Age and extent of the Barents and Kara ice sheets in Northern Russia

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The youngest ice marginal zone between the White Sea and the Ural mountains is the W–E trending belt of moraines called the Varsh–Indiga–Markhida–Harbei–Halmer–Sopkay, here called the Markhida line. Glacial elements show that it was deposited by the Kara Ice Sheet, and in the west, by the Barents Ice Sheet. The Markhida moraine overlies Eemian marine sediments, and is therefore of Weichselian age. Distal to the moraine are Eemian marine sediments and three Palaeolithic sites with many C-14 dates in the range 16–37 ka not covered by till, proving that it represents the maximum ice sheet extension during the Weichselian. The Late Weichselian ice limit of M. G. Grosswald is about 400 km (near the Urals more than 700 km) too far south. Shorelines of ice dammed Lake Komi, probably dammed by the ice sheet ending at the Markhida line, predate 37 ka. We conclude that the Markhida line is of Middle/Early Weichselian age, implying that no ice sheet reached this part of Northern Russia during the Late Weichselian. This age is supported by a series of C-14 and OSL dates inside the Markhida line all of >45 ka. Two moraine loops protrude south of the Markhida line; the Laya–Adzva and Rogavaya moraines. These moraines are covered by Lake Komi sediments, and many C-14 dates on mammoth bones inside the moraines are 26–37 ka. The morphology indicates that the moraines are of Weichselian age, but a Saalian age cannot be excluded. No post-glacial emerged marine shorelines are found along the Barents Sea coast north of the Markhida line.

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The Quaternary history of Northern Russia is fascinating because large ice sheets from time to time expanded from the shallow Barents and Kara seas (Fig. 1) and greatly affected the Eurasian continent. When they existed, these ice sheets represented a white mountain about the size of Tibet, between the Eurasian continent and the Arctic Ocean, considerably increasing the albedo, blocking oceanic circulation, and probably creating a stable high pressure in the atmosphere. These ice sheets also dammed the large north-flowing Russian rivers that today provide most of the freshwater input to the Arctic Ocean; they diverted the drainage southward, changing the hydrology of much of the Eurasian continent.

The extent and especially the timing of these ice sheets are still controversial, however (Rutter 1995). For the last glacial maximum (18–20 ka) they represent one of the largest uncertainties in global ice volume. In this paper we report observations from the Pechora Basin in the European part of Russia, including the Polar Urals, addressing the last glaciations (isotope stages 5–2). Our data also have implications for the possible extent of Weichselian ice sheets in West Siberia and the Barents and Kara seas.

A large Late Weichselian ice sheet (Fig. 1), proposed in a series of papers by Grosswald (e.g. 1980, 1993, 1998; Grosswald & Hughes 1995), was subsequently supported by a group of geologists, headed by A. S. Lavrov, who conducted extensive air-photo interpretation and field work in the Pechora Basin over two decades (Arslanov *et al.* 1987). These reconstructions, channelled into the international literature by Grosswald, have had a profound impact on palaeoglaciological models (Denton & Hughes 1981; Peltier 1994).

Earlier, Lavrov and co-workers (1985), cited for example by Faustova & Velichko (1992) and Velichko *et al.* (1997), had proposed what may be described as an intermediate-sized glacial maximum (Fig. 2). A restricted glacial maximum, with its southern limit along the Markhida moraine was proposed by Yakovlev (1956), who considered the Markhida moraine to be of Early Weichselian age, whereas Guslitser *et al.* (1985) dated it to the Late Weichselian. In contrast, Arslanov *et al.* and Grosswald (*op. cit.*) ascribed it an age at about 9

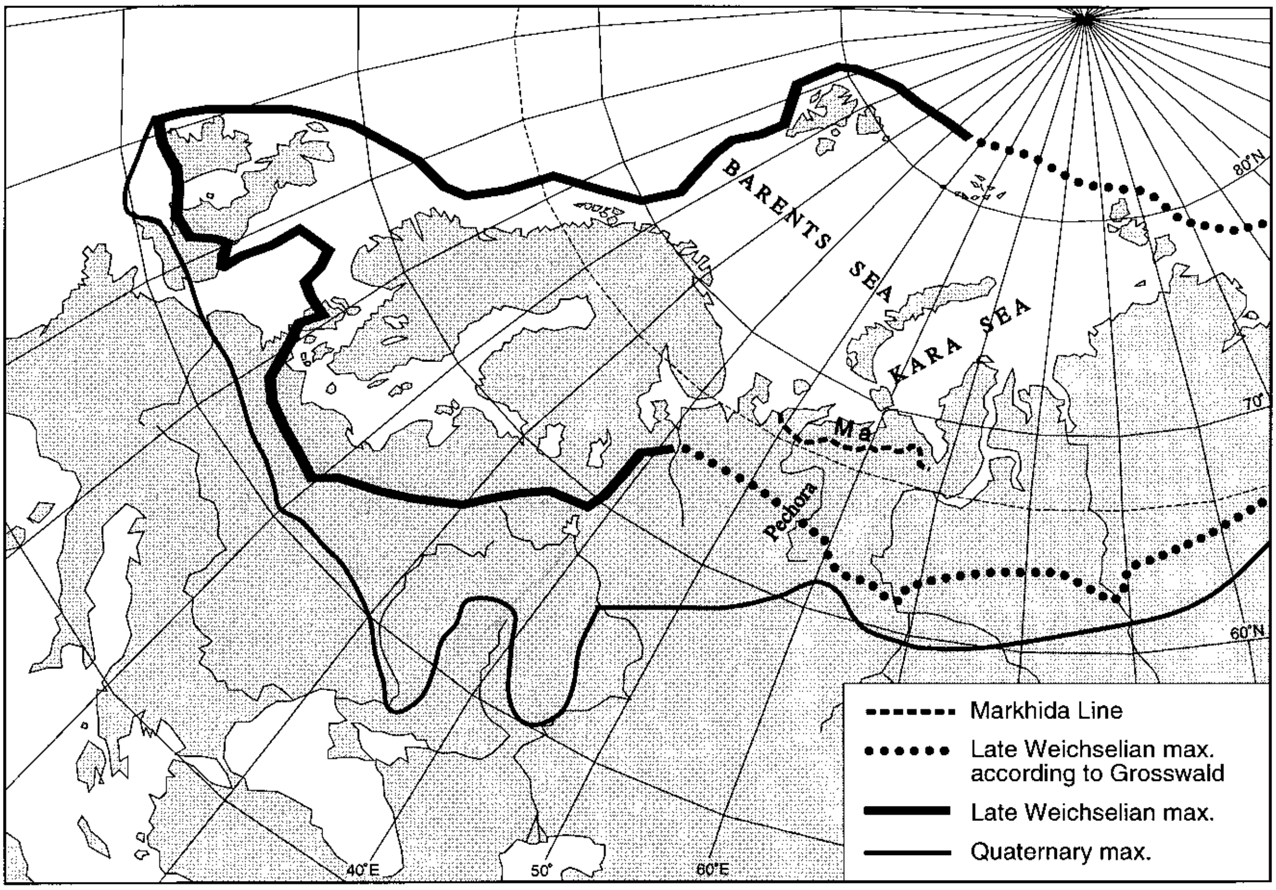


Fig. 1. Map of Europe and parts of Asia with some glacial limits. "Quaternary max." marks the asynchronous maximum extent of ice sheet glaciations in northern Eurasia. "Late Weichselian max." shows a commonly cited limit for the Scandinavian and the western limit of the Barents ice sheets. The dotted line shows the Late Weichselian ice limit around the Barents and Kara ice sheets according to Grosswald (1993). The Markhida line from the Timan Ridge in the west across the Ural Mountains in the east is according to Astakhov *et al.* (1999). We conlude that this line is of Middle or Early Weichselian age and shows the maximum Weichselian glaciation. During the Late Weichselian the Kara Sea was ice-free, and the southeastern limit of the Barents Ice Sheet unknown.

ka. Note that Astakhov *et al.* (1999) mapped the eastward extension of the Markhida moraine (Harbei–Halmer–Sopkay moraines) with considerable differences from some of the reconstructions referred to above. There is also a school of geologists, so-called "marinists", who claim that all diamictons in this area are glacimarine sediments, and that glaciers never moved from the shelf onto land.

Scientists of our group, who have previously studied various other parts of the Barents Sea and Kara Sea ice sheets (hereafter the Barents and Kara ice sheets), have arrived at different conclusions about the age of the last culmination of shelf glaciers. In the Svalbard–Barents region it probably reached its maximum extent during the Late Weichselian, and this was the only time when Weichselian glaciers covered the entire western and central Barents Sea (Landvik *et al.* 1998; Mangerud *et al.* 1998). In contrast, data from Siberia indicate that the Late Weichselian ice in the Kara Sea was much smaller than during the Middle or Early Weichselian (Astakhov 1992, 1997, 1998). Signs of ice flow from the Kara Sea over most of the described region imply that the postulated older Weichselian glaciation also reached European Russia. Taking these results from adjacent areas at their face value, our initial presumption was that ice sheets centred in the Barents and Kara seas should have reached the Pechora Basin during both the Late and Middle/Early Weichselian.

In 1992 we started a research project in the Pechora basin. A summary of the earlier Russian literature is given by Astakhov (1994). Results from our project were presented by Astakhov *et al.* (in press) and Tveranger *et al.* (1995, 1998), and preliminary results in several symposia (e.g. Mangerud *et al.* 1994, 1995, 1997).

In this volume we present three co-ordinated papers: Astakhov *et al.* (1999) publish a new geomorphologic map showing the boundaries of Weichselian ice sheets. In some places the youngest limit is marked by end moraines or other distinct ice marginal features, but

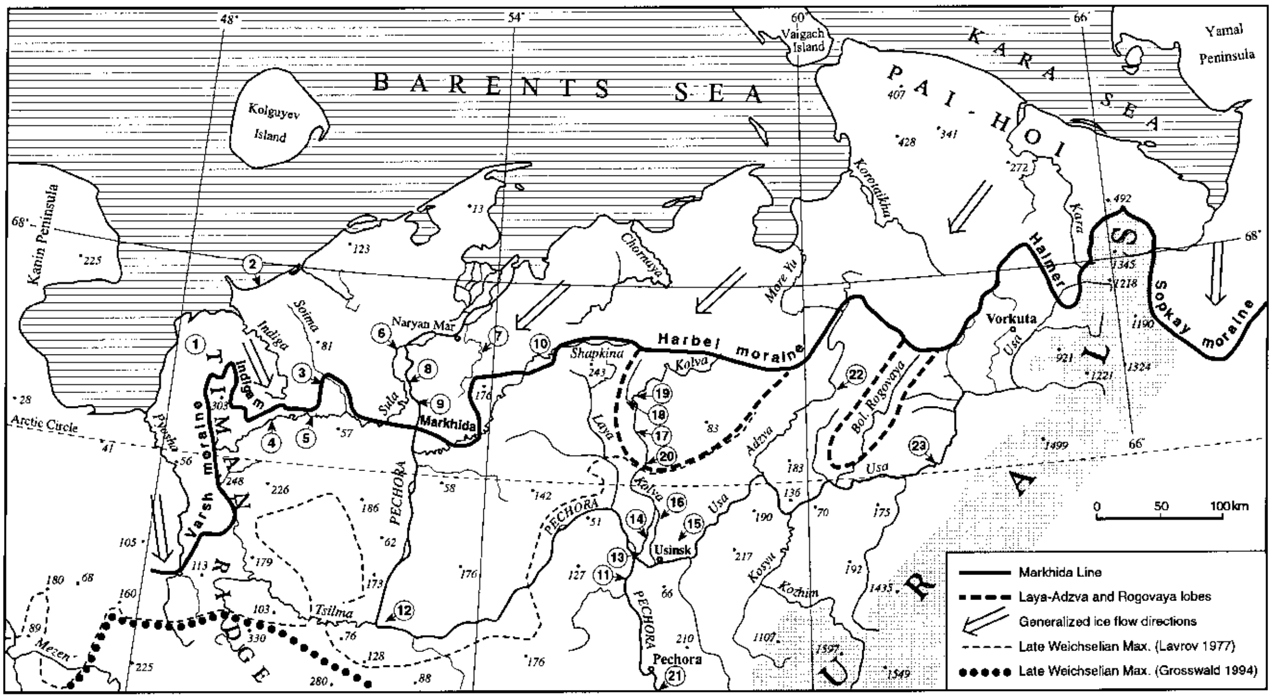


Fig. 2. Map of the Pechora Basin; for location see the Markhida line in Fig. 1. The Varsh–Indiga–Markhida–Harbei–Halmer–Sopkay line, collectively called the Markhida line, represents the limit of the last ice advance from the Kara and Barents seas. The Laya–Adzva and Rogovaya lobes are older than the Markhida line, although possibly not much older. All limits are plotted according to Astakhov *et al.* (1999), and the locality-numbering is identical to Fig. 2 in that publication. The Late Weichselian glacial boundary of Grosswald (1993) is seen only in the southwest corner of the map; along the Pechora River it is more than 400 km south of the Markhida line. Localities marked with numbers: 1 Bolvan bog at the Timan Ridge; 2 Timan coast section; 3 Urdyuzhskaya Viska; 4 Sula site 7; site 12 is downstream of 7; 5 Sula site 22; site 21 is upstream of 22; 6 Hongurei; Sopka is downstream of Hongurei; 7 Upper Kuya; Kuya Bridge is between this and Naryan-Mar; 8 Vastiansky Kon; 9 Markhida; 10 Upper Shapkina; 11 Akis; 12 Garevo; 13 Ust-Usa; 14 Novik; 15 Ozyornoye; 16 Bolotny Mys; 17 Yaran-Musyur; 18 Haryaha; 19 Podkova-1; 20 Yarei-Shor; 21 Byzovaya; 22 Pymva-Shor; 23 Mamontovaya Kurya.

over long stretches it is only a boundary between a "young" glacial landscape to the north, and an "old" landscape to the south (Astakhov *et al.* 1999). In the west this boundary consists of the Varsh and Indiga moraines (Fig. 2) deposited around the northern Timan Ridge by the Barents Ice Sheet. Farther to the east it represents the southern boundary of young morainic landscapes affected by the Kara Ice Sheet: the Markhida, Harbei and Halmer moraines in the Pechora Basin and the Sopkay moraine east of the Urals (Fig. 2). In the present paper we assume that the southern boundary of the Varsh–Indiga–Markhida–Harbei–Halmer–Sopkay moraines represents one quasi-synchronous ice limit, and for simplicity and correlation purposes we call the entire limit the Markhida line (or the Markhida moraine for topography-forming deposits), emphasizing that the different segments retain their names for future discussions of correlations and synchroneity. The Markhida line corresponds roughly with the D-moraine of Grosswald (1993). The southernmost glacial limit discussed by Astakhov *et al.* (1999) consists of the two older Laya–Adzva and Rogovaya morainic loops, which protrude south of the Markhida line (Fig. 2). In the present paper we describe stratigraphical sequences and other observations that can be used to date the Markhida and Laya–Adzva lines. This is an overview paper, and more detailed descriptions of some of the sites will be given in subsequent publications. In the third paper, Tveranger *et al.* (1999) utilize the Markhida line for a three-dimensional reconstruction of the last Kara Ice Sheet.

We use the stratigraphical nomenclature of western Europe, because the main interglacial marker in the Pechora region is readily correlated with the marine Eemian in western Europe, and only via that with the continental Mikulino interglacial in Russia. The names Weichselian and Valdaian are both equally related to the Scandinavian Ice Sheet. We postulate that the Russian Mikulino and Valdaian correlate with Eemian and Weichselian, respectively (Devyatova 1982). We also assume the ages of about 130–117 ka for the Eemian (correlated with the deep sea isotope stage 5e), 117–74 ka for the Early Weichselian – (isotope stages 5d–5a), 74–25 ka for the Middle Weichselian – (isotope stages 4–3), and 25–10 ka for the Late Weichselian (Mangerud 1989).

Methods

This paper is based on extensive fieldwork carried out during the course of 6–8 weeks each summer from 1993 to 1998. The sequences described have been located from the existing literature and by air photo interpretation. In the northernmost areas, most of the sections were reached by helicopter. Along minor rivers we travelled by inflatable boats, whereas when investigating exposures on the Pechora banks we used speedboats and larger vessels. Many deposits not known previously have been described from man-made sections around the cities of Naryan-Mar, Ust-Tsilma, Usinsk and Pechora (Fig. 2). Key sites were visited by at least two of the authors to ensure concurrent interpretation. The most problematic sites, and the most extensively discussed in the literature, such as Markhida, Vastiansky Kon and Byzovaya, were visited repeatedly over the years to benefit from differently exposed bluffs and progressing excavations.

Radiocarbon samples were dated at different laboratories (Table 1). The St. Petersburg laboratory (prefix LU-) uses scintillation counters (Arslanov & Svezhentsev 1993), whereas the Trondheim laboratory (prefix T) uses proportional counting (CO_2 gas). AMS dated samples of organic matter are all hand-picked macrofossils of terrestrial plants identified by Dr. Hilary H. Birks. The prefix TUa- is used for samples where the target was prepared in Trondheim, and the accelerator mass spectrometry (AMS) measurements were performed at Uppsala University. Some samples were also provided by Beta Analytic (prefix Beta-), and some were prepared at INSTAAR, University of Colorado and measured at the Lawrence-Livermore National Laboratory (prefix CAMS-). Fine-grained thermoluminescence (TL) dates were provided by Dr. N. C. Debenham using the method described in Debenham (1985).

All optically stimulated luminescence (OSL) dates on sand grains were performed at the Nordic Laboratory for Luminescence Dating, Denmark. Dating was performed on both the feldspar and quartz fractions; normally the feldspar fraction yielded significantly younger dates. Here we report the quartz dates only, because quartz does not show anomalous fading (Wintle 1997) or a possible shallow trap effect (Mejdahl *et al.* 1992). The results of the comparison between the two fractions will be published later by Murray *et al.* Gamma dose rates were measured for most samples using a field scintillator, whereas beta was measured in the laboratory. Based on porosity measurements on sand from Svalbard (J. Mangerud), an average water content of $14 \pm 7\%$ was used. OSL measurements were made using automatic Risø readers, and blue–green (420–550 nm) or blue (470 ± 30) stimulation sources (B-J 1998). Most measurements were made using the Single Aliquot Regenerated (SAR) dose protocol (Murray & Mejdahl 1999; Murray & Roberts 1998).

Till-covered sequences north of (proximal to) the Markhida line

The age of sediments beneath the surficial till north of the Markhida moraine would provide a maximum age of the last ice advance. According to the official Russian stratigraphic scheme for this region there is only one post-Eemian till; namely the Polar Till and deposited by ice flow from the northeast (Guslitser *et al.* 1985). The surficial till south of the Markhida line in this scheme is considered to have been deposited by pre-Eemian glaciers that advanced from northwest. However, Arslanov *et al.* (1987) concluded that both of these surficial tills show similar petrographic composition and ice-flow directions. Thus, there are possibly two tills with different ages, but with similar properties; we therefore avoid the term Polar Till.

Marine sediments of the “Boreal transgression”, containing a mollusc fauna requiring considerably warmer sea water than at present (January temperature 4–8°C warmer), are widespread along the Arctic coast of Russia. For the Pechora basin they have already been described by Chernyshchev (1891). Reviews of the Boreal transgression are given by Yakovlev (1956), Raukas (1991) and Astakhov (1994), and fauna lists for the Pechora basin by Lavrova (1949), Troitsky (1965) and Golbert *et al.* (1973). The sediments are characterized by boreal mollusc and cirriped species which now have their northern limit along the Murmansk coast or further to the south along the west coast of Norway. At the localities described in this paper we found such boreal species as *Heteranomia squamula, Cerastoderma edule, Spisula elliptica, Arctica islandica, Zirpheae crispa, Balanus improvisus, Balanus hammeri* and *Semibalanus balanoides*. These are all shallow-water species associated with the Atlantic Current, and restricted to year-round ice-free areas. This implies that the Atlantic Current extended much further to the east than in the Holocene.

From the warm boreal fauna, the setting below the youngest till and the pollen stratigraphy, its last interglacial age and correlation with the Eemian of the western Europe has been accepted for a long time (Devyatova 1982). This age is also supported more recently by amino acid D/L ratios (Miller & Mangerud 1985) and ESR dating (Molodkov & Raukas 1988). Following these arguments we accept an Eemian age for this formation, also supported by our TL/OSL dates.

In the northern part of the Pechora Basin the Eemian marine sediments are either overlain by till or incorporated in till (Golbert *et al.* 1973; Krasnov 1971; Yakovlev 1956). The implication is that there has been at least one advance of the Kara and Barents ice sheets onto European Russia after the Eemian. Here we will briefly describe some sections.

Fig. 3. A glaciotectonic dragfold in Eemian marine sediments at Sopka (northeast of loc. 6 in Fig. 2). The shovel is about 1 m. Above the shovel is a thrust plane, and at the top of the photo the base of the till. Ice movement from right (northeast) to left.

Sopka

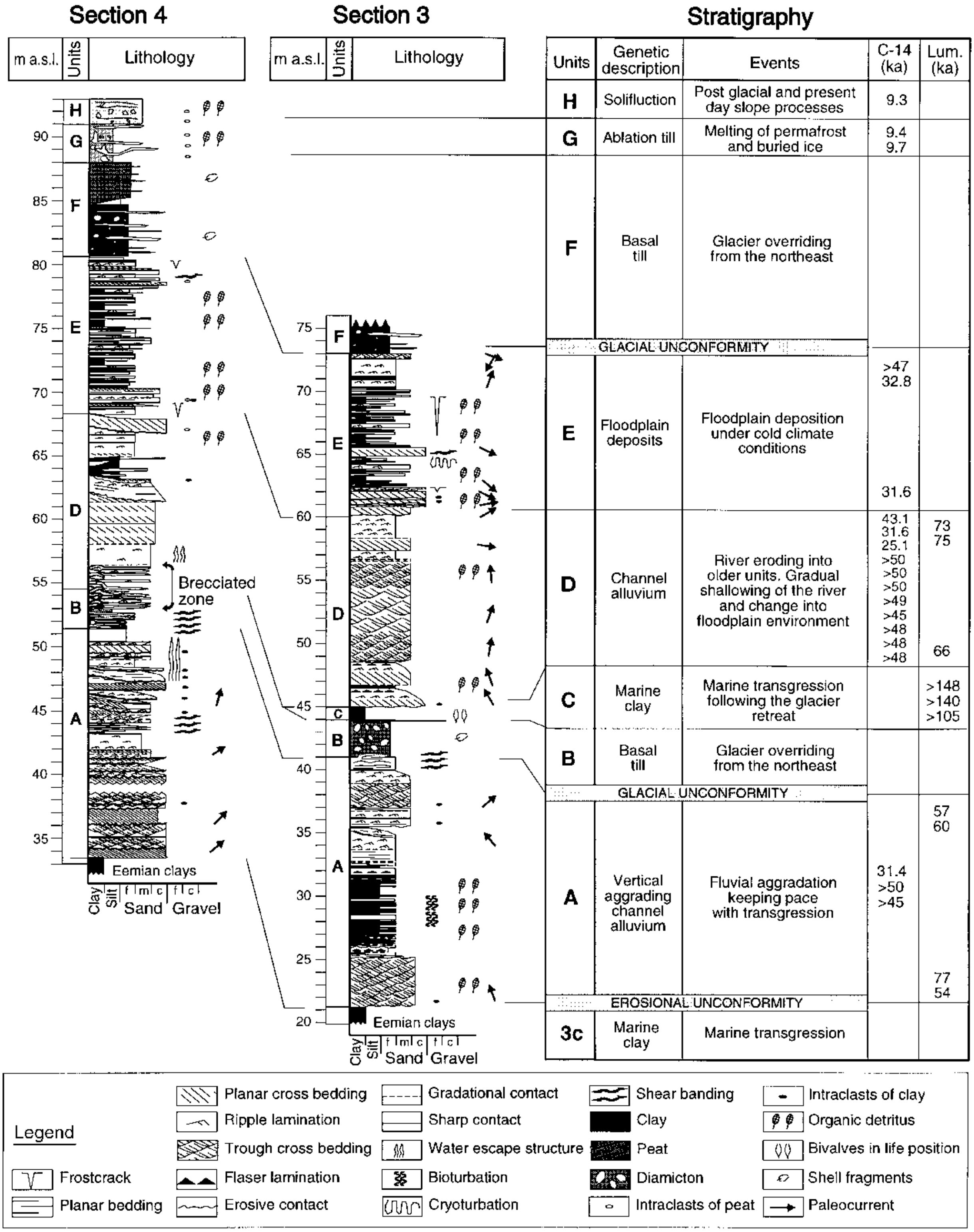
Near Sopka (NE of loc. 6 on Fig. 2) there is a 4 km long and about 15 m high bluff along the Pechora River. In some places the lower part consists of cross-bedded alluvial sand containing large (interglacial) wood and twigs, and in other places of deltaic, low-angle dipping beds with marine shells. These units are overlain by a 4 to 7-m-thick sandy diamicton, where low angle thrust-faults and dragfolds along the lower boundary show that the diamicton is a basal till deposited from the NE (Fig. 3). Incorporated in the till are floes of marine sand and clay containing paired *Arctica islandica*. The surface of the till is represented by low, NE–SW-oriented, flute-like ridges. The same type of diamicton, sometimes with very big boulders, can be seen overlying the Eemian sand in many sections along the left bank of the Pechora downstream to the coast, where the thin till is often eroded away to leave only boulder lag or an eolian mantle over the sandy Eemian sediments.

Vastiansky Kon

This is a classical site (loc. 8 on Fig. 2) studied by many scientists previously. A description, including a review of the Russian language literature, is provided in Tveranger *et al.* (1998). Here we emphasize that in the lower part there are interglacial marine sediments consisting of a thick, dark clay with rare shells (unit 3c on Fig. 4) overlain by a gravel lag with abundant Eemian fauna (not seen on logs in Fig. 4). Above are younger alluvial sediments, glaciotectonically upthrusted, that elsewhere mainly occur below the present river level and therefore cannot be studied. These sediments provide an opportunity to obtain maximum dates of the last ice advance. Earlier finite dates (25–29 ka) were reported from the sediments below the upper till (unit F in Fig. 4) (Golbert *et al.* 1973). However, redating of the same beds yielded 43 ka to non-finite ages (Arslanov *et al.* 1987), which we initially accepted. During the first phase of our study we therefore did not submit samples for radiocarbon dating from this section. Based on our experience from other sites, however, we later became suspicious that there might be a mixture of redeposited interglacial wood and *in situ* moss and other plant fragments, and therefore we attempted another series of radiocarbon dating.

Above the Eemian there are some 20 m of alluvial channel sand, including an infilled oxbow lake (unit A, Fig. 4). Then follows a thin till layer (unit B) with a marine clay (unit C) atop; we have earlier discussed whether units B and C rest in their primary stratigraphical position or whether they have been upthrusted from underlying units (Tveranger *et al.* 1998). Alluvial channel sand (unit D) grading into floodplain silt and sand (unit E) overlies unit C. Unit E contains a plant macro fossil flora indicating a colder climate than the present. Capping the section is a nearly 10-m thick basal till (unit F) covered by solifluction.

First we obtained both finite and non-finite radiocarbon dates from units D and E (Table 1), the former including 25 ka (Beta-099885, Table 1) on hand-picked moss stems, and 32 ka (T-13050) on a piece of *Salix* wood. These dates, and several bulk peat dates that yielded similar ages, previously led us to conclude that the overlying till was of Late Weichselian age (Mangerud *et al.* 1997; Tveranger *et al.* 1998). However, when re-dating hand-picked moss stems from the same or corresponding samples with AMS, we obtained only non-finite ages. Redeposition is considered to be the



Stratigraphy

Units	Genetic description	Events	C-14 (ka)	Lum. (ka)
H	Solifluction	Post glacial and present day slope processes	9.3	
G	Ablation till	Melting of permafrost and buried ice	9.4 9.7	
F	Basal till	Glacier overriding from the northeast		
GLACIAL UNCONFORMITY				
E	Floodplain deposits	Floodplain deposition under cold climate conditions	>47 32.8 31.6	
D	Channel alluvium	River eroding into older units. Gradual shallowing of the river and change into floodplain environment	43.1 31.6 25.1 >50 >50 >50 >49 >45 >48 >48 >48	73 75 66
C	Marine clay	Marine transgression following the glacier retreat		>148 >140 >105
B	Basal till	Glacier overriding from the northeast		
GLACIAL UNCONFORMITY				
A	Vertical aggrading channel alluvium	Fluvial aggradation keeping pace with transgression	31.4 >50 >45	57 60 77 54
EROSIONAL UNCONFORMITY				
3c	Marine clay	Marine transgression		

Fig. 4. Logs from Vastiansky Kon (loc. 8 in Fig. 2), modified from Tveranger *et al.* (1998). The lowermost unit (3c) shown is the Eemian marine sediments. The basal till on top (unit F) is the till correlated with the Markhida moraine. All units below F are more or less glaciotectonically thrusted.

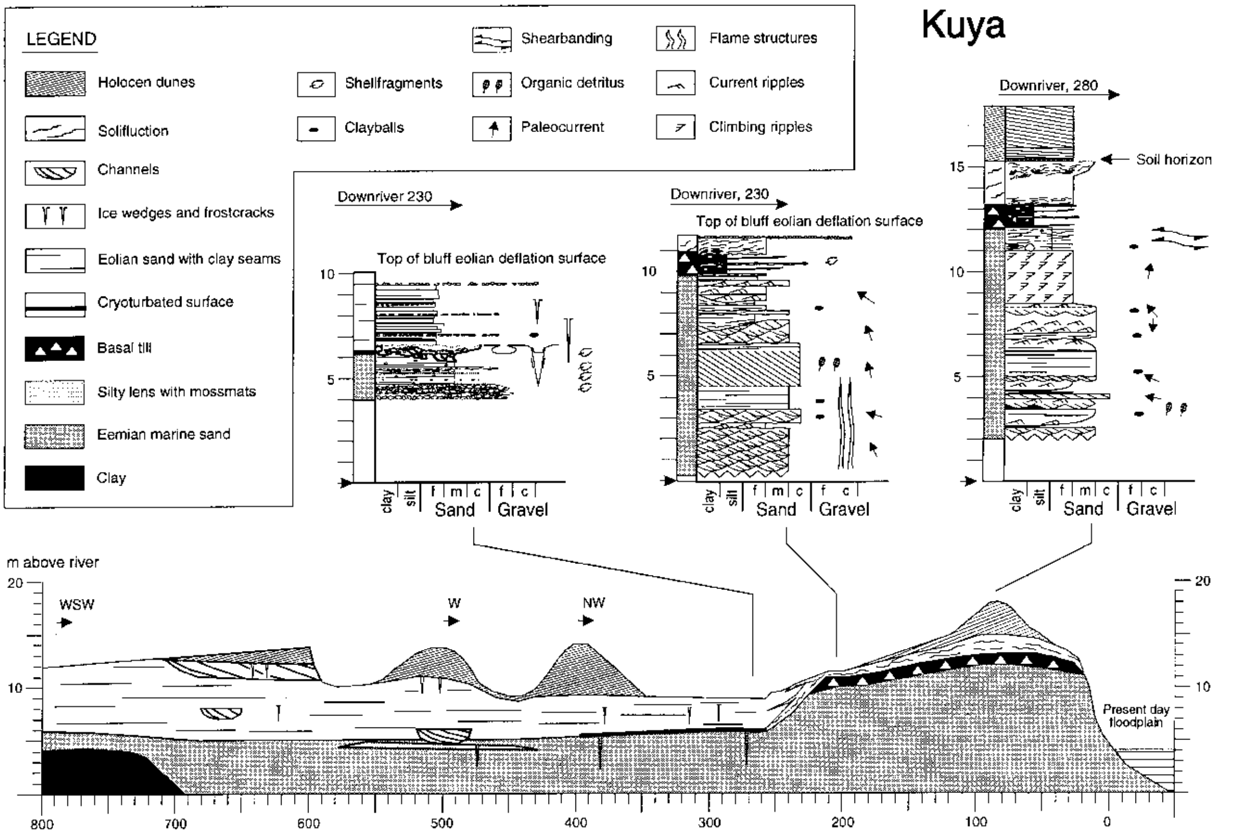


Fig. 5. Upper Kuya section, some 20 km east of Naryan-Mar (loc. 7 in Fig. 2). In the lower part there is Eemian marine sand including silty lenses with mossmats (tidal flat). In the downstream part (0–200 m) this formation is overlain by a basal till with frequent shear planes. Upstream of 200 m the till is removed, and between 250 and 400 m this erosional unconformity is marked by a strongly cryoturbated surface. Resting on this is eolian coversand with some hanging channels of coarser sand.

only source of error that could make the dates considerably older than the enclosing sediment. However, we find it unlikely that fragile moss stems were redeposited from older layers. By re-dating, nearly all finite radiocarbon dates were falsified, and we now conclude that formation D is older than 40 ka. Unfortunately, we have neither AMS dates on small plant fragments nor any OSL dates from unit E, the uppermost sediments below the till. We have dated a mammoth tusk collected by I. Krasnov to 32 and 39 ka (LU-3973 and T-13200, Table 1). It was found in a gully in the section, and Krasnov's interpretation was that it came from the sediments just below the upper till. This is the most likely stratigraphical position, although we cannot completely rule out the possibility that it originated from above the till.

The seven OSL dates from the alluvial sand formations A and D all yielded ages 54–77 ka (Table 2, Fig. 4) supporting the above-mentioned non-finite radiocarbon dates. They indicate that unit D is of about the same age as unit A and therefore that D is upthrusted. More important in this context is that the OSL dates indicate a maximum age for the Markhida till in the range 60–70 ka.

Upper Kuya

A section at the left bank of the Kuya River (loc. 7 on Fig. 2) provides a typical example of the relationships between the Pleistocene formations in the catchment area of the lower Pechora River. Dark-grey clay with bands of grey silt, similar to the marine clay in the Vastiansky Kon section, is exposed in the upstream part of the bluff (700–800 m in Fig. 5). It is overlain by light-grey sand with lenses of plant detritus. In the sand there is a 0.2 to 0.6-m-thick gravel bed containing numerous shells of boreal molluscs, and laminated silt with moss mats. A radiocarbon date on the moss mat yielded a non-finite age (Table 1). Shell fragments are also distributed in the upper part of the sand. These sediments are interpreted as a regressive Eemian marine formation, grading into tidal flat silt and deltaic sand.

Between 0 and 200 m (Fig. 5) the marine formation is cut by shear planes below the base of a brownish, finely

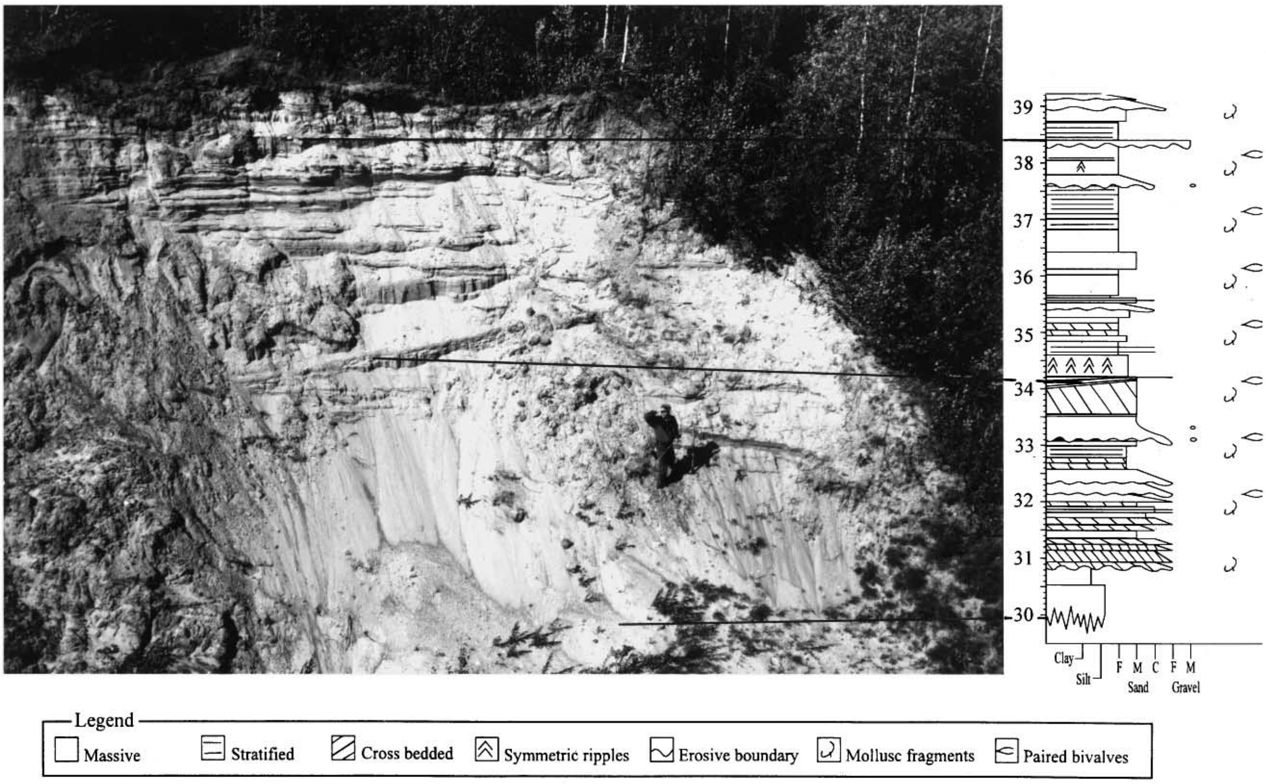


Fig. 6. Photo of the low-angle dipping Eemian marine beds in a small tributary gully on the right bank at Sula site 22 (loc. 5 in Fig. 2). Hundreds of shells of typical Eemian fauna are found in the sand. Note the man for scale. Sula is outside the photo to the right. The slopes from the gully floor just below the photo (30 m a.s.l.) down to the river (about 17 m a.s.l.) are covered by slumped material and vegetation. To the right is a log from this section.

banded diamicton with rare pebbles and numerous flattened sand balls that we interpret as a basal till. The till is covered by pebbly diamictic sand with solifluction flow structures.

Between 250 and 800 m the till and some of the Eemian sediments have been removed by (fluvial?) erosion, the unconformity being marked by a cryoturbated surface with narrow ice wedge casts. The solifluction layer on the till interfingers with a thick formation of tan, irregularly laminated, eolian coversand, similar to sand described at Kuya bridge and Markhida below. In the sand are narrow intrachannels of coarser trough-bedded sand. The sequence is capped by a podsol soil with Holocene dunes on top.

Markhida

The Markhida type site (loc. 9 in Fig. 2) is described in Tveranger *et al.* (1995), and some additional dates for the deglaciation are given in the next section. Here we point out that we have redated the alluvial sand underlying the moraine, providing a maximum age of the last ice advance. The new, and presumably better, OSL dates on quartz 58–63 ka are older than the previous dates and therefore no longer an argument for a Late Weichselian age of the overlying till (Tveranger *et al.* 1995).

Sites south of (distal to) the Markhida and Laya–Adzva lines and not covered by till

Eemian marine sediments, Sula site 22

Along the Sula River we have studied 23 exposures, including two large sections with marine sediments only covered by non-glacial continental deposits. At site 22 (loc. 5 in Fig. 2) there are 8–9 m of well-exposed marine sand and gravel (Fig. 6), the upper part of which we traced about 650 m along the river. The sand is underlain by dark silt and clay which was poorly exposed at the time. However, Lavrova (1949) reported *Cardium ciliatum, Natica clausa, Neptunea despecta*, abundant *Saxicava arctica* and rare *Portlandia arctica*, i.e. a rather cool mollusc fauna from the clay. It probably dates from the Late Saalian/Early Eemian transition.

The sandy unit begins with a thin gravel in tabular foresets containing paired *Mytilus edulis* overgrown by barnacles (*Balanus improvisus* and *Semibalanus bala-*

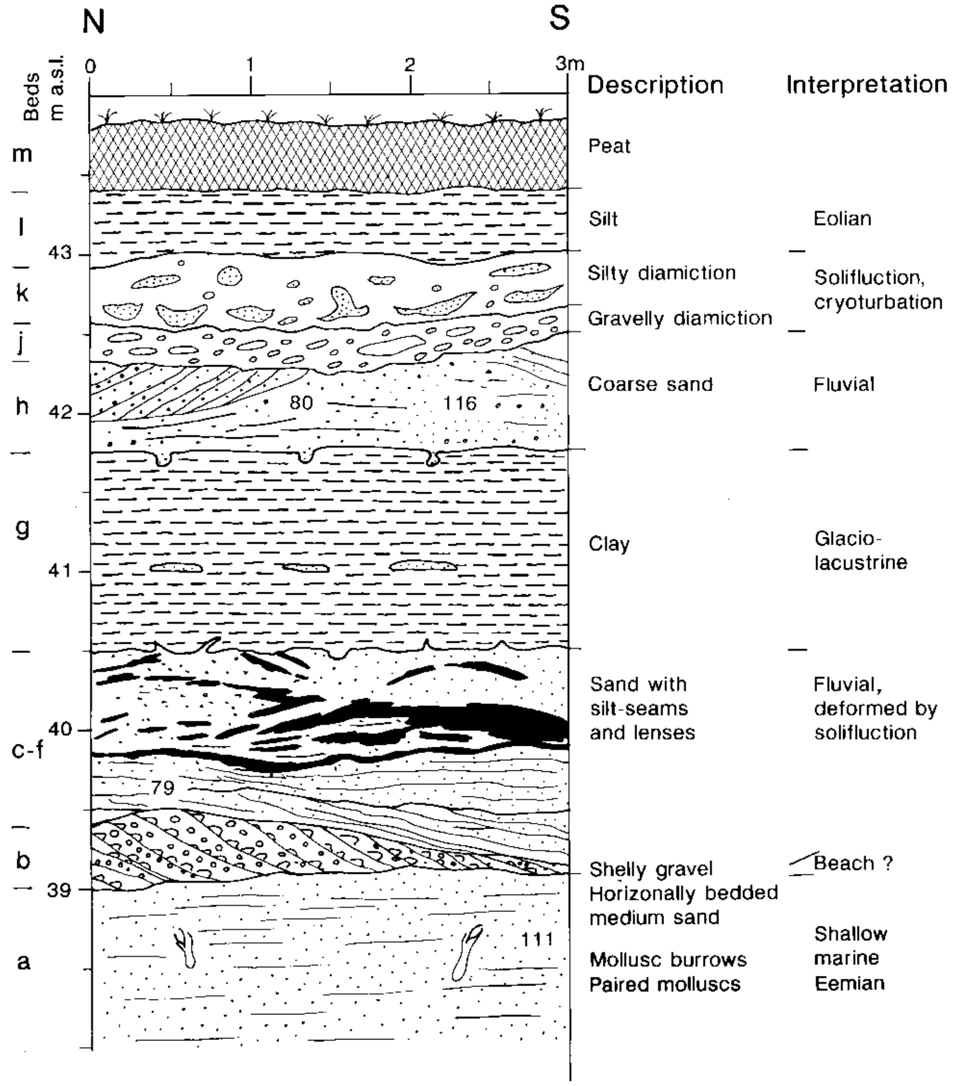


Fig. 7. A measured section of the sediments capping the marine sediments at Sula site 22. This is a few tens of meters up gully from Fig. 6, and the marine sand is exposed continuously in full thickness between the two sections. The important features are that no till exists above the Eemian marine sediments, and no glaciotectonic structures are seen in the section. The glaciolacustrine clay was probably deposited in Lake Komi. OSL dates from Table 2 are marked without error limits.

noides). The gravel is interpreted as a foreshore facies and is overlain by a generally upward fining sand (31–37 m on log, Fig. 6) with a parallel increase in bioturbation. The fauna is dominated by large *in situ* individuals of *Arctica islandica* and with a few *Cerastoderma edule* and *Zirphaea crispata*. The marine formation is topped by a cross-bedded gravel (bed b, Fig. 7), possibly a beach bar, resting unconformably on the sand and with numerous half-shells of *Arctica islandica* and *Spisula elliptica*. The marine sequence is interpreted to reflect a relative sea level rise followed by a regression.

The occurrence throughout most of the sequence of the boreal fauna demonstrates an interglacial, and most probably of Eemian age. The latter age (as opposed to an older interglacial age) is supported by OSL dates, although they yielded younger than expected ages (64, 97 and 111 ka, Table 2, Fig. 7).

Above the marine unit there is faintly parallel laminated sand with silt seams (beds c–f) that we interpret as a fluvial/eolian deposit. In the sand are many secondary flow structures and normal low-angle faults caused by sliding of wet sediments along the silt seams. Above the sand there is a well-defined, 1.3 to 2.5-m-thick layer of massive dark clay with rare scattered dropstones. The lower boundary is an angular unconformity. The clay is interpreted as of lacustrine or glacilacustrine origin, possibly deposited in Lake Komi (see below).

Above the clay there is locally a thin bed of coarse, cross-bedded sand (bed h) that presumably was deposited from a local stream. There then follows a 15 to 30-cm-thick diamictic layer with numerous stones (bed j), and a more silty diamicton (bed k) with a weak bedding and abundant pockets of sand. Both diamictons have restricted horizontal extension. They are interpreted as local solifluction deposits. The upper minerogenic bed (l) is a massive silt that we frequently observed at the

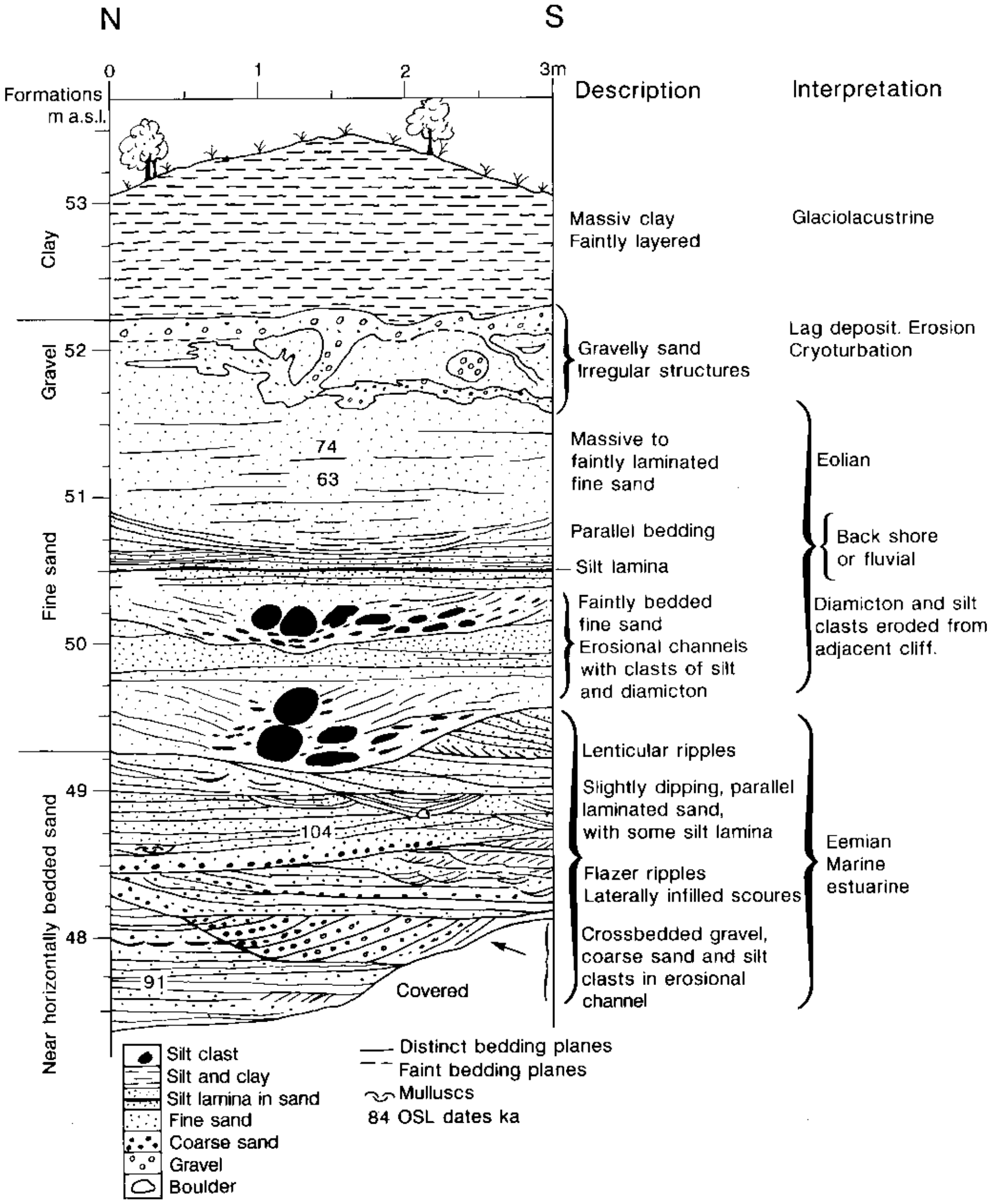


Fig. 8. The upper part of the Sula site 21 (4 km upstream of loc. 5 in Fig. 2). Only the upper parts of the 6-m-thick Eemian marine sediments are shown. They indicate a relative sea level about 50 m above the present. The Eemian sediments are covered by continental and lacustrine sediments; no till or glaciotectonic structures were observed. OSL dates from Table 2 are marked without error limits.

base of the tundra soil; it is of mainly eolian origin. The section is capped by about 0.4 m of Holocene peat. The main conclusion is that there is neither till nor any glaciotectonic structure in or above the Eemian marine sediments.

Eemian marine sediments, Sula site 21

This site is 4 km upstream of section 22 as the crow flies, and the river is about 21 m a.s.l. The lower slopes are obscured by slides and vegetation. In the lower part of the exposure, 3-m-thick cross-bedded sand and gravel, probably deposited in tidal or fluvial channels during the marine transgression, rest on a glacimarine diamicton. Above there is a 3-m-thick formation (the upper part is shown in Fig. 8) dominated by tens of centimetres of thick lenticular beds (<2 m long) of medium and coarse sand. Cross-bedding and parallel lamination are the most common internal structures. In the more fine-grained beds, wavy flaser bedding and ripples with alternating sand and silt laminae occur. The beds are cut by scours and sand-filled channels. Molluscs occur in pockets around scattered boulders. *Macoma calcarea* dominates, but the boreal *Balanus improvisus* and *Semibalanus balanoides* as well as a few *Mytilus edulis* and *Arctica islandica* were also found. This unit was deposited in a tidally influenced environment, probably in an estuary, with relative sea level at

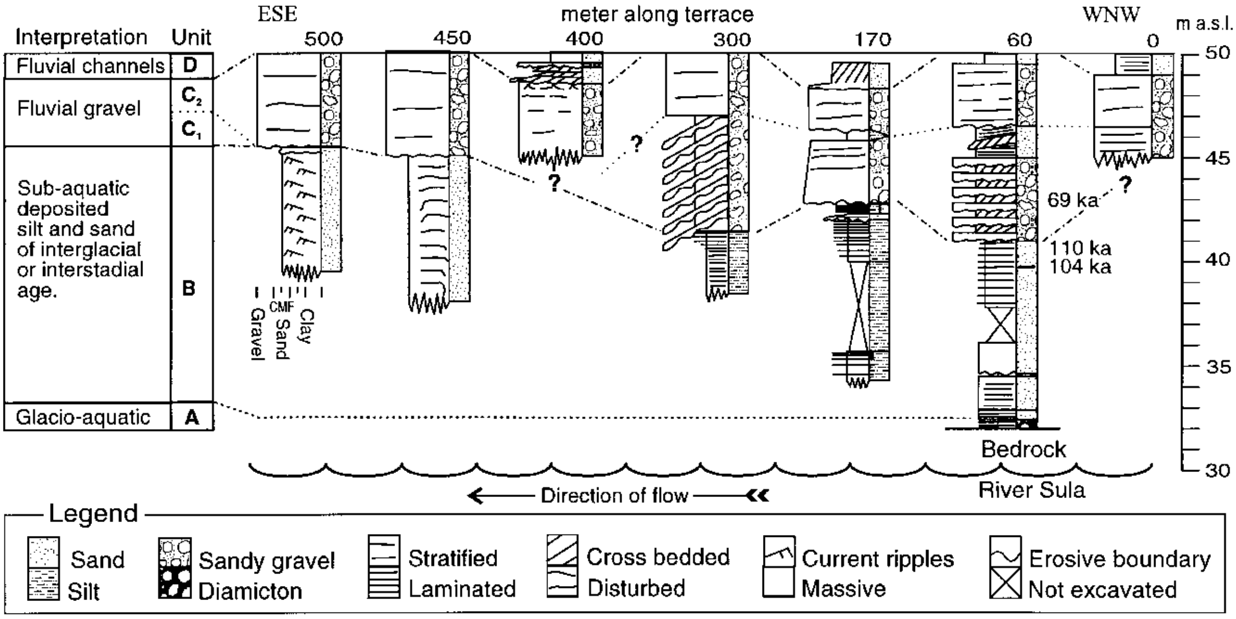


Fig. 9. Sections in the terrace at Sula site 12 (downstream of loc. 4 in Fig. 2). Large ice-wedge casts from the surface are not shown. OSL dates (Table 2) are plotted without error limits. Note that neither till nor glaciotectonic structures were found in the sections.

least 50 m above the present. Based on molluscs, altitude and facies we consider the correlation with site 22 clear, and thus conclude it is of Eemian age.

Resting on the marine sediments is a formation dominated by a faintly laminated, well-sorted fine sand (49.5 to 52 m in Fig. 8). In the lower part are two conspicuous channels with mud balls and clasts of unconsolidated silt and diamicton. The simplest sedimentological interpretation is that the sandy formation was deposited during the Eemian, in a back-shore environment dominated by eolian sedimentation, and that the clasts were transported from a cliff formed by marine erosion. However, the OSL dates (Fig. 8, Table 2) from the sand indicate a considerably younger age. Possibly the clasts were eroded by fluvial processes at a much later stage, an alternative supported by the fact that in nearby sections cross-bedded fluvial sand occur in this stratigraphic position.

The section is capped by a massive, dark grey clay, similar to the clay (bed g) at site 22. The only clasts are randomly dispersed, sometimes in clusters of 3–4, poorly rounded stones 5 to 20 cm in diameter. The stones are mostly far-travelled crystalline rocks with subvertical orientation of their long axes. The clay, here and in several other sections, contains no visible particles of the underlying sand. We therefore deduce that it was deposited in a deep ice-dammed lake affected by ice-rafting.

Terrace, Sula site 12

On the western margin of the Pechora basin, where the Sula River emerges from its bedrock valley in the Timan Ridge, there is a 0.5-km-long and 0.4-km-wide terrace, about 20 m above the river and 50 m a.s.l., along the right river bank (10 km downstream of loc. 4 in Fig. 2). The flat, fluvially eroded surface is cut by fossil ice-wedge polygons, the latter ending as gullies through the river bank. The river has recently shifted away from the bluff which is already vegetated.

Four main formations were identified (Fig. 9). On the bedrock there is a 40-cm-thick waterlain, laminated diamicton. This formation seems to pinch out downstream. Above there are 9–12 m of horizontally laminated silt and sand clearly deposited in quiet water. Some shell fragments of marine molluscs were found. The OSL dates yielded ages 104–110 ka, compatible with an Eemian age when compared with other dates from known Eemian sediments (see above). These formations are overlain by 4–8 m gravel, the lower part is cross-bedded sandy gravel, whereas the upper is coarse gravel with crude bedding. The upper gravel is certainly a fluvial deposit, as is probably the lower gravel, although shell fragments may indicate a marine origin for this latter unit. A shell fragment is radiocarbon-dated to 40 ka (Table 1), which we consider a minimum age; an OSL date yielded about 69 ka (Fig. 9, Table 2). Some fluvial channels with cross-bedded sand occur near the surface. A similar sequence with laminated silt and sand overlain by fine gravel and sand with shell fragments, and even one whole *Macoma*, was found in another section in the same flat surface, 3 km to the southeast. This sequence is also interpreted as marine Eemian. No till or other evidence

Fig. 10. The Sula site 7 (loc. 4 in Fig. 2), the river running from left to right. On top of the marked basal till is eolian dune sand, obviously not overrun by ice. OSL dates of the eolian sand yielded 134 and 149 ka. A fossil thermokarst hollow is stipled.

of glaciation above the interglacial sediments was found in the sections.

Eolian sand, Sula site 7

This section is situated on the Timan Ridge, on the left bank of the Sula (loc. 4 in Fig. 2). A cross-bedded whitish sand and well-sorted gravel is found at the base. The gravel consists of well-rounded pebbles derived from the local Permian limestone. It is overlain by 1 m of reddish till, upwards grading into an 8-m-thick grey till (Fig. 10). Several thrust planes along the lower boundary show ice movement from the northwest. The direction is supported by the pebble composition: basalts from west of the site constitute 50% in the lower, 40% in the middle and 34% in the upper part of the grey till.

On top of the till there are 10 m of well-sorted, loose, fine to medium sand, without any clay or gravel seams. The sand lies in long foresets cutting each other along low-angle dipping boundaries. The sand is interpreted as a remnant of an eolian dune. Subvertical faults in the sand, a thermokarst hollow (Fig. 10), and covering patches of soliflucted diamicton, demonstrate the earlier existence of buried glacial or ground ice. The eolian sediments should provide reliable luminescence dates. The ages found (134–149 ka, Table 2) suggest that the till, and thus the last glaciation of the site, is of pre-Eemian age, which is concordant with its basal position in other Sula sections.

Sediments along river Urdyuzhskaya Viska

Along this small river draining Lake Urdyuga, several sections (loc. 3 in Fig. 2) have been investigated by Arslanov *et al.* (1980). The sites studied by us are situated only some 2–8 km distal to a lobe of the Markhida moraine (Astakhov *et al.* 1999). At our sites, the river is about 21 m a.s.l. The sections show three main units (Fig. 11). At river level there is a flat-bedded, fine to medium sand with ripples, interbedded with thin seams of silt and organic mats containing mosses, leaves and wood. It is most likely of shallow lacustrine or marine origin. Arslanov *et al.* (1980) interpreted them as oxbow-lake sediments. A 7 to 8-m-thick, yellowish sand and fine gravel overlies the lower unit. Cross-beds are generally less than 0.5 m thick and were probably deposited in shallow river channels of a braided river. The structures reflect variable current directions with a mean towards the northwest, i.e.

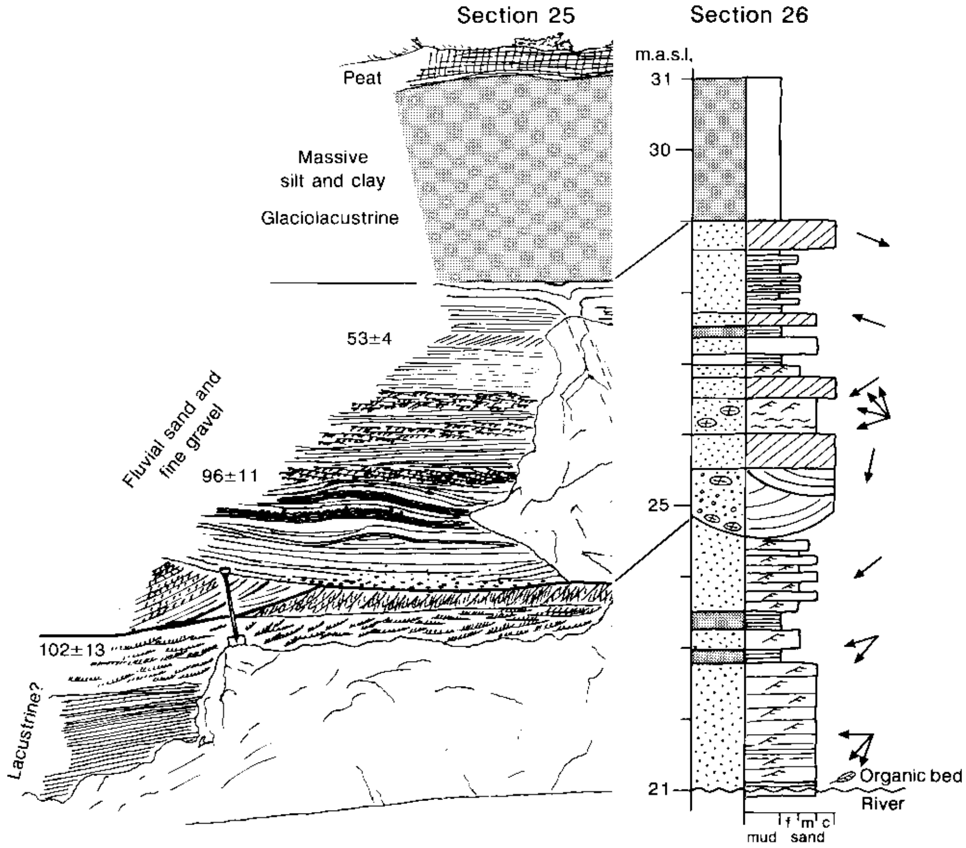


Fig. 11. Sites at Urdyuzkaya Viska (loc. 3 in Fig. 2); note they are located just outside the Markhida line. To the left a drawing of site 25. OSL dates are plotted. Organic matter found at river level some few hundred metres upstream yielded a non-finite radiocarbon age. To the right a log of site 26, about 1 km to the west of 25. Arrows show flow directions, other signs as in Fig. 9. Lines show correlation of the sections. The upper silt was probably deposited in Lake Komi. No till or glaciotectonic structures were observed.

towards the Barents Sea coast and opposing the present river flow direction which is forced by the Markhida moraine (Fig. 12). Many twigs and branches were found in the sand.

All sections are capped by a 2 to 3-m-thick dark-grey, nearly massive silt and clay, which apparently covers large areas of the surrounding boggy tundra. From its appearance it is similar to the clay at Sula sites 22 and 21, and we conclude they were probably deposited in the same ice-dammed lake.

Arslanov *et al.* (1980) reported a radiocarbon date of 43 ka from the organic sediments at river level. We also obtained ages of 41 and 44 ka on wood samples from these sediments (Table 1). However, two AMS dates on plant macro fossils (leaves, moss, etc.) yielded non-finite ages and a third yielded 50 ka, also considered as non-finite (>44 ka). We conclude that the real age of the organic bed is >45 ka. OSL dates yielded 102–53 ka (Fig. 11, Table 2).

The main conclusion is that the sequence has not

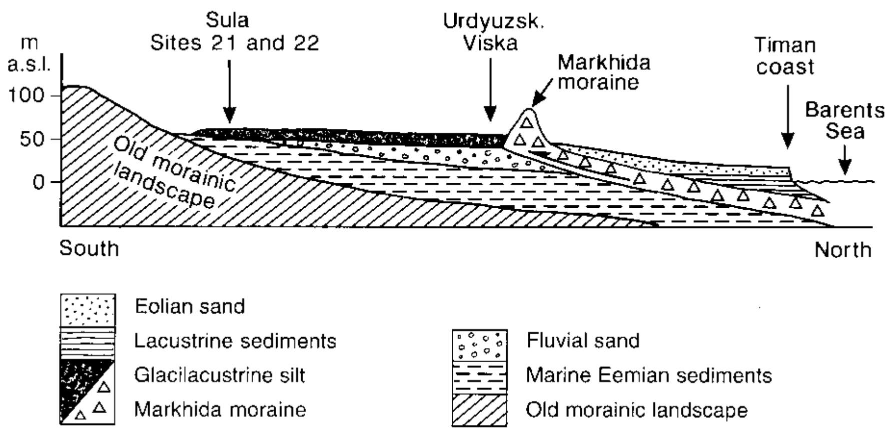


Fig. 12. A simplified, conceptual stratigraphic cross-section from the Barents Sea to south of Sula. Some sites described in the text are marked. In the legend the formations are given in the correct stratigraphic order with the right column below left. The only uncertainty is the relation between the glaciolacustrine silt and the Markhida moraine. Here we have given our interpretation; that the silt was deposited in a lake dammed by the Markhida ice.

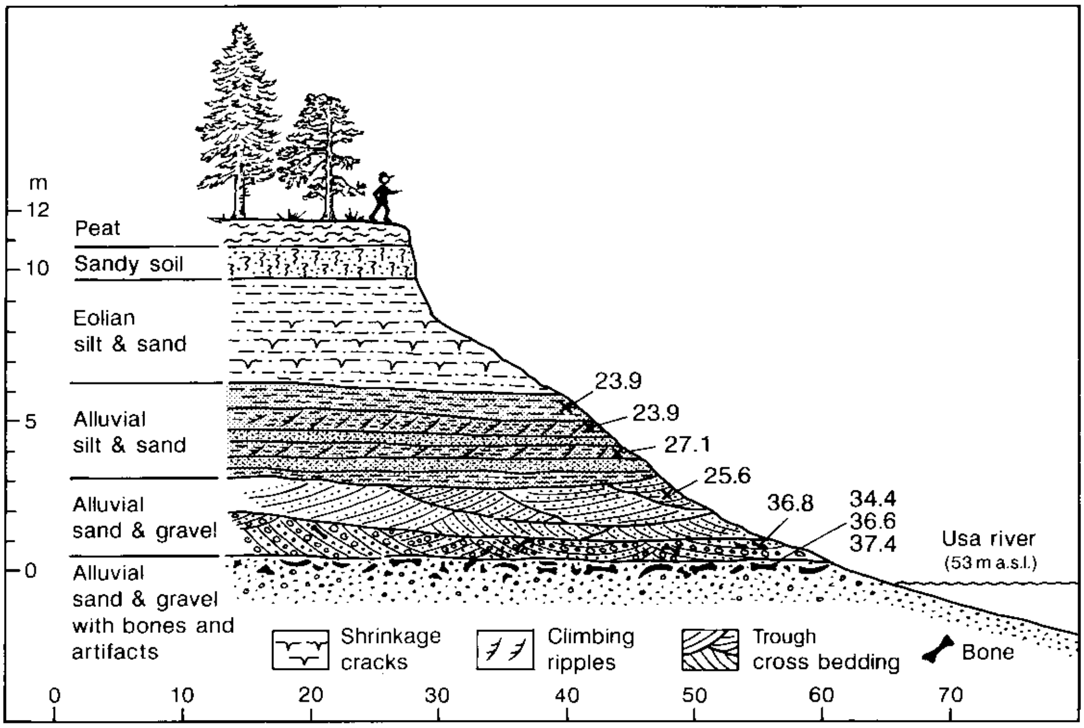


Fig. 13. The excavated section at Mamontovaya Kurya (loc. 23 in Fig. 2), somewhat idealized. The four lower radiocarbon dates are on bones, the others on terrestrial plant material.

been overrun by glaciers, and the dates therefore suggest the site was not glaciated after about 100 ka. The Markhida glacial advance eroded and thrusted the fluvial sediments north of this site, and therefore the moraine post-dates the fluvial sediments with the OSL dates 102–53 ka (Fig. 12).

The Palaeolithic site Byzovaya

This site is situated in an open tributary gully on the right bank of Pechora (loc. 21 in Fig. 2), about 65 m a.s.l. Some 250 artefacts and about 3000 bones (mainly of mammoth, but also including rhinoceros, bison, horse, reindeer, bear and others) have been unearthed from this site (Kanivets 1976, P. Pavlovs excavations, and finds from our 1997 excavation). The artefacts are of the older Late Palaeolithic types, an age supported by 13 radiocarbon dates on bones which yielded ages in the range 26–29 ka and one date with a large standard deviation that yielded 33 ka (Table 1).

The artefacts and bones were found in a gravelly diamicton with large boulders resting directly on the Triassic bedrock. The internal structures show that the diamicton was deposited by solifluction and debris flows down the slopes of the short, wide tributary gully in which the site is situated. Both the good preservation of the bones and the topography testify to a short transportation, probably over a few tens, or at most some few hundreds, of meters. The extreme concentration of bones can only be explained by human activity, i.e. they were collected and transported to the site by humans.

Sediments covering the Palaeolithic cultural layer vary across the site in composition and thickness, with a maximum of 10 m. The overlying sediments are mainly eolian sand and silt, whereas some are slope (creek, solifluction, debris flow) deposits. A detailed study of these sediments will be published later. For the present paper, the main conclusion is that there is no till covering the Palaeolithic site; we rule out the possibility that the artefacts and bones have been overridden by glacial ice. In addition, we did not find any glacilacustrine sediments above the cultural layer.

The Palaeolithic site Mamontovaya Kurya

Mamontovaya Kurya is situated on the left bank of the river Usa (53 m a.s.l.), approximately 100 km to the south of the Markhida line (loc. 23 in Fig. 2). During our excavations, several Palaeolithic stone artefacts and a large number of mammalian bones (including mammoth, horse and bison) were found under a 12–15-m thick sequence consisting of alluvial and eolian sediments (Fig. 13). Three radiocarbon dates on bones from the cultural layer and four AMS dates on terrestrial plant remains from the alluvial sediments above yielded ages 34–37 ka and 23–27 ka, respectively. We can firmly conclude from the stratigraphy that the area has

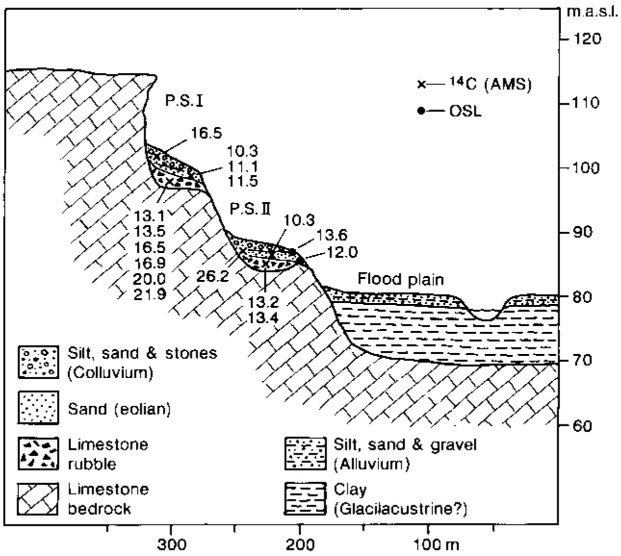


Fig. 14. A schematic drawing of Pymva Shor excavations I and II (marked P.S. I and II) (loc. 22 in Fig. 2). Note that at both sites the basal bed consists of angular limestone rubble weathered from the underlying bedrock and including bones dated to the Late Weichselian.

not been covered by glacial ice during the last 37 ka, and there is no indication that the site has been flooded by an ice-dammed lake during this period. Considering that the site is situated only 53 m a.s.l., this implies that the Lake Komi shorelines (ca. 100 m a.s.l.) are older than 37 ka. The section contains sediments showing a normal fluvial drainage in the Usa river valley until at least 23 ka; during the Late Weichselian only eolian sediments accumulated at this site.

The Palaeolithic site Pymva-Shor

This site (loc. 22 in Fig. 2) is situated about 50 km distal to the Markhida line and between the Laya–Adzva and Rogovaya lobes. Pymva–Shor is a small tributary to the river Adzva. The investigated site is located within a narrow valley entrenched into a limestone plateau, presumably by meltwater from one of the former ice sheets. Two adjacent localities, Pymva–Shor I and II, were excavated in this valley. In broad outline, the excavations revealed similar stratigraphical successions containing abundant mammalian bones suitable for radiocarbon dating (Fig. 14).

Pymva–Shor I is located on a bedrock ledge just in front of the overhanging limestone plateau about 100 m a.s.l. At the base of the sequence there is a 0.5 to 1-m-thick layer of *in situ* weathered limestone rubble derived from the underlying bedrock. From this layer several flint artefacts were uncovered. This bed is covered by a thin layer of sorted sand, most likely of eolian origin. On top is a wedge of blocky (Holocene) colluvium. Radiocarbon dates on bones from the basal limestone rubble yielded ages 22–13 ka (Table 1).

Pymva–Shor II is located on a lower ledge of the same valley side, approximately 10 m below Pymva–Shor I and 8 m above the present flood plain. The bedrock here is covered by weathered limestone rubble overlain by a one-pebble-thick gravel of lithologically diverse clasts which must have been brought to the site by fluvial transport. The pebble lag is covered by up to 2 m of a nearly massive sand that can be traced hundreds of meters at approximately the same level along the valley side. This sand is interpreted to be of eolian origin. Along the inner edge of the terrace the sequence is capped by up to 2 m of colluvium, as at Pymva–Shor I. Radiocarbon dates of mammalian bones from the limestone rubble under the fluvial pebble layer yielded ages in the range 13–13.5 ka, whereas one date from the overlying eolian sand yielded an age of 10.2 ka (Fig. 14). Another bone from Pymva–Shor II gave an age of 27 ka, but it is unclear whether it came from the basal limestone rubble or from the colluvium.

The radiocarbon dates from Pymva–Shor indicate that the site has remained ice-free at least since 27 ka, and thus that a Late Weichselian ice sheet did not extend beyond the Markhida line. Furthermore, there are no indications that the Pymva–Shor valley was inundated by an ice-dammed lake during the Late Weichselian. On the contrary, the dates show that the valley hosted a terrestrial fauna, indicating a cold and dry environment, throughout this period. The thick clay below the recent floodplain pre-dates the Late Weichselian deposits, and was probably deposited in the ice-dammed Lake Komi (see below).

Sites between the Markhida and Laya-Adzva moraines and not covered by till

We investigated several gravel pits in river terraces along the Kolva River, including three pits in the second (counted from river level) alluvial terrace about 20 m above the river, all inside the Laya–Adzva moraine.

Podkova-1

The Podkova-1 pit (loc. 19 in Fig. 2), about 4 km upstream of the Haryaha oil settlement, exposes a 0.5-km-wide terrace on the right bank of Kolva. The pit is nearly empty and landscaped, and only remnants of the original sedimentary cover could be seen. Nevertheless, the main geomorphic and stratigraphic features are clear (Fig. 15). On the floor of the gravel pit we collected a number of bones. One sample is a lamella of a mammoth molar, obviously from the fluvial gravel, radiocarbon dated to 36.5 ka (Table 1); some other bones could be identified as recent. The workers of the former pit told us that numerous large bones, mammoth

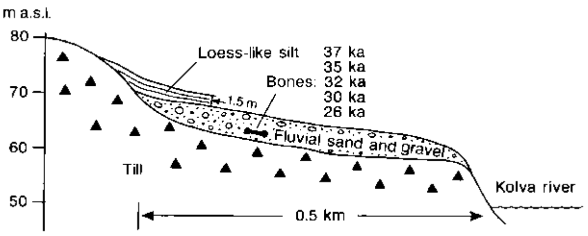


Fig. 15. Cross-section of the Kolva river terrace Podkova 1 (loc. 19 in Fig. 2). Almost all the gravel and sand had been exploited, and the section therefore only gives some main reconstructed features. The loess-like silt probably covered the entire terrace. The marked radiocarbon dates give unambiguous minimum dates of the Laya–Adzva moraine.

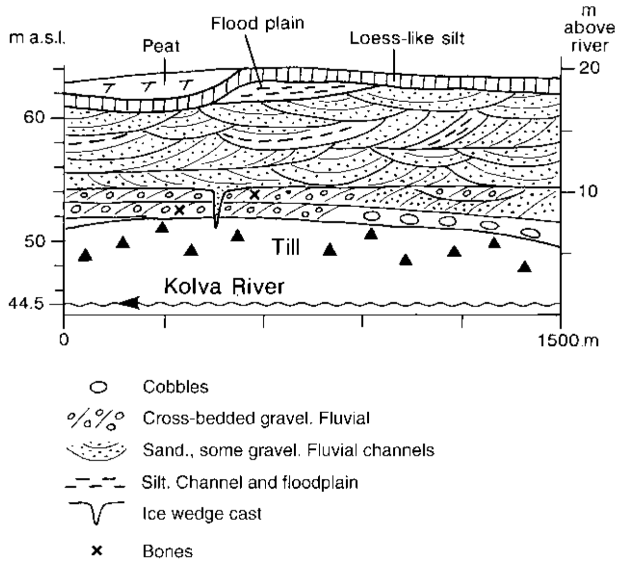


Fig. 16. Sketch of the gravel pit at Yarei-Shor (loc. 20 in Fig. 2). Bones are frequent in the lower fluvial gravel, below a distinct unconformity with ice-wedge casts. A radiocarbon date has yielded 27 ka.

tusks, etc., were unearthed from the gravel. We obtained a piece of a mammoth tusk from excavator engineer Oliferenko, Usinsk, who used the large tusk and a lower mammoth jaw with intact teeth as decorations at his home. The tusk was dated to 34.6 ka at the St. Petersburg and 32.2 ka at the Trondheim laboratory (Table 1). Local amateur archaeologist Pergalo also found many mammoth remains which have been donated to the Usinsk Museum. We have dated two of them to 26 and 36 ka (Table 1).

Yarei-Shor

Another site is the active gravel pit Yarei-Shor (loc. 20 in Fig. 2) some 20 km upstream of Verkhnekolvinsky oil settlement. This is a well-defined, 1-1.5-km wide terrace with a pronounced knickpoint along the 70 m isohypse, the river level being 44.5 m a.s.l. The terrace base, 5–10 m above the river, is a grey clayey diamicton with rare pebbles. The lowest terrace bed is a 4–5 m thick gravel with cross-beds dipping downstream (Fig. 16). It grades into coarse sand and a thin cobble lag and pinches out towards the upstream end of the pit. The gravel is cut by an erosional unconformity with ice-wedge casts (Fig. 17) and is overlain by an 8–9-m-thick formation of trough cross-bedded sand with lenses of fine gravel and up to 0.5-m-thick silt. Typically, these sediments fill in 10 to 20-m-wide channel-like troughs. This channel alluvium of a braided river is capped in places by 0.5 to 1-m-laminated floodplain silt. A mantle of up to 1.5-m-thick loess-like silt makes the top of the Pleistocene sequence.

Numerous bones have been unearthed from the base of the lowermost gravel by pit workers. We picked up some bone fragments in the wake of an operating excavator and also obtained paired mammoth vertebrae, in anatomic order, from bulldozer operator Kukharenko, radiocarbon-dated to 27 ka (Table 1).

The bones from both Podkova-1 and Yarei-Shor provide reliable minimum dates (26–37 ka) for the glaciation that formed the Laya–Adzva moraines. Our geomorphological interpretation is also that the river Kolva cut its present valley into the floor of the proglacial Lake Komi (described below), and thus that the terraces post-date that lake. However, we did not observe deep-water lacustrine facies along the Kolva valley and therefore cannot stratigraphically prove that the valley is incised into the former lake floor.

Sites above till north of (proximal to) the Markhida line

These sites provide a minimum age of the Markhida moraine, and thus of the last time the Barents or Kara ice sheets reached the area.

Markhida

A description of the type site (loc. 9 in Fig. 2) for the Markhida moraine, with references to the older literature, is given in Tveranger *et al.* (1995). In that paper we cited several radiocarbon dates on twigs from formation D (Fig. 18, diamictons, interpreted as flow tills and debris flows), which provided a minimum age of about 10 ka for ice retreat from the Markhida line. Later, a nearly complete musk-ox cranium was found by N. Smirnov on the river bank. Many cavities in the skull contained the bluish-grey diamicton from formation D, and therefore it seems quite clear that the skull came from that formation. Two teeth were AMS dated and yielded ages 13.0 and 13.9 ka (Table 1). The latter was the largest and gave the most reliable date, providing an

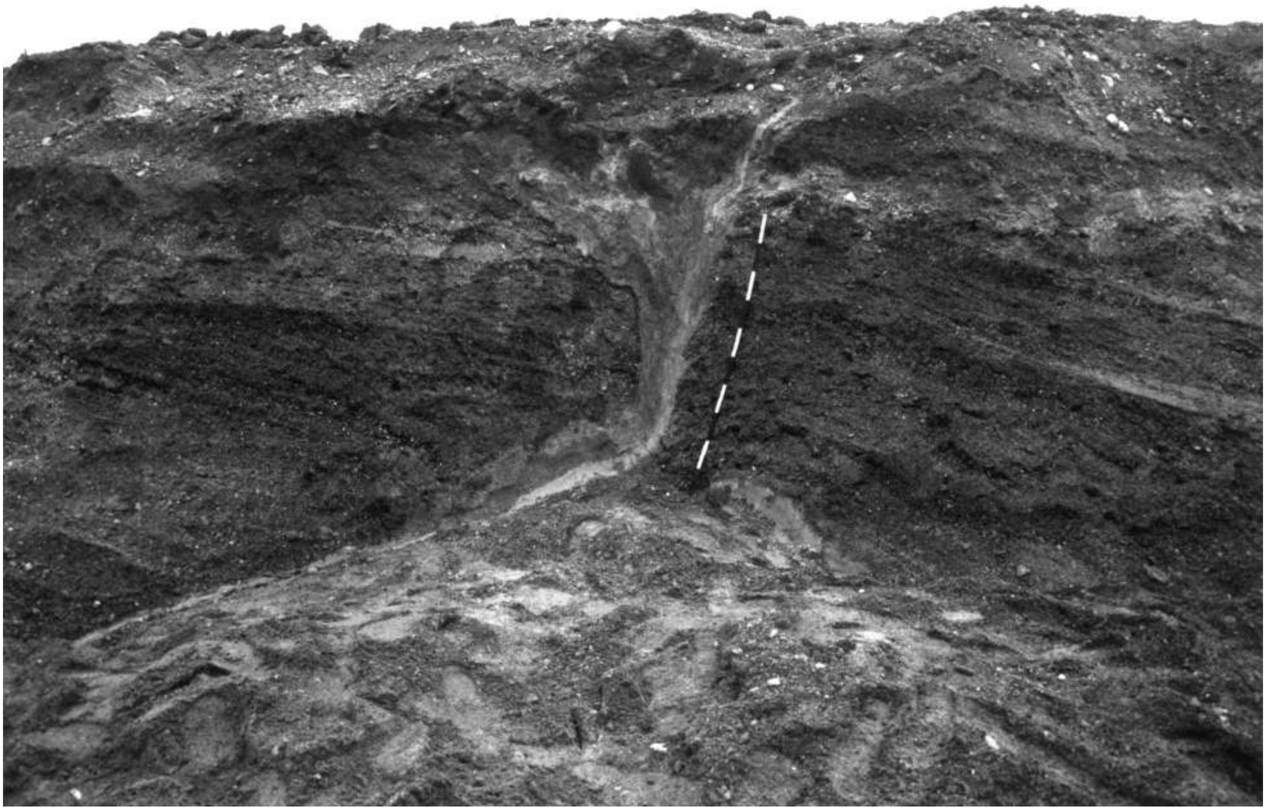


Fig. 17. The bone-bearing, cross-bedded gravel in the lower part of the sequence at Yarei-Shor (Fig. 16). Note the cross-cutting ice-wedge cast. The stick is 1 m.

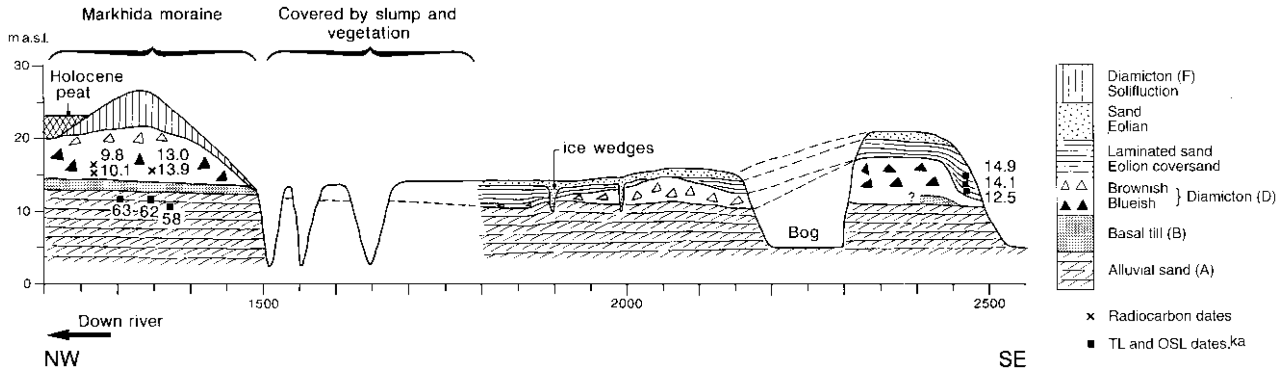


Fig. 18. The Markhida section (loc. 9 in Fig. 2) along the right bank of Pechora. The down-river part, the Markhida moraine proper, is slightly modified from Tveranger *et al.* (1995). The radiocarbon dates 13.0 and 13.9 ka plotted in diamicton D are from a musk ox cranium found on the shore, but confidently related to diamicton D by sediments in cavities in the skull. In the up-river part (1800–2500 m) laminated eolian coversand overlies the diamictons, but is shown to interfinger with diamicton D in the down-river part.

older minimum age for the Markhida moraine than that cited above.

We have now undertaken a study of the upstream extension of the section, starting from "formation G, periglacial alluvium" of Tveranger *et al.* (1995). The two exposures are separated by 200 m of covered bluffs, including three vegetated gullies. In Fig. 18 we employ the same horizontal scale and the same letters for formations as in Tveranger *et al.* (1995).

The lowermost alluvial sand can be more or less

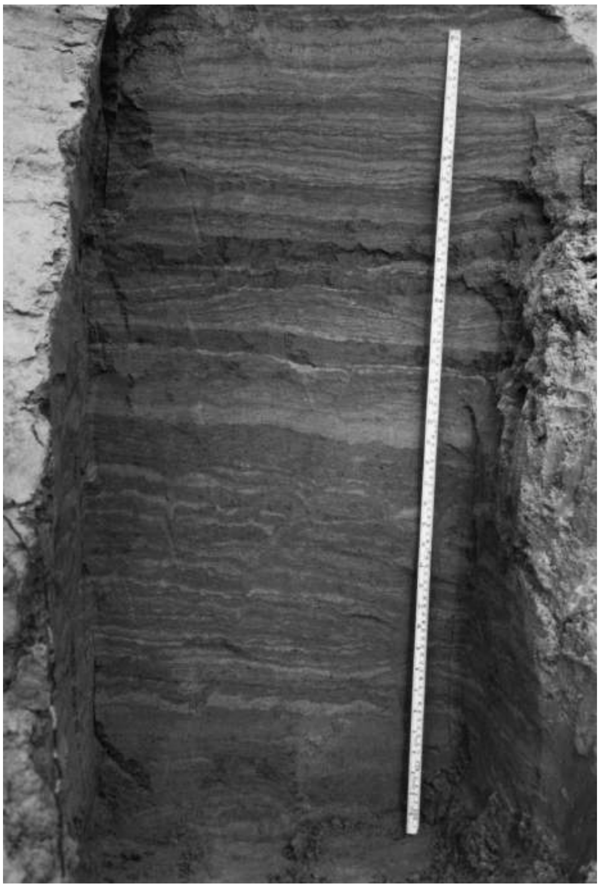


Fig. 19. The lower part of the eolian coversand at 1880 m at Markhida (Fig. 18). Note the wavy and partly discontinuous bedding. The stick is 1 m.

directly traced to formation A of the main section. At 2440 m we excavated 1-m-thick strongly sheared diamicton on top of the alluvial sand. We correlate this basal till with formation B, the implication being that the glacier has overridden the entire site. With a sharp boundary follows a nearly 7-m-thick bluish-grey diamicton, the upper 80 cm of which is brownish due to weathering. This diamicton can be followed laterally across the ridge 2300–2500 m as a topography-forming unit. The ridge slopes steeply toward the bog in the west, while gently grading into a low terrain in the north. The diamicton is similar to, and correlated with, the flow till in the lower part of formation D. The mound was probably surrounded by burried glacial ice when the diamicton was deposited.

Between 1790 and 2200 m there is a brownish sandy diamicton, or in places a 10 to 30-cm-thick gravel lag, atop the alluvial sand. Stones of sedimentary rocks are weathered, whereas crystalline rocks are fresh. Flow structures show a westward mass movement from the area of the present bog at about 2250 m. We interpret the diamicton as deposited by debris flows from dirt-covered dead ice, and correlate it with a younger part of formation D than the bluish-grey diamicton. There is a gradual transition from the upper, cryoturbated part of the diamicton to the overlying eolian sand.

The overlying unit is a well-sorted, irregularly laminated fine sand and coarse silt without any larger clasts (Fig. 19). Due to its mantling of the top of the ridge and the striking sedimentological similarity with the coversand in Germany and The Netherlands (Schwan 1986, 1987, 1988), we interpret this unit as an eolian sand sheet. The main criteria are the very restricted grain size, the wavy uneven bedding planes, the lenticular bedding, pockets of sand, low hummocks, numerous small frost cracks, indistinct paleosols and the complete lack of fluvial ripples or cross-beds. Many of the irregularities were probably caused by deposition of wind blown sand atop snow or together with it. The silt could have been deposited by adhesion to wet surfaces during snow melt or rain, whereas the sand resulted from horizontal drifting (traction) over a flat surface. Small remnants of this sand and silt can be recognized in the middle and upper part of formation D in the main section. This means that eolian sand was deposited on top of the still melting ice in the main section (0–1500 m) when all ice was already melted at 1800–2500 m, where primary bedded eolian sand mantles the present topography. Similar eolian coversand is discovered at numerous other sites in the Pechora Basin, including the Byzovaya Palaeolithic site.

Three fine-grained TL dates from the coversand gave ages 12.5–14.9 ka, although in reverse age order (Fig. 18, Table 3). The interpretation of the new observations from Markhida is that after the active ice retreated there was a period of rapid melting with deposition of flow tills, followed by a period of cold arid environments with deposition of eolian coversand, partly on stagnant glacier ice. Radiocarbon and TL dates indicate ages 10–15 ka for these events, providing a minimum age for the deglaciation.

Kuya Bridge

Just upstream of the bridge across the Kuya River (between loc. 7 and Naryan-Mar in Fig. 2) is a left bank exposure. The entire sequence is cut into the youngest till, as seen from nearby exposures where the till surface is 20 m above the river. From low river level and to 4–5 m upwards is a tan sand with 0.5 to 1-cm-thick persistent (up to 30-m-long) laminae of black clay (Fig. 20), similar to the tan formation of upper Kuya section. Close to the water level the clay laminae are thicker (1–5 cm) and more tightly spaced. Many clay laminae are broken up into fragments, millimetres to centimetres in diameter, by desiccation. Some laminae consist of sand-sized rounded clay clasts. Our interpretation is that the formation was deposited in a wind-dominated, dry and cold environment with seasonal

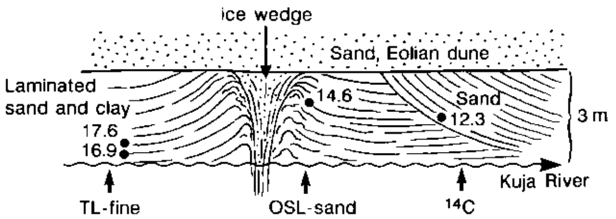


Fig. 20. A sketch of the section near the bridge across the Kuya River (between loc. 7 and Naryan–Mar in Fig. 2). Dates obtained by different methods are marked; TL with the fine-grained method (Table 3), OSL on sand grains (Table 2) and radiocarbon (Table 1).

shallow ponds where fines accumulated. It is probably a dynamic counterpart of the coversand described above at the Markhida site.

This formation is cut by 1-m-wide ice-wedge casts making polygons 15–20 m across. The casts, filled with the light dune sand proceed well below river level. They increase their width just above river level, thereby suggesting syngenetic growth. In places the tan formation was also cut by troughs filled with pale fine sand. All described formations are cut by an unconformity overlain by light yellow, diagonally bedded, loose, medium sand, clearly an eolian dune up to 16 m high. Dates obtained by TL, OSL and radiocarbon methods yielded ages 12–17 ka for the eolian sequence (Fig. 20), which we consider as reliable minimum ages of the last deglaciation.

Timan coast sections

About 200 km to the west of the Pechora delta are up to 20-m-high coastal cliffs dissected by gullies (loc. 2 in Fig. 2). The sections are situated proximal to the Indiga moraines (of the Markhida line) deposited from the Barents Ice Sheet. The sequence has been divided into six formations, labelled A–F starting from the base (Fig. 21).

The lowermost formation (labelled A), which is seen only in a few, very small exposures at the base of the coastal cliffs, consists of mollusc-bearing marine clay and sand. The overlying formation B is a poorly exposed, heavily contorted silt and sand with a high content of terrestrial plant macrofossils. Presumably, the sediments originally were deposited in a shallow lake or in a flood plain environment. We were not able to determine whether the contortions were caused by slumping and/or glaciotectonic deformation.

The base of formation C is a 10 to 30-cm-thick, pebbly diamicton with a high content of heavily

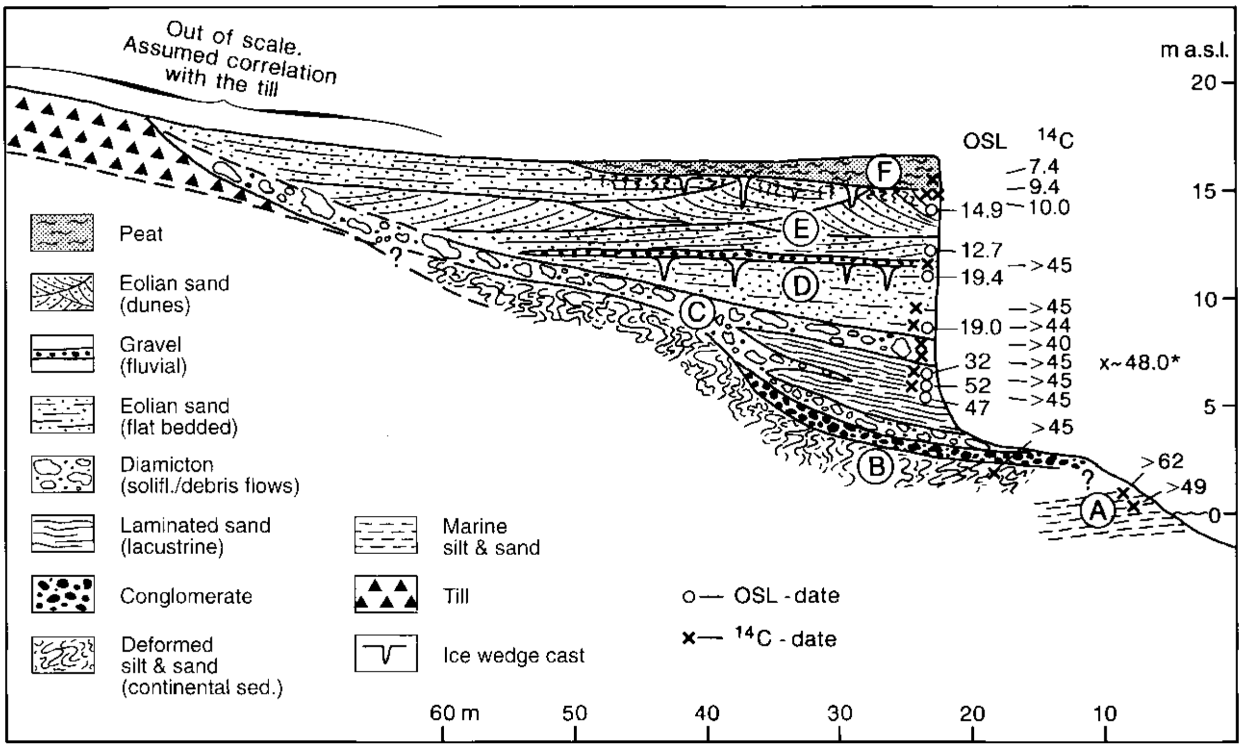


Fig. 21. The sections along the Timan coast (loc. 2 in Fig. 2). Most of the figure shows one measured section; except that Formation A was exposed only laterally to this section, formation B was poorly exposed but is here drawn continuously, beyond 60 m on the horizontal scale this is an interpreted stratigraphic relationship. The legend shows the formations in correct stratigraphic order from till upwards. The radiocarbon date marked with a star is from a large mammoth tusk found on the beach, and assumed to originate from formation C.

weathered stones resting discordantly on formation B. It may represent a terrestrial surface. Most of the formation is laminated sand, evidently deposited in a shallow pond. Several 5 to 10-cm-thick diamictic lenses, including a thicker (0.5–1 m) bed in the top, interfinger with the lacustrine sand. The top bed can be traced as a boulder horizon several hundred metres along the coast. The sediment consists of irregular lenses of diamicton, sand and clay, and contains glacially abraded (some striated) pebbles and boulders. It has a rather high content of organic material, including plant remains and twigs. All structures show downslope flow. We conclude that the diamictons were deposited by solifluction and faster gravity flows into the lake. The clasts indicate that some of the sediment was derived from till, but the physical connection to the till was not observed in the field. On the beach we found a well-preserved mammoth tusk which presumably was washed out of this formation.

Formation D is a 5 to 10-m-thick, well-sorted sand that has been mapped for several kilometres along the coast. It is greenish grey and is characterised by a vague horizontal bedding. It is similar to, and has been interpreted genetically (and partly also chronologically) as the eolian coversand at Markhida. Ice-wedge casts are frequent in the uppermost part of the formation, mainly originating from the boundary to the overlying formation.

Formation E is a 5 to 10-m-thick, yellowish grey, well-sorted, loose medium sand. It is partly flat bedded (as is formation D), but long tabular cross-beds dominate. This formation is also eolian, but is separated from formation E by an erosional unconformity, several places marked by a thin fluvial gravel and/or a gravely lag. Along the coastal cliff there are several paleo-ravines that were eroded into the underlying formations and subsequently filled with formation E. Cryoturbation structures occur along the upper boundary. The sequence is capped by a discontinuous layer of Holocene peat (formation F) that may be up to 3–4 m thick in depressions. In some ravines the base of the peat is below the present sea level, showing that a transgression has occurred after the peat started to accumulate.

Two AMS dates (Table 1, Fig. 21) on mollusc shells from formation A yielded non-finite ages. This unit is tentatively correlated with the Eemian marine sediments that in the Pechora delta area are covered by till. AMS dates on terrestrial plant material from formation B yielded non-finite ages (Table 1, Fig. 21), but, as stated above, we are unsure whether this unit was overrun by a glacier or not.

We did not observe over-compaction or any glaciotectonic structures in the well-exposed formations C–F, and conclude that this sequence post-dates the last ice advance across the site. Several AMS dates on terrestrial plant material from formation C have yielded non-finite ages, whereas three OSL dates yielded ages in the interval 32–52 ka (Tables 1 and 2, Fig. 21). These dates indicate that the area remained ice-free at least from about 52 ka. The fact that the basal diamicton in formation C is heavily weathered supports the view that the sediment has been sub-aerially exposed for a long time. However, this interpretation must be treated with caution, because we cannot rule out the possibility that the dated plant material has been redeposited from the organic rich formation B. Furthermore, a rapid deposition of the lacustrine sediments may have prevented the sand grains from being sufficiently exposed to sunlight, causing too old OSL ages. On the other hand, the dates from this section yielded a stratigraphically consistant series, supporting the possibility that they are correct.

OSL dates from formations D and E gave ages about 19 ka and 13–15 ka, respectively. The eolian sand should be well suited to luminescence dating and the consistent results support their reliability. However, all AMS dates on small plant fragments in formation D yielded non-finite ages. The concentration of organics was extremely low in the eolian formations and the dated fragments very small. We therefore postulate that the organic remains, together with the sand grains, were eroded from the underlying sediments. The radiocarbon dates from the peat indicate that it started to accumulate at the very beginning of the Holocene, around 10 ka.

Timan Ridge lake sequences

The Timan Ridge is a low north–south trending bedrock ridge forming the western boundary of the Pechora Basin. On the northern part of this ridge we have cored one of the Harius lakes (labelled by us Bolvan I), situated at an altitude of 160 m a.s.l. (loc. 1 in Fig. 2). This is 5–10 km inside the Varsh–Indiga moraines deposited from the Barents Ice Sheet. The coring was undertaken with a manually operated Russian peat sampler from the surface of the bog.

Bolvan I, which is a bog with a small pond in the middle, has a round shape with a diameter of approximately 1 km. On the slopes north of the basin there is 1–2 m of lacustrine silt and clay that could be traced up to 170–180 m a.s.l. The silt covers a weak terrestrial soil, showing that the slopes had been dry land before the lake level rose. Along this slope there is also a distinct shoreline incised into the silt at an altitude of about 170 m a.s.l. Shorelines at the same altitude have been mapped from air photos in adjacent areas, and they outline a more than 20 km^2 large paleolake that was dammed by a prominent north–south trending esker. When the lake was filled, the outflow river started to erode through the esker and probably lowered the outflow rapidly to its present level. The large paleolake was then split into several small lakes and ponds, of which Bolvan I is one.

The cores in Bolvan I show that below 3 m of Holocene gyttja and peat there is a nearly massive silt and clay. In one core we recovered 2.3 m of the silt, but

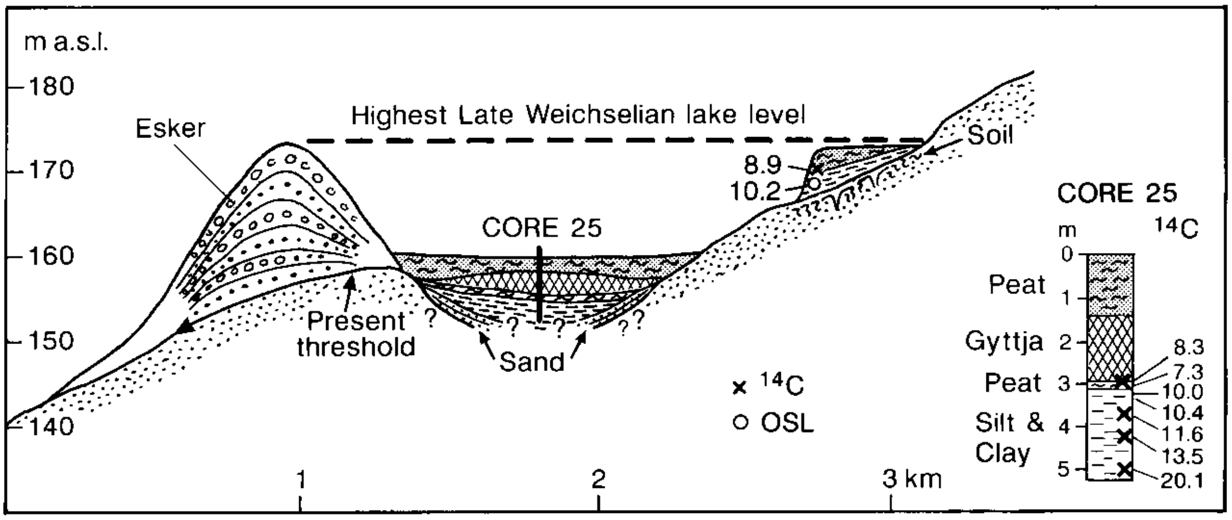


Fig. 22. The sections along the Timan coast (loc. 2 in Fig. 2). Most of the figure shows one measured section; except that Formation A was exposed only laterally to this section, formation B was poorly exposed but is here drawn continuously, beyond 60 m on the horizontal scale this is an interpreted stratigraphic relationship. The legend shows the formations in correct stratigraphic order from till upwards. The radiocarbon date marked with a star is from a large mammoth tusk found on the beach, and assumed to originate from formation C.

unfortunately we did not manage to penetrate deeper at this site with our coring equipment. However, at several other core sites the silt is less than 1 m thick and is directly underlain by sand and gravel. Pollen stratigraphy and radiocarbon and TL-dates (Fig. 22) show that the silt in the cores correlates with the silt described on the slopes of the basin, and both were deposited during the Late Weichselian. An AMS date on bulk sediments from near the base of the silt in the deepest core yielded 20 ka. The content of organic carbon in the sediment is very low, and the age may therefore be too old because of a hardwater effect and redeposited organic matter and coal. However, the basal date agrees well with three more AMS dates on bulk sediment higher up in the sequence, and this is not unrealistic judging from the pollen stratigraphy and sedimentation rate. The basal part of peat resting on the silt on the slope above the present lake is dated to about 9 ka, showing that the paleolake was drained at that time (Fig. 22).

Our conclusion is that the large paleolake existed during the later part of the Late Weichselian (according to pollen including the Allerød–Younger Dryas) and that it was drained at the onset of the Holocene as a result of fluvial down-cutting through the damming esker. It seems unlikely that the large lake existed prior to the Late Weichselian, because then the outlet river would have eroded through the esker at a much earlier time. The simplest interpretation is that the area was glaciated during early parts of the Late Weichselian (>20 ka), and that the lake was filled up by water after the ice margin melted away. However, it should be noted that older lacustrine sediments may exist below the level where our coring stopped. It is also a possibility that the basin was filled by dead ice after the deglaciation, and that the lake basin was formed during a thawing episode prior to 20 ka. That the area was deglaciated at an earlier date is supported by the fact that the lacustrine silt on the slope is underlain by a soil.

Ice-dammed lake sediments

Because the ice moved up slope from the Kara and Barents seas onto the mainland it is assumed that the advancing glaciers during each major glaciation dammed the northward flowing rivers to produce large proglacial lakes in the Pechora lowland. Such lakes have been postulated for the Late Weichselian maximum; either from the altitudes of the possible overflow passes to the Caspian Sea 130–145 m a.s.l. (Kvasov 1979; Grosswald 1980; Archipov *et al.* 1995) or from mapped terrace-like flatlands at 80–100 m a.s.l. along the Pechora river, interpreted as having formed in short-lived lakes without any spillways (Lavrov 1975; Lavrov & Potapenko 1989). In accordance with the idea of a very extensive Late Weichselian ice, the cited authors have suggested shorelines of the proglacial lake only south of the sites described below. The only chronological control given for these lakes is provided by radiocarbon dates in the range 12.6 to 10.7 ka from low alluvial terraces interpreted to have been flooded by a younger, late glacial lake with a level about 40–55 m a.s.l. (Lavrov & Potapenko 1989).

Shorelines and shallow-water sediments

Exposed sections in shorelines were mainly found

Fig. 23. Section in the Lake Komi shoreline 100 m a.s.l. at Garevo (loc. 12 in Fig. 2). Low-angle dipping beds of sand and well-rounded, flattened gravel. Note also the floating pebbles in the sand beds. The stick is 1 m. An OSL date from this section yielded 93 ± 13 ka, and two dates from slightly deeper water facies close by yielded 76 ± 12 and 88 ± 11 ka.

around the Usinsk oil fields, where beach sediments excavated in shallow pits are used by the petroleum industry as construction gravel. A full description, including results from OSL dates in progress, will be given in a later paper.

All shorelines mapped from air photos (Astakhov *et al.* 1998) or studied in the field, have uniform altitudes, rising from about 90 m a.s.l. in the south (Byzovaya, loc. 21 in Fig. 2) to about 110 m a.s.l. in the north (Haryaha, loc. 18 in Fig. 2). We consider they were formed in a huge proglacial lake that inundated all the lowlands of the Komi Republic. We name the former reservoir Lake Komi and its gravelly and sandy beach and shallow-water facies the Komi Formation, its stratotype area embracing gravel pits in the Ust–Tsilma and Usinsk–Haryaha areas. For the time being we consider all shorelines of the same altitude as synchronous, although lakes theoretically could reach similar levels during different glaciations, as the levels are predetermined by the altitude of the overflow passes.

At Garevo (loc. 12 in Fig. 2) there is a 20 to 25-m-long and 3-m-high road section that shows long, low-angle (<6°) dipping beds of coarse sand and well-rounded gravel. The sand beds contain floating, mostly flattened stones. The internal structures are long lenticular laminations subparallel to the main bed boundaries (Fig. 23). Typical of all studied sections are thin (1–5 cm), laterally persistent laminae of very fine, well-sorted gravel. The top of the section is a platform 100 m a.s.l., cut by ice-wedge casts. About 7 m lower, and a 100 m down the road, we excavated a 1.7-m-high section. Here, finely laminated silt to coarse sand, with ripples in some levels, reflect deeper water facies than those found in the road cut. The same formations were observed in nearby pits just below a sharp knickpoint at 100 m a.s.l. Three OSL dates from Garevo (Table 2) range from 76 to 93 ka, i.e. an Early Weichselian age. These are the only dates available at the present time from the shorelines.

Around Usinsk–Haryaha (locs. 13–19 in Fig. 2) we studied eight gravel pits in the 90–110 m a.s.l. shoreline, located both distally (south of) and proximally to the Laya–Adzva moraine. Thus, Lake Komi clearly post-dates the Laya–Adzva moraine. The gravel pits are some hundreds of meters, up to a maximum of 1.5 km long. The upper 1–3 m, sometimes up to 8 m, is dominated by sandy gravel, in places with cobbly lags, underlain by sand. Internal structures in the sand are mainly plane laminations, although cross-bedding and ripples are also common. In three deeper pits the lower strata are laminated sand with silt laminae (Fig. 24). The entire sequences are dominated by long, nearly parallel, low-angle dipping (2–10°) beds. In two sections, intraformational ice-wedge casts were found in the beach gravel, indicating that at the time of Lake Komi cold permafrost (which today exists only north of 68°N) occurred at least down to 65°N.

The top of the beach sediments is penetrated by post-depositional ice-wedge casts and disturbed by cryoturbation in all sections. Eolian sand and/or solifluction sediments overlie the beach sediments at most sites. In none of the pits is the base of the beach sequence exposed, although it can be inferred from nearby sections that it is often a till.

Deep-water facies

Deep-water facies of lacustrine sediments are described in only a few places. At most low elevation sites (20–40

Fig. 24. Sand-pit in the Lake Komi shoreline about 90 m a.s.l., at Bolotny Mys (loc. 16 in Fig. 2). Gravel and coarser sand can be seen in the upper part of the section. The photo shows somewhat deeper facies. The thin dark beds are massive silt; the light beds are plan-laminated fine sand, with some zones with ripples. The stick is 1 m.

m a.s.l.), where fine sand and silt were previously interpreted as sediments of a low-level, late-glacial lake (Lavrov 1975; Lavrov *et al.* 1985; Lavrov & Potapenko 1989), we found only a subaerial mantling formation consisting of eolian sand sheets and loess-like sediments with cryogenic structures.

An erosional remnant of deeper water facies was found on a flat surface at 70 m a.s.l. in the village Ust-Usa (loc. 13 in Fig. 2), some 2 km south of the Novik pit, which reveals 8 m of beach gravel about 100 m a.s.l. At Ust–Usa there is a 13-m-thick sequence of finely laminated clay to fine sand with rare dropstones, the bulk volume being coarse silt and fine sand. This is no doubt a deep-water facies of lacustrine sediments, mainly turbidites, filling in a pocket several hundred meters wide in the underlying till. These sediments were probably deposited on the floor of Lake Komi. Thousands of tiny normal faults, from millimetres to centimetres of amplitude, suggest post-sedimentary sagging. The dark silty clay described at Sula sites 21 and 22 and along Urdyuzhskaya Viska (see above) are also candidates for the deeper-water facies of Lake Komi.

At Hongurei (loc. 6 in Fig. 2) there is a 7.5-m-thick, strongly laminated silt and clay on top of the youngest till. The laminated clay grades upwards into a 4-m-thick, completely massive clay, similar to the one described at Sula sites 21 and 22. The laminated clay is clearly glacilacustrine; probably the entire sequence was deposited in an ice-dammed lake. The laminae appear to be varves, and by counting the well-exposed parts, we estimated that there are about 600–800 annual layers. The clay is situated near the top of a ridge, 56 m a.s.l., and with the present topography it is nearly impossible to envisage a local lake. The easiest interpretation is that the clay was deposited in Lake Komi, as postulated for the clay at Sula sites 21 and 22. If correct, the final phases of Lake Komi were onlapping the Markhida moraine, i.e. the lake transgressed the morainic surface in front of the retreating ice. An attempt to date the clay with the fine-grained TL method yielded ages >130 ka (Table 3). Considering that the clay is situated above the Eemian and Weichselian formations, these ages are evidently too old.

Age of Lake Komi relative to the end moraines

It is quite clear that Lake Komi (or at least younger phases of it) post-dates the Laya–Adzva moraine, because it is mapped well inside the moraine ridges. The relation to the Markhida–Harbei moraines is described in Astakhov *et al.* (1998). The shorelines are traced directly to the moraines, and in places apparently even penetrate them. If this latter relation is correct, Lake Komi was dammed by the ice depositing the Markhida moraines. This is the most logical and probable interpretation, supported by the fact that former meltwater channels from the Markhida ice margin are rarely incised below the 100 m level. Also, along the Rogovaya River is a sandur that from the Harbei moraines grades down to the 100 m level, where the glacifluvial gravel overlie lacustrine sand.

Still, we will not yet completely rule out the possibility that Lake Komi was dammed by an older ice advance. The implications would be that the shorelines end at the Markhida moraine because farther north they were removed by the Markhida advance and also that the Markhida glacier did not dam a lake.

Dating Lake Komi

The three OSL dates from Garevo, with a mean age of 86 ka, are the only dates obtained so far directly on the beach sediments (Table 2, Fig. 25), although four preliminary dates from such sediments at Byzovaya yielded similar ages. If we accept that OSL dates provide maximum ages because of the possibility of incomplete zeroing during deposition, these demonstrate a Weichselian age of the lake. If the silt and clay formations in the Sula 21 and 22 and Urdyuzhskaya Viska sections had been deposited in Lake Komi, the underlying Eemian sediments prove a Weichselian age, and the OSL dates of the underlying sediments provide maximum ages. At Sula 22 (Fig. 7) two dates above the clay yielded 80 and 116 ka on a sediment where full zeroing during deposition is considered unlikely. Given the limitation of these OSL dates we conclude that they indicate an age in the range 55–80 ka (Fig. 25).

As described above, we consider the second terrace of the river Kolva (sites Podkova 1 and Yarei–Shor), dated by mammoth bones to 26–37 ka, to be incised into the floor of Lake Komi (Fig. 25). The sand and silt covering

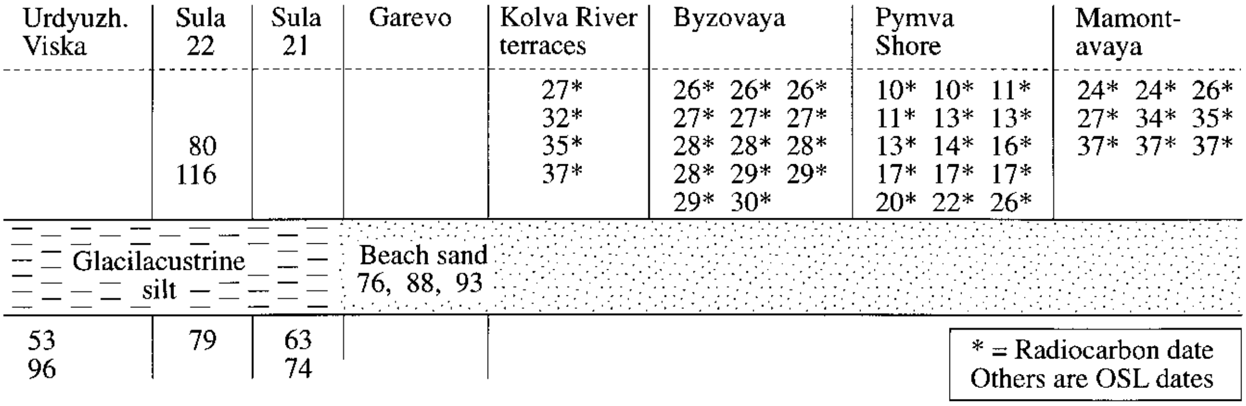


Fig. 25. Dates related to Lake Komi. Dates with stars are radiocarbon dates (Table 1), the others are OSL dates on the sand fraction (Table 2). Dates marked above the deposits are interpreted as minimum ages, dates below as maximum ages. At Garevo the beach sand is dated. It is not unambiguously shown that the glaciolacustrine silt was deposited in Lake Komi.

the Palaeolithic site Byzovaya were interpreted by Guslitser (manuscript 1971) as sediments of the last ice-dammed lake. However, as described above, we are confident that these sediments are of terrestrial origin. The gully with the Palaeolithic site is incised into a wide plateau at 90 m a.s.l., built of beach gravel exposed in a ravine just upstream of Byzovaya village. Therefore, the beach gravel is certainly older than the Palaeolithic site with the 26–33 ka dates (Fig. 25). A similar situation is found at the older Palaeolithic site Mamontovaya Kurya. The mammoth bones of the cultural layer dated to 34–37 ka are overlain by normal alluvium dated to 23–27 ka and a thick loess-like silt (Fig. 13), all at altitudes below the 100 m shoreline and without signs of lacustrine activity on top. The third Palaeolithic site, Pymva–Shor (Fig. 14) has provided dates on terrestrial mammals throughout the Late Weichselian; consequently, the ice-dammed lake has to be older.

It is concluded that Lake Komi was an ice-dammed reservoir which pre-dates many sites with radiocarbon dates in the range 23–37 ka (Fig. 25). The OSL dates show that it is of Weichselian age, most likely in the interval 55–90 ka, i.e. the Middle or Early Weichselian.

Marine shorelines

Glacio-isostatic uplifted marine shorelines are a classical tool for reconstructing the large-scale distribution pattern of former ice sheets, and for decades have been a main argument for a large Late Weichselian ice sheet over the northern and western Barents Sea (Landvik *et al.* 1998).

The flat lowland along the southeastern Barents Sea coast of the Pechora lowland has been interpreted as marine terraces with elevations up to 40–60 m by Krasnov (1971) and 15–17 m a.s.l. by Arslanov *et al.* (1987). However, our detailed investigation of the best-exposed part of the Timan coast described above show neither marine sediments nor any real terraces. Helicopter reconnaissance routes and airphoto studies confirmed that the same flatland without any uplifted shorelines persists everywhere between the Timan Ridge and Pai-Hoi.

The absence of uplifted shorelines in a glaciated area is normally a result of either the ice being too thin for any significant isostatic depression, or deglaciation going on during a low eustatic sea level, or both. The reconstructed ice sheet ending at the Markhida line is thin (Tveranger *et al.* 1999). If our conclusion of a Middle or Early Weichselian age is correct, then the eustatic sea level has been low. Even if the Markhida line should be of Late Weichselian age, the deglaciation started early (>20 ka), when eustatic sea level was low. The lack of glacio-isostatically emerged shorelines therefore is probably due to the combined effect of a thin glacier and a low eustatic sea level during deglaciation, independently of the age of the Markhida line. This lack of uplifted shorelines from the last deglaciation is in striking contrast to the 50-m-high Eemian shorelines (Sula sites 21 and 22). The latter can only be explained by isostatic depression produced by the large Saalian (isotope stage 6) ice sheet.

Discussion

Spatial and timing relationship between the Kara and Barents ice sheets

The last ice-flow direction was from northeast of the entire coastal area from Pai-Hoi to west of the Pechora River (Fig. 2), and therefore most of the sites described in this paper are within the domain of the Kara Ice Sheet. Only the Indiga and Varsh moraines (Lavrov 1977) around the northern tip of the Timan Ridge (Fig. 2) were deposited by ice flow from due north or north-northwest, i.e. by the Barents Ice Sheet. The sites described on the Timan Ridge and the Timan coast, and also the Sula sites, relate to the Barents Ice Sheet. We did not observed any crosscutting, or any morphological differences in the moraines that would indicate a major time difference between the moraines deposited from the Kara and the Barents ice sheets. On the contrary, the moraines apparently constitute one continuous morainic belt. Therefore, we postulate they are of (nearly) identical ages, although this question must certainly be addressed again in the near future.

Maximum ice-sheet extent since the last interglacial

North of the Markhida line, within the domain of both the Barents and Kara ice sheets, there are Eemian marine sediments that have been overrun by glacial ice. Thus, it is clear that northern Russia was invaded by at least one Weichselian ice advance from the continental shelf. Immediately south of the Markhida line, along the rivers Sula and Urdyuzhskaya Viska, there are several sites with Eemian interglacial and younger sediments that are not covered by till and which show no other sign of glacial overriding. We do not consider the lack of till and glaciotectonic structures at any individual site as proof that ice did not overrun the site. There are two main arguments that the Markhida line represents the Weichselian glacial limit (Figs. 2 and 12): (1) The consistent picture of missing till and glaciotectonic structures in all Eemian (and other) sections in the Sula River area that we visited, and (2) just south of Sula River there is an old dissected and eroded morainic upland with well-developed drainage pattern (Fig. 2 in Astakhov *et al.* 1998). In some sections we observed the old morainic landscape sticking out of the Eemian marine plain, with beach gravel overlapping the till. Therefore the old morainic landscape pre-dates the Eemian. We conclude that the Markhida line represents the maximum limit of Weichselian glaciations, possibly except for the area of the Laya–Adzva and Rogovaya lobes (see below).

This means that the Late and/or Early Weichselian ice sheets are much too large in the reconstructions presented by for example Astakhov (1984), Arslanov *et al.* (1987), Grosswald & Hughes (1995), Velichko *et al.* (1997) and Grosswald (1998). Only Guslitser *et al.* (1985) and Yakovlev (1956) have suggested previously that ice did not extend beyond the Markhida line during the Weichselian.

Age of the Laya–Adzva–Rogavaya moraines

The Markhida moraines truncate and therefore are younger than the Laya–Adzva and Rogavaya lobes. However, this relationship does not imply a major time difference; the possibility exists that they represent different stages of the same main advance. Even though the Laya–Adzva and Rogavaya lobes protrude about 100 km south of the Markhida line, the extent of the ice sheets that deposited these moraines was not very different. The main difference is in the pattern of the ice front, the Laya–Adzva and Rogovaya lobes being much longer than any lobe along the Markhida line (Fig. 2). Also the Laya–Adzva ridge is much wider and higher than the Markhida ridges, and the till within the lobe is apparently thicker (up to 20 m) than the Markhida basal till, which is normally only 2 to 5-m-thick along the lower Pechora River.

Bones from the Kolva River terraces inside the Laya–Adzva moraine yielded radiocarbon ages in the range 26–37 ka; these provide minimum ages for the moraine. Thus this moraine certainly pre-dates the Late Weichselian. The next question is whether it is of Early/Middle Weichselian age or if it pre-dates the Eemian. We cannot provide a definite answer to this. However, the Laya–Adzva moraine has a distinctly fresher topography, including several deep lakes, than the pre-Eemian morainic landscape south of Sula. We therefore suggest a Middle or Early Weichselian age for the Laya–Adzva moraines, as has been suggested by Lavrov (1966) and Astakhov (1984).

Age of the Markhida line

The landscapes inside the Markhida line, especially the Halmer moraines, have a fresh appearance (Astakhov *et al.* 1998), and comparison with the morphology of moraines of other glaciated terrains in the world would suggest a Late Weichselian age. However, the fresh morphology is to a large extent a result of late melting of the thick permafrost, still existing in this area (Astakhov *et al.* 1998). Thus, buried glacial ice may have survived from any Weichselian ice advance and started to produce glaciokarst topography only during the warming in the Early Holocene, as is the case with relict Early Weichselian glacial ice in Siberia (Astakhov & Isayeva 1988).

We conclude that the Markhida line is probably of Middle or Early Weichselian age. The main argument is that the ice-dammed Lake Komi is of this age (Fig. 25), and its shorelines abut the Markhida line. Meltwater streams from the ice sheet ending at the Markhida line apparently flowed into Lake Komi, and the shorelines appear to interfinger with the Markhida moraine (Astakhov *et al.* 1998). If these relationships are correct, it follows that the Markhida moraine was deposited by the same ice sheet that dammed Lake Komi during the Middle or Early Weichselian.

Stratigraphically the Middle/Early Weichselian age of the Markhida line is supported by the series of AMS 14C and OSL dates from the sediment sequence above the youngest till on the Timan coast (Fig. 21). From western Yamal (Fig. 2), inside the eastward extension of the Markhida line, Gautaulin & Forman (1997) reported two radiocarbon dates about 29 ka from peat above till. Also Mahaney (1998) and Michel (1998) argue that no glaciers approached Yamal during the Late Weichselian.

Timan coast	Bolvan Bog	Kuya Bridge	Markhida	Vastiansky Kon
13 40*				
15 >40*	10.0*			
19 >45*	10.4*		10.1*	
19 >45*	11.3	12.3*	13.9*	
32 >45*	11.6*	14.6	12.5	
47 >45*	13.5*	16.9	14.1	
52 >45*	20.1*	17.6	14.9	
Till (Markhida)				
			58	66 54
			62	73 57
			63	75 60
				77

* = Radiocarbon date
Others are OSL dates

Fig. 26. Dates related to the youngest till, correlated with the Markhida moraine. Dates marked with stars are radiocarbon dates (Table 1), the others are OSL dates on the sand fraction (Table 2) or TL dates on the fine fraction (Table 3). Dates are listed according to age, not stratigraphical position. At Vastiansky Kon the dates from the two probably overthrusted units are listed in their own column. All radiocarbon dates below the till, including several that yielded finite ages in the range 25–43 ka, are omitted, as none can be proven reliable. The dates indicate an age 50–60 ka for the Markhida moraine.

In Fig. 26 we have compiled limiting dates for the till correlated with the Markhida moraine. If correct, they constrain the age of the till to about 45–60 ka, which corresponds reasonably well with the limiting dates for Lake Komi (Fig. 25), except that the OSL dates conducted on the beach sand itself yielded older ages than the maximum dates in both compilations.

In spite of the strong evidences in favour of a Middle/Early Weichselian age for the Markhida line, we feel it is not definite, and here we explore the possibility that it could be of Late Weichselian age. This would imply that Lake Komi was dammed by an ice sheet that ended near, or north of the Markhida line during the Middle/Early Weichselian, and that a Late Weichselian advance eroded the Lake Komi shorelines that may have existed north of the Markhida line. This model further requires that a Late Weichselian ice sheet was so thin and/or short-lived that it did not impound the drainage system, as no traces of such a young ice-dammed lake have been found. Even though the ice sheet ending at the Markhida line was very thin and flat (Tveranger *et al.* 1998b), a young ice advance is not supported by stratigraphic evidences. Arslanov *et al.* (1987) reported several finite radiocarbon dates older than 35 ka from deposits below till. We have redated some of these deposits and all dates yielded non-finite ages. From Vastiansky Kon (Fig. 4) we previously obtained finite dates as young as 25–31 ka below the till, most of which we subsequently falsified and proved to be non-finite. If the postulated stratigraphic position and the dates are correct, the mammoth tusk dated to 32 and 39 ka (Table 1) would suggest a Late Weichselian age of the youngest till. At present we discard all existing finite radiocarbon dates that have been obtained below the till, because in no section do they provide a consistent stratigraphical sequence of ages.

The sites we have investigated proximal to the Markhida line are compatible with both a Middle/Early and a Late Weichselian age for the line (Fig. 26), except the Timan coast section discussed above, which supports a Middle/Early Weichselian age.

Maximum ice extent during the Late Weichselian

Even though we cannot yet completely rule out the possibility that an ice sheet reached northern Russia during the Late Weichselian, we consider it proven that it did not reach beyond the Markhida line. The main arguments are the existence of well-preserved and radiocarbon-dated terraces and Palaeolithic sites situated south of the Markhida line: Podkova-1 (five dates 26–36 ka), Yarei-Shor (27 ka), Pymva-Shor (7 dates 16–26) ka, Mamontavaya (9 dates 24–37 ka), Byzovaya (14 dates 26–33 ka), and also the interglacial sites along Sula River. We also conclude that the Markhida line is probably of Middle or Early Weichselian age, and that the Late Weichselian limit therefore must be localized on the continental shelf north of Russia. This means that we find it proven that the ice-sheet reconstructions for the Late Weichselian published by Grosswald (1980, 1993, 1998; Grosswald & Hughes 1995) are much too large for the European part of Northern Russia. The implication is that his reconstructions for West Siberia, showing a large ice sheet, are also wrong, because it is impossible to connect the Markhida line around the Polar Urals with an ice limit far south (Fig. 1). If our conclusion that the Markhida line is of Middle/Early Weichselian age is correct, then even the small ice masses reconstructed in West Siberia by Astakhov (1998) and Velichko *et al.* (1997) are too large. In fact, we conclude that Pai-Hoi, Vaigach Island, Yamal and the southern Kara Sea remained unglaciated during the Late Weichselian. Probably the Late Weichselian ice sheet over the Barents Sea and Novaya Zemlja was restricted by the deep Novaya Zemlja Trough along the southeast coast of the islands.

Furthermore, both the minimum and maximum models in the classical reconstructions of Denton & Hughes (1981), as well as the frequently cited ICE-4G model (Peltier 1994), largely exaggerate the extension and thickness of the Barents and Kara ice sheets. The obvious global implication is that the large ice masses responsible for the unaccounted component of sea level fall during the Last Glacial Maximum should be sought in other parts of the world (Antarctica?).

Even the minimalistic reconstruction of Velichko *et al.* (1997), which proposes a much smaller ice sheet in the northern and western Barents Sea than Landvik *et al.* (1998), draws the last ice sheet limit too far south in the Pechora Basin. They also picture an elongated ice sheet centred on the Polar Urals, which according to our data did not exist. In summary, if our conclusion of a Middle or Early Weichselian age for the Markhida line is true, then all current Late Weichselian palaeoglaciological models show too large an ice sheet extent.

There is general agreement among most scientists that a large Late Weichselian ice sheet occupied the northern and western parts of the Barents Sea (Landvik *et al.* 1998). No ice marginal deposits from this ice sheet have been reported from the seismically well-explored central-eastern Barents Sea. On the contrary, Late Weichselian glacimarine sediments, with radiocarbon dates about 13 ka, are described as resting directly on till in the eastern Barents Sea (Gataullin *et al.* 1993; Polyak *et al.* 1995), supporting a Late Weichselian glaciation of that area. If this is correct, and if the Markhida line is of Middle or Early Weichselian age, as we conclude, then the southeastern margin of the Late Weichselian Barents ice sheet has to be searched for in the shallow, extreme southeast part of the Barents Sea, the Pechora Sea.

Polyak *et al.* (1997) demonstrated that the deglaciation of the Saint Anna Trough north of Novaya Zemlya occurred about 13–14 ka, and concluded that during the Late Weichselian the major ice masses draining through the trough had been located in the northeast Barents Sea, but they also infer a smaller ice cap on the Northern Kara Plateau. This reconstruction, without any major Kara ice sheet during the Late Weichselian is compatible with our observations and conclusions. Also Lambeck's (1996) isostatic modelling results, with a major Barents Ice Sheet, some ice on Novaya Zemlya, but little or no ice in the Kara Sea, are compatible with our observations.

A reconstruction of the entire Late Weichselian Barents Ice Sheet is being completed during the printing process of the present paper (Svendsen *et al.* 1999).

One or more glacial advances during the Weichselian?

Several scientists have concluded that there has been only one Weichselian ice advance from the Kara and Barents seas onto northern Russia (Guslitser *et al.* 1985; Faustova & Velichko 1992), whereas others postulate one Early/Middle and one Late Weichselian advance (Astakhov 1984; Arslanov *et al.* 1987; Faustova & Velichko 1992; Grosswald 1993; Tveranger *et al.* 1998). We will not discuss this issue here, except to point out some implications of our conclusions. The Laya–Adzva moraine pre-dates Lake Komi, whereas the Markhida line is of the same age as the lake (or possibly post-dates it). Therefore these moraines represent two different Middle/Early Weichselian glacial extensions; either two separate advances, or, alternatively, the Laya–Adzwa represents the maximum extention and Markhida a retreat line of the same main advance. If our conclusion on the age of the Markhida line should be wrong, and it is of Late Weichselian age after all, then there were at least two Weichselian advances, the earlier one dammed Lake Komi prior to 37 ka, and the later (Markhida) did not impound a lake.

The warm Eemian Sea

We have mentioned the warm water molluscan fauna during the high relative sea level stand of the Eemian Sea. Mangerud *et al.* (1998) proposed that the exceptionally warm sea water along the Russian Arctic coast during the Eemian partly resulted from a larger portion of the Atlantic Current at that time turning to the east north of Norway, rather than continuing to the north along western Spitsbergen, as it does today. The background for this suggestion was that the Eemian sea water apparently was not correspondingly warm at Spitsbergen.

During the period of high relative sea level stand there was an open connection between the Baltic Sea and the Barents Sea (Raukas 1991). Probably a large volume of fresh water draining into the Baltic Sea flowed out from this sound rather than from the straits between Denmark and Sweden as it does today. Because the Baltic Water constitutes a major part of the present-day coastal current along Norway, that current would have been weakened. This would again allow the Atlantic Water to flow closer to the Norwegian coast, and therefore more easily turn to the east north of Norway, bringing more warm water into the Barents Sea and less northwards to Svalbard.

Cold climate eolian sand

We have described some sections in eolian sand sheets and dunes, and studied several more sections not included in this publication. Some of the sand fields are mapped by Astakhov *et al.* (1999). The sand in the sheets has the typical sedimentary structures of the coversand in Germany and The Netherlands (Schwan 1986, 1987, 1988). We conclude that the European eolian sand belt, discussed by for example Koster (1988) and Zeeberg (1998), extends to the Pechora lowland.

Conclusions

1. The last major ice-dammed lake in northern Russia, named Lake Komi, is of Middle or Early Weichselian age.
2. The huge morainic loops, the Adzwa–Laya and Rogovaya ridges, pre-date Lake Komi. They may pre-date the Eemian, although we assume they are of Early Weichselian age.

3. The youngest ice-marginal deposits in northern Russia, collectively named the Markhida line, formed in front of the Kara Ice Sheet in the eastern area and the Barents Ice Sheet in the western area. We conclude that Lake Komi was dammed by this ice front and therefore that the Markhida line is of Middle/Early Weichselian age, although we do yet not completely rule out a Late Weichselian age.
4. If our conclusion is correct, that the Markhida line is of Middle/Early Weichselian age, then the implications are that the Late Weichselian Barents Ice Sheet had its southeastern margin offshore mainland Russia and that most of the Kara Sea remained unglaciated.

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Table 1. Radiocarbon dates. The first two digits in the field sample number indicate the year of collection. The laboratories are: T – Trondheim; Tua – prepared at Trondheim, measured at the accelerator in Uppsala; LU – St Petersburg University; Beta – Beta Analytic; CAMS – Prepared at University of Colorado, INSTAAR and measured at Lawrence-Livermore National Laboratory.

Locality no. in Fig. 2	Field sample no.	Lab no. *means AMS date	Age	C-13 *means assumed value	Material dated	Stratigraphy. Comments
1 Bolvan bog, Timan	94-Bol. 25	T-11913A	8265 ± 140	−28.2	Gyttja	Core 25, depth 296 cm.
1 Bolvan bog, Timan	94-Bol. 25	TUa-1154	7345 ± 75	−27.2	Terrestrial plant remains	Core 25, in peat.
1 Bolvan bog, Timan	94-Bol. 25	Beta-116425*	10,020 ± 90	−25.3	Organic silt	Core 25, depth 320–325 cm.
1 Bolvan bog, Timan	94-Bol. 25	Beta-116426*	10,440 ± 110	−25.1	Organic silt	Core 25, depth 328–332 cm.
1 Bolvan bog, Timan	94-Bol. 25	TUa-1155A	11,620 ± 105	−25.5	Organic silt	Core 25, depth 370 cm.
1 Bolvan bog, Timan	94-Bol. 25	Beta-116427*	13,470 ± 110	−21.9	Organic silt	Core 25, depth 420–430 cm.
1 Bolvan bog, Timan	94-Bol. 25	TUa -989A	20,100 ± 230	−24.5	Organic silt	Lower part of core 25, depth 504–495 cm.
1 Bolvan bog, Timan	94-2116	Beta-099884	9640 ± 60	−26.9	Twig (Salix?)	Just beneath gyttja in core B.
1 Bolvan bog, Timan	94-2150	T-11916A	10,400 ± 100	−33.2	Gyttja	Section 170 m a.s.l. Just above sample below (P15A:119). To old, not plotted in Fig. 22
1 Bolvan bog, Timan	P15A:119	Beta-88789	8880 ± 60	−28.6	Twig (Betula)	Section 170 m a.s.l. Thin peat above lacustrine silt.
2 Timan coast	94-2102	T-11864	7430 ± 140	−30.7	Peat	Lower part of formation F, Holocene peat.
2 Timan coast	94-2101	T-12202A	9445 ± 105	−26.4	Peat	Base of formation F, Holocene peat.
2 Timan coast	93-18B/5	T-11200	9970 ± 110	−29.5	Peat	Base of formation F, Holocene peat.
2 Timan coast	94-2032	TUa-1127*	>45,000	−21.9	Fragm. of terrestrial plants	Fluvial sequence over lacustrine.
2 Timan coast	94-2015	TUa-1124*	>45,000	−20.1	Fragm. of terrestrial plants	Lower part of formation D, eolian sand.
2 Timan coast	94-2014	TUa-990*	>39,935	−23.5	Organic detritus	Lower part of formation D, eolian sand.
2 Timan coast	94-2095	T-11509	$39{,}570\ ^{+7780}_{-3880}$	−29.8	Twigs	Solifluction sediment in formation C.
2 Timan coast	94-2095B	TUa-927*	>45,000		Twig	Solifluction sediment in formation C.
2 Timan coast	94-2111	T-11497	$48{,}020\ ^{+4450}_{-2850}$	−21.7	Tusk of mammoth	Collected on beach, probably from formation C.
2 Timan coast	94-2017	TUa-1125*	>45,000	−28.2	Organic detritus	Lacustrine sand. Upper part of formation C.

Table 1. (Continued).

Locality no. in Fig. 2	Field sample no.	Lab no. *means AMS date	Age	C-13 *means assumed value	Material dated	Stratigraphy. Comments
2 Timan coast	94-2096	TUa-1128*	>45,000	−28.1	Fragm. of terrestrial plants	Lacustrine sand. Upper part of formation C.
2 Timan coast	94-2028	TUa-1126*	>45,000	−29.4	Fragm. of terrestrial plants	Deformed sediment, formation B.
2 Timan coast	93-19/2	TUa-814*	>62,090	1.0*	Shell	Lag on top of formation A.
2 Timan coast	93-18/3 + 18/4	TUa-808*	$48{,}955\ ^{+3355}_{-2360}$	1.0*	Shell	Marine clay, formation A.
3 Urdyuzhskaya Viska site 28	94-0168	T-11888	>44,950		Wood	Fluvial sand.
3 Urdyuzhskaya Viska site 26	93-26/3	TUa-809*	$49{,}680\ ^{+3855}_{-2595}$	−28.9	Fragm. of terrestrial plants	Handpicked plants. Lacustrine (?) sand, below fluvial sand.
3 Urdyuzhskaya Viska site 26	93-26/3	Beta-70905*	>47,700		Fragm. of terrestrial plants	Same sample as above.
3 Urdyuzhskaya Viska site 25	94-0179	TUa-1141*	>45,000		Moss stems	Handpicked from lacustrine (?) sand, below fluvial sand.
3 Urdyuzhskaya Viska site 25	94-0182	T-11889	$44{,}150\ ^{+1900}_{-1500}$		Wood	Lacustrine (?) sand, below fluvial sand.
4b Sula site 12	94-0045	TUa-1138B*	6255 ± 55	−24.0	Bulk sample	Remnants of soil at floor of channel 1.5 m below surface, at 400 m. Contaminated by younger C?
4b Sula site 12	94-0062	TUa-1139*	39,815 ± 640	1.0*	Shell fragments	Redeposited shell fragments in fluvial sand. At 60 m horizontal scale, 47 m a.s.l.
5 Sula site 22	94-0115	T-11887	$44{,}600\ ^{+3400}_{-2400}$		Shell fragments	Eemiam marine sand. Should have nonfinite radiocarbon age.
7 Upper Kuya	97-2036	LU-3974	36,140 ± 910		Bone of mammoth	Found on river bank. Stratigrphic position unclear.
7 Upper Kuya	96-3020	LU-4021	>41,000		Organic	Moss mat from upper part of Eemian marine sediments.
7b Kuya Bridge	93-24/2	Beta-70901*	12,300 ± 60		Bulk sample. Low organic cont.	Eolian sand postdating large ice wedges.
8 Vastiansky Kon		LU-3973	32,440 ± 850		Mammoth tusk	In gully below the upper till. Collected by I.I. Krasnov in 1936. From collections at VSGEI.
8 Vastiansky Kon		T-13200	39,000 ± 850	−21.4	Mammoth tusk	Same tusk. Large sample.
8 Vastiansky Kon section 4	93-11/4.	TUa-1377*	>47,000	−23.8	Wood. Picea or Larix	Unit E, 79 m a.s.l. Redeposited wood.
8 Vastiansky Kon section 4	93-11/5.	T-12339	32,870 ± 1010	−27.7*	Peat	Unit E, 78 m a.s.l. Bulk date of transported peat clast.
8 Vastiansky Kon section 4	93-11/6.	T-12340	31,620 ± 560	−28.0	Peat	Unit E, 68 m a.s.l. Bulk date of transported peat clast.
8 Vastiansky Kon section 4	93-11/7	T-12341	43,100 ± 1300	−26.1*	Wood, Picea or Larix	Unit D, 66 m a.s.l. Redeposited wood.
8 Vastiansky Kon section 4	93-11/8.	T-12342	31,665 ± 910	−26.9	Peat	Unit D, 64 m a.s.l. Bulk date of in situ peat.
8 Vastiansky Kon section 4	93-19-23 A	Beta-099885*	25,120 ± 150		Moss	Unit D, 64 m a.s.l. Same peat as 93-11/8. Handpicked moss stems.
8 Vastiansky Kon section 4	93-19-23 B	Beta-099886*	>50,590		Fragile Salix remains	Handpicked leaves, bud scales, etc. of Salix. From same sample as above.
8 Vastiansky Kon between sections 3 and 4	96-0044A	Beta-110565*	>50,790	−26.9	Moss	Unit D. 60 m a.s.l. Handpicked moss stems from top of 30 cm thick peat.
8 Vastiansky Kon between sections 3 and 4	96-0044B	Beta-110566*	>50,780	−27.9	Moss	Handpicked moss stems from middle of same peat.
8 Vastiansky Kon between sections 3 and 4	96-0044C	Beta-110567*	>49,190	−26.9	Moss	Handpicked moss stems from base of same peat.
8 Vastiansky Kon section 3	95-6512A	TUa-1910*	>45,800	−24.3	Moss	Unit D. 56 m a.s.l. Handpicked moss stems.
8 Vastiansky Kon section 3	95-6512B	Beta-110569*	>48,090	−26.3	Moss	Same sample.

Table 1. (Continued).

Locality no. in Fig. 2	Field sample no.	Lab no. *means AMS date	Age	C-13 *means assumed value	Material dated	Stratigraphy. Comments
8 Vastiansky Kon section 3	95-6511A	TUa-1911*	>48,450	−26.6	Moss	Unit D. 46 m a.s.l. Handpicked moss stems.
8 Vastiansky Kon section 3	95-6511B	Beta-110568*	>48,490	−26.9	Moss	Same sample.
8 Vastiansky Kon section 4	93-11/17A	T-13050	31,350 ± 880	−26.1*	Wood. Salix	Unit A. 45 m a.s.l.
8 Vastiansky Kon section 4	93-11/17B	TUa-1908*	>45,150	−28.4	Leaves	Same sample. Handpicked leaves of Betula.
8 Vastiansky Kon section 4	93-11/17C	Beta-110571*	>50,300	−25.7	Moss	Same sample. Handpicked Betula nana leaves.
9 Markhida	Pechora-94	T-11510	13,065 ± 370	−21.0	Tooth of musc ox	Whole cranium found on river bank. Sediments in cavities show it came from solifluction on top of the till.
9 Markhida	Pechora-94B	TUa-926*	13,980 ± 90	−19.0	Tooth of musc ox	Same as Pechora 94. Larger and better sample.
9 Markhida	Pechora-94	TUa-925*	39,710 ± 880	−20.8	Bone of mammoth	Found on river bank. Unknown stratigraphic position.
19 Podkova-1	97-2010	LU-3970	34,600 ± 700		Tusk of mammoth	Fluvial gravel in 20 m terrace along Kolva. Piece from large tusk received from gravel pit worker.
19 Podkova-1	97-2010	T-13135	32,155 ± 510	−24.0	Tusk of mammoth	Same tusk as LU-3970.
19 Podkova-1	97-0019A	T-13134	$36{,}540\ ^{+2150}_{-1700}$	−21.7	Lamel of mammoth molar	Found on floor of gravel pit. Small sample.
19 Podkova-1	97-2037	LU-3975	36,140 ± 910		Bone of mammoth	From Usinsk Museum. Collected by amateur archeologist Pergalo.
19 Podkova-1	97-2039	LU-3976	26,220 ± 240		Bone of mammoth	From Usinsk Museum. Collected by amateur archeologist Pergalo.
20 Yarei-Shor	97-2004	LU-3971	27,150 ± 300		Bone of mammoth	Fluvial gravel in 20 m terrace along Kolva River. Neck bones received from gravel pit worker.
21 Byzovaya		LE-3048	14,140 ± 150		Bone	Sand above artefact-bearing diamicton.
21 Byzovaya	97-3075	LU-4010	28,230 ± 920		Tusk of mammoth	Sand above artefact-bearing diamicton. Probably redeposited.
21 Byzovaya	97-3070	T-13439	28,485 ± 290	−22.3	Bone of mammoth	Top of bone- and artefact-bearing diamicton.
21 Byzovaya	97-3057	T-13441	27.915 ± 365	−21.4	Bone of mammoth	From bone- and artefact-bearing diamicton.
21 Byzovaya	97-3087	T-13438	26,555 ± 250	−22.6	Bone of wooly rhinoceros	From bone- and artefact-bearing diamicton.
21 Byzovaya	97-3087	LU-3992	28,510 ± 310		Bone of wooly rhinoceros	Same bone as T-13438
21 Byzovaya	97-3058	T-13440	28,075 ± 255	−21.3	Tusk of mammoth	Top of bone- and artefact-bearing diamicton.
21 Byzovaya	97-3058	LU-3983	29,170 ± 340		Tusk of mammoth	Same bone as T-13440
21 Byzovaya		T-11498	27,740 ± 480		Tusk of mammoth	From bone- and artefact-bearing diamicton.
21 Byzovaya	97-3088	LU-3989	27,490 ± 330		Bone	From bone- and artefact-bearing diamicton.
21 Byzovaya	97-3059	LU-3995	27,110 ± 240		Bone of mammoth	From bone- and artefact-bearing diamicton.
21 Byzovaya		LE-3047	25,740 ± 500		Bone	From bone- and artefact-bearing diamicton.
21 Byzovaya			25,540 ± 380		Bone	From bone- and artefact-bearing diamicton.
21 Byzovaya	97-3069	LU-3979	29,160 ± 430		Rib of mammoth	Base of bone and artefact-bearing diamicton.
21 Byzovaya	97-3030	LU-4007	33,180 ± 2030		Rib of mammoth	Middle part of bone and artefact-bearing diamicton.
22 Pymva Shor I	PSI 150/95	TUa-1395*	16,530 ± 100	−20.2	Bone of musc ox	Middle of colluvium.
22 Pymva Shor I	PSI 145/95	TUa-1394*	11,125 ± 80	−18.8	Bone of reindeer	Base of colluvium.
22 Pymva Shor I	PSI 95/95	TUa-1393*	11,460 ± 80	−21.7*	Bone of horse	Sand, above limestone rubble.
22 Pymva Shor I	PSI exc.3 E/9	TUa-1396*	10,255 ± 85	−21.7	Tooth of bison	Sand, above limestone rubble.

Table 1. (Continued).

Locality no. in Fig. 2	Field sample no.	Lab no. *means AMS date	Age	C-13 *means assumed value	Material dated	Stratigraphy. Comments
22 Pymva Shor I	95-109	CAMS-38221*	13,090 ± 60		Bone of hare	Limestone rubble, 0–5 cm below upper boundary.
22 Pymva Shor I	95-142	CAMS-38222*	13,530 ± 60		Bone of hare	Limestone rubble, 0–5 cm below upper boundary.
22 Pymva Shor I	95-87	CAMS-38220*	15,760 ± 60		Bone of reindeer	Limestone rubble, 0–5 cm below upper boundary.
22 Pymva Shor I	95-112	CAMS-38224*	16,860 ± 80		Bone of hare	Limestone rubble, 5–10 cm below upper boundary.
22 Pymva Shor I	95-143	CAMS-38224*	16,510 ± 60		Bone of hare	Limestone rubble, 15–20 cm below upper boundary.
22 Pymva Shor I	PSI 82/95	TUa-1397*	20,035 ± 140	−21.2	Bone of arctic fox	Limestone rubble.
22 Pymva Shor I		T-11501	21,910 ± 250		Bone	Limestone rubble.
22 Pymva Shor II	95-0181	TUa-1327*	10,265 ± 80	−20.5	Bone of reindeer	Sand, above limestone rubble.
22 Pymva Shor II	95-0129	TUa-1328*	13,180 ± 75	−20.8	Bone of hare	Limestone rubble.
22 Pymva Shor II	95-2165	TUa-1331*	13,425 ± 85	−18.9	Bone of grouse	Limestone rubble.
22 Pymva Shor II		T-11502	26,230 ± 360		Bone	Uncertain context, probably from limestone rubble.
23 Mamontovaya Kurya	96-4068	Beta-119501*	23,860 ± 120	−25.8	Handpicked terrestrial moss	Alluvial silt, 2.7 m above cross-bedded gravel.
23 Mamontovaya Kurya	96-4069	Beta-119502*	23,890 ± 140	−26.0	Handpicked terrestrial moss	Alluvial silt, 1.7 m above cross-bedded gravel.
23 Mamontovaya Kurya	96-4072	Beta-4072*	27,130 ± 180	−26.4	Handpicked terrestrial moss	Alluvial silt above sand and gravel.
23 Mamontovaya Kurya	96-4105	TUa-1514*	25,650 ± 535	−28.2	Terrestrial plants	Cross-bedded alluvial sand over bone layer.
23 Mamontovaya Kurya		T-11503	$36,770\,^{+2620}_{-1980}$		Bone of horse	Cross-bedded alluvial sand and gravel above bone layer.
23 Mamontovaya Kurya	97-1239	LU-3994	34,920 ± 1040		Tusk of mammoth	Alluvial gravel. Uncertain level.
23 Mamontovaya Kurya		T-11403	$36,630\,^{+1310}_{-1130}$		Tusk of mammoth	Alluvial sand and gravel with bones and artefacts.
23 Mamontovaya Kurya		T-11504	34,360 ± 630		Bone of mammoth	Alluvial sand and gravel with bones and artefacts.
23 Mamontovaya Kurya	97-1236	LU-4001	37,360 ± 970		Tusk of mammoth	Alluvial sand and gravel with bones and artefacts.

Table 2. OSL dates on quartz, using the sand grain fraction. All dates performed at the Nordic Laboratory for Luminescence Dating, Risø. In the column for paleodose, the number of independant estimates of the paleodose used for the given mean is indicated in parentheses.

Locality	Loc. no. in Fig. 2	Field sample no.	Lab. no. Risø	Dose rate Gy/ka	Paleodose Gy (no. of estimates)	Age, ka	Sediment, stratigraphy. Comments.
Timan coast	2	94-2038	952517	1.55	23 (4)	14.9 ± 1.3	Eolian sand. Formation E
Timan coast	2	94-2037	952518	1.95	25 (4)	12.7 ± 1.1	Eolian sand. Formation E
Timan coast	2	94-2036	952519	2.19	43 (12)	19.4 ± 1.6	Eolian cover sand. Formation D
Timan coast	2	94-2035	952516	2.07	40 (9)	19 ± 2	Eolian cover sand. Formation D
Timan coast	2	94-2108	962505	2.83	90 (10)	32 ± 3	Lacustrine sand. Formation C
Timan coast	2	94-2034	952515	2.07	109 (9)	52 ± 4	Lacustrine sand. Formation C
Timan coast	2	94-2033	952514	2.09	98 (13)	47 ± 4	Lacustrine sand. Formation C
Urdyuzhskaya Viska	3	94-178	962511	1.94	104 (3)	53 ± 4	Fluvial sand. Upper sample.
Urdyuzhskaya Viska	3	94-176	962510	1.22	118 (3)	96 ± 8	Fluvial sand
Urdyuzhskaya Viska	3	94-175	962509	2.43	248 (3)	102 ± 10	Lacustrine (?) sand. Lowest sample
Sula 7	4	94-029	952511	1.76	235 (6)	134 ± 11	Eolian sand dune on till.
Sula 7	4	94-027	952510	1.66	247 (6)	149 ± 13	Eolian sand dune on till.
Sula 12	Near 4	94-056	962507	1.12	77 (4)	69 ± 7	Sand bed in unit C 1. Fluvial
Sula 12	Near 4	95-055	962506	1.57	163 (3)	104 ± 11	Sand in unit B. Marine?
Sula 12	Near 4	94-057	962508	1.20	131 (3)	110 ± 17	Sand in unit B. Marine?
Sula 22	5	94-114	952502	1.14	91 (6)	80 ± 6	Fluvial coarse sand atop of glacila-custrine clay. Bed h.
Sula 22	5	94-148	952505	1.29	149 (7)	116 ± 10	Fluvial coarse sand atop of glacila-custrine clay. Bed h.
Sula 22	5	93-25/3	952501	1.29	103 (3)	79 ± 6	Eolian or fluvial sand resting on the Eemian. Bed c-f
Sula 22	5	94-147	952504	1.49	165 (11)	111 ± 12	Eemian marine sand. Top of sand.
Sula 22	5	94-146	952503	1.47	142 (7)	97 ± 7	Eemian marine sand. Upper part.
Sula 22	5	93-25/2	942513	1.67	108 (4)	64 ± 6	Eemian marine sand. 3 m below top.
Sula 21	Near 5	94-232	952506	1.98	145 (7)	74 ± 8	Eolian sand between the Eemian and the overlying glacilacustrine clay.
Sula 21	Near 5	94-086	952508	1.94	122 (7)	63 ± 5	Eolian sand between the Eemian and the overlying glacilacustrine clay.
Sula 21	Near 5	94-084	952507	1.55	161 (7)	104 ± 11	Fine sand with ripples. One m below top of the Eemian
Sula 21	Near 5	94-097	952509	1.56	139 (6)	91 ± 15	Fine sand in channel. Eemian estuarine bed.
Kuya Bridge	Near 7	93-24/1	942510	2.00	29 (4)	14.6 ± 1.2	Eolian sand, bent up by ice-wedge.
Markhida	9	93-1A/7	942501	0.83	53 (4)	63 ± 5	Alluvial sand below the Markhida moraine. Re-dating with quartz. Three feldspar dates yielded 25–30 ka (Tveranger *et al.* 1995).
Markhida	9	93-1B/6	942502	1.30	79 (3)	62 ± 5	As above. One feldspar date 66 + 7.
Markhida	9	93-1C/1	942503	1.96	114 (4)	58 ± 7	As above. One feldspar date 27 + 3.
Garevo	12	96-2020	972505	1.12	134 (3)	93 ± 13	Lake Komi. Sand bed in beach gravel 100 m a.s.l., 3 m below surface.
Garevo	12	96-2023	972506	1.87	142 (3)	76 ± 10	Lake Komi. About 100 m from above sample. Laminated fine sand about 92 m a.s.l.
Garevo	12	96-2024	972507	1.91	168 (4)	88 ± 9	Lake Komi. Fine sand with ripples. 50 cm above sample 2023.
Pymva Shor II	22	95-055	962521	2.06	26 (4)	12.0 ± 0.9	Eolian sand above main bone-bearing bed.
Pymva Shor II	22	95-056	962522	1.68	23 (3)	13.6 ± 1.2	As above.

Table 3. TL dates using the fine-grained method. All dates performed by N.C. Debenham, England.

Locality	Loc. no. in Fig. 2	Field sample no.	Lab. no.	Age ± st.d. ka	Stratigraphy. Comments
Bolvan bog. Timan Ridge	1	94-25D	PEC 3	11.3 ± 1.0	Core 25D in Bolvan I, depth 430–435 cm.
Timan Ridge site 12	1	94-2140	PEC 2	10.2 ± 1.0	Clay and silt deposited in paleolake dammed by an esker. 53–58 cm below surface.
Hongurei	6	96-1181	PEC 29	>148	Massive clay, 185 cm above base, 2 m below surface.
Hongurei	6	96-1185	PEC 30	>132	Massive clay, 115 cm above base.
Hongurei	6	96-1179	PEC 28	>145	Massive clay, 50 cm above base (75 cm above sample below).
Hongurei	6	96-1177	PEC 27	>107	Top of laminated clay. 25 cm below boundary to massive clay. Glacilacustrine sediment on top of Markhida moraine.
Kuya bridge	Near 7	96-2148	PEC 14	17.6 ± 2.6	Clay lamina in interbedded shallow lacustrine and eolian sediments.
Kuya bridge	Near 7	96-2150	PEC 15	16.9 ± 2.9	As above. 40 cm below sample 96-2148. Close to river level.
Markhida	9	96-2123	PEC 11	12.5 ± 1.5	Eolian sand. At 2480 m on horizontal scale. 40 cm above base of eolian sand.
Markhida	9	96-2129	PEC 12	14.1 ± 1.5	Eolian sand. As sample 96-2123. 130 cm above base.
Markhida	9	96-2128	PEC 13	14.9 ± 2.1	Eolian sand. As sample 96-2123. 230 cm above base.

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