Signature of the last shelf-centered glaciation at a key section in the Pechora basin, Arctic Russia

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ABSTRACT: The Vastiansky Kon' is the largest exposure of Quaternary deposits in the Pechora lowland, northern Russia. Morphologically the site belongs to the so-called Markhida Moraine; a complex, east–west trending zone of ice-marginal landforms deposited by the Kara Sea Ice Sheet during the last glaciation. The site exhibits a succession of sediments more than 100 m thick that, according to previous studies, covers the interval from the end of the Elsterian to the beginning of the Holocene. Unfortunately both the strong glaciotectonic deformation of the sedimentary succession and few absolute dates have made the chronological interpretation of the section difficult. The present paper reviews previous studies of the site published in Russian, and presents the results of a reinvestigation focusing on the post-Eemian stratigraphy. A marine Eemian clay more than 8 m thick is overlain erosionally by 20 m of fluvial deposits of Late Eemian or Early Weichselian age. The fluvial succession is overlain by a till and a marine clay, which, according to one interpretation, may represent an Early or Middle Weichselian advance of the Kara Ice Sheet followed by a transgression. The clay shows a transition into 15 m of estuarine and fluvial sediments overlain by more than 12 m of tundra–floodplain deposits. The whole succession has been upthrusted glaciotectonically by the last ice advance, which deposited a more than 12 m thick till on top of the section. Based on a number of subtill radiocarbon age-estimates from the site, in the range 25–32 ka BP, the youngest ice advance is considered to be of late Weichselian age, although a Middle Weichselian age cannot be excluded. © 1998 John Wiley & Sons, Ltd.

KEYWORDS: Barents–Kara ice-sheets; Markhida Moraine; Weichselian stratigraphy; Pechora basin.

Introduction

The fluctuations of the Barents and Kara ice-sheets in space and time onto the Pechora lowland are poorly known, and several controversial interpretations currently exist (Astashkov, 1994; Rutter, 1995). Unfortunately very little of the extensive material compiled by Russian and former USSR geologists over the last 70 yr has been made available for non-Russian-reading scientists. This paper is an effort to somewhat alleviate that fact by giving a detailed review of the published material from one of the largest sections on the southern Barents Sea coast, the Vastiansky Kon', and to present results of a reinvestigation of the section undertaken by the authors. Except for a short note by Grosswald (1994) and a review by Astakhov (1994) this extraordinary site has remained largely unknown in the western literature. Some key papers on the Quaternary of the Pechora lowland (Golbert et al., 1973; Arslanov et al., 1975, 1980, 1987; Lavrov, 1975; Loseva and Duryagina, 1975; Loseva, 1978; Guslitser and Isaychev, 1983; Guslitser et al., 1985; Epstein, 1990) are translated into English by the PECHORA (Paleoenvironment and Climatic History of the Russian Arctic) project.

The Vastiansky Kon' site belongs morphologically to the so-called Markhida Moraine, a complex of ridges formed by the last ice advance on to the Pechora lowland (Fig. 1). The Pechora river cuts through the Markhida Moraine at Vastiansky Kon', eroding the foot of the exposure and creating a bluff that is 3 km long and 90–100 m high, which is subject to frequent landslides and slumps. Grosswald et al. (1974) and Grosswald (1980, 1983, 1994) claimed the Markhida Moraine to be the result of an Early Holocene readvance of the Barents–Kara Ice Sheet, but a reinvestigation of the type section at Markhida (Tveranger et al., 1995) indicates it to be older than 10 ka BP.

The stratigraphic nomenclature of western Europe will be used throughout this paper. The equivalent names for European Russia are: Likhvin (Holstein), Mikulino (Eem) and Valdai (Weichsel).
Previous investigations

The published Russian literature about the site is extensive (Krasnov, 1947; Lavrova, 1949; Popov, 1963; Danilov, 1963; Troitsky, 1964; Ryumina, 1967; Zagorskaya et al., 1969; Yakhimovich, 1970; Golbert et al., 1973; Lavrov, 1981; Epstein 1990), and the number of unpublished studies possibly even larger. The available documentation comprises mainly specialised studies covering only selected aspects of the section, such as pollen stratigraphy, Mollusca, clay mineralogy, Foraminifera or structural geology, which sometimes arrive at incompatible conclusions. Efforts at synthesis of all observations have been published only by Golbert et al. (1973), Lavrov (1981) and less rigorously by Epstein (1990).

The most comprehensive presentation of the site, compiled and published by Golbert et al. (1973), is shown in Fig. 2. Based on all the data available from the section, including a borehole core from river level down to bedrock made by Popov (1963), Golbert et al. (1973) proposed the stratigraphical interpretation summarised in Fig. 3 and presented in detail below with some later additions by Lavrov (1981) and Epstein (1990).

Pre-Holsteinian deposits (units a to g)

Units a to g (Fig. 3) are known only from boreholes down to bedrock and reflect a development from nearshore conditions with influx of ice-rafted material (units a to d) to deep-water glaciomarine sediments (unit e), deep-water marine deposits (unit f) and fine-grained brackish sediments with possible ice-rafted material (unit g) (Danilov, 1963; Popov 1963). Results from pollen analysis (Zagorskaya et al., 1969) indicate severe subarctic conditions punctuated in unit f by a period with interglacial forest tundra vegetation. Units a to g have not been dated directly, but are considered older than the overlying Holsteinian units.
Holsteinian deposits (units 1 and 2)

Units 1 and 2 constitute the lowermost strata exposed in the section (Figs 2 and 3). They are interpreted as a regressive sequence, with sediments changing from sublittoral laminated clay to shallow-water coastal deposits with cross-bedded medium sand with mud layers (Golbert et al., 1973).

The mollusc fauna in unit 1 includes low arctic species such as Macoma calcarea and Hiatella arctica, and typical arctic ones such as Portlandia arctica, Yoldia hyperborea, Propeamussium groenlandicum and Cerastoderma ciliatum. The presence of the boreal gastropod Buccinum undatum was interpreted as contemporaneous redeposition of sediments accumulated in shallower water, and thus an indicator of higher-than-present water temperatures near the coast. No shells were found in unit 2. Foraminifera assemblages in unit 1 also indicate interglacial conditions, and suggest warming accompanied by a change to shallow-water marine/brackish conditions in unit 2 (Zagorskaya et al., 1969). Pollen samples within unit 1 reflect conditions close to the present, with forest tundra vegetation changing gradually into birch–spruce forest in unit 2.

Golbert et al. (1973) considered these interglacial deposits to be of Holsteinian age because they are separated from the overlying Eemian beds by an erosional unconformity. The combination of Abies, Fagus and Corylus found in pollen samples from units 1 and 2 (Zagorskaya et al., 1969) were also considered to be typical for the Holsteinian by Golbert et al. (1973).

Eemian deposits (units 3a to 3d)

Unit 3a is a coarse ferruginous sand, up to 200 cm thick, overlying an erosional unconformity. It contains occasional pebbles, intraclasts of clay and lens-like accumulations of marine shells, and can be traced as a marker for some distance along the section (Fig. 2). The mollusc fauna contains 21% boreal species, including Buccinum undatum, Macoma baltica, Modiolula modiolus, Arctica islandica, Zirphea crispa, Mytilus edulis and Balanus balanoides (Lavrova, 1949; Zagorskaya et al., 1969). Some of these species are currently only found west of the North Cape and indicate water temperatures higher than present. Preservation of the shells is highly variable, corroborating the interpretation of unit 3a as a littoral/upper sublittoral deposit.

The foraminifer fauna reflects shallow water with temperatures 3° to 5°C higher than at present. It includes few stenohaline species, which is common for coastal environments with fluctuating input of freshwater. The fauna includes for the first time Quinqueloculina oviformis. According to Golbert et al. (1973) this species is known only from deposits of Eemian age or younger in this area. Pollen spectra (Zagorskaya et al., 1969) show an interglacial birch-forest–tundra vegetation, which at present is common for the warmer and more humid climate farther to the west.

Unit 3b is described as a ‘till-like loam’ consisting of sandy-silty clay with scattered pebbles and a gradual lower boundary. Pollen samples reflect a further climatic amelioration with birch–spruce forest. The Foraminifera assemblages reflect increasing water depth, low salinity and water temperatures of 2–3°C (Zagorskaya et al., 1969). This unit is thought to represent a transition between the littoral unit 3a and the sublittoral clay 3c.

Unit 3c is a laminated marine clay with thickness varying between 10 m and 37 m (Fig. 2). Molluscs reflect a rapid change to a sublittoral environment. Deep-water conditions with water temperatures higher than at present are also inferred from the occurrence of the foraminifers Alabaminoides mitis, Eponides wrightii, Bolivina sp. and Protelphidium parvum. Alternations of spruce–birch and birch–spruce forest identified in the pollen spectra (Zagorskaya et al., 1969) are considered correlative with similar vegetation changes in Eemian deposits of West Siberia (Golbert et al., 1973).

Unit 3d unconformably overlies 3c and consists of medium and coarse sand with seams of mud, gravel and intraclasts of peat. The upper boundary is erosional and marked by a thin lag of pebbles and small boulders. As seen in Fig. 2, unit 3d is found only locally along the bluff. Pollen spectra of unit 3d resemble those of unit 3c. The mollusc fauna, which includes 31% boreal species, reflects...
an upper sublittoral environment with estimated bottom-water temperatures 3° to 5°C higher than at present and includes *Spisula elliptica* and *Cerastoderma edule*, which in northern Europe and Siberia occur only in Eemian deposits (Lavrova, 1949; Troitsky, 1964; Zagorskaya et al., 1969).

**Weichselian deposits (units 4a to 8)**

Units 4a to 8 all overlie the Eemian beds and are considered to be of Weichselian age. As seen from Fig. 2 the Weichselian beds have been subjected to glacial thrusting in the upstream part of the section. The thrusting apparently has caused stacking of the deposits, either as distinct thrust blocks (Golbert et al., 1973) or continuous sheets (Epstein, 1990) separated by thrust-faults, which are partly highlighted by discontinuous diamict beds (4d and 6). The section is capped by a basal till (unit 8) deposited by the same glacial overriding that caused the upthrusting.

Unit 4a consists of 2.5 m of medium sand with pebbles and small boulders at the base. Locally it directly overlies the marine clay unit 3c. Golbert et al. (1973) interpreted unit 4a as a lag deposit from an Early Weichselian glaciation, without presenting any corroborating observations supporting this interpretation. Unit 4b is a discontinuous, 0.2 to 2 m thick, unit of black, plastic clay with rare pebbles.

Units 4c, 5 and 7 are described by Golbert et al. (1973) as more or less identical, consisting of cross-bedded fine and medium sand with 2–4 cm thick intercalated beds of poorly sorted sand, clay and silt. Organic remains include fine plant detritus, pieces of wood and seams of allochthonous peat, which can be traced for tens of metres. Shell fragments are rare, exfoliated, rounded and corroded, and considered to be redeposited. Pollen analyses reflect a cold climate environment with tundra and periglacial vegetation punctuated by a few interstadial-like, warm intervals with forest tundra vegetation (Fig. 3). These units are interpreted as delta and delta flat deposits by Zagorskaya et al. (1969), Yakhimovich (1970) and Golbert et al. (1973), but both a marine (Popov, 1963) and an alluvial depositional environment (Epstein, 1990) have been suggested.

The diamict units 4d and 6, which are found along thrust-planes between the glaciotectonically displaced blocks, were interpreted as downward injections from unit 8 generated during upthrusting of the deposits (Troitsky, 1964; Lavrov, 1981). However, *Elphidium atlanticum* appears for the first time and dominates the Foraminifera assemblages in unit 8, and is not found in units 4d and 6, where *E. subclavatum* dominates (Zagorskaya et al., 1969). These faunal contrasts lead Golbert et al. (1973), Popov (1963) and Zagorskaya et al. (1969) to interpret units 4d and 6 as *in situ* marine deposits from ingressions on to the delta flat. These beds later acted as slip planes and were heavily deformed during the subsequent glacial upthrusting.

Unit 8 is a sandy diamict 3.5 to 20 m thick, with boulders, pebbles and frequent shell fragments. It contains numerous heavily disturbed rafts of black marine clay and fine sand, ranging in size from a few centimetres to tens of metres. Unit 8 is interpreted as a basal till deposited by an ice advance from the northeast, which also caused the glaciotectonic upthrusting (Lavrova, 1949; Golbert et al., 1973; Lavrov, 1981; Epstein, 1990).

**Structure of the section**

The glaciotectonic nature of the section was first reported by Troitsky (1964) and is described extensively in Golbert et al. (1973), Lavrov (1981) and Epstein (1990). The bluff has, according to previous workers, the general structure of a large anticline, with a series of thrust blocks separated by discontinuous muddy diamict beds and thrust faults constituting the upstream limb (Fig. 2). Thrust faults throughout the section are all described as dipping towards the northeast at low angles, reflecting glacier push from that direction.

Origin of the overall structure, especially that of the diamict beds, has been much debated. Golbert et al. (1973) considered the individual thrust blocks to be of local provenance, and the interbedded diamict beds partly as *in situ* muddy layers, acting as slip planes during subsequent upthrusting, and partly as dykes injected along shear planes during deformation. Epstein (1990) divided the section into three identical, vertically stacked thrust sheets resting on a heavily deformed substratum, claiming that the diamict units derived from the underlying Eemian clay (3c).

**Methods**

Our reinvestigation of the site focused on the presumed Weichselian units 4a to 8 overlying the Eemian clay unit 3c. It aimed at elucidating both the overall structure and the sedimentology of these deposits as well as placing them into a firmer chronological framework.

Several clearings 3–15 m wide were made along the bluff and described in terms of glaciotectonic structures and sedimentology (see Fig. 8). The boundaries of the described units were traced along the bluff between the beyond the clearings by a combination of field mapping and studies of photomosaics of the bluff (see e.g. Fig. 5A).

Luminescence samples (see Table 2) were collected by attaching a light-proof sample bag to a 110 mm pipe and using this as a hand-driven horizontal corer, in order to avoid exposure to light. Organic-rich horizons and pieces of wood and peat were sampled for pollen- and macropalaeontological analysis and radiocarbon dating. Samples for microfauna-palaeontological work were picked from the marine beds. Molluscs from the same units were also collected, identified and used for a few experimental U/Th age-estimates and amino-acid analyses.
The overall structure

A number of surface lineations trending NW–SE, consisting of ridges 1–2 m high, can be traced on aerial photographs of the bluff. These low ridges are orientated perpendicular to the clast fabric of the upper till and the direction of glaciotectonic upthrusting (see Fig. 5). The latter features show that the youngest ice advance overrode the site from the northeast. The surface lineations can thus be interpreted as transverse moraines and/or outcropping thrustplanes. The section is orientated obliquely to the given ice movement. The overall structure of the section changes from a large fold (0–500 m, see Fig. 5A) in the downstream part to a series of large upthrusted blocks in the upstream direction. By projecting these main features of the section (lithological boundaries, bedding, large-scale thrust-faults) on to a plane parallel to the ice movement, and removing the vertical scale exaggeration, a simplified but principally correct image of the style of glaciotectonic deformation can be obtained (see Fig. 5B). At least three major thrusts faults could be identified cutting through the exposed part of the sedimentary succession and terminating at the base of the uppermost till, showing that the plane of décollement is seated underneath the exposure. Inspection of the exposed parts of the Eemian clay and underlying units also revealed a number of smaller blind overthrusts that have caused a thickening of these units, a feature not documented previously and not observed in the overlying sandy strata (see Fig. 4). It appears that the bulk of the strain during the glaciotectonic deformation was accommodated by the Eemian clays and underlying fine-grained deposits, causing thickening of these units and uplift of the overlying sediments.

Stratigraphy

Locations of the logs presented later in Fig. 8 are shown in Figs 4 and 5. The logs, on which subsequent descriptions are mainly based, cover the interval from the top of the Eemian clay (3c) to the top of the bluff, and correspond roughly to units 4c to 8 in the stratigraphical scheme (Fig. 3) of Golbert et al. (1973). Units 3d, 4a and 4b could not be identified by us along the bluff. As the existing subdivision was not supported by our observations, we have subdivided the succession overlying the Eemian clay unit (3c) into eight genetic lithostratigraphical units lettered A to H from bottom to top. Distribution and thickness of the individual units is shown in Fig. 5A (the stratigraphy and its interpretation is summarized in Fig. 8).

Unit A, fluvial deposits

Unit A consists of a succession of sandy and silty sediments (see Fig. 8). The lowermost parts comprise large-scale trough cross-beded medium to coarse sand, interpreted as interchannel fluvial deposits; a fining in the uppermost part reflects channel abandonment. The lower boundary is sharp and erosive as indicated by frequent clay balls from the underlying Eemian clays in the lowermost 40 cm.

In section 3 the overlying 7 m consist of reddish brown, planar laminated peaty silt and clay and laminated fine sand, interpreted as infill of an ox-bow lake or abandoned channel. Some of the thicker sand beds show evidence of intense bioturbation, which has homogenised the sediment. The peaty beds contain numerous macrorems, including a ‘non-arctic’ Coleoptera fauna (J. Böcher, pers. comm.) and plants including Picea abies, Betula nana, Salix reticulata, Salix phylici-tolia, a number of arctic wetland plants and Corispermum hyssopifolium, the latter presently growing only south of 58° latitude. The organic remains reflect a forest tundra environment similar to the present (O. Bennike, pers. comm., H. Birks, pers. comm.). The ox-bow lake is topped by 3 m of ripple- and planar laminated fine sand with no peaty beds, incised by shallow channels with a fining upward infill and overlain by large-scale trough cross-bedded sand reflecting renewed in-channel deposition.

Unit B, basal till

Unit B is a matrix supported, very compact diamicton up to 275 cm thick. The matrix consists of silty sand; grey coloured in the lower part, bluish-grey in the upper part. Clasts are generally less than 15 cm and constitute less than 5% of the sediment. Small worn shell fragments are found throughout the unit, suggesting a partly marine source of sediment. The structure of the diamicton is mainly massive except for occasional sheared lenses of fine and medium sand in the lowermost part, decreasing in number and thickness upwards in section. Catchment structures were observed at several places along the lower boundary, but not along the upper. The underlying fluvial deposits show an increasing degree of deformation from 1 to 2 m below the diamicton and up towards its lower boundary. Two fabric analyses carried out at two different places, 0.5 to 1 m above the lower contact of unit B, show a distinct NE–SW orientation of clasts (see Fig. 8). Striae on small boulders and orientation of catchment structures along the base of the diamicton give the same direction. We interpret unit B as a subglacial till deposited by an ice advance from the northeast.

Moving from section 3 to section 4 the till thins and its structure changes from very compact to loose, and shows an increasing degree of secondary deformation by intraformational shear, which is indicated by folding of originally subhorizontal subtil till shearplanes, and brecciation of the contact between the till and the overlying deposits, as seen in section 4 (see Fig. 8). At 1000 m along the bluff (Fig. 5A) the basal till B is cut by the younger till unit F (see below). Between 0 and 600 m along the profile, till B is missing, possibly due to fluvial erosion relating to unit D.

Unit C, marine clay

From 1200 to 1550 m along the bluff (Fig. 5A), till B is capped by a discontinuous single-clast gravel lag and up to 15 cm planar- to ripple-laminated fine sand. The sand bed has been deformed by a lateral shear movement, which was
Figure 4  Part of the Vastiansky Kon’ bluff. Height of the exposure is approximately 90 m. Sections 3 and 4 are indicated as in Fig. 5A. Units are marked with letters as in Fig. 8 and in the text. Note the sharp boundary between the Eemian clay (unit 3c) and the overlying sand. The light sand beds visible in the lower, dark clay part of the section are repetitions of unit 2 and 3a (cf. Fig. 3) caused by glaciotectonic stacking. Thrust faults causing stacking and thickening of beds were only positively identified in the units underlying 3c.

measured to be less than 10–15 cm (Fig. 6). The sand bed is conformably overlain by a massive bluish clay up to 150 cm thick, containing rare pebbles and an almost monospecific mollusc assemblage of *Hiatella arctica* in living position. Analysis of a sample series taken at 25 cm intervals through this clay in section 3 revealed a foraminifer fauna dominated by *Cassidulina reniforme*, *Haynesina orbiculare* and *Elphidium excavatum*, reflecting arctic marine conditions and showing an increasing input of freshwater towards the top of the unit (M.-S. Seidenkrantz, pers. comm.). Where not deformed by subsequent glaciotectonic deformation the clay thickens in local depressions in the underlying till, and pinches out around elevations. Where deformed by subsequent shear it has been mixed with the underlying till and locally has been injected into brecciated zones in the overlying sand.

In the thickest part of unit C the upper 30 cm of the clay exhibit a number of irregularly shaped, 2–10 mm wide, subvertical cracks with no obvious pattern. As there are no signs of a subaerial phase between unit C and D, and the cracks in the marine clay are filled with sand from the overlying estuarine/fluvial deposits (see description below), we interpret them as synaeresis cracks induced by salinity change in the depositional environment (Plummer and Gostin, 1981; Collinson and Thompson, 1989).

Unit C can be interpreted as representing a marine transgression following the retreat of the ice which deposited unit B. Units B and C have been described by previous authors as one bed (4d in Fig. 3). A comparison with previous interpretations and consequences of our reinterpretation of B and C will be addressed below.

**Unit D, estuarine and fluvial deposits**

The top of the marine clay is cut by an erosional unconformity (Fig. 6). Overlying it in section 3 (45–48 m a.s.l.) is a succession of bars up to 1.5 m high, with unidirectional forests of coarse and medium sand. The bars are separated by laminated beds of silt and clay 10–12 cm thick, occasionally including laminae of peaty silt or gyttja. The size of the sand bars and the inferred strong fluctuations in current velocity lead us to interpret them as part of minor mouth bar/crevasse channel complexes, typically found in interdistributary areas of fluvial-dominated deltas (Elliott, 1986). The bars show no signs of modification by wave action, suggesting deposition in a sheltered estuarine embayment. These presumed estuarine deposits are found only locally along the bluff. Laterally they merge into the same sequence of fluvial deposits that also overlies them.

Overlying the estuarine deposits is a succession of trough cross-bedded medium sand interpreted as in-channel deposits of a large river draining northwards. In the middle part, troughs are up to 150 cm deep containing scattered twigs and branches. Locally abandoned channels have been filled by a mixture of redeposited coarse organic detritus and *in situ* growth of moss and peat.

Apparently the main channel shifted westwards during deposition, leaving the site in a marginal position on the eastern bank, as indicated by the uppermost 3.5 m of unit D, reflecting sediment transport towards the east, decreasing grain size and diminishing size of the sedimentary structures (see Fig. 8). Unit D is interpreted as having been deposited by a fluvial-dominated delta prograding into and filling in a shallow marine- or estuarine embayment.
The location of the profile shown in Fig. 2 and sections 1, 3 and 4 shown in Fig. 8 are marked. (B) A hypothetical cross-section along the line X-X' in Fig. 5A. Note that the vertical scale is exaggerated in 5A, but not in 5B. The section was constructed by projecting observed and measured features (faults, bedding, sediment body geometry) onto a plane parallel to the inferred direction of ice movement and removing the vertical-scale exaggeration. This approach was made possible by the fact that the large-scale geometry of the different parts of the section showed no major aberrations along the bluff. The resulting cross-section gives a principally correct picture of the overall glaciotectonic structure and geometry of the section. The most notable feature is that the orientation of till unit B and the associated clay C follows the bedding of the units above and below and not any large scale thrust plane cutting across the bedding, suggesting that these units lie in their correct stratigraphical position.

Unit E, floodplain alluvium

The transition between units D and E in section 3 is marked by a series of tabular cross-bedded coarse sand beds with sharp, erosional lower boundaries highlighted by scattered clay balls. Thickness of individual beds varies between 10 and 55 cm, occasionally separated by truncated layers of massive or laminated clay up to 5 cm thick. Palaeocurrent measurements reflect sediment transport towards the east and southeast. Cryoturbation features and frost-cracks up to 20 cm deep were observed in several places and suggest at least seasonal subaerial exposure. We interpret these sediments as showing a transition to an overbank environment following the westwards shift of the main channel.

The sand beds are overlain by a 12 m thick succession of interbedded mud and fine to medium sand. Sand beds are light brown to pale yellow and range from 2 to 40 cm in thickness. They are either massive or exhibit parallel or ripple lamination. Iron staining in some of the massive beds produces a mottled appearance, typical for well-sorted windblown deposits. The soles of single beds are generally sharp but conformable; no clearly erosional contacts could be identified. The interbedded mud layers are 0.3 to 40 cm thick and black to reddish brown, contain fine-grained organic detritus, and often drape current ripples in the sand beds. The whole unit is cut by frost-cracks at varying levels indicating periodic subaerial exposure and freezing of the ground. Some frost-cracks are polycyclic, reaching a maximum length of up to 3 m.

Unit E is interpreted as a tundra floodplain deposit. Deposition took place during alternating periods of sheet-floods inundating the plain, and periods of subaerial exposure characterised by aeolian activity and freezing of the ground.

Unit F, basal till

Unit F (Fig. 7) is a well-consolidated, matrix-supported diamicton containing less than 5% clasts. Apart from ubiquitous shell fragments no organic remains were observed. The diamicton can be separated into two distinct horizons by colour and structure.

The lower 4 m of unit F is bluish-black with a sandy silty-clay matrix. Thin, discontinuous seams of sand give the diamicton a stratified appearance and show streamlining

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Figure 6  Clearing between sections 3 and 4. The fluvial sand D has an erosional lower boundary, which here cuts through the marine clay C and into the basal till B. Bedding of the fluvial sand is continuous laterally across the boundary from B to C. A number of small thrust-faults can be seen fanning out from between till B and the marine clay C where it pinches out. Displacement along each of these thrusts is less than 5 cm. This illustrates that the contacts between units B and C and C and D are sedimentary and lie in correct stratigraphical succession.

Figure 7  Uppermost part of section 4 (Figs 4, 5 and 8) showing floodplain deposits E, the basal till F, the ablational complex G and solifluction H.
around boulders and large rafts of coarse sand, bluish silt and massive black clay.

The upper part of unit F is dark grey with a slightly more sandy matrix, fewer clasts and only scattered sand seams. It exhibits numerous closely spaced, ferruginated cracks, which give the sediment a reddish appearance at distance.

Two clast-fabric-analyses from the upper and lower part of the diamicton show a preferred NE-SW long-axis orientation of clasts. The fabric is parallel to the sharp northeast-dipping lower boundary of the diamicton, which cuts the underlying sediments at a low angle. Sand seams, defining shear planes oriented subparallel to the lower boundary of the diamicton, show the same direction of dip towards the northeast, as do shear bands and small thrust-faults in the underlying sand. Unit F is interpreted as a basal till deposited by a glacier advancing from the northeast.

Unit G, flow till/ablational complex

The contact between F and G is marked by a zone where lenses of unit F are surrounded by a matrix of unit G. Unit G consists of a diamicton with a granulated silty sand matrix and numerous lumps of peat and pieces of wood. Clasts constitute less than 5% of the sediment and are generally less than 40 cm in diameter. The diamicton is characterised by numerous flow-structures with varying orientations, appearing as discontinuous lenses and diapirs of sand with gravel and intraclasts of clay (Fig. 7). Normal faults cutting these sand bodies are ubiquitous and show varying but locally consistent dip directions.

Unit H, solifluction

There is a gradual transition from the flow-till (unit G) to the overlying unit H, which is a brownish, sandy diamicton with less than 5% clasts (Fig. 7). The uppermost part is modified by present-day soil processes. The diamicton has a stratified appearance, with thin, discontinuous seams of sorted sand reflecting downslope flow. Pieces of wood are common and peat clasts seen embedded in the diamicton are surrounded by flow structures. Pebbles are often angular as opposed to the underlying tills, where clasts are mainly rounded or subangular. Unit H is interpreted as a solifluction deposit; the angular pebbles may indicate frost shattering.

Dating

Radiocarbon and luminescence age-estimates are listed in Tables 1 and 2 respectively, and summarised in Fig. 8. Luminescence age-estimates are listed in Table 3.

Unit G is interpreted as a series of amalgamated debris flows and outwash-sediments partly deposited during thermokarst collapses caused by melting of the permafrost. A genetic association between the underlying basal till, unit F, and the upper part of F. The presence of peat and wood in the sediment suggests that the permafrost was covered by vegetation prior to melting of the permafrost. Similar sediments have been described from the Markhida type site (Tveranger et al., 1995).

### Table 1

List of radiocarbon age-estimates. Samples prefixed by T were dated by the Laboratory for Radiologic Dating, University of Trondheim, Norway; these prefixed by TUA were prepared at the Trondheim Laboratory and measured at the Swedberg Laboratory, Uppsala University, Sweden; these prefixed by BETA were dated by Beta Analytical Inc., Florida, USA; those dated by AMS are marked with an asterix. Note that BETA-099885 and BETA-099886 were taken from a 4 cm interval of a peat bed within the fluvial sediments. BETA-110565, BETA-110566 and BETA-110567 were taken from a lateral correlative of the same peat bed.

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<tr>
<td>T-12339</td>
<td>11/5</td>
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<tr>
<td>T-12340</td>
<td>11/6</td>
</tr>
<tr>
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<td>11/7</td>
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<tr>
<td>T-12342</td>
<td>11/8</td>
</tr>
<tr>
<td>BETA-099885*</td>
<td>19-23A</td>
</tr>
<tr>
<td>BETA-099886*</td>
<td>19-23B</td>
</tr>
<tr>
<td>BETA-110565*</td>
<td>960044A</td>
</tr>
<tr>
<td>BETA-110566*</td>
<td>940044B</td>
</tr>
<tr>
<td>BETA-110567*</td>
<td>960044C</td>
</tr>
<tr>
<td>TUA-1910*</td>
<td>956512A</td>
</tr>
<tr>
<td>BETA-110569*</td>
<td>956512B</td>
</tr>
<tr>
<td>TUA-1911*</td>
<td>956511A</td>
</tr>
<tr>
<td>BETA-110568*</td>
<td>956511B</td>
</tr>
<tr>
<td>BETA-110571*</td>
<td>11/17C</td>
</tr>
<tr>
<td>TUA-1908*</td>
<td>11/17B</td>
</tr>
</tbody>
</table>

Unit, location

- H, section 4 at 92 m a.s.l.
- G, section 4 at 89 m a.s.l.
- G, section 4 at 89 m a.s.l.
- E, section 4 at 79 m a.s.l.
- E, section 4 at 78 m a.s.l.
- E, section 4 at 68 m a.s.l.
- D, section 4 at 66 m a.s.l.
- D, section 4 at 64 m a.s.l.
- D, section 4 at 64 m a.s.l.
- D, section 4 at 64 m a.s.l.
- D, section 4 at 64 m a.s.l.
- D, section 4 at 64 m a.s.l.
- D, section 3 at 56 m a.s.l.
- D, section 3 and 56 m a.s.l.
- D, section 3 at 46 m a.s.l.
- D, section 4 at 60 m a.s.l.
- D, section 3 at 60 m a.s.l.
- D, section 3 at 60 m a.s.l.
- D, section 3 at 46 m a.s.l.
- A, section 4 at 45 m a.s.l.
- A, section 4 at 45 m a.s.l.

Dated material

- Wood (Salix), redeposited
- Wood (Salix), redeposited
- Wood (Salix), redeposited
- Wood (Picea or Larix), redeposited
- Bulk sample, peat clast, redeposited
- Bulk sample, peat clast, redeposited
- Wood (Picea or Larix), redeposited
- Bulk sample, peat clast, in situ peat
- Hand-picked moss stems, in situ peat
- Hand-picked moss stems, in situ peat
- Hand-picked moss stems, in situ peat
- Hand-picked moss stems
- Hand-picked moss stems
- Hand-picked moss stems
nescence dating of unit 2 in the stratigraphical scheme of Golbert et al. (1973) (Fig. 3) yielded age-estimates between 91 and 110 ka BP (Table 2), and three U/Th dating of mol-

Table 2

<table>
<thead>
<tr>
<th>Laboratory number</th>
<th>Sample</th>
<th>Unit, location and sediment</th>
<th>Mineral</th>
<th>Dose rate (Gy ka(^{-1}))</th>
<th>(D_e) (Gy)</th>
<th>Age (ka)</th>
<th>Age (F/Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-962519</td>
<td>956509</td>
<td>D, section 3, 57 m a.s.l. Ripple laminated fine sand</td>
<td>Q</td>
<td>1.70</td>
<td>128(_i)</td>
<td>75 ± 14</td>
<td>0.67</td>
</tr>
<tr>
<td>R-962520</td>
<td>956510</td>
<td>D, section 3, 57 m a.s.l. Ripple laminated fine sand</td>
<td>Q</td>
<td>1.42</td>
<td>104(_i)</td>
<td>73 ± 8</td>
<td>0.64</td>
</tr>
<tr>
<td>R-962518</td>
<td>956507</td>
<td>D, section 3, 46 m a.s.l. Ripple laminated medium sand</td>
<td>Q</td>
<td>1.45</td>
<td>96(_i)</td>
<td>66 ± 8</td>
<td>0.68</td>
</tr>
<tr>
<td>PEC20</td>
<td>960041</td>
<td>C, section 3, Marine clay</td>
<td></td>
<td></td>
<td></td>
<td>&gt;148</td>
<td></td>
</tr>
<tr>
<td>PEC21</td>
<td>960042</td>
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<td></td>
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<td></td>
<td>&gt;140</td>
<td></td>
</tr>
<tr>
<td>PEC22</td>
<td>960043</td>
<td>C, section 3, Marine clay</td>
<td></td>
<td></td>
<td></td>
<td>&gt;105</td>
<td></td>
</tr>
<tr>
<td>R-962517</td>
<td>956506</td>
<td>A, section 3, 39.5 m a.s.l. Ripple laminated fine sand</td>
<td>Q</td>
<td>1.52</td>
<td>87(_i)</td>
<td>57 ± 7</td>
<td>0.84</td>
</tr>
<tr>
<td>R-962516</td>
<td>956505</td>
<td>A, section 3, 38 m a.s.l. Trough cross-bedded medium sand</td>
<td>Q</td>
<td>1.68</td>
<td>101(_i)</td>
<td>60 ± 9</td>
<td>0.73</td>
</tr>
<tr>
<td>R-962515</td>
<td>956504</td>
<td>A, section 3, 23 m a.s.l. Trough cross-bedded medium sand</td>
<td>Q</td>
<td>1.06</td>
<td>82(_i)</td>
<td>77 ± 11</td>
<td>0.58</td>
</tr>
<tr>
<td>R-962514</td>
<td>956503</td>
<td>A, section 3, 22 m a.s.l. Trough cross-bedded medium sand</td>
<td>Q</td>
<td>1.29</td>
<td>69(_i)</td>
<td>54 ± 7</td>
<td>0.85</td>
</tr>
<tr>
<td>R-942504</td>
<td>93-11/16</td>
<td>2, section 4, 26 m a.s.l. Tabular foresets in medium sand</td>
<td>Q</td>
<td>1.76</td>
<td>194(_i)</td>
<td>110 ± 14</td>
<td>0.89</td>
</tr>
<tr>
<td>R-962512</td>
<td>956501</td>
<td>2, at 700 m (Fig. 5A)   Tectonised fine sand</td>
<td>Q</td>
<td>1.92</td>
<td>174(_i)</td>
<td>91 ± 10</td>
<td>0.95</td>
</tr>
<tr>
<td>R-962513</td>
<td>956502</td>
<td>2, at 700 m (Fig. 5A)   Tectonised fine sand</td>
<td>Quartz</td>
<td>2.37</td>
<td>221(_i)</td>
<td>92 ± 10</td>
<td>1.17</td>
</tr>
</tbody>
</table>
We interpret the results as showing unit D to be older than unit E and conclude tentatively that the youngest dates (25–32 ka BP) reflect the age of the beds. This is supported by macrofossil analysis of in situ peat beds, reflecting a cooler-than-present shrub tundra vegetation (H. Birks, pers. comm.).

The luminescence datings of unit D yielded age-estimates between 66 and 75 ka BP. This is similar to the dates obtained from the underlying unit A (54–77 ka BP). The young radiocarbon dates from unit D may, however, suggest that the luminescence datings of unit D probably are due to incomplete zeroing of the luminescence signal prior to deposition of the samples dated; an interpretation supported by the inferred rapid deposition of unit D.

Radiocarbon dating of wood fragments from the ablational complex unit G yielded 9420 ± 105 and 9790 ± 130 yr BP (Table 1). A further wood fragment from the lower part of unit H yielded an age of 9395 ± 80 yr BP. These age-estimates support the interpretation of these deposits as generated during the Early Holocene degradations of forested permafrost.

Discussion and conclusions

Unit A, Eemian/Early Weichselian fluvial deposits

Our genetic interpretation of unit A as fluvial is in agreement with previous workers (Zagorskaya et al., 1969; Golbert et al., 1973; Epstein, 1990), but with the following modifications: unit A probably represents an interglacial or inter-stadial setting. We find no supporting evidence that the lower boundary of unit A represents a major erosional unconformity including an Early Weichselian ice advance, as suggested by Golbert et al. (1973). In our opinion unit A can be considered a normal facies succession from the underlying Eemian clay, representing a coastal progradation possibly linked to a relative sea-level fall at the end of the Eemian. Support for this view is also found in the fact that Golbert et al. (1973) identified a marine sand (3d, not observed by us) overlying the Eemian clay and containing the highest number of boreal mollusc species in the section. The presence of ox-bow lakes overlain by a second set of channels suggests that the upper part of unit A was deposited during a period of relative sea-level rise.

Units B and C, Early to Middle Weichselian ice advance and transgression

These two units were described previously as a single unit of ‘till-like loam’ by Golbert et al. (1973). All previous workers agree that these beds have been subjected to shear and deformation caused by the glaciotectonic deformation of the section. Epstein (1990) considers them the lower part of separate thrust sheets, with the clay component deriving from the Eemian clay. Lavrov (1981) interpreted these diamict beds as ‘till . . . dumped into open hollows in fault zones between sliced blocks’ and originating from the basal till on top of the section. Injection from above was also suggested by Golbert et al. (1973), but a partly in situ marine origin of the clay component was postulated as well, based on the contrasting foraminiferal assemblages of the ‘till-like loam’, as compared with the Eemian clay and the basal till on top of the section.

During our reinvestigation we followed units B and C along the bluff where they were exposed. As previously described, the degree of secondary deformation of these two units varies widely as does their thickness and appearance. Differentiation between units B and C was possible only where subsequent deformation has been slight or absent altogether. Around section 3 both units appear virtually undisturbed. Here deformational features include only shear and catchment structures normally found underneath basal tills, and evidence of 10–15 cm lateral movement along the sand layer between units B and C. No deformation features were observed immediately above unit C. Where till B and the marine clay C have acted as shear planes, the overlying sandy unit D always shows evidence of brecciation and intraformational shear indicating secondary deformation of units B, C and D. Both the very strong fabric of unit B as well as the presence of shells in living position in unit C exclude any origin of these beds due to injection or ‘dumping into hollows’. Furthermore our observations indicate that units B, C and D were deposited in succession (Fig. 6), this is also supported by the Foraminifera of unit C reflecting an increasing input of fresh water up towards the lower boundary of the fluvial unit D.

We are confident in the interpretation of unit B as a basal till. If we accept this, the age and origin of this till can be interpreted in three different ways:

1. Till B is pre-Eemian and glaciotectonically upthrusted to its present position by the youngest ice advance. The marine clay C could in this interpretation be of Eemian age, as indicated by the TL age-estimates. There is, however, no documented older till underlying the Eemian beds at this site, and the youngest documented pre-Eemian till in the region has a pronounced NW–SW and locally even W–E fabric (Guslitser et al., 1985). It would thus be noteworthy if the fabric of this till, when upthrusted by the last ice advance from the northeast, would show the same direction of ice movement as the surrounding deformation structures, i.e. northeast and not northwest, as is the case at Vastiansky Kon’.

2. The till represents an early phase of the last ice advance, which subsequently deposited till F. Here the marine clay C is considered a raft of marine clay within till B, and units D and E are considered stacked on top of till B by the last ice advance which subsequently deposited till F. This interpretation is compatible with the luminescence dates of units A and D. However, this alternative is largely invalidated by the observation shown in Fig. 6 because it requires the boundary C–D to be of tectonic
origin. It is also in conflict with the foraminifer faunas
and interpretation of the sedimentary facies, which both
indicate that the transition from unit C to D reflects a
normal marine-to-estuarine/fluvial facies succession.

3. Till B and the overlying marine clay C are situated in
their original stratigraphical position and represent a
 glaciation followed by a transgression. The age of these
events is bracketed by the age of the underlying
Eemian/Early Weichselian deposits and the presumed
Middle to Late Weichselian age of the overlying units D
and E.

Interpretation 1 and 2 envisage units A and D/E deposited
originally in lateral succession and subsequently glaciocen-
tically superimposed. This may explain the large strati-
graphical thickness of the post-Eemian succession (Fig. 8).
Interpretation 3 envisages that the site was situated in deep
water during the Eemian and within the main fluvial depo-
centre of the Pechora lowland during the subsequent sea-
level fall and coastal progradation. Combined with a postu-
lated glacioisostatic downwarping during the ice advance
depositing till B, which created further accommodation
space, and a slow isostatic recovery accompanied by abun-
dant sediment influx, a vertical accumulation of 30 m of
sediments prior to the last ice advance is considered feasible.
For comparison, similar sediment thicknesses (50–60 m) have
been reported from boreholes in Eemian deposits of the
Severnaya Divina area (Plishevtseva and Grib, 1965).

A conclusive test in favour of interpretation 3 versus 1
and 2 would be if we could prove the marine clay C to be
considerably younger than the Eemian. Dating of clay C by
TL failed to prove this (Table 2). Amino acid D/L ratios on
a single, well preserved specimen of *Hiatella arctica* from
clay C yielded HYD values of 0.057 and 0.061, but the
large spread in D/L values from the same species collected
from the Eemian beds of Vastiansky Kon’ and well-dated
Eemian localities along the River Sula (Mangerud et al.,
1998) ranging from 0.038 to 0.101, allow no conclusions
as to the relative age of clay C versus the Eemian.

If interpretation 3 is correct it implies that there have been
at least two advances of the Kara Sea Ice Sheet on to the
Pechora lowland during the Weichselian. The existence of
an Early or Middle Weichselian glaciation in this area has
not been documented previously but its existence has been
postulated based on circumstantial evidence (Y. Lavrushin,
pers. comm.) and comparison with the glacial history of the
Kara Sea Ice Sheet in West Siberia (Astakhov, 1992).
Although a possible Early/Middle Weichselian glaciation
needs to be corroborated by further field studies, we propose
the chrono- and event-stratigraphic scheme shown in
Figure 8 based on the material from Vastiansky Kon’.

Units F, G and H, Late Weichselian ice
advance and deglaciation

The diamict unit F, which caps the bluff, represents the
previously identified till of the last ice advance, which also
caused the glaciotectonic deformation. The age of till F is
apparently sandwiched between the finite radiocarbon age-
estimates (25–32 ka BP) from the underlying unit, and the
Early Holocene dates from the ablational complex (unit G).
A corresponding diamict sequence with similar age restric-
tions was reported by Tveranger et al. (1995) from the
Markhida type site, but recent re-dating of the subtilt lumi-
nescence samples providing the maximum age of the till
yielded age-estimates between 58 and 62 ka BP (A. Murray,
pers. comm.). We tentatively conclude that the last ice
advance in the area took place during the Late Weichselian,
the finite age-estimates from the floodplain unit E are, how-
ever, too few in number to allow us to positively exclude
an older age of the youngest ice advance.

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References

demic Press, New York.

ARSLANOV, KH. A., BERDOVSKAYA, G. N., LOSEVA, E. I. and
FILINOV, B. A. 1975. New data on the terrestrial Mikulino
deposits on the Lower Pechora, *Vestnik, Leningrad University,*
N24(4), 139–142. Translated 1994 by A. Zamoruyev and V. Astak-
hov.

ARSLANOV, KH. A., LAVROV, A. S., LYADOV, V. V., NIKIFIROVA,
L. D., POTAPENKO, L. K. and TERTYCHNAYA, T. V. 1980. The
radiochronology and paleogeography of the Mid-Valdai
interval and last ice sheet in the North-East of the Russian Plain.
In: *Geokhronologa chetvertichnogo perioada*. M. Nauka, Moscow.
Translated 1994 by A. Zamoruyev and V. Astakhov.

ARSLANOV, KH. A., LAVROV, A. S., POTAPENKO, L. M., TERTY-
CHNAYA, T. V. and CHERNOV, S. B. 1987. New data on the
