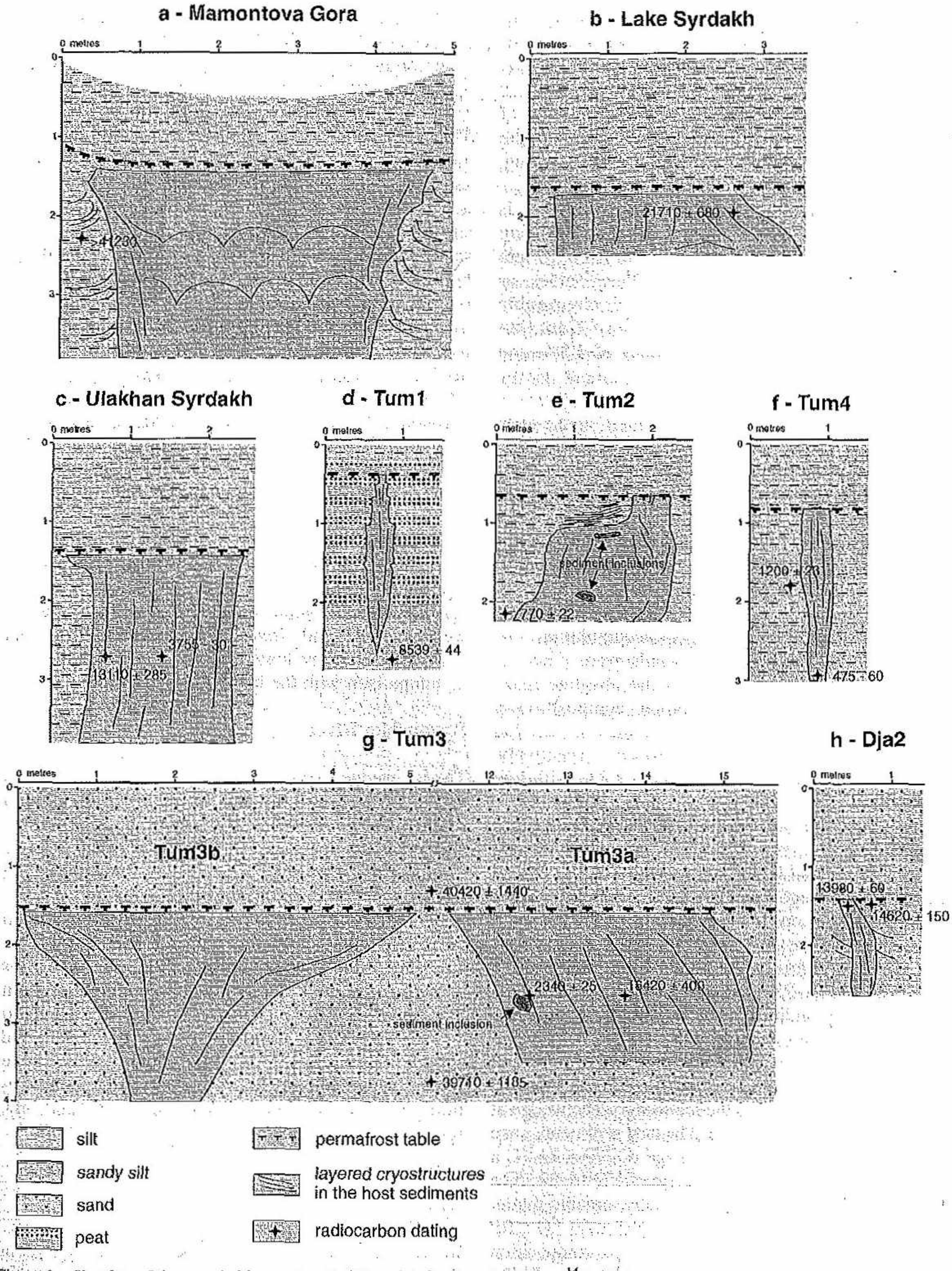


Figure 2 Sketches of the sampled ice wedges and the related radiocarbon ages (^{14}C a BP).



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palaeosols characterise the silty sediments. At *Ulakhan Syrdakh*, the top of the exposed ice wedge is approximately 2.1 m in width and 2.3 m in length. The whole ice wedge, however, probably extends more than 10 m into the ground, to at least the level of the thermokarst lake below. At site *Lake Syrdakh*, the exposed ice wedge is around 3 m wide and 0.8 m long, but the true extent is probably similarly great.

The mean isotopic composition of the ice is −31.3‰ for δ^{18}O and −246‰ for δD at the *Ulakhan Syrdakh* site and −30.8‰ and −245‰ for δ^{18}O and δD, respectively, at *Lake Syrdakh*. These values, as well as the low variability of the data, are comparable to the isotopic record at site *Mamontova Gora*, but differ by lower mean *d* excess values of 1.8‰ and 4.5‰, respectively.

Tumara River

Ice wedges were exposed at four sites along the Tumara River banks (see Figure 1). Site *Tum1* is situated within a broad glacially carved valley in the mountains. This ice wedge developed within a 2-m thick peat deposit overlying river gravel (Figure 2d). The 0.4 m wide and 1.8 m long wedge likely penetrated epigenetically into the basal sands, and then grew syngenetically with the peat accumulation. Organic remains from the basal sands were dated to 8539 ± 44 ^{14}C a BP. This age is the absolute maximum age for the ice. The isotopic composition is relatively enriched, showing mean values of −25.9‰ and −199‰ for oxygen and hydrogen, respectively. The mean *d* excess value amounts to 8.2‰ with low variability.

Sites *Tum2* and *Tum4* exhibit syngenetic ice wedges of different sizes. The first one is up to 1.3 m wide whereas the second is only 0.2 m wide (Figure 2e and 2f). The visible lengths of about 2 m for both ice wedges show a transition zone to the host sediments with an ice-rich matrix and for site *Tum2*, layered ice structures. Both ice wedges formed on flood plain terraces of the Tumara and Aldan Rivers. The ice bodies are embedded in mainly silty sediments with high gravimetric ice content (46–175%). The growth of *Tum2* appears to have been affected by rapid accumulation of overbank deposits with higher sand content, resulting in a narrow width in the upper part of the ice wedge. The wedge at *Tum4* shows a constant width. The host sediments were dated at both sites, providing an age of 770 ± 22 ^{14}C a BP for *Tum2* (Figure 2e) and an age of 1200 ± 23 ^{14}C a BP for *Tum4* (Figure 2f). Additionally, organic matter enclosed in the ice shows an age of 475 ± 60 ^{14}C a BP for the ice wedge *Tum4*. The mean isotopic composition of both wedges is around −28‰ for δ^{18}O and −214‰ for δD with a mean d excess value of 11‰ and 10‰, respectively.

In contrast to the other *Tum* sites, *Tum3* is situated approximately 20 m above the river within a retrogressive thaw slump more than 30 m in diameter. This thaw slump is underlain by basal till, acting as an impermeable bed for the overlying ice-bearing sandy deposits. Several ice wedges with widths of up to 5 m were exposed, of which two were sampled at this site (*Tum3a* and *Tum3b*). Radiocarbon dating of the sandy sediments resulted in an age around 40 ka BP at both 1.2 m and 3.9 m depths (Figure 2g). At least one of these two samples was likely biased by refrozen slope material or other thaw-freeze related processes. Infrared stimulated luminescence (IRSL) dating nearby the ice wedges, however, provided an age of 48500 ± 3900 a BP (G. Stauch *et al.*, Luminescence chronology from the Verkhoyansk Mountains, north-eastern Siberia, submitted), constraining the age of the host sediments as middle Weichselian. Dating of organic matter in the ice resulted in contradictory ages of 2340 ± 25 ^{14}C a BP at the left margin near a sediment inclusion and 16420 ± 400 ^{14}C a BP in the middle part of *Tum3a* (Figure 2g). The mean isotopic composition of around −28‰ for δ^{18}O and −220‰ for δD closely agrees with the isotopic signal in the late Holocene ice wedges *Tum2* and *Tum4*. On the other hand, the *d* excess differs by lower values of 6.0‰ and 8.2‰ in comparison with the late Holocene ice (Table 2).

Dyanushka River

The ice wedge exposed at site *Dja2* is 0.3 m in width and >1.2 m in length and is enclosed in alluvial sediments. The sediment sequence is about 10 m thick and forms the upper part of an old terrace step above the modern Dyanushka River valley floor, overlying basal diamicton. The terrace surface exhibits a polygonal pattern. Curved and layered cryostructures and an ice-rich matrix (40–52%) characterise the permafrost deposits. Syngenetic growth of the wedge is evident from the dating results. Organic matter from the upper part of ice wedge *Dja2* is dated to 13980 ± 60 ^{14}C a BP and the nearby sediments yield an age of 14620 ± 150 ^{14}C a BP (Figure 2h). The ice wedge has a relatively heavy mean isotopic composition of −22.4‰ and −172‰ for δ^{18}O and δD, respectively, with a mean *d* excess value of 7.5‰.

DISCUSSION

In general, melting of snow and its refreezing in thermal contraction cracks is accepted as the main

Table 2 Stable isotope data (δ^{18}O, δD and *d* excess minima, mean and maxima) as well as the standard deviation, slope and intercept of all sampled ice wedges of the study area. The recent precipitation was sampled in Yakutsk. Samples of river water apply to the Tumara and Dyanushka Rivers during fieldwork in the summers 2002 and 2003.

Site	N	δ^{18}O (‰) min	δ^{18}O (‰) mean	δ^{18}O (‰) max	δ^{18}O (‰) s.d.	δD (‰) min	δD (‰) mean	δD (‰) max	δD (‰) s.d.	d (‰) min	d (‰) mean	d (‰) max	d (‰) s.d	Slope	Intercept	r^2
Mam.G.	18	−31.31	−30.52	−29.37	0.61	−243.1	−236.6	−227.5	4.8	6.4	7.6	8.9	0.6	8.02	8.09	0.98
Ulakh.Syr.	24	−31.99	−31.30	−30.50	0.40	−252.1	−245.6	−238.2	3.9	3.2	4.5	6.0	0.8	9.60	53.32	0.98
Syrdakh	23	−31.16	−30.79	−30.42	0.20	−247.9	−244.5	−241.9	1.7	0.9	1.8	3.1	0.6	7.99	1.34	0.90
Tum1	22	−27.57	−25.94	−24.43	0.94	−211.0	−199.4	−187.9	7.1	7.1	8.2	9.7	0.8	7.48	−5.43	0.99
Tum2	21	−29.26	−28.33	−27.27	0.48	−222.5	−215.7	−207.6	3.5	8.7	11.0	13.2	1.0	7.06	−15.51	0.94
Tum3a	24	−29.59	−28.13	−27.09	0.77	−228.2	−219.1	−210.6	5.1	3.6	6.0	8.7	1.4	6.53	−35.50	0.97
Tum3b	22	−29.04	−28.68	−27.47	0.35	−223.7	−221.3	−211.3	2.7	6.8	8.2	9.2	0.7	7.41	−8.84	0.94
Tum4	20	−29.85	−27.64	−24.96	1.20	−226.6	−210.9	−190.8	9.1	8.9	10.2	12.5	0.9	7.56	−1.99	0.99
Dja2	15	−24.09	−22.36	−21.74	0.58	−181.7	−171.5	−167.5	3.6	5.7	7.5	11.0	1.6	5.91	−39.38	0.91
River water	5	−21.25	−20.84	−20.58	0.28	−160.6	−158.4	−156.3	1.9	7.3	8.4	10.1	1.3	—	—	—
Recent precipitation:																
rain	35	−22.06	−12.15	−5.09	3.70	−177.4	−105.5	−68.1	24.9	−32.3	−8.3	8.3	10.4	6.34	−28.46	0.89
snow	38	−43.12	−32.56	−20.92	6.57	−336.6	−252.1	−168.8	50.6	−8.1	8.3	16.9	5.7	7.66	−2.90	0.99

reason for recent ice-wedge formation (e.g. Mackay, 1983; Vaikmäe, 1989; Vasil'chuk, 1992; Lauriol *et al.*, 1995). The isotopic signal in ice wedges therefore is strongly related to the stable-isotope composition of winter precipitation. The isotopic composition of both winter and summer precipitation at a given site is the result of various processes. The initial formation of a vapour-bearing air mass over the oceans by evaporation and advection towards the continent is accompanied by significant isotopic fractionation in terms of the rain-out effect, which is described by the Rayleigh model (Dansgaard, 1964). As a result, the moisture reaching Yakutia by the Westerlies is depleted in δ^{18}O and δD values in comparison with the initial vapour mass (Kurita *et al.*, 2004), known as the continental effect. Seasonal variations in the stable-isotope content of precipitation are attributed to the temperature-dependent fractionation processes (Jouzel *et al.*, 1997). Intra-seasonal variations in the isotopic composition may be related to mixing of different air masses labelled by different isotopic ratios and the additional contribution of recycled water from the land surface. The latter process in particular influences summer precipitation (Figure 3), modifying the isotopic ratio of rain in eastern Siberia (Kurita *et al.*, 2003). In contrast, winter precipitation in Yakutia is not significantly altered by kinetic fractionation processes, as suggested by a mean *d* excess value of 8.3‰ and a slope value of 7.6, which closely agree with the GMWL (Figure 3). The mean isotopic composition of the sampled snow amounts to −32.6‰ for δ^{18}O and −252‰ for δD with a relatively large variability of more than 20‰ and 160‰, respectively (Table 2).

During snowmelt in spring, the isotopic signal in the melt changes through time. The initial snowmelt is highly depleted in comparison with the average snowpack and the snow becomes enriched in oxygen and hydrogen stable isotopes. The progressive melting results in the enrichment of ^{18}O and D in both the snowmelt and the residual snowpack (Taylor *et al.*, 2001). Sub-recent ice wedges younger than 700 years (*Tum2, 4*) show enriched mean isotopic compositions in comparison with the average snow. This may be the result of filling the frost-cracks during a later stage of snowmelt (Lauriol *et al.*, 1995). However, the lack of isotopic data in recent ice veins, which could refer to distinct average winter precipitation, makes this interpretation difficult to prove.

The freezing of the snowmelt in the frost-crack represents a reverse fractionation process, with exchange occurring between the water and the ice. The first ice is enriched in ^{18}O and D and with continued freezing, both the ice and the remaining water gradually become depleted in ^{18}O (Clark and Fritz, 1997).

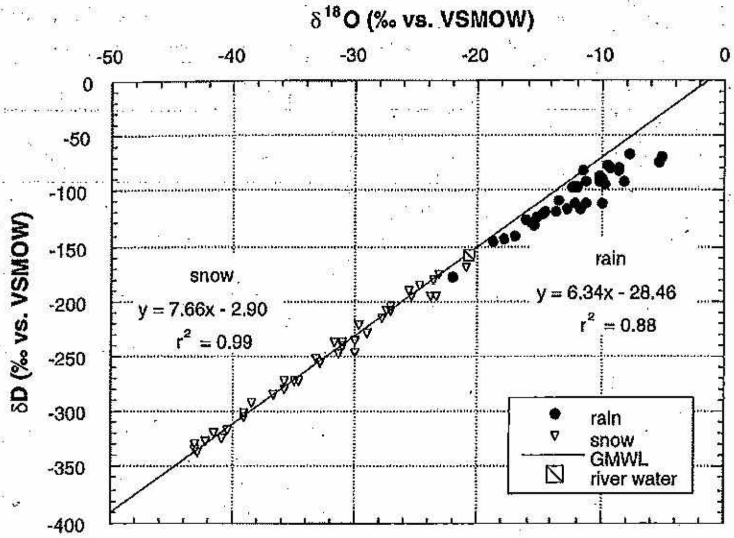

Figure 3 $\delta^{18}O$-δD diagram for snow, rain and river water in Central Yakutia. The rain samples were collected in summer 1997 (June–August) and the snow samples reflect the winter 1997–8 (November–April) in Yakutsk. The square represents the mean isotopic composition of waters from the Tumara and Dyanushka Rivers, sampled during fieldwork in the summers 2002 and 2003.

Non-equilibrium fractionation is negligible when the freezing rate is faster than 2 mm/h (F.A. Michel, unpublished PhD thesis, 1982). Apparently, the considered processes predominantly follow the Rayleigh distillation with no significant kinetic fractionation as shown by the isotopic composition in most of the ice wedges (Table 2). In particular the isotopic compositions of Holocene ice wedges closely agree with the GMWL (Figure 4). Kinetic fractionation that might have occurred is likely related to sublimation and metamorphism of the snowpack during winter as well as to the additional contribution of waters of different origin. Other processes, such as vapour diffusion within the ice, which would result in a smoothing of isotope gradients with time (Jean-Baptiste *et al.*, 1998), can be excluded for the young ice wedges. Even in late Pleistocene ice wedges, this process is of minor importance as discussed by Meyer *et al.* (2002a). Furthermore, water migration at the interface of ice and sediment may occur, which results in mixing effects between wedge ice and segregated ice (Meyer *et al.*, 2002a). Therefore, we excluded the data points of the marginal ice wedge samples from the scatter plots (Figure 4), to avoid false interpretations.

In conclusion, the major shifts in the mean isotopic composition among the ice wedges reflect different condensation temperatures of precipitation that are basically controlled by the ambient air temperature and therefore provide a signal of palaeo-winter temperatures. The variability in the isotopic data thus would indicate climatic changes for particular periods of the past. The character of variations among the isotopic compositions is illustrated in Figure 5, which shows three groups that comprise the Pleistocene ice wedges, the Holocene ice wedges and one outlier, respectively.

In order to test whether the variability of $\delta^{18}O$ and δD among the ice-wedge sites is statistically different, an analysis of variance (ANOVA) was performed, using the software ‘StatView’ (version 4.5). The sites *Tum2* and *Tum4* as well as *Tum3a* and *Tum3b* were each combined into a single group because they are assumed to represent comparable environments in terms of their isotopic compositions, host sediments and ages. The results of ANOVA show that the isotopic compositions among the ice wedges are significantly different, meaning that the statistical samples originate from independent populations. A multiple comparison test (Bonferroni/Dunn procedure, Table 3) showed that the sites and *Lake Syrdakh* and *Ulakhan Syrdakh* are not statistically different in regard to both $\delta^{18}O$ and δD values. This suggests that the 3755 ± 30 ^{14}C a BP date from the middle of the wedge at *Ulakhan Syrdakh* (Figure 2c) is unlikely to be correct and probably represents contamination of

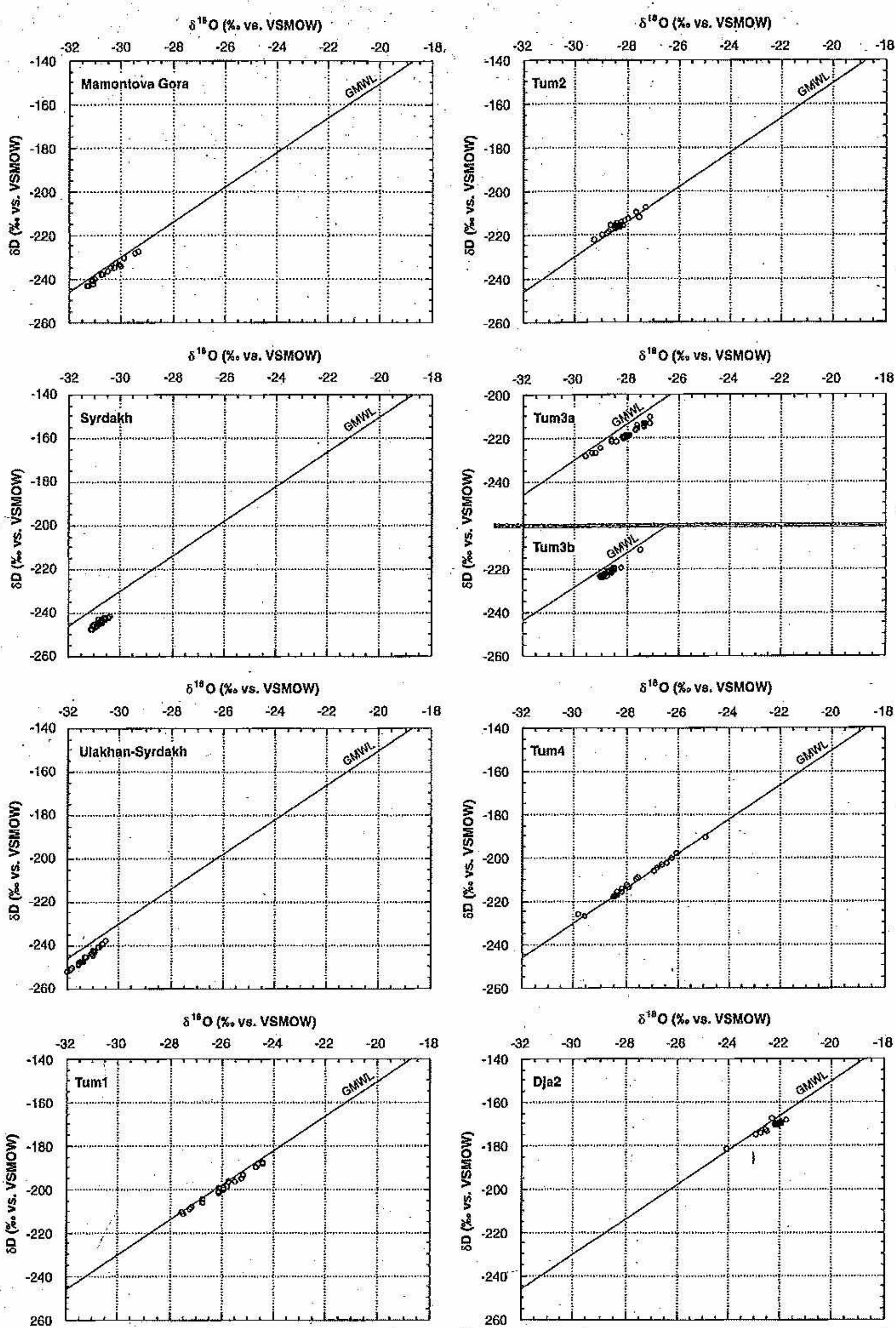

Figure 4 δ^{18}O-δD diagrams for all sampled ice wedges in relation to the Global Meteoric Water Line (GMWL).

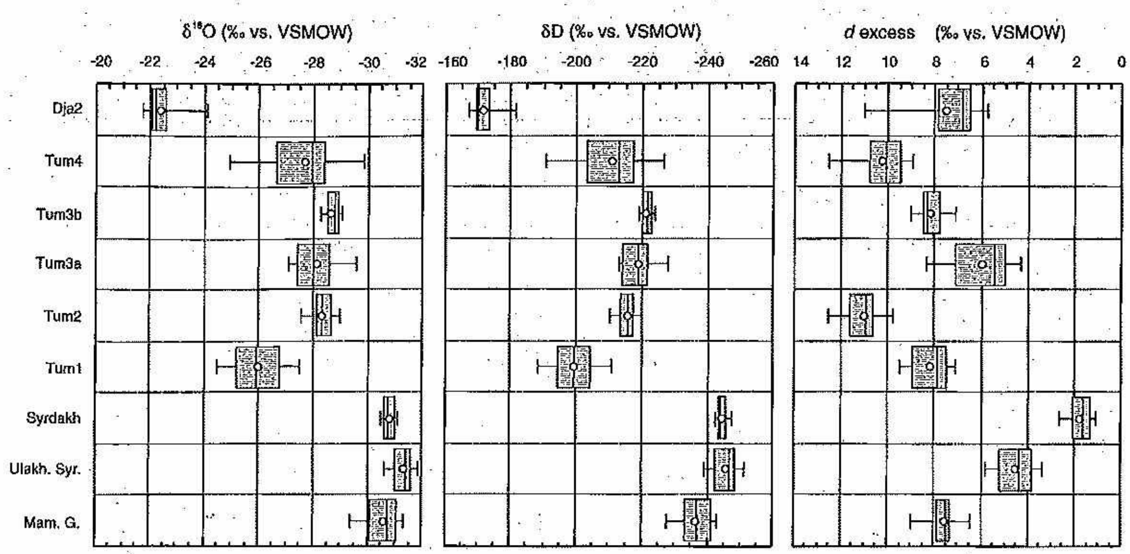

Figure 5 Box plots of the isotopic composition ($\delta^{18}O$ and δD) and the *d* excess values of the ice-wedge sites. The boxes enclose 50% of the respective data with the median value (black line therein) and the mean value (white circle therein). The bottom and the top of the boxes (right and left definitions) represent the first and the third quartiles, respectively. The lines extending from the boxes enclose 90% of the data by marking the 0.05 and the 0.95 percentiles, respectively. These limits were chosen in order to exclude extreme values and outliers from the diagrams.

the ice vein by younger organic matter by infilling or redeposition and subsequent freezing on the ice surface.

Taking only the $\delta^{18}O$ values into account, no significant differences were revealed for the sites *Mamontova Gora* and *Syrdakh* as well as for *Tum2, 4* and *Tum3*, respectively. The disparities in the multiple comparisons of $\delta^{18}O$ and δD values may be attributed to kinetic fractionation processes, affecting oxygen and hydrogen stable isotopes in different ways. However, the results of the ANOVA and the multiple comparison test show similarities in the isotopic data of mainly Pleistocene ice wedges as well as distinct differences in isotopic compositions between Pleistocene, middle Holocene and late Holocene ice wedges that serve as the basis for the palaeoclimatic interpretation of the data.

PALAEOCLIMATIC IMPLICATIONS

The Pleistocene ice wedges are characterised by the lightest isotopic composition that reflects the coldest winter temperatures within the considered time span (Figures 4 and 5). In particular, at the sites *Ulakhan Syrdakh* and *Syrdakh*, the isotope values of up to −32.0‰ and −252‰ for $\delta^{18}O$ and δD, respectively, reveal very severe climate conditions for the late Weichselian around 21 ka and 13 ka BP (Table 1). The older ground ice at *Mamontova Gora* shows a slightly warmer isotopic signal with a larger variability than the former sites that may be attributed to the climatically more variable Kargin interstadial (equivalent to MIS 3) (e.g. Schirrmeister *et al.*, 2002, Hubberten *et al.*, 2004). The isotopic composition, however, which averages −30.5‰ for $\delta^{18}O$ and −237‰ for δD, still indicates a very cold winter environment around 40 ka BP. The similarity of the winter conditions during the middle and late Weichselian, emphasised by the results of the ANOVA, is also reported from the Ice Complex at the Laptev Sea coast and neighbouring regions in northeast Siberia (Vasil'chuk, 1991; Meyer *et al.*, 2002a). These results suggest severe winter conditions over wide expanses of Yakutia during that time.

Unlike the other Ice Complex sections, the site *Dja2*, which is dated to around 14 ka BP (Table 1), presents a relatively enriched mean isotopic composition of −22.4‰ and −172‰ for $\delta^{18}O$ and δD, respectively (Figures 4 and 5). This signature would indicate more favourable winter conditions at that time than during the postglacial warming, which is not consistent with findings from other proxy data across the Siberian Arctic, such as fossil insects, pollen records, mammals and other isotopic data (e.g. Meyer *et al.*, 2002a; Schirrmeister *et al.*, 2002;

Table 3 ANOVA for comparison of $\delta^{18}O$ and δD data among the seven ice-wedge sections (note that sites *Tum2* and *Tum4* as well as *Tum3a* and *Tum3b* are each combined into a group). Table 3a presents the results of ANOVA, showing that significant differences between the sampled sites do exist (indicated by the p-value of <0.0001). Table 3b exhibits the results of the multiple comparison test (Bonferroni/Dunn procedure) revealing which sites are different at the level of significance of 5%. A statistically significant difference is indicated if the p-value ranges below 0.0024. Only three sites (italicised) do not fulfil the latter criterion in reference to the $\delta^{18}O$ variable.

a)

Source of variation	d.f.	Sum of squares	Mean squares	F-value	p-value
Sites $\delta^{18}O$	6	1093.943	182.324	364.591	<0.0001
Residual	182	91.014	0.500		
Sites δD	6	81014.343	13502.390	500.413	<0.0001
Residual	182	4910.809	26.982		

b)

	Bonferroni/Dunn for $\delta^{18}O$			Bonferroni/Dunn for δD		
Sites	Mean Diff.	Crit. Diff.	p-value	Mean Diff.	Crit. Diff.	p-value
Dja2, Mam.G.	8.157	0.762	<0.0001	65.090	5.596	<0.0001
Dja2, Syrdakh	8.423	*0.723*	*<0.0001*	*73.075*	*5.312*	*<0.0001*
Dja2, Tum1	3.581	0.730	<0.0001	27.926	5.359	<0.0001
Dja2, Tum2, 4	5.629	0.658	<0.0001	41.899	4.830	<0.0001
Dja2, Tum3	6.028	0.648	<0.0001	48.651	4.759	<0.0001
Dja2, Ulakh.Syr.	8.894	0.717	<0.0001	74.152	5.268	<0.0001
Mam.G., Syrdakh	*0.266*	*0.686*	*0.2336*	*7.985*	*5.037*	*<0.0001*
Mam.G., Tum1	−4.576	0.693	<0.0001	−37.164	5.087	<0.0001
Mam.G., Tum2, 4	−2.527	0.616	<0.0001	−23.191	4.526	<0.0001
Mam.G., Tum3	−2.129	0.606	<0.0001	−16.439	4.450	<0.0001
Mam.G., Ulakh.Syr.	0.738	0.679	<0.0001	9.062	4.991	<0.0001
Syrdakh, Tum1	−4.842	*0.650*	*<0.0001*	*−45.148*	4.773	*<0.0001*
Syrdakh, Tum2, 4	−2.793	0.568	<0.0001	−31.176	4.170	<0.0001
Syrdakh, Tum3	−2.395	0.556	<0.0001	−24.424	4.088	<0.0001
Syrdakh, Ulakh.Syr.	0.472	0.636	*0.0234*	1.078	4.670	*0.4780*
Tum1, Tum2, 4	2.049	0.576	<0.0001	13.972	4.230	<0.0001
Tum1, Tum3	2.447	0.565	<0.0001	20.725	4.149	<0.0001
Tum1, Ulakh.Syr.	5.314	0.643	<0.0001	46.226	4.724	<0.0001
Tum2, 4, Tum3	0.398	0.468	*0.0094*	6.752	3.438	<0.0001
Tum2, 4, Ulakh.Syr.	3.265	0.560	<0.0001	32.254	4.114	<0.0001
Tum3, Ulakh.Syr.	2.866	0.549	<0.0001	25.502	4.030	<0.0001

Hubberten *et al.*, 2004; Kienast *et al.*, 2005; Sher *et al.*, 2005). These studies reveal a pronounced continental climate with very cold winters and summers distinctly warmer than today under extremely dry conditions between 20–15 ka BP. These contradictions can be resolved by taking into account the probable origin of the water that fed the ice wedge. Given that the isotopic composition exhibits no strong alteration by kinetic fractionation processes (Figure 4), it appears most likely that the water originated from spring flooding because the site is located on fluvial terrace deposits. Modern river water shows a similar isotopic composition of −20.8‰ and −158‰ for oxygen and hydrogen, respectively, as well as a similar range in the d excess values (Table 2). If this interpretation is correct, the lighter isotopic composition of the ice wedge would be the result of the prevailing climate conditions, affecting the surface waters. Consequently, the results from this ground ice are not comparable with the other ice-wedge data.

In comparison with the Ice Complex data, the Holocene ice wedges are characterised by an enriched isotopic composition relative to the Pleistocene ice wedges (Figures 4 and 5), indicating warmer conditions. The oldest postglacial site is *Tum1*, showing enriched oxygen and hydrogen compositions of around 5‰ and 35‰, respectively. The age of the ice wedge at this site remains uncertain because radiocarbon dating provides only a maximum age of 8.5 ka BP. Given the relatively warm isotopic signature of −25.9‰ for $\delta^{18}O$ and −199‰ for δD, however, we believe that the ice wedge grew during the favourable middle Holocene period. Pollen-based studies from lakes in Central Yakutia revealed a climate optimum between 6.0 ka and 4.5 ka BP (Andreev *et al.*, 2002a). The general warming trend, however, started during the Boreal period around 8.0 ka BP in northern Yakutia and neighbouring areas (Andreev and Klimanov, 2000; Andreev *et al.*, 2002b; Naidina and Bauch, 2001). Thus, the isotopic composition of *Tum1* may reflect postglacial climate amelioration in northeast Siberia, most likely between 8.5 ka and 4.5 ka BP.

The isotopic composition of ice wedges changed to relatively light towards the late Holocene and subrecent time. Ground ice at the sites *Tum2* and *Tum4* is interpreted as being younger than 1.2 ka BP based on dating results of the host sediments. The mean isotopic composition is around −28‰ for oxygen and −214‰ for hydrogen (Figures 4 and 5). These values document the climate deterioration, which started at around 4.5 ka BP according to pollen records in northern Yakutia (Andreev *et al.*, 2002b, 2004). Similarly light but also slightly enriched isotopic compositions of late Holocene ice wedges are reported from the Laptev Sea coast between 3.5 ka and 1.0 ka BP (Meyer *et al.*, 2002a, 2002b). Both regions demonstrate the impact of climate on the stable-isotope composition in young ground ice, even though northern and Central Yakutia differ by being in the tundra and taiga zone, respectively.

Site *Tum3* is excluded from the chronological palaeoclimatic interpretation because of the uncertain age dating of the ice. The mean isotopic composition of around −28‰ for oxygen and around −220‰ for hydrogen for both sampled ice wedges matches the late Holocene isotopic signal of *Tum2* and *Tum4* (Figures 4 and 5) and would be consistent with the radiocarbon age of 2.3 ka BP. On the other hand, the middle Weichselian host sediments and the other age marker from the ice around 16 ka BP give inconsistent age indications.

CONCLUSIONS

The interpretations of the isotopic data support the assumption that ice wedges are basically fed by meteoric water, released during snowmelt in spring and provide an isotopic signal of winter precipitation. Secondary kinetic fractionation processes play a subordinate role, whereas the contribution of surface waters, which possibly diluted the snowmelt water and biased the primary precipitation signal, had a significant influence on the isotopic composition of some wedges.

The ice wedges with mostly unaltered isotope signals indicate that pronounced variations in winter conditions occurred over the past 40000 years. The middle Weichselian, around 41 ka BP, was characterised by cold and severe winter conditions in Central Yakutia. Similar and even colder conditions are indicated for the late Weichselian Ice Complex around 21 ka and 13 ka BP. The early Holocene showed a winter climate optimum, as indicated by isotope signals in the ice, dating to a maximum of 8.5 ka BP. The late Holocene was characterised by a deterioration in winter conditions in Central Yakutia, indicated by 'cold' isotopic signals in ice wedges younger than 1000 years. Variations in winter temperatures were consistent with parallel changes in summer temperatures, as indicated by pollen records from Central Yakutia, which reflect warm-season climate conditions.

The palaeoclimatic interpretation of isotopic composition of ice wedges in Central Yakutia is a promising technique but requires more detailed information on boundary conditions that control the depositional environment of the host sediments as well as accurate age determinations.

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