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The chronology of a large ice-dammed lake and the Barents–Kara Ice Sheet advances, Northern Russia

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Abstract

Beach and shoreface sediments deposited in the more than 800-km long ice-dammed Lake Komi in northern European Russia have been investigated and dated. The lake flooded the lowland areas between the Barents–Kara Ice Sheet in the north and the continental drainage divide in the south. Shoreline facies have been dated by 18 optical stimulated luminescence (OSL) dates, most of which are closely grouped in the range 80–100 ka, with a mean of 88 ± 3 ka. This implies that that the Barents–Kara Ice Sheet had its Late Pleistocene maximum extension during the Early Weichselian, probably in the cold interval (Rederstall) between the Brørup and Odderade interstadials of western Europe, correlated with marine isotope stage 5b. This is in strong contrast to the Scandinavian and North American ice sheets, which had their maxima in isotope stage 2, about 20 ka. Field and air photo interpretations suggest that Lake Komi was dammed by the ice advance, which formed the Harbei–Harmon–Sopkay Moraines. These has earlier been correlated with the Markhida moraine across the Pechora River Valley and its western extension. However, OSL dates on fluvial sediments below the Markhida moraine have yielded ages as young as 60 ka. This suggests that the Russian mainland was inundated by two major ice sheet advances from the Barents–Kara seas after the last interglacial: one during the Early Weichselian (about 90 ka) that dammed Lake Komi and one during the Middle Weichselian (about 60 ka). Normal fluvial drainage prevailed during the Late Weichselian, when the ice front was located offshore. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ice-dammed lake; Early Weichselian; northern Russia; luminescence dating; lake beaches; glacial history

1. Introduction

When ice sheets on the continental shelves of the Barents and Kara seas expanded onto the Russian mainland, the north-flowing rivers were blocked (Fig. 1). As a result, large ice-dammed lakes formed between the ice-sheet in the north and the continental drainage divide in the south (Figs. 2 and 3) (e.g. Arkhipov et al., 1995; Grosswald, 1980; Kvasov, 1979; Lavrov, 1975; Lavrov and Potapenko, 1989). The damming of the West Siberian rivers (Yenissei and Ob) led to an overflow to the Aral Sea with further drainage to the Caspian and Black seas (Fig. 1). All the authors cited above suggest a Late Weich-

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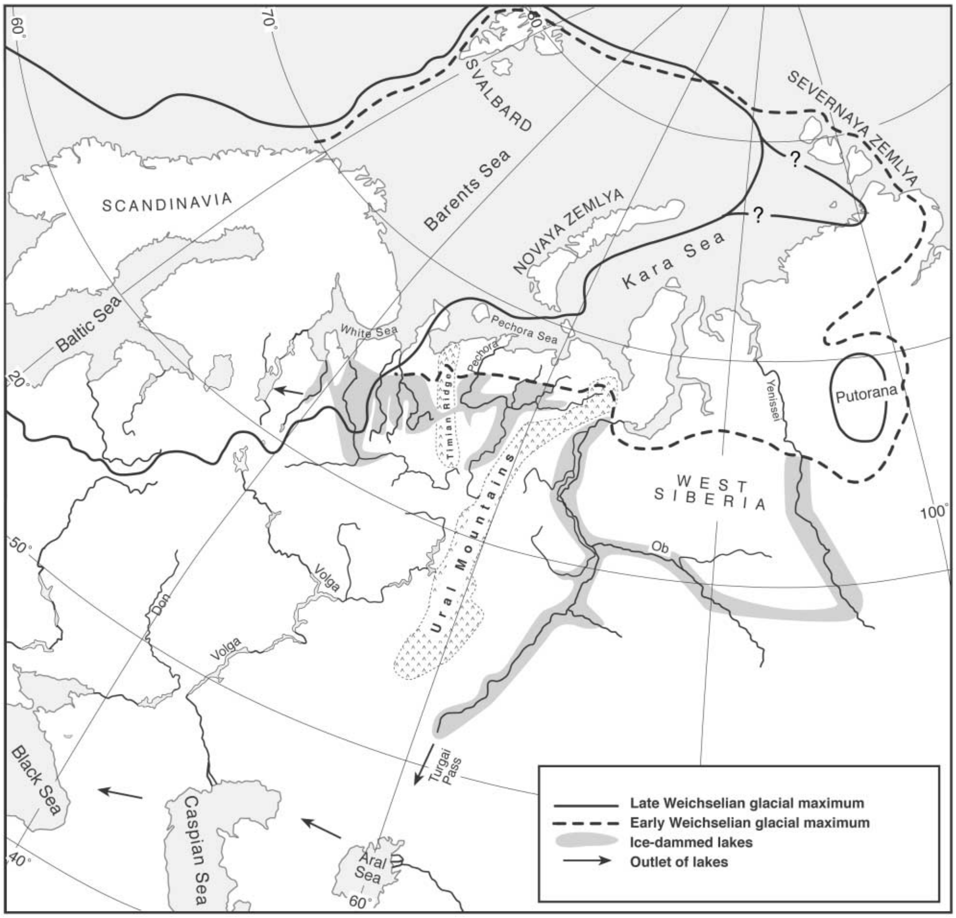

Fig. 1. Sketch map of northern Russia and adjacent areas. The limit of the Late Weichselian maximum of the Barents–Kara Ice Sheet is slightly modified from Svendsen et al. (1999). The Early Weichselian glacial limit is also from Svendsen et al. (1999), but subsequent work has indicated that it is not a synchronous line. Here the line is shown more as an example of an ice sheet blocking all northward drainage in both the West Siberia and European Russia. Lake Komi is the ice-dammed lake west of the Ural Mountains, shown in more detail in Fig. 2. Postulated contemporaneous ice-dammed lakes in West Siberia are also shown. Arrows mark overflow passes.

selian age for the last lakes in European Russia. This latter assumption was recently falsified by Astakhov et al. (1999) and Mangerud et al. (1999). They demonstrated that the last ice-dammed lake, named Lake Komi, existed in front of an Early Weichselian Barents–Kara Ice Sheet, and that the Russian mainland remained ice-free during the Late Weichselian (Svendsen et al., 1999). The latter conclusion was subsequently supported by Polyak et al. (2000) and Gataullin et al. (2001) based on sea floor mapping and dating of cores, and by Forman et al. (1999) based on studies on the Yamal Peninsula.

The shorelines of Lake Komi have been mapped in the Pechora lowland and can be traced across the Timan Ridge into the catchments of the Mezen and Dvina rivers (Fig. 2) (Astakhov et al., 1999). The shoreline is about 90 m a.s.l. in the southern part of the Pechora Valley and about 110 m a.s.l. close to the former ice sheet margin in the north (Fig. 3). Lake Komi extended along the Pechora Valley for a length of more than 800 km, and the maximal extension from NE to SW was 1400 km (Fig. 3). The outlet was probably located near Lake Onega, with further drainage towards the Baltic Sea (Maslenikova and Mangerud, 2001).

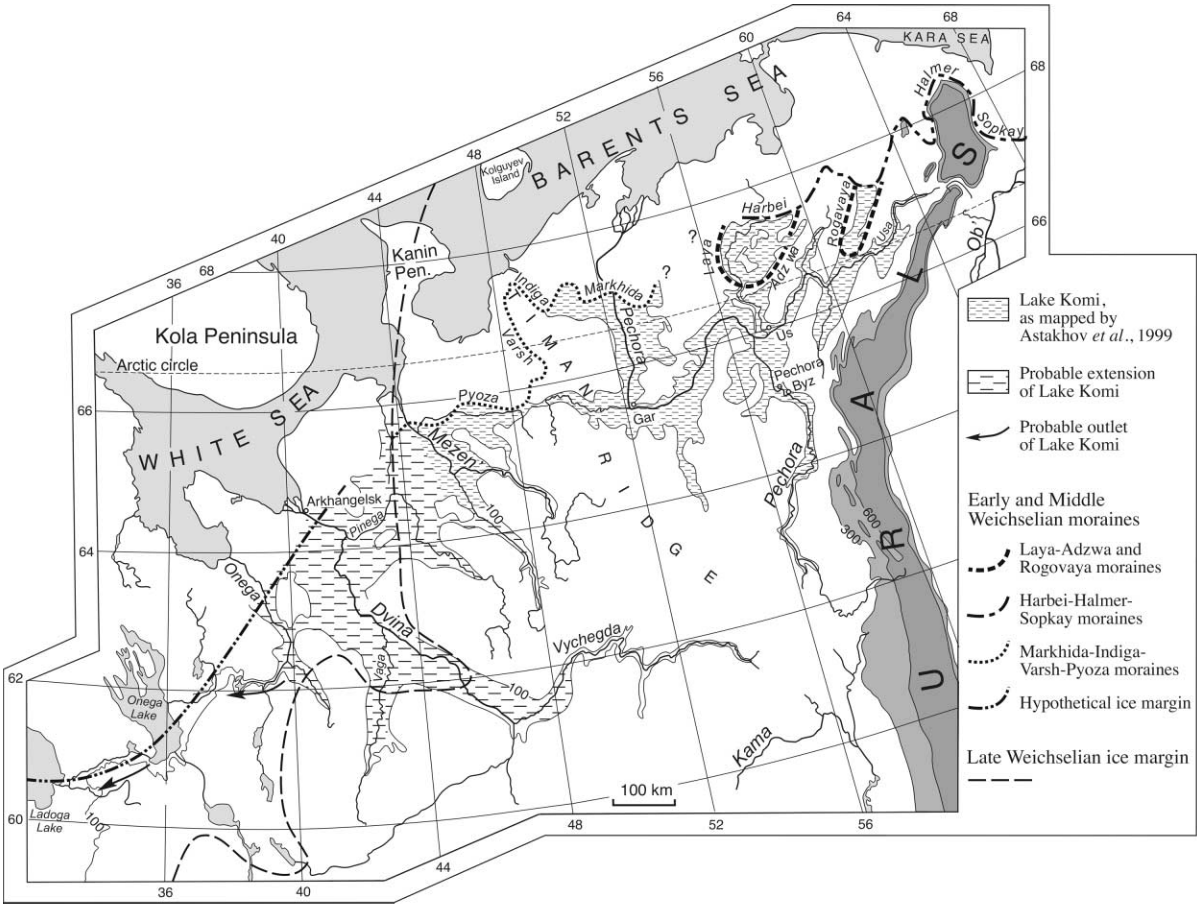

Fig. 2. Map of Lake Komi modified from Maslenikova and Mangerud (2001). Names are given on the different moraines that earlier were correlated and collectively called the Markhida Line (Astakhov et al., 1999). In the alternative hypothesis presented in this paper, the Markhida–Indiga–Varsh–Pyoza moraines are postulated to be about 60 ka old and Harbei–Halmer–Sopkay of the same age as Lake Komi, about 90 ka. The Laya–Adzwa and Rogovaya lobes are clearly older than the youngest phase of Lake Komi, but probably contemporaneous with the older part. Us: Usinsk, Gar: Garevo, Byz: Byzovaya.

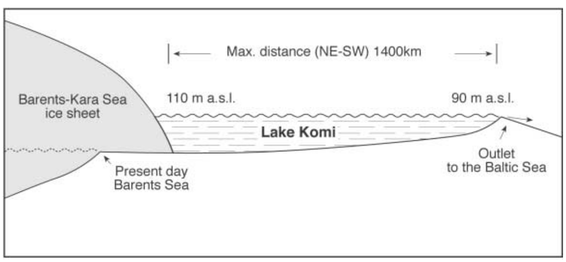

Fig. 3. Conceptual N–S cross-section of northern European Russia at 90 ka. Lake Komi is dammed between the Barents–Kara Ice Sheets in the north and the continental water divide to the south. Beach elevation differences are due to the later glacio-isostatic tilting.

In this paper, we describe five exposed sections of Lake Komi shorelines in the Pechora lowland, distal from the ice front. We present the results of 18 OSL dates from these sections, indicating an Early Weichselian (80–100 ka) age for the existence of the lake, and we discuss the implications for the glacial history.

2. Methods

Samples for luminescence dating were taken by driving plastic tubes (11-cm diameter), each with a black plastic bag taped over their outer end, into a sediment face. The cut surface, representing a very small fraction of the sample, was exposed for less than 2 s during sampling. The rest of the sample flowed through the tube and into the bag without any exposure. In the laboratory, the bags were opened under dim red/orange light (similar to a photographic darkroom). One portion was taken for dose rate measurements, and another portion was sieved to extract the appropriate grain size (in the range 90–300 μm, depending on the sample). This subsample was then treated with HCl, H_2O_2 and HF, and the dry grains mounted for measurement using silicone oil (Silspray) on 9.7-mm diameter stainless steel disks. The absence of feldspars was confirmed by measuring the infrared stimulated luminescence following a laboratory regenerative beta dose greater than or equal to the anticipated equivalent dose. No sample was rejected following this test.

All luminescence dates used the Single Aliquot Regenerative (SAR) dose protocol applied to quartz to estimate the equivalent dose. This protocol is described in detail by Murray and Wintle (2000). Most of the equivalent dose lies in the range 100–200 Gy. A representative growth curve for a single aliquot is given in Fig. 4. Results of the internal tests

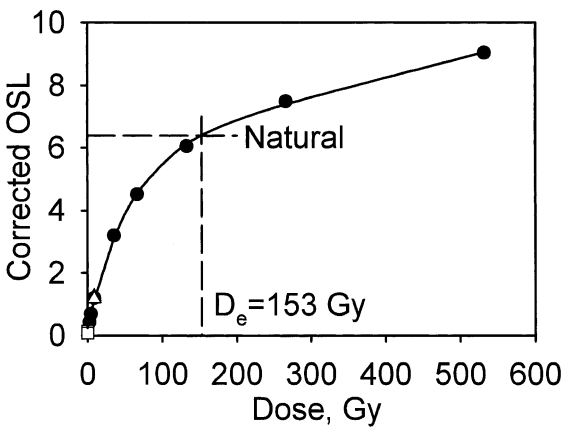

Fig. 4. Single-aliquot regenerative dose growth curve for an aliquot of sample 992527 derived using the protocol described in Murray and Wintle (2000). The dashed line represents the interpolation of the corrected natural OSL signal onto the growth curve. The derived value of the equivalent dose (D_e) is also shown. After the largest regeneration dose (530 Gy) cycle was completed, the 9-Gy point was repeated (open triangle) and the origin was measured using a 0-Gy cycle (open square).

recommended by Murray and Wintle (2000), i.e. repetition of a small regenerative dose after the large doses (open triangle, Fig. 4), and measurement of the zero dose response (open square) are also shown. The sensitivity-corrected natural response intersects the growth curve in the nonlinear region, as the growth curve begins to saturate. The number of aliquots (n) used to obtain each mean estimate of the equivalent dose is given in Table 1. All samples were also analysed for natural series radionuclide concentrations using high-resolution gamma spectrometry as described in Murray et al. (1987). These concentrations were converted into dose rates using the conversion factors listed in Olley et al. (1996). A correction was made for the internal alpha activity in quartz using an average value based on unpublished concentration measurements using neutron activation by Mejdahl (personal communication, 1996). The a value was taken as 0.15. This internal contribution is typically only a few percent of the total dose rate, and so large uncertainties in the assumed values do not affect the overall result. Dose rates were corrected for water content effects (Aitken, 1985) before the addition of a cosmic ray dose contribution. The saturated water content of these sediments has been estimated from laboratory settling experiments using various degrees of compaction at $27 \pm 3\%$ with respect to dry weight. The importance of this assumption is evaluated in Section 6.

3. Sedimentary facies and shoreline terminology

The processes active on a clastic lake shore are generally the same as those on a marine shore, except for the absence of tides and a shorter wave fetch (Talbot and Allen, 1996). The sediments described here also lack traces of bioturbation. In this paper, we use a simplified shoreline terminology modified from that pertaining to marine shores (Fig. 6 in Reading and Collinson, 1996):

The term "beach" is used to include the berm and swash zone. Our beaches comprise low-angle dipping gravel beds, generally clast supported, and coarse sand facies, interpreted as deposited from bed-load traction driven by wave movement.

The term "shoreface" is used for the zone between the beach and the fair-weather wave base. The

Table 1
List of all dates from Lake Komi sediments and one sample (Risø no. 982509 yielding 141 ka) from underlying sediments
A water content of 27% is used for age calculations for all listed samples.

Risø laboratory no.	Field no. PECHORA	Site	Sediment, stratigraphy, etc.	Age (ka)	Uncertainty (ka)	Equivalent dose (Gy)	*n*	Annual dose rate (Gy/ka)
972505	1996–2020	Garevo	depth 3 m; sand bed in the beach gravel	99	13	134 ± 15	7	1.06
972507	1996–2024	Garevo	depth about 7.5 m; ripple-laminated fine sand	94	8	168 ± 11	4	1.78
972506	1996–2023	Garevo	depth about 8 m; laminated fine sand	82	10	142 ± 15	3	1.74
982505	1996–2093	Byzovaya	depth 1 m below top of gravel, corresponding to 1.7 m in logged section; massive sand bed in gravel	84	9	41 ± 3	11	0.49
982506	1997–3083	Byzovaya	depth 0.7 m below the thick gravel, corresponding to 5.7 m depth in log; cross-stratified fine sand	53	4	87 ± 4	23	1.63
992526	1996–2092	Byzovaya	depth 7.0 m; from 20-cm thick bed of cross-stratified sand	106	11	98 ± 8	15	0.93
982507	1997–1005	Byzovaya	depth 11 m; 15–20-cm thick sand bed that laterally grades to gravel	78	6	62 ± 3	32	0.79
982508	1997–1003	Byzovaya	depth 12.3 m; parallel-laminated fine sand, 30 cm below gravel	83	8	91 ± 7	56	1.08
982509	1997–3081	Byzovaya	depth corresponding to 23.5 m in log; from 0.5 m silty sand in rust-stained gravel underlying Lake Komi sediments	141	15	262 ± 23	26	1.86
982517	1997–34	Bolotny Mys	depth 1.4 m; cross-stratified medium sand	97	23	104 ± 23	14	1.07
992527	1997–35	Bolotny Mys	depth 2.0 m; ripple cross-laminated fine to medium sand	171	13	166 ± 8	15	0.98
982518	1997–36	Bolotny Mys	depth 3.0 m; oscillation ripple-laminated fine sand	68	6	90 ± 6	15	1.32
982516	1997–29	Bolotny Mys	depth 5.9 m; cross-stratified medium sand	82	12	104 ± 14	13	1.27
982515	1997–28	Bolotny Mys	depth 7.0 m; oscillation ripple-laminated fine sand	82	14	123 ± 20	36	1.49
982519	1997–40	Ozyornoye	depth 2.6 m; horizontally bedded medium sand	97	10	112 ± 10	15	1.16
982520	1997–45	Ozyornoye	depth 3.8 m; fine sand; includes beds with horizontal lamination and oscillatory ripples	97	18	140 ± 24	9	1.44
982521	1997–52	Ozyornoye	depth 5.8 m; fine sand with oscillatory ripples	98	8	140 ± 7	15	1.44
982522	1997–59	Novik–Bozh	sand below the beach gravel in the N-end of the pit	97	8	192 ± 9	17	1.98
982523	1997–61	Novik–Bozh	sand below the beach gravel in the S-end of the pit; the two samples were collected at nearly the same elevation, so we assume they are nearly of the same age	106	8	183 ± 8	12	1.94

deposits of this zone are characterised mainly by alternating beds of parallel stratified and ripple cross-laminated fine sand, usually with bidirectional oscillatory ripples. In some outcrops, the shoreface deposits include large-scale cross-sets of fine to coarse sand, probably deposited by wave-generated currents. Isolated paleochannels are attributed to rip currents.

The term "offshore-transition" is used for the zone between the mean fair-weather and storm wave base, which would typically be represented by silt-dominated mud deposited from suspension, intercalated with storm-derived sand beds.

The outcrop sections described in this paper have been selected by their suitability for optical stimulated luminescence (OSL) dating and we have, therefore, chosen the beach and shallow water sediments with very little silt.

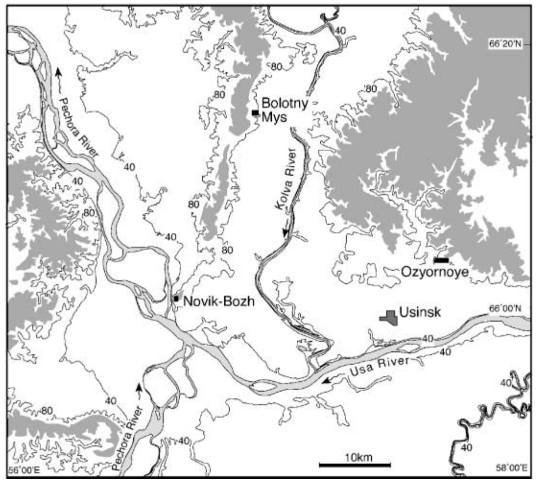

Fig. 5. Map of the area around the city of Usinsk. Shaded areas above the 100 m contour indicate approximately land areas around Lake Komi. The 80- and 40-m contours are included to indicate approximate paleobathymetry. The sites Ozyornoye, Bolotny Mys and Novik–Bozh (see text) are indicated.

4. Description of sites

We have obtained OSL dates from the five different sites described below. Ozyornoye, Bolotny Mys and Novik–Bozh are excavated pits around the city of Usinsk, used by the petroleum industry to extract beach sand and gravel for construction work. The Garevo site is a road cut, and the Byzovaya Ravine is a natural section. All sections are located well south of the ice front that dammed the lake (Fig. 2).

4.1. Ozyornoye

This abandoned pit (location on Fig. 5) is about 3 km long and 100–200 m wide. It is located between the 80- and 100-m map contours, with the top surface apparently close to 90 m a.s.l. We estimate that a 2–5-m thick layer of gravel and coarse sand has been exploited.

In the eastern end of the main pit, there was an even deeper excavation (Figs. 6 and 7). From 3.5 to 8 m depth on the composite scale on Fig. 6, the exposure is dominated by nearly horizontal beds of parallel-stratified, or ripple cross-laminated, fine sand, interpreted as shoreface facies. The upper metre of this excavation (3–4 m depth on Fig. 6), which is exposed over a length of 30 m, shows alternating beds of well sorted gravel and coarse sand, dipping about 5° (Fig. 7)—clearly a beach deposit. The occurrence of an ice wedge cast indicates subaerial exposure of the beach. The beach gravel is covered by gently (5–10°) dipping beds of shoreface sand capped by another beach gravel. This sequence indicates a rise of the lake level of at least 3 m after formation of the first beach and ice wedge cast.

Three samples from this section have been OSL dated, yielding consistent ages 97–98 ka (Fig. 6, Table 1). The sand sampled at about 3.5 m depth was deposited in a water depth of less than a metre; the two others at water depths of 2–3 m. Judging by the geometry of the deposit, most of the sand was deposited following wave erosion of the shoreline. This is supported by the fact that the southerly fetch was about 100 km. Some of the sediment could have been supplied to the beach through runoff from the upland which consists of till and other unconsolidated sediments.

4.2. Bolotny mys

This pit (location on Fig. 5) is several hundred metres long and adjacent to another pit in similar sediments 1 km to the north. The top of the gravel was measured with barometer to 89 m a.s.l. using Kolva River as reference level.

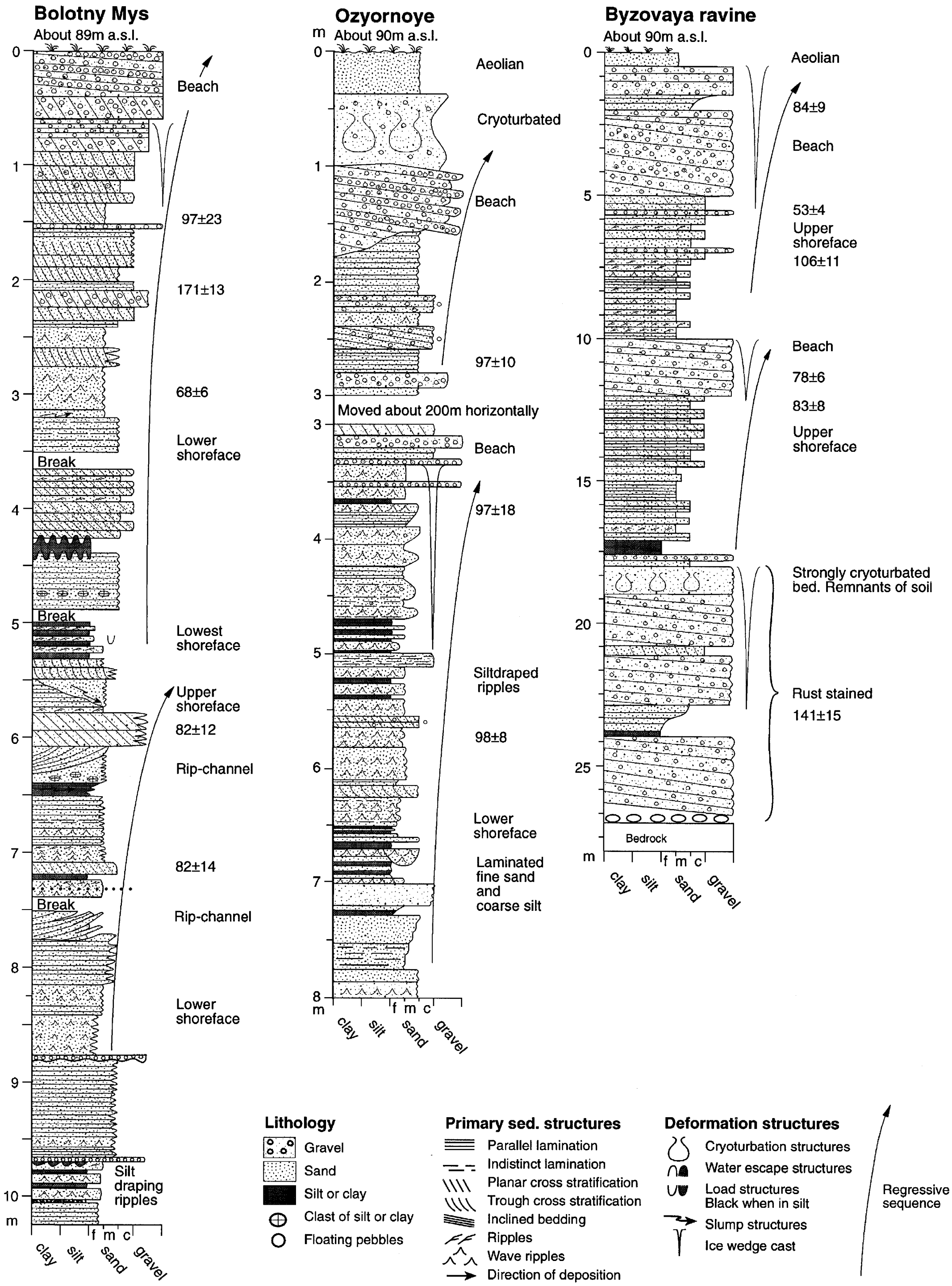

Fig. 6. Sedimentological logs from the sites Bolotny Mys and Ozyornoye presented on the same vertical scale. Simplified log from the Byzovaya ravine in a different vertical scale. OSL dates are indicated at correct depths (compare Table 1). According to the convention in the PANGEA database (http://www.pangaea.de/Info/) all thickness measurements are given from the top of the sections.

Fig. 7. The lower section at Ozyornoye from 3–8 m depth on Fig. 5. The scale sticks are 1 m (each black and yellow section 10 cm). An ice wedge cast is seen to the left of the upper stick.

In the lower part of the pit is a 4-m-high section with faintly parallel stratified, fine sand interbedded with about 30 silt beds that were only a few centimetres thick (shown as Fig. 24 in Mangerud et al., 1999). We interpret this sequence, which is not included in the log on Fig. 6, as offshore-transition facies.

The lower 5 m of the logged section (Fig. 6) consists of low-angle ($< 5°$) dipping beds (Fig. 8). There is a transition from parallel stratified or ripple cross-laminated fine sand in the lower part to cross-stratified, coarser sand in the upper, which is interpreted as a shallowing from lower to upper shoreface. The silt beds at about 5 m (Fig. 6) indicate deeper water and, thus, a rising lake level. From this level, there is a coarsening upward sequence to the beach gravel capping the section.

The Bolotny Mys pit is situated on the flank of a morainic ridge which formed a long and narrow (2 km) island in Lake Komi (Fig. 5). Sediment to the

Fig. 8. The lower part of the section at Bolotny Mys before the section was cleaned. The beds are generally parallel and dipping less than 5° as seen against the water table. The silt at 5 m in the log Fig. 5 is the dark bed in the upper right corner, whereas 10 m depth of the log is in the lower left corner.

beach could, therefore, only have been supplied by wave erosion and long-shore transport. All dated samples were taken from beds presumably deposited at water depths of less than 3 m.

Five samples in stratigraphic sequence are dated from this section. Four samples yielded ages from 68 ± 6 to 97 ± 23 ka, whereas one gave a significant higher age of 171 ± 13 (Fig. 6, Table 1).

4.3. Novik–Bozh

This pit (location on Fig. 5) is a few hundred metres long, but at present, only a small section is exposed. The upper surface of the gravel was measured with a barometer to 92 m a.s.l., using the Pechora River as a reference level.

The section exposes a 7.5-m thick sequence of gently dipping beds of well-sorted and well-rounded gravel. In both ends of the section, we observed a 1-m high exposure of foreshore sand below the gravel. The gravel is covered by (poorly exposed) solifluction deposits and up to 2 m of aeolian sand. Both units obviously post-dating Lake Komi.

The gravel formed a wide beach on the southern end of a narrow morainic island in Lake Komi (Fig. 5), evidently the result of strong wave action. One OSL sample was collected from each of the two sand exposures below the gravel, the results being 97 ± 8 and 106 ± 8 ka. The sand is found 8 m below the top of the beach deposit, indicating the maximum possible water depth during deposition.

4.4. Garevo

This site (location on Fig. 2) is described in Mangerud et al. (1999). The investigated sediments consist of sandy and gravelly beach deposits with a top surface at about 100 m a.s.l. The gravel is underlain by sand, interpreted as shoreface facies. One sample from the beach and two from the lower sand unit have been dated (Table 1), yielding ages in the range 82–99 ka. Note that these samples now are reported 6 ka older than in Mangerud et al. (1999) because now a water content of 27% is used in the calculations, compared to previously 14%.

4.5. Byzovaya

This is the southernmost of the studied sites (Fig. 2), situated 65° S in a ravine (Fig. 9) cut into the right bank of the Pechora River on the eastern fringe of the Byzovaya village. The ravine dissects a horizontal terrace about 90 m a.s.l., measured with a barometer using the Pechora River as a reference level.

From the flood level of the river upward, about 10 m of Triassic sandstone is exposed (27 m below surface at Fig. 6). Resting on this bedrock is a

Fig. 9. The Byzovaya Ravine. Note the man on top for scale. The lower part of the picture is about 17 m below the surface, i.e. just above the pre-Eemian gravel. The gravel 10–12 m below the surface is marked.

7–10-m thick unit of coarse gravel gently dipping northwards and interpreted as an old beach. The gravel is topped by a heavily cryoturbated sandy bed, including remnants of a paleosol with ventifacts and a large ice wedge cast, indicating long subaerial exposure. The gravel also differs from the overlying beds by being strongly rust-stained. We conclude that this lower unit is significantly older than the overlying Lake Komi sediments. An OSL date from a sand bed in the lower gravel gave an age of 141 ± 15 ka, suggesting that the unit pre-dates the Eemian.

This lower unit is overlain by two regressive sequences of Lake Komi shoreline sediments (Fig. 6). Above the cryoturbated sand follows a distinct coarsening upward sequence starting with laminated silt and ending with beach gravel at 10 m below the surface. A large ice wedge cast cutting into the top of this regressive sequence indicates subaerial exposure at a time when permafrost extended at least 3° farther south than today. This frozen beach was drowned by another lake level rise, as shown by the overlying coarsening upwards sequence, which starts with fine sand and ends with gravel forming the nearly horizontal terrace at 90 m a.s.l. (Fig. 9). The uppermost gravel consists partly of beds of well-sorted, fine gravel dipping 8° towards south and gradually flatting upwards to the surface (Fig. 10).

The paleogeographical situation at the time of Lake Komi was different at Byzovaya compared to the other sites. Byzovaya was located at the western edge of a large morainic plateau dissected by the Pechora River. Therefore, coarse sediment could have been transported to this site by rivers, although most sedimentary structures in the outcrop indicate final deposition by waves. Two of the samples were collected from sand in beach gravel. Sand sampled at the 12.3 m depth was deposited just below the beach, whereas the two other samples were deposited in slightly deeper water, but certainly less than 7 m.

Five samples have been dated by OSL (Table 1, Fig. 6). Four gave ages in the range 78 ± 6–106 ± 11 ka, but not in stratigraphic order. One yielded a younger age of 53 ± 4 ka (see discussion below).

5. Lake levels

Lake Komi must have started to flood the river valleys as soon as the Barents–Kara Ice Sheet blocked the Pechora and other north-flowing rivers. At that time, the relative sea level along the Pechora coast was probably lower than at present due to lower eustatic sea level. When the ice front moved southward, the dam became higher and raised the lake level. Nevertheless, onlapping beach gravel has not been observed at the base of the described sections.

The top layers in all five outcrops shows similar regressive sequences from foreshore sand to beach gravel. The altitude is about 90 m a.s.l. at Byzovaya, Bolotny Mys, Ozyornoye and Novik–Bozh, and 100 m at Garevo. Different altitudes are probably due to differential isostatic upwarping with a greater uplift close to the ice sheets.

At Byzovaya, there is also a buried regressive sequence from 18 to 10 m below the surface, showing that the rising lake level made a temporary halt at 80 m a.s.l. This level was stable long enough for formation of a beach and development of large ice wedges in the exposed gravel. There is also a buried beach at Ozyornoye, but the level is shallower—only

Fig. 10. The upper gravel in the Byzovaya Ravine. The beds are inclined 6–8° towards left (south). Cross-stratifications up the inclined beds, visible to the left and right of the trowel, are interpreted as the result of up-slope wave transportation on the beach.

3 m compared with 10 m at Byzovaya—so the correlation is uncertain. At Bolotny Mys the top of a lower regressive sequence is located at 5.4 m, but beach facies are missing here. If the differences in facies are borne in mind, the buried regressive sequences at Ozyornoye and Bolotny Mys may easily be correlated.

The altitude of the outlet pass determined the lake level. However, the outlet may first have been across lower passes, which were subsequently blocked by glacial ice, causing a stepwise rise of the lake level. The outlet during the highest lake level was probably located near Lake Onega, and the outlet river drained towards the Baltic Sea (Maslenikova and Mangerud, 2001). Lowering of lake levels could be caused by erosion of the outlet channels.

6. Discussion of the OSL dates

The basic question concerning luminescence dating of sediments is whether the samples were completely bleached (zeroed) during deposition. All samples reported here were collected from beach or shallow water sand facies, which had been transported and deposited by waves. Judging by stratigraphic depths, all sampled sand were deposited at water depths less than 8 m, and most samples considerably shallower. Sand of seven samples was deposited on, or close to the beach. This means that most of the sand was likely to have been exposed to light as the grains were wave-washed back and forth on the beach. Sand that was exposed to direct daylight when temporarily deposited on the subaerial beach should have been rapidly zeroed. Underwater zeroing is slower (see discussion in Aitken, 1985) which may have affected some of the samples.

Most of the OSL dates are closely grouped between 78 and 98 ka (Fig. 11). This range is consistent with the average uncertainty in age for individual samples, the standard deviations of measured values being about 10 ka (range 3–23 ka). The close clustering of most of the ages is a further argument in favour of zeroing of the samples, and that the ages accurately date the Lake Komi sediments. If zeroing was poor, the ages should have been spread over a range skewed to older ages, with a spread much wider than expected from uncertainties. We conclude that most samples probably were well zeroed, although we cannot evaluate the degree of zeroing for each individual sample, not to speak of each individual sand grain in the samples.

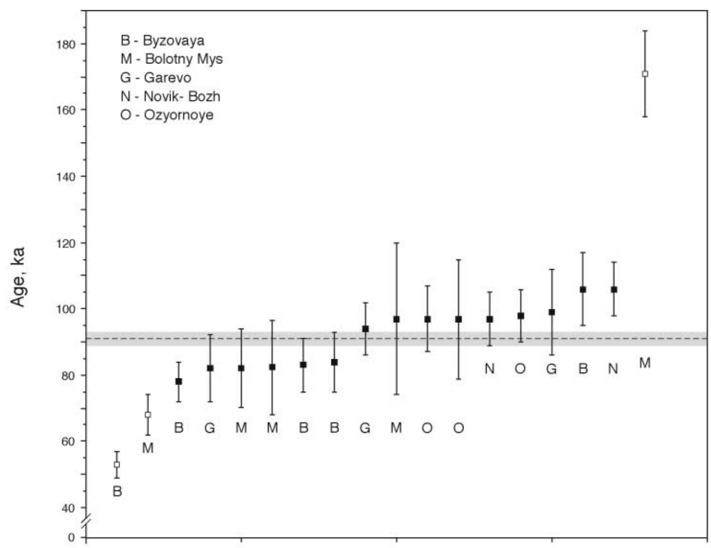

Fig. 11. All OSL dates (Table 1) from the Lake Komi beach and shoreface sediments. Plotted according to increasing OSL ages (and not stratigraphical order). Each sample is marked with locality name. Stippled line with shading gives the mean $\pm$ 1 S.D. when the outliers (open squares) are omitted.

Only one date from Bolotny Mys (sample 992527 in Table 1, 171 ± 13 ka) yielded a considerably older age than the others. It is located between samples giving much younger ages (Fig. 6). This anomalous result has a large palaeodose (Table 1) and the simplest explanation for this discrepancy is incomplete zeroing during deposition.

Two samples yielded ages considerably younger than 80 ka. The youngest of these (from Byzovaya, 982506 in Table 1, 53 ± 4 ka) has an unusually high dose rate for the Lake Komi deposits at this location. If the dose rate from the stratum immediately below is used instead, the age would be 93 ka, consistent with the ages above and below this sample. It is possible that either (i) there has been some movement of radioactivity by ground water, or (ii) more likely, there has been some laboratory error. In any case, this age should be ignored. There is no such check for the other young age from Bolotny Mys (982518, 68 ± 6 ka). However, it is interesting to note that this sample was taken just below the anomalously old age sample discussed above (171 ± 13 ka). This mismatch could be explained a by recent leaching of radioactivity from the upper to the lower stratum, leading to a too low annual dose rate in the upper layer, and a too high rate in the lower, compared to the dose rate for the entire burial time. Laboratory error is less likely in these cases, because the two samples were processed 1 year apart.

The water content of the sediment influences the annual dose, because water absorbs some of the radiation. All dated samples lay at some depth in the profile when considering the situation prior to recent erosion or excavation. We, therefore, assume the deposits have been water saturated throughout the burial period and use the experimentally derived water content of 27 ± 3% with respect to dry weight. If the water content instead had been 15%, the calculated ages would have been about 10% younger. If the sediments had not been frozen any further uncertainty concerning water content would have been negligible. However, permafrost existed at all sites for most of the post-depositional time, probably from the disappearance of Lake Komi to about 13 ka. First, this supports the above assumption that the sediments have been water (ice) saturated during this period. However, it introduces the problem that ice is not as evenly distributed in permafrozen sediments as water is in unfrozen sediments. If ice lenses were located close to some of the dated samples, or if sand grains even were enclosed in an ice lens, the annual dose rate could have been considerably less than measured by us in the thawed sediment. The result would be that the calculated OSL age is too young. Some of the variation in the apparent ages, and possibly also some of the anomalous young ages, may be due to inaccurate estimates of the water or ice content.

The distribution of the ages shows two modes, one with a mean about 98 ka and one about 82 ka (Fig. 11). All samples from Ozyornoye and Novik–Bozh belong to the older group, and most from Byzovaya to the younger. At Garevo, Bolotny Mys and Byzovaya, both groups are represented. However, they are in reversed or mixed stratigraphical order, showing that the bimodal age distribution has no geological meaning.

Although we are not able to estimate the duration of Lake Komi, the OSL dates constrain the age of the maximum lake level to the range 80–100 ka (Fig. 11). The weighted mean of all dates except the one yielding 171 ka is ($n = 17$) 88 ± 3 ka. If samples younger than 78 ka and older than 100 ka are excluded, the mean ($n = 12$) is 91 ± 2 ka.

There is no other dating method available to test directly the accuracy of the dates on Lake Komi sediments. However, we have earlier obtained five OSL dates from shallow marine Eemian sediments from this area, which from the point of view of light exposure should be comparable to the Lake Komi samples. The results were four ages in the range 91–111 ka, whereas one outlier yielded 64 ka, when using a water content of 14 ± 7% (Mangerud et al., 1999). When recalculated to a more probable water content of 27% (used for Lake Komi sediments), the ages would be in the range 98–118, with the outlier at 69 ka. One further of the Eemian samples has been dated recently, with the same protocol as the Lake Komi samples, and yielded 117 ± 7 ka. The expected ages for Eemian samples are 130–120 ka, so on this evidence the OSL ages are slight underestimates. These dates on Eemian beach sediments support the assumption that the Lake Komi samples were zeroed during deposition, and that the accuracy of OSL ages for this type of sediment is good. Since the Eemian samples provided small underestimates in the age, it may be that the age of Lake Komi is closer to 100 than to 80 ka.

7. Implications for the glaciation history

The existence of Lake Komi sediments unambiguously shows that the Barents–Kara Ice Sheet blocked the Pechora lowland between the Urals and the Timan Ridge (Fig. 2). Shorelines of Lake Komi traced on air photographs across the Timan Ridge and into the Mezen and Dvina drainage basins show that the Barents–Kara Ice Sheet also blocked the mouth of the White Sea at the same time (Fig. 2) (Astakhov et al., 1999). The OSL ages for Lake Komi sediments indicate that this glaciation occurred about 90 ka, probably during the cold interval (Rederstall) between the Brørup and Odderade interstadials in Western Europe, correlated with marine isotope stage 5b.

We have previously suggested that the ice sheet that formed the Markhida moraine also dammed Lake Komi (Astakhov et al., 1999); thus Mangerud et al. (1999) stated that OSL dates « ... constrain the age of the Markhida till to about 45–60 ka, which corresponds reasonably well with the limiting dates for Lake Komi, except that the OSL dates conducted on the beach sand itself yielded older ages.... » Additional OSL dates on subtill fluvial sediments in the Pechora Valley have strengthened the conclusion that the Markhida moraine is younger than about 60 ka (Henriksen et al., 2001) and, as mentioned above, the dates reported in the present paper strongly indicate that Lake Komi is about 90 ka old. If we accept these dates, Lake Komi and the Markhida moraines must represent two ice sheet advances of different ages. We therefore present here an alternative hypothesis which accommodates the OSL ages of both events (Fig. 12), but which has not been fully demonstrated by field observations.

Astakhov et al. (1999) and Mangerud et al. (1999) correlated a series of end moraines across the Pechora Lowland, from west to east named the Varsh–Indiga–Markhida–Harbei–Halmer–Sopkay moraines (Fig. 2). They, therefore, also collectively named the entire morainic belt the Markhida Line assuming that it represented a synchronous ice sheet limit. In our new hypothesis, we consider this line as an ice marginal complex formed during two separate advances, about 90 and 60 ka, respectively. The name Markhida Line is, therefore, misleading and in the present paper, we use Markhida only for the moraine close to the Pechora River (the type site). Field observations and new (unpublished) OSL dates indicate that the eastern moraines (Harbei–Halmer–Sopkay) were formed during the 90-ka advance (which dammed Lake Komi). The continuation of this moraine towards the west is obscurred by the younger (60 ka) advance, although the oldest advance probably reached farthest south in the areas west of the Pechora River. The younger advance, about 60 ka, reached the Markhida moraine, and the correlation outlined above towards the west of the Markhida–Indiga–Varsh moraines is probably correct (Fig. 2). This is also supported by OSL dates for the western extension of the Varsh moraine, the Pyoza moraine (Houmark-Nielsen et al., 2001). The continuation of the Markhida moraine east of the Pechora River is not known; it may turn towards the NE. An age of 60 ka for the Markhida moraine is also compatible with all minimum ages obtained from sediments above the till (Mangerud et al., 1999; Forman et al., 1999; Polyak et al., 2000; Gataullin et al., 2001). We assume that the Markhida ice-advance correlates with the deep sea isotope stage 4.

Observations and dates in other areas along the periphery of the Barents–Kara Ice Sheet support the hypothesis of two separate advances at about 90 and 60 ka. On land, similar results were obtained from the Taymyr Peninsula (Alexanderson et al., 2001). In the area west of the Timan Ridge, Houmark-Nielsen et al. (2001) described ice-dammed lake sediments of Lake Komi age and, as mentioned above, dated the continuation of the Markhida moraine. Both the 90- and 60-ka ice sheets probably reached the shelf edge in the Western Barents Sea (Svendsen et al., 1999). In cores from the continental slope west of Svalbard, there are peaks of ice rafted detritus (IRD) about 100 and 60–50 ka, both of which correlate with ice sheet expansions recorded on land on Svalbard (Mangerud et al., 1998). IRD peaks with similar ages, plus an additional peak at 80 ka, were also found in marine cores north of Severnaya Zemlya (Knies et al., 2000, 2001). Unfortunately, the resolution of the $\delta^{18}O$ curve and, therefore, the dating accuracy, is poor in all these cores. We suggest that the older IRD peak

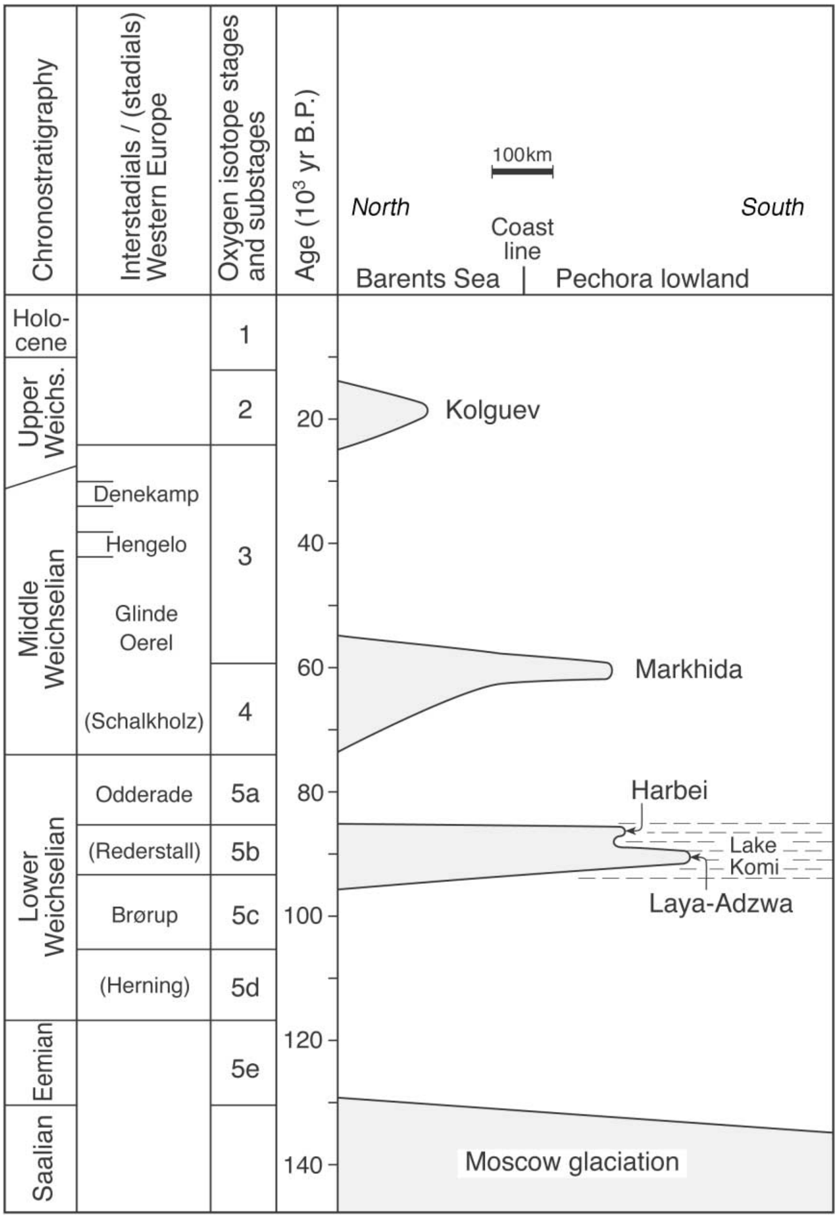

Fig. 12. The proposed glaciation curve for the southern flank of Barents–Kara Ice Sheet, here drawn as a profile through the southern Barents Sea (the Pechora Sea) and the Pechora lowland. The Laya–Adzwa (and Rogovaya) ridges are overlain by Lake Komi sediments, but here we consider these ridges as formed by an early phase of the same advance that formed the Harbei (and Halmer–Sopkay) moraines and dammed Lake Komi. As indicated, the Late Weichselian ice advance did not reach the coastline. The shrinking of the ice sheet to the Northern Barants Sea between each glacial advance is based on results from Svalbard (Mangerud et al., 1998).

in these cores reflects the break up of the ice sheet that dammed Lake Komi 100–80 ka and of glaciation C on Svalbard (Mangerud et al., 1998). The Markhida moraine (about 60 ka) correlates with glaciation E on Svalbard and the IRD peaks 60–50 ka in the cores both west of Svalbard and north of

Severnaya Zemlya. In addition, glaciological climatic modelling indicates ice advances about 90 and 60 ka, compatible with our alternative hypothesis (Siegert et al., 2001).

Finally, we emphasise again that the Late Weichselian ice sheet did not reach mainland Russia along the White Sea–Pechora lowland coast (Svendsen et al., 1999; Polyak et al., 2000; Gataullin et al., 2001).

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