Polarforschung 70: 3 – 11, 2000 (erschienen 2002)

The Sedimentological, Mineralogical and Geochemical Composition of Late Pleistocene Deposits from the Ice Complex on the Bykovsky Peninsula, Northern Siberia

by Christine Siegert[1], Lutz Schirrmeister[1] and Olga Babiy[2]

Summary: This paper presents results of sedimentological, mineralogical and geochemical studies of Ice Complex deposits from the Mamontovy Khayata site, Bykovsky Peninsula, near the Lena Delta. According to new radiocarbon dating, the investigated sequence was formed more or less continuously from about 60 ky BP until the beginning of the Holocene. Geochemical data, mainly affected by the character of soil formation during the accumulation period, allow to distinguish between cooling and warming stages. Grain size characteristics and the small maturity of clastic material provide evidence for a nearby source area. The mineralogical composition of the studied Ice Complex deposits indicates that the neighbouring parts of the Kharaulakh Mountains have continuously acted as a denudation area and have not been covered by an ice sheet within the investigated time span. Only a restricted mountain glaciation can be considered.

Zusammenfassung: Die Arbeit enthält Resultate sedimentologischer, mineralogischer und geochemischer Untersuchungen von Ablagerungen des Eiskomplexes am „Mamontovy Khayata" auf der Bykovsky-Halbinsel, südöstlich des Lena-Deltas. Entsprechend den neu vorliegenden Radiokarbon-Datierungen wurde die untersuchte Abfolge kontinuierlich zwischen etwa 60.000 J.v.h. und dem Beginn des Holozäns gebildet. Die geochemischen Eigenschaften der Ablagerungen wurden in erster Linie durch den Charakter der postsedimentären Bodenbildung bestimmt. Sie erlauben es, Abkühlungs- und Erwärmungsphasen zu unterscheiden. Die Korngrößen-Parameter und die geringe Reife des klastischen Materials zeugen von einem nahe gelegenen Liefergebiet. Die mineralogische Zusammensetzung der untersuchten Eiskomplex-Ablagerungen weist darauf hin, daß die benachbarten Berge des Kharaulakh beständig als Denudationsgebiet gewirkt haben. Das heißt, während der untersuchten Zeitspanne können diese nicht von einem größeren Eisschild bedeckt gewesen sein. Es könnte nur eine begrenzte Gebirgsvergletscherung angenommen werden.

INTRODUCTION

The term „Ice Complex" is applied to permafrost sequences usually consisting of fine-grained loess-like sediments with a high content of segregated ice and polygonal ice wedges. These deposits cover wide areas in northern Siberia and were formed under strong continental cold-climate conditions mainly during the Late Pleistocene. All sediments „stored" in the Ice Complexes were affected by syngenetic freezing and soil formation and turned into permafrost more or less simultaneously with their accumulation. As a result, a lot of proxy data for paleoenvironmental reconstruction are preserved in the Ice Complex, representing relatively clear defined time spans. Firstly, like glacier ice, the stable isotope composition of ground ice in polygonal ice wedges reflects paleoclimatic characteristics. Secondly, a lot of different well preserved plant and animal fossils included in the Ice Complex provide evidence for the paleoenvironmental conditions during their lifetime. Thirdly, geochemical and other features of sediments and paleosols caused by facial conditions during a distinct period are preserved after their transfer into permafrost. That is, the Ice Complex represents a unique archive for paleoenvironmental reconstruction. On the other hand, the complicated reactions of such ice-rich permafrost on natural and anthropogenic impacts are very significant in territories which are inhabited and economically used. This explains the large number of previous investigations. In addition, the genesis of sediments forming the Ice Complex remains still debatable.

This paper presents results of sedimentological, mineralogical and geochemical studies of deposits from a famous key section of the Ice Complex in Arctic Siberia, the Mamontovy Khayata site on the Bykovsky Peninsula, near the Lena Delta (Fig. 1). Investigations were carried out within the scope of the German-Russian research project „Laptev Sea System 2000". They complete previous studies performed by the Cryolithological Laboratory of the Permafrost Institute in Yakutsk (SLAGODA 1991, 1993).

STUDY AREA

The Bykovsky Peninsula is situated in the foreland of the Kharaulakh Mountains and probably represents a relict of a Late Pleistocene accumulation plain. The position at the western margin of the Ust'-Lena Rift means that intense vertical block tectonics and strong seismic activity characterise this terrain (GRIGORIEV et al. 1996, DRACHEV et al. 1998). The position of the Bykovsky Peninsula in a zone of subsidence explains the large thickness of the Ice Complex at these locations (IVANOV & KATASONOVA 1978).

In a phyto-geographical sense the study area belongs to the typical tundra subzone of the Eurasian Arctic (CHERNOV & MATVEEVA 1997). The following climatic data are obtained from the meteorological station in the Tiksi Bay: mean annual temperatures -13.4 °C, mean January temperature -33.3 °C, mean July temperature 7.0 °C. These data as well as the absolute minimum and maximum temperatures of -54 °C and +33 °C, respectively, illustrate the very harsh continental climate of this region. The mean annual precipitation amounts to 240-260 mm. Continuously distributed permafrost with temperatures between -8 and -13 °C at the depth of zero annual amplitude has a thickness of 500-650 m (GRIGORIEV 1993).

[1] Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Telegrafenberg A43, D-14473 Potsdam, Germany. <csiegert@awi-potsdam.de>
[2] Permafrost Institute, Siberian Branch Russian Academy of Sciences, 677010 Yakutsk, Russia.

Manuscript received 16 January 2001, accepted 01 August 2001

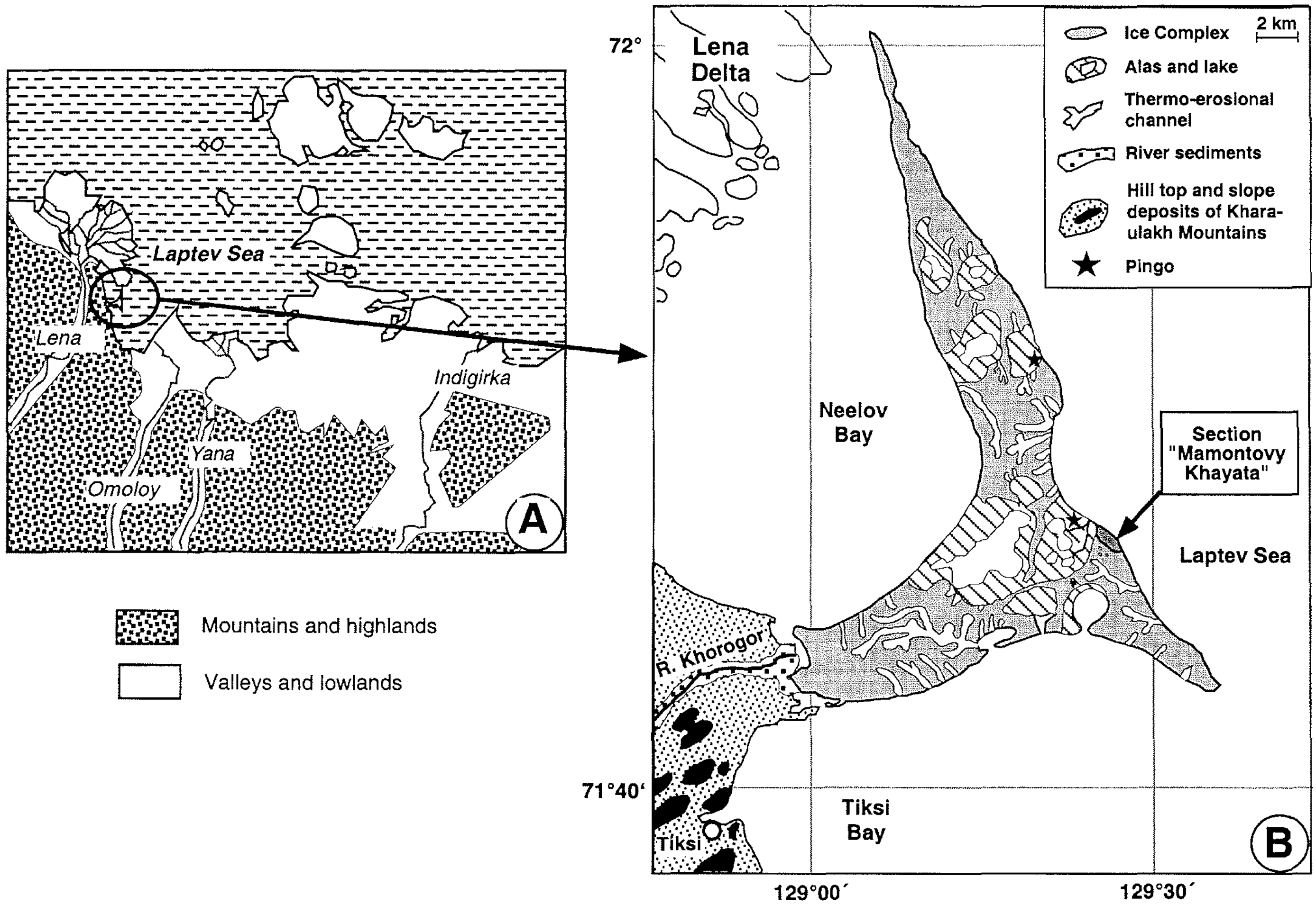

Fig. 1: (A) Map of the eastern Laptev Sea region with location of the Bykovsky Peninsula; (B) Geomorphological map of the Bykovsky Peninsula and its surroundings (according to GRIGORIEV 1993) with the location of the Mamontovy Khayata site.

Abb. 1: (A) Karte der östlichen Laptewsee-Region mit Lage der Bykowsky-Halbinsel. (B) Geomorphologische Karte der Bykowsky-Halbinsel und ihrer Umgebung (nach GRIGORIEV 1993) mit Lage des „Mamontovy Khayata".

The modern morphology of the Bykovsky Peninsula mainly results from thermal erosion and thermokarst developed on the Ice Complex during the Holocene. A well subdivided landscape with numerous lakes within thermokarst depressions and thermo-erosional valleys characterise the area (Fig. 1). Sediment and soil formation are accompanied by different cryogenic processes, such as frost cracking, ice wedge formation, cryoturbation and ice segregation.

The Mamontovy Khayata exposure and the adjacent terrain on the eastern coast of the Bykovsky Peninsula have been studied by Arctic scientists since the nineteenth century (BUNGE 1895). ADAMS (1807) described the first mammoth carcass from this place. It was also an important location for permafrost research during the last decades (TOMIRDIARO & CHERNENKY 1987, KUNITSKY 1989, SLAGODA 1991, 1993, GRIGORIEV 1993, FUKUDA 1994, NAGAOKA 1994). However, despite these numerous former investigations the genesis of the Ice Complex deposits at this key location remains unsolved. TOMIRDIARO & CHERNENKY (1987) interpreted the whole section as cryogenic-eolian sediments. According to KUNITSKY (1989) the formation of these deposits was determined mainly by nival processes connected with the spread of snow patches during the Weichselian. On the basis of extensive mineralogical and petrographical investigations SLAGODA (1991, 1993) inferred that the sediments of the Ice Complex on the Bykovsky Peninsula were accumulated by fluvial and proluvial processes on the foreland of the Primorsky Range, the near part of the Kharaulakh Mountains. NAGAOKA (1994) considered this permafrost sequence as deposits of the Lena Delta. Our aim is to solve this probleme. In addition, the influence of changing climatic conditions, as indicated by results of palynological and paleontological studies from this site (ANDREEV et al. 2001, KUZMINA et al. 1999), on denudation and sediment transport in the area will be examined.

MATERIAL AND METHODS

The Ice Complex at the Mamontovy Khayata site is exposed as an almost 40 m high coastal cliff. The sequence consist of ice-rich silty-sandy deposits with several more or less pronounced paleosols and thick ice wedges. Alternating massive ice belts of some mm to cm thickness and sediment layers with a reticulated lens-like or simple lens-like structure form a belt-like cryogenic structure and evidence syngenetic freezing of these deposits.

The original permafrost deposits are getting destroyed in various steps by thermal erosion. During our field work the lower part of the Ice Complex, at altitudes of about 0-9 m a.s.l., was poorly exposed and available for study and sampling only in two small profiles. Slope deposits and other products of thermal denudation of the Ice Complex covered the main part of this level. Deposits of the middle and upper part of the Ice Complex were exposed mainly as thermokarst mounds (baidzharakhs) within melting ice wedge systems (Fig. 2). In the core of these mounds original sediments of the Ice Complex are mostly preserved in undisturbed position. To combine individual profiles from each thermokarst mound to a entire sequence a lot of survey marks were installed and used for the stratigraphic correlation. After cleaning the wall of each chosen mound from thawed material the cryogenic, sedimentary and pedogenic features of the deposits were studied and samples taken for determination of the ice content and for sedimentological, mineralogical and other analyses. In that way the main part of the profile was studied and sampled in summer 1998 (SCHIRRMEISTER et al. 1999). Additionally the group of A. Sher (SHER et al. 2000) took samples for our analytical investigations during field research in summer 1999.

At first, a detailed age determination of the whole section was carried out by means of AMS and conventional radiocarbon methods. Our new age model indicates that the accumulation of the studied Ice Complex has occurred more or less continuously from about 60 ky BP until the beginning of the Holocene (SCHIRRMEISTER et al. 2001). This is in contrast to results of FUKUDA (1994) suggesting that the Ice Complex accumulation occurred from about 40 ky until 24 ky BP, that is only during the Kargin (Middle Weichselian) interstadial. Therefore, this sequence provides the possibility to investigate which influence the climate change has had on the character of denudation and cryolithogenesis in the study area during this whole period. For this grain size, and the mineralogical and geochemical composition of the sediments were analysed.

Grain size characteristics were obtained from 120 samples taken in 1998 and 1999 from all available stratigraphic levels using the Laser particle analyzer COULTER LS 200. The dried untreated sediment samples (5-10 g) were dispersed in 0.01 normal ammonia solution and shaken more than 48 hours. The suspension was sieved through a 1 mm sieve in order to avoid large plant remains. After that, the sample was repeatedly split into 8 sub-samples to a solid content of 8 – 12 % (sufficient transparency for laser beam). Three or more subsamples of each main sample were analysed and the single grain size distribution was combined and calculated with the analytical software.

The mineralogical composition of 32 samples characterising almost all typical sediment horizons of the investigated Ice Complex section was studied. For this, heavy and light minerals of the size fractions 63-125 µm and 125-250 µm were analysed. Mineral grains were separated using sodium metatungstate $Na_6(H_2W_{12}O_{40})$ with a density of 2.83 g/cm^3. After 20 min centrifugation, the heavy fraction was frozen in liquid nitrogene (FESSENDEN 1959, SCULL 1960). The heavy minerals were divided into magnetic and nonmagnetic fractions by a weak laboratory magnet. The mineralogical composition was analysed under the polarisation microscope in slides using immersion liquids with n = 1.54 and n = 1.68 for the light and heavy fraction, respectively. At least 300 grains of the heavy and light fraction were counted. The mineralogical composition was calculated in grain percentages. Rock fragments and stable soil aggregates in the investigated slides were tallied in addition. For the main minerals the grain form and signs of weathering on the grain surface were noted.

In order to reveal changes in the condition of accumulation and postsedimentary transformation of sediments, that is, to test additional factors which can influence the mineralogical composition of sediments, data of geochemical analyses (TC, TOC, $C_{carb.}$ N, S, $\delta^{13}C$ of TOC) and measurements of the mass specific magnetic susceptibility were used. These parameters were obtained by the following methods: The content of total and organic carbon was determined with a CS-Autoanalyzer (ELTRA CS 100/1000 S). The analysis of the carbonate content was carried out gasvolumetrically by means of the Scheibler-apparatus. The total nitrogen and sulphur contents were measured by a CNS-Microanalyzer (LECO 932). BAR-

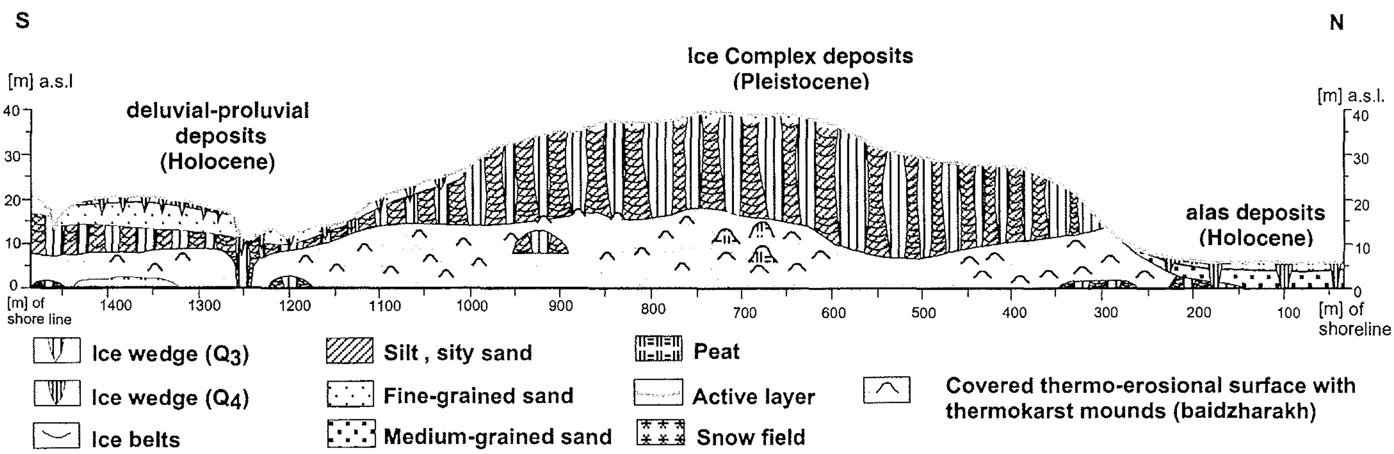

Fig. 2: Generalized section of the Quaternary deposits exposed on the Mamontovy Khayata in summer 1998.

Abb. 2: Schematisches Profil der im Sommer 1998 am „Mamontovy Khayata" aufgeschlossenen Quartärablagerungen.

TINGTON MS2 and MS2B were used for the determination of the mass-specific magnetic susceptibility. The $\delta^{13}C$-values of bulk organic carbon were determined on decarbonated samples by high-temperature combustion in a Heraeus Elemental Analyzer coupled with a Finnigan MAT Delta S mass-spectrometer.

The mineral fractions were investigated in the Permafrost Institute in Yakutsk. All other analyses were carried out in laboratories of the Alfred Wegener Institute in Potsdam.

RESULTS AND DISCUSSION

Geochemical and physical characteristics

The results of geochemical analyses and measurements of the magnetic susceptibility are compiled in Figure 3. On the basis of these data the Ice Complex sequence was subdivided into four main levels. In accordance to the age model (SCHIRRMEISTER et al 2001) these levels were formed during periods at about 60-50 ky BP (A), 47-28 ky BP (B), 28-12.5 ky BP (C) and younger than 12.5 ky BP (D).

The lower level (A) has a total organic carbon content (TOC) of 2-3 %, C/N values between 9-14 and $\delta^{13}C$ values varying around –26 ‰. These data characterise a relative low intensity of organic matter accumulation and its decomposition under rather aerobic conditions, it may be under seasonally or interannually changing hydrological conditions of the active layer. The carbonate content reflects a low intensity of carbonate accumulation. The main distinctive feature of the lower level is the relative high magnetic susceptibility of these sediments. But amounts of the magnetic fraction (4-6 %) of heavy minerals are only insignificantly higher than in the level C. Fine-disperse magnetic sulphides which could be observed as a new formation on plant detritus in these samples can perhaps explain the magnetic features.

Level B is characterised by notably lower values of the magnetic susceptibility. In addition, the TOC, C/N and $\delta^{13}C$ values indicate changing conditions of soil formation. This is especially noticeable in the upper part of this level (about 15-22 m a.s.l.) which is related to the age interval c. 40-28 ky BP. While deposits at altitudes between 8-15 m a.s.l. show markedly higher carbonate contents than all other investigated deposits, the slightly increased TOC as well as the C/N and $\delta^{13}C$ values indicate conditions rather in between level A and the upper part of level B.

The geochemical characteristics of the deposits at altitudes of 15-22 m a.s.l. indicate a clear increase of organic matter accumulation. Relative high amounts of TOC in this level are accompanied by high values of C/N and the most depleted $\delta^{13}C$ values. Such characteristics point to an accumulation of well preserved plant material in peaty soils. The landscape conditions were more humid and probably more favourable for plant growth. This assumption is in good agreement with the results of pollen analysis showing a distinct climate amelioration during this time (ANDREEV et al. 2002). Variations in the geochemical characteristics within level B seem to indicate that periods of stable soil formation were interrupted by events

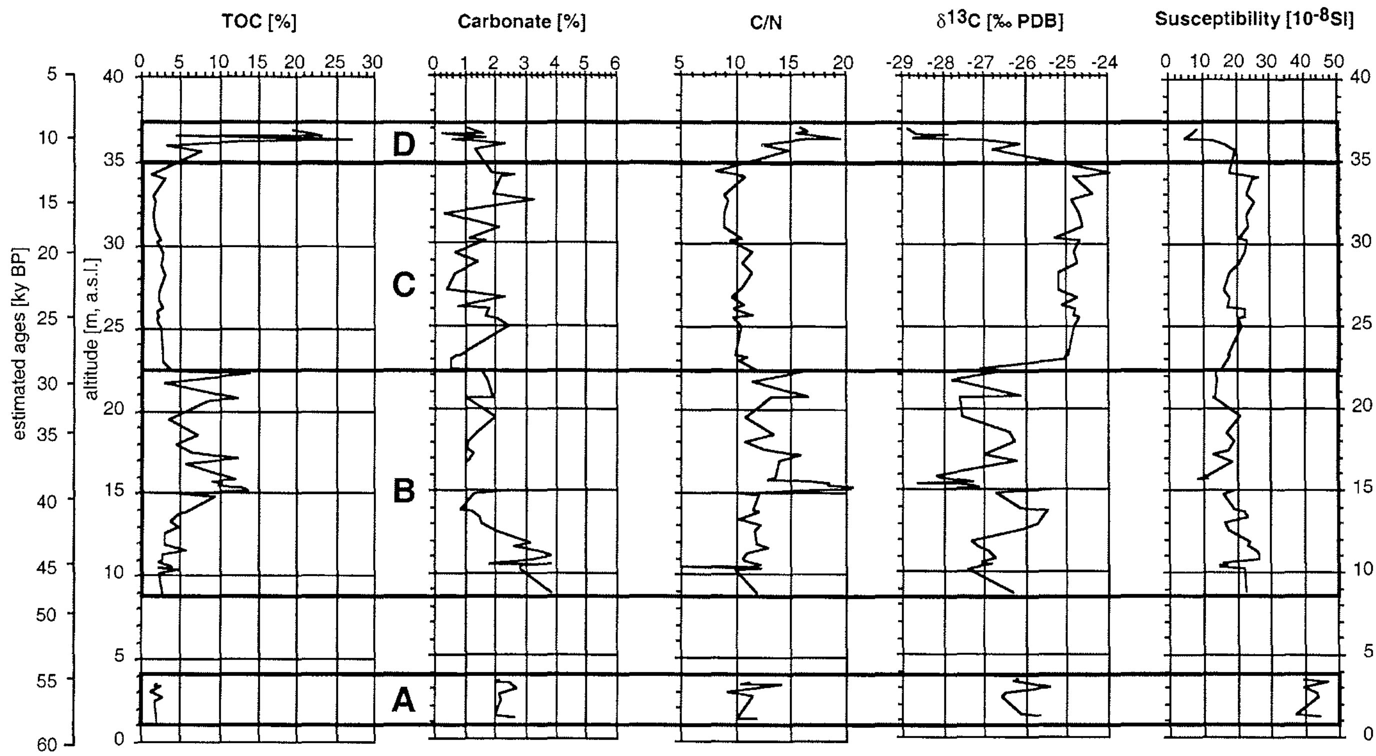

Fig. 3: Geochemical characteristics and mass specific magnetic susceptibility of Ice Complex deposits for a generalized vertical profile at the study site Mamontovy Khayata. The age scale is based on SCHIRRMEISTER et al. (2002).

Abb. 3: Geochemische Eigenschaften und massenspezifische magnetische Suszeptibiltät der Ablagerungen des Eiskomplexes in einem generalisierten Vertikalprofil am „Mamontovy Khayata". Altersskala nach SCHIRRMEISTER et al. (2002).

of sediment accumulation or soil destruction with more unfavourable plant growth conditions.

Sediments which accumulated after 28 ky BP in level C clearly differ in their TOC, C/N and $\delta^{13}C$ values from deposits formed earlier. According to pollen analyses and paleontological studies (ANDREEV et al. 2002, KUZMINA et al. 1999) the harshest climatic conditions of the whole period of Ice Complex formation can be assumed. Low variations in the geochemical characteristics suggest that pedogenic and other postsedimentary processes have changed only slightly during this time (Fig. 3). Relative heavy $\delta^{13}C$ values and low C/N values prove that more constant aerobic conditions must have existed in the active layer than in the periods before.

Deposits of the uppermost layer (level D), related to the termination of the Pleistocene and the early Holocene, initially show similar geochemical characteristics as deposits formed between about 40 and 28 ky BP. Unstable surface conditions are indicated.

Sedimentological characteristics

Grain size analyses indicate that the Ice Complex deposits and their Holocene cover are composed of poorly sorted sandy silt to silty sand. This means that the general accumulation did not change very strongly, but there is a large spectrum of fine-grained silty sands. Only some samples from the uppermost Holocene cover have a real sandy grain size distribution.

The plot of the arithmetic mean of the grain size distributions of several combined subprofiles against the altitude indicates alternating accumulations of more or less fine-grained material (Fig. 4). These rhythmic patterns seem to be characteristic for the Ice Complex formation in the Laptev Sea Region. In general, a trend towards coarser more sandy sediments is evident considering the entire profile. The rapid changes of the mean grain size are clearly seen in the grain-size frequency curves of single subprofiles as well (right column of Fig. 4).

The grain size frequency of single samples is characterised by bi- or polymodal curves, which consist of numerous single po-

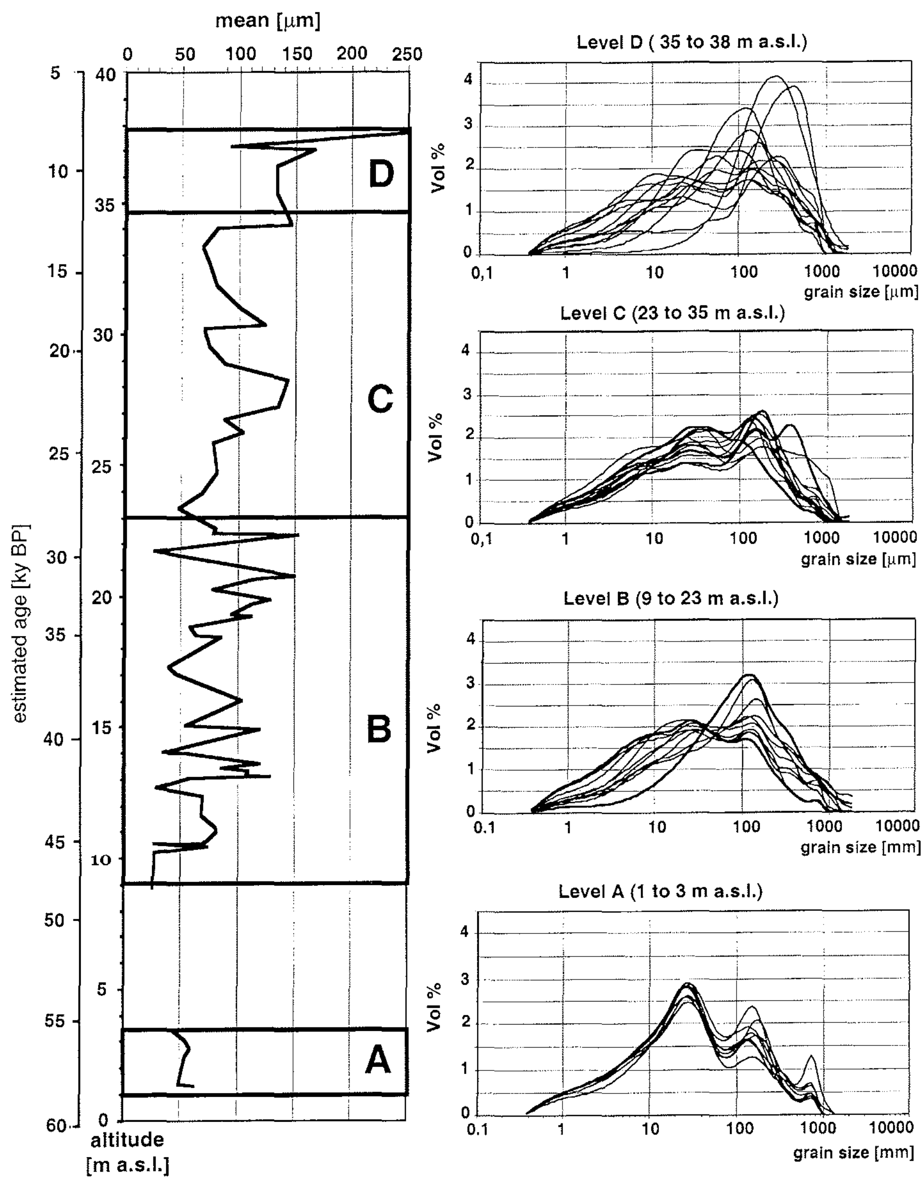

Fig. 4: Arithmetic mean of the grain size distribution in deposits of the Ice Complex and Holocene cover sediments in a generalized vertical profile, and grain size frequency curves for the different levels A-D at the study site Mamontovy Khayata.

Abb. 4: Arithmetisches Mittel der Korngrößenverteilung in Ablagerungen des Eiskomplexes und der holozänen Decksedimente in einem generalisierten Vertikal-Profil vom „Mamontovy Khayata" und Korngrößen-Häufigkeitskurven für die verschiedenen Niveaus A-D.

pulations of grain size distributions. This fact indicates that different transport and accumulation processes have participated in the Ice Complex formation. Within the investigated sequence some types of deposits can be distinguished:

(1) Sediments of the lowest level A, dated older than 50 ky BP, have a three-modal grain size distribution. Such patterns could reflect conditions of graded bedding by currents of variable hydrodynamic energy or by different transport processes. In the latter case the participation of water and wind transported material can be supposed.

(2) An alternation between fine-grained silt and fine-grained sand can be observed in the central part of the sequence at 9-23 m a.s.l. (level B), which is characterised by the frequent presence of peaty cryosols. According to the radiocarbon ages these deposits were formed from about 47 ky until 28 ky BP (Fig. 4). However, some better-sorted fine-grained sand layers also occur in this level. Therefore, it can be supposed that periods of proluvial runoff have alternated with periods of surface stabilisation where only some local deposition/or redeposition took place.

(3) The alternation described for level B is less pronounced in level (C), between 23-35 m a.s.l. These sediments, which were formed during the period 28-12.5 ky BP, are less affected by pedogenic processes. The frequency curves point to wide polymodal patterns. We assume that proluvial runoffs with relative high hydrodynamic energy like in the former period do not occur much during that time. Different processes of soil redeposition within the accumulation area may have influenced the specific features of these deposits.

(4) Poorly sorted silty sand with flat distribution curves without any obvious maximum and well sorted fine and middle grained sands compose the uppermost level (D) formed during the termination of the Pleistocene and the early Holocene.

Mineralogical characteristics

The mineralogical composition of Ice Complex deposits at Mamontovy Khayata is characterised on the whole by a low content of heavy minerals. The main part of the samples contains less than 1 % heavy minerals in the fine sand fraction (63-125 μm). The heavy mineral content in the coarser fraction 125-250 μm is, as might be expected, still lower. As shown in Figure 5, a correlation with the arithmetic mean of the grain size distribution is not noticeable.

A general characteristic for all samples is the high content of rock fragments in the investigated fractions. Rock fragments consist mainly of chlorite and chlorite muscovite metashales, and of shale stones. Different sandstones and quartzitic fragments are also frequent. In the heavy fraction limonitic rock fragments and soil aggregates often occur in significant amount (Tab. 1).

The heavy mineral composition in both investigated fractions is dominated by minerals of the pyroxene and amphibole groups. The first group consists mainly of greyish brown augite with rare occurrence of diopsite and hypersthen in minor amounts. The amphibole group is dominated by ordinary green coloured hornblende. In addition, soda amphibole was sometimes observed. In significant amounts ilmenite, leucoxene and epidote are present, followed by garnet, apatite and sphene. Zircon and tourmaline are continuously observed in minor amounts. Some amounts of chlorite also occur in most samples. Weathered mica is less frequently present. In small but marked amounts some sediments contain rutile, disthen, chloritoid, staurolith and andalusite. The last minerals were summarised a metamorphic group. The heavy mineral distribution through the whole section is shown in Fig. 5.

A striking fact is the predominance of angular, not worn (completely fresh) quartz grains in the light fraction, probably a result of cryogenic weathering (Konishev 1981). However, most other mineral grains are slightly rounded. Angular intergrowths of pyroxene, amphibole and opaque minerals occur. Aggregation of these minerals with feldspars can be also observed. Augite and hornblende are mainly untouched and only a minor part shows signs of weathering (limonitisation, irregular colouring). The presence of minerals in different states of weathering suggests that rocks of the source area were partly transformed by weathering already during pre-Quaternary times. This clearly indicates a small separation of clastic material from the area of denudation by different transport processes, that is it provides evidence for a nearby source area, the Kharaulakh Mountains.

Deposits on the neighbouring Primorsky Ridge of the Kharaulakh Mountains, with altitudes of 150-170 m a.s.l. belonging to the catchment area of the Khorogor River (Fig. 1) were investigated by Slagoda (1993) in the core drilling profile X-89. This sequence of 31 m thickness is built up of gravel, sandy gravel and badly sorted gravelly sands with some loamy interlayers of about 1 m thickness. The deposits include ground ice as cement, crusts on pebbles and debris, and as lenses in more fine-grained material. The horizon at the depth between 2-15.5 m contains small ice wedges. According to Slagoda (1993) this deposits can be considered as a Late Weichselian Ice Complex. The heavy mineral composition of the fine-sand fraction (50-100 μm) of these deposits is very similar to the composition of the Ice Complex deposits on the Mamontovy Khayata (Tab. 1). The heavy mineral composition of sediments from the Lena River is notably different, showing higher amounts of amphibole and garnet as well as a lower abundance of pyroxene (Behrends et al. 1999), (Tab. 1). Therefore, we have indications, that the main source area for the Ice Complex on the Bykovyky Peninsula is in the neighbouring ridge of the Kharaulakh Mountains.

It seems that mainly basic rocks of the gabbro-diabase group have supplied products of weathering for the formation of the Ice Complex. Only such an assumption can explain the predominance of pyroxene within the heavy minerals and the extraordinary high amounts of feldspars in the light fraction of the whole investigated sequence. The significant occurrence of leukoxene in connection with ilmenite is also an evidence for a source area with a high abundance of basic rock material. In addition, the low activity of chemical weathering in permafrost regions and the short transport way from the denudation area to the accumulation site have determined the character of the mineralogical composition. Horizons with an increase of limonitic rock fragments seem to be caused mainly by locally or short-time exposed limonitic rocks in the denudation area and less by pedogenic processes at the accumulation site. Only a small part of aggregates can be considered as result of pedogenic processes which have taken place in the active layer

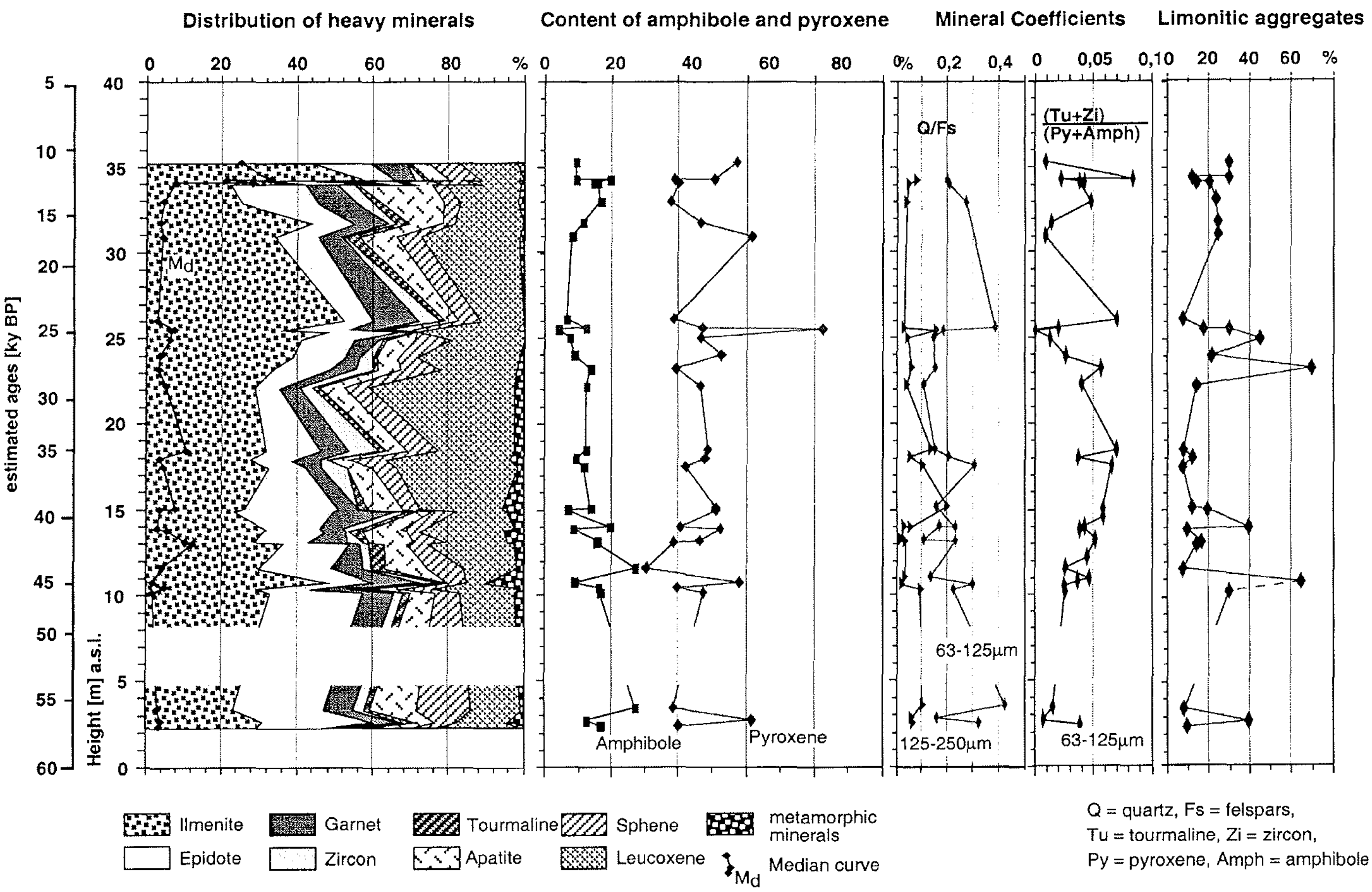

Fig. 5: Mineral distribution in the Ice Complex deposits and covering sediments in a generalized vertical profile of the sequence Mamontovy Khayata. Heavy mineral contents are given for the fraction 63-125 µm, the contents of the dominant pyroxene and amphibole are shown separately as curves, other heavy minerals as relative distribution diagram.

Abb. 5: Mineralverteilung in Ablagerungen des Eiskomplexes und der Decksedimente in einem generalisierten Vertikalprofil vom „Mamontovy Khayata". Schwermineralgehalte der Fraktion 63-125 µm, Gehalte der dominierenden Pyroxene und Amphibole einzeln als Kurve, die übrigen Schwerminerale als relatives Verteilungsdiagramm.

during the Ice Complex formation. In some layers the new formation of magnetic iron sulphides of the greigit-mackinavite group on plant remains has been determined. In addition, small amounts of authigenic carbonates of the calcite-rhodochrosite and siderite groups occurs. It can be assumed that these horizons were affected by anaerobic soil formation in a alkaline milieu, under a relative high activity of sulphur compounds (SIEGERT 1987).

CONCLUSIONS

The investigated Ice Complex deposits from the Mamontovy Khayata site show a mineralogical composition, that is similar to those of the neighbouring Kharaulakh Mountains (SLAGODA 1993) but different to Lena River sediments. That is, during the time of Ice Complex accumulation the source area of the majority of clastic material was most probably in the hills of the Kharaulakh Mountains, located near the Bykovsky Peninsula (Fig. 1). A similar „local" origin of clastic material for the Ice Complex was shown by Schwammborn (personal communication) in the western Lena Delta, in the foreland of the Chelanovsky Ridge.

Changes in the environmental conditions during the accumulation of the Ice Complex, revealed from our geochemical studies and from pollen analyses (ANDREEV et al. 2001) and paleontological investigations (KUZMINA et al. 1999), are not indicated by the mineralogical data. Thus, weathering and denudation in the source area seem to have been relatively constant throughout the examined Late Pleistocene time. Soil formation and other geochemical processes in the active layer have not led to marked variations in the mineralogical composition of clastic mineral compounds.

According to their grain-size characteristics deposits from the lower level of the Ice Complex can be considered as mainly formed by fluvial processes. On the contrary, deposits of the levels B and C are regarded as polygenetic formations. In our opinion, primarily accumulated material was again eroded, transported and redeposited by surface water, solifluction, nival processes around snow fields, and most likely also by wind. On drained slopes suprapermafrost water has also participated in the redistribution of fine-grained material. It is assumed that this repeated redeposition by different processes has resulted in a general flattening of the whole accumulation area. Furthermore, specific geochemical, textural and other features are caused by the near-surface position of the perma-

Sediment	Number of analyses	Mean content of heavy minerals [grain %]											Miner. coefficients		
		Opake minerals	Epidote	Pyroxene	Amphibole	Garnet	Zircon	Tourmaline	Rutile	ZTR	Apatite	Sphene	ZTR/Py+Am	Pyroxene/Amphibole	Quartz/Feldspar
Surface sediments, Lena (all)[1]		25.8	5.4	19.7	23.6	14.3				4.4	1.3	2.3	0.102	0.8	
Surface sediments, Lena Delta[1]		24.3	4.5	21.1	27.4	11.5				3.4	1.6	3.2	0.070	0.8	
Primorsky Range, Holocene deposits[2]	3	36.8	1.3	48.6	0.9	2.2	5.1	2	0.3	7.4	0.5	0.5	0.148	54.0	0.51
Primorsky Range, Late Pleistocene I[2]	6	40.6	1.5	34.8	3.0	2.3	4.2	1.3	0.3	5.8	4.3	0.6	0.154	11.5	0.79
Primorsky Range, Late Pleistocene II[2]	6	44.1	2.8	32.9	3.25	2.3	3.3	0.8	0.2	4.2	4.3	0.4	0.116	10.1	0.76
Ice Complex , Mamontovy Khayata (A)	3	18.2	7.2	45.6	18.4	2.2	0.9	0.9	0	1.8	3.8	3.1	0.028	2.5	0.30
Ice Complex , Mamontovy Khayata (B)	14	22.8	6.3	45.4	13.9	3.2	1.3	0.9	0.2	2.4	2.9	2.7	0.040	3.3	0.20
Ice Complex , Mamontovy Khayata (C)	13	15.1	5.8	47.4	11.2	3.1	1.5	0.5	0.2	2.2	0.5	2.6	0.038	4.2	0.20
Cover Sand (D)	1	6.5	5.3	57.6	9.2	3.2	0	0.3	0	0.3	0.3	2.7	0.004	6.3	0.12

Tab. 1: Mineralogical composition of Ice Complex deposits from the Mamontovy Khayata section in comparison with surface sediments of the Lena River and late Quaternary cover in the Primorsky Range, near Tiksi. 1 data according to BEHRENDS et al. (1999); 2 data from the fraction 50-100 µm according to SLAGODA (1993).

Tab. 1: Mineralogische Zusammensetzung der Ablagerungen des Eiskomplexes im Profile „Mamontovy Khayata" im Vergleich zu Oberflächensedimenten der Lena und Decksedimente in der Primorsky-Gebirgskette bei Tiksi. 1 Daten nach BEHRENDS et al. (1999); 2 Daten für die Korngrößenfraktion 50-100 µm nach SLAGODA (1993).

frost table and the polygonal micro-relief of the area in which the formation of the Ice Complex occurred.

Assuming a cold periglacial environment more or less without any plant cover in the nearby hill country during the late Pleistocene a high activity of exogenic processes can be supposed. Bedrock was strongly affected by cryogenic weathering. Different slope processes led to a lowering and flattening of slopes and partial filling of valleys. Bedrock outcrops became more and more covered by slope deposits. Sandy and silty material was transported to the foreland by seasonally active rivers forming proluvial (subaerial) fans. The presence of shallow, unstable lakes in front of the mountains, especially in subsiding areas can also be assumed. Polygonal landscapes with varying hydrological conditions were linked to such environments.

According to VASKOVSKY (1970) only a restricted glaciation has taken place in the northern Kharaulakh Mountains. MEZHVIL (1961) and recently GROSSWALD & SPEKTOR (1993) reported on the occurrence of glacial erosion forms south of Tiksi. However, significant contradictions exist on the character of the glaciation. While the first author suggests that mountain glaciers moved from SW to NE, the latter established a hypothesis on an extended ice cap coming from the shelf area, that is from NE to SW, during the Late Weichselian (Sartan) stadial. The results obtained during our study indicate: (i) since about 50 000 years BP the formation of syngenetic ice-rich permafrost has occurred in periglacial landscapes on the Bykovsky Peninsula; (ii) the neighbouring parts of the Kharaulakh Mountains have acted as denudation area, which suggests that they had not been covered by any ice sheet or larger local glaciers over the last 50 000 years. In addition, latest results from paleoecological studies (SHER et al. 2001, KIENAST et al. 2001) provide evidence for a pronounced continental climate with a thin snow cover during this time, that is for conditions which have counteracted any significant glaciation. In our opinion, the transport of clastic material both in the hill country and in the foreland has taken place particularly during seasonally thawing of the irregularly distributed snow cover, that is of the snow and firn fields, which were probably widespread in this area (KUNITSKY 1989, GALABALA 1997). Deflation processes were active in periods with surface drying and have probably also participated in the transport of fine-grained material from the hill country and within the foreland.

ACKNOWLEDGMENTS

This study was funded by the German Ministry for Education and Research (BMBF) through the German-Russian research project „Laptev Sea System 2000". Andrei Sher supplied the important complement samples taken in 1999. Christine Flemming and Tina Paschkin carried out the mineral separation. Christian Hjort and two anonymous reviewers gave valuable comments, which helped to improve the manuscript. Many thanks to all persons for their help.

References

Adams, M. (1807): Some account of a journey to the Frozen Sea and of the discovery of the remains of a mammoth.- Philos. Magazine 29: 141-153.

Andreev, A.A., Schirrmeister, L., Siegert, Ch., Bobrov, A.A., Demske, D., Seiffert, M. & Hubberten, H.-W. (2002): Paleoenvironmental changes in Northeastern Siberia during the Late Quaternavy - evidence from pollen records of the Bykovsky Peninsula.- Polarschung 70: 13-25.

Behrends, M., Hoops, E. & Peregovich, B. (1999): Distribution patterns of heavy minerals in Siberian rivers, the Laptev Sea and the eastern Arctic Ocean: An approach to identify sources, transport and pathways of terrigenous matter.- In: H. KASSENS, H.A. BAUCH, I. DMITRENKO, H. EICKEN, H.-W. HUBBERTEN, M. MELLES, J. THIEDE & L. TIMOKHOV (eds.), Land-Ocean systems in the Siberian Arctic: dynamics and history, Springer, Berlin: 265-286.

Bunge, A. (1895): Die Lena Expedition 1881-1884.- In: A. TILLO (ed.), Beobachtungen der russischen Polarstation an der Lenamündung.- Expedition der Kaiserlichen Russischen Geographischen Gesellschaft, St. Petersburg: 1-96.

Chernov, Yu.I. & Matveeva, N.V. (1997): Arctic ecosystems in Russia.- In: F.E. WIELGOLASKI (ed.), Ecosystems of the World 3: Polar and Alpine Tundra. Elsevier, Amsterdam: 361-507.

Drachev, S.S., Savostin, L.A., Groshev, V.G. & Bruni, I.E. (1998): Structure and geology of the Laptev Sea, Eastern Russian Arctic.- Tectonophysics 298: 357-393.

Fessenden, F.W. (1959): Removal of heavy liquid separates from glass centrifuge tubes.- J. Sed. Petrol. 29: 269-280.

Fukuda, M. (1994): Occurrence of Ice Complex (Edoma) in Lena River Delta region and Big Lyakhovsky Island, High Arctic, Eastern Siberia.- In: G. INOUE (ed.), Proceedings, Second Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1993, Tsukuba, Japan: 5-13.

Galabala, R,O. (1997): Pereletki and the initiation of glaciation in Siberia.- Quaternary International 41/42: 27-32.

Grigoriev, M.N. (1993): Cryomorphogenesis of the Lena River mouth area.- Permafrost Institute, SO AN SSSR, Yakutsk: 176 pp. (in Russian),

Grigoriev, M.N., Imaev, V.S., Imaeva, L.P., Koz'min, B.M., Kunitsky, V.V., Larionov, A.G., Mikulenko, K.I., Skryabin, R.M. & Timirshin, K.V. (1996): Geology, seismicity and cryogenic processes in the Arctic areas of western Yakutia.- Yakutian Scientific Center, SO, RAN, Yakutsk: 84 pp. (in Russian).

Grosswald, M.G. & Spektor, V.B. (1993): The glacial relief of the Tiksi region (west shore of the Buor-Khaya Inlet, Northern Yakutia). – Polar Geography and Geology 17(2): 154-166.

Ivanov, M.S. & Katasonova, E.G. (1978): Pecularities of cryolithogenic deposits of the Muostakh Island.- In: N.P. ANISIMOVA & E.G. KATASONOVA (eds.), Geokriologicheskie i gidrogeologicheskie issledovaniya in Yakutia (Geocryologic and hydrogeologic research in Yakutia), Permafrost Institute, SO AN SSSR, Yakutsk: 12-25 (in Russian).

Kienast, F, Siegert, C., Schirrmeister L. & Hubberten, H.-W. (2001): Plants as climatic indicators. - Results of plant macrofossil studies from Late Quaternary permafrost sequences of the Laptev Sea region, Northern Siberia.- EUG XI. J. Conf. Abstracts 6: 213.

Konishev, V.N. (1981): Formation of dispersed rock composition in the cryolithosphere.- Nauka, Novosibirsk: 197 pp. (in Russian).

Kunitsky, V.V. (1989): Cryolithogenesis of the Lower Lena.- Permafrost Institute, SO AN SSSR, Yakutsk: 162 pp. (in Russian).

Kuzmina, S., Kuznetsova, T., Sulerzhitsky, L. & Sher A. (1999): The Late Pleistocene fauna of the Laptev Sea Shelf grassland: Insects and mammals.- Fifth Workshop on Russian-German Cooperation: Laptev Sea System 2000, Terra Nostra 99/11: 48-49.

Mezhvil, A.A. (1961): Quaternary deposits of the Northern Kharaulakh.- Geology and Prospects for Oil and Gas in the Arctic (Trudy NIIGA, 117, issue 15), Moscow: 113-125 (in Russian).

Nagaoka, D. (1994): Properties of Ice Complex deposits in Eastern Siberia.- In: G. INOUE (ed.), Proceedings, Second Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1993, Tsukuba, Japan: 14-18.

Schirrmeister, L., Siegert, C., Kunitsky, V. Dereviagin, A., Krbetschek, M., Kusnetsova, T., Kuz'mina, S., Meyer, H., Sher, A. & Tumskoy, V. (1999): Paleoclimate signals of ice-rich permafrost.- In V. RACHOLD (ed.), Expeditions in Siberia 1998. Rep. Polar Research 315: 145-259.

Schirrmeister, L., Siegert, Ch., Kunitsky, V. V, Grootes, P. & Erlenkeuser, H. (2002): Late Quaternary ice-rich permafrost sequences as a paleoenvironmental archive for the Laptev Sea Region in northern Siberia– International of European Earth Sciences (Geol. Rundschau) 91: 154-167.

Scull, B.J. (1960): Removal of heavy liquid separates from glass centrifuge tubes. Alternative Method.- J. Sed. Petrol. 30: 626.

Sher, A., Parmuzin, I. & Bortsov, A. (2000): Ice Complex on the Bykovsky Peninsula.– In: V. RACHOLD (ed.), Expeditions in Siberia in 1999. Rep. Polar Research 354: 169-182.

Sher, A.V, Kuzmina., S.A, Kuznetsova, T.V., Sulerzhitsky, L.D., Schirrmeister, L., Siegert, C., Andreev, A.A., Grootes, P.M., Kienast, F. & Hubberten, H.-W. (2001): The last glacial environment in the unglaciated Arctic Shelf land – New Evidence from the Laptev Sea Coast.- EUG XI. J. Conf. Abs. 6: 207.

Siegert, Ch. (1987): Greigit and mackinawite in Quaternary perennially frozen rocks of Central Yakutia.- Mineralogical Zhurnal 9(5): 75-81 (in Russian).

Slagoda, E.A. (1991): Microstructural features of the deposits of Ice Complexes in Northern Yakutia (by the example of the Bykovsky Peninsula).- In: D.A. GILICHINSKY (ed.), Kriologia pochv (Cryology of soils), Pushchino IPFS PNTs AN SSR: 38-47 (in Russian).

Slagoda, E.A. (1993): Genesis and microstructure of cryolithogenic deposits of the Bykovsky Peninsula and the Muostakh Island.- PhD Thesis: Permafrost Institute, SO AN SSSR, Yakutsk: 218 pp. (in Russian).

Tomirdiario, S.V. & Chernen'ky, B.I. (1987): Cryogenic-eolian deposits of the eastern Arctic and Subarctic.- Nauka, Moscow: 196 pp.(in Russian).

Vaskovsky, A.P. (1970): Geomorphology. Geology of the USSR. Vol. 30(2), Northeast of the USSR, Nedra, Moscow: 424-458 (in Russian).