

Evidence for the intrusion of marine Atlantic waters into the West Siberian Arctic during the Middle Pleistocene

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Marine sediments occupy a significant portion of the Quaternary succession in the West Siberian Arctic but, until recently, their ages and distributions have been strongly debated. Based on new geological, palaeontological and geochronological data obtained within the last decade, we hereby postulate the following: (i) Two different Pleistocene interglacial marine formations are exposed across the West Siberian Arctic. The older Kheta marine formation, sandwiched between two Middle Pleistocene till beds, yields optically stimulated luminescence (OSL) ages of *c.* 200 ka (MIS 7). The younger Karginsky/Payuta marine formation, overlying the Middle Pleistocene Taz till, contains a boreal mollusc fauna and has an OSL age of *c.* 115 ka (MIS 5e). These Middle and Upper Pleistocene marine beds have been correlated across a vast region between the Ob' and Yenisey estuaries. (ii) The marine transgression during MIS 7 spread as far south into West Siberia as 65°N, almost 1000 km southwards from the present-day Kara Sea shoreline. Meanwhile, the smaller marine transgression during MIS 5e reached as far south as 68°N. (iii) Both marine formations contain a boreal molluscan fauna, which is not found in the modern Kara Sea but is characteristic of the North Atlantic. We propose that warmer Atlantic waters penetrated much further eastwards during both MIS 7 and MIS 5e than at present. The diagnostic extinct mollusc species *Cyrtodaria jensenseae* has only been found in the older Kheta marine formation (MIS 7).

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One of the long-standing uncertainties concerning the Quaternary geology of West Siberia has been the possible outcrop and distribution of Middle Pleistocene interglacial marine formations. Sachs (1953) considered deposits of the Sanchugovka beds (Table 1), exposed in bluffs along the Lower Yenisey River, as Middle Pleistocene marine beds. However, Kaplyanskaya & Tarnogradsky (1975) showed that these diamicton beds actually represent a basal till comprising reworked shell fragments. Zubakov (1972) obtained U/Th ages of 233 or 170 ka for the Pupkovsky marine strata, 100 km south of Turukhansk (Fig. 1B, site 7). However, these ages were obtained from *Arctica islandica* shells picked partly from slumped deposits, casting doubt on the validity of these ages and a Late Pleistocene age for the Pupkovsky beds was subsequently assumed (Troitsky 1975). All outcrops of marine sediments in the Lower Yenisey basin were subsequently shown to be younger than Middle Pleistocene age. More recently, Gusev *et al.* (2019) have dated deposits on the right side of the Yenisey River, downstream from Nikitinsky Yar, as Middle Pleistocene in age based on infrared stimulated luminescence (IRSL). However, the origin of the dated sand is unclear and requires further investigation. It is now believed that the so-called Kazantsevo marine formation is of Middle Pleistocene age (Astakhov 2013), as first proposed by

Zubakov (1986), yet considerable geological support for this age assertion has been lacking until recently. Furthermore, modern investigations demonstrate that marine strata in the Kazantsevo stratotype area are of Late Pleistocene age and can be correlated with the MIS 5a interglacial (Gusev *et al.* 2016).

We believe that the extinct mollusc *Cyrtodaria jensenseae* (Fig. 1C) can be used as a diagnostic fossil for the presence of Middle Pleistocene marine sediments in West Siberia. This assumption is founded on the absence of *C. jensenseae* in marine sediments younger than the Kazantsevo formation, i.e. younger than marine sediments currently considered as Middle Pleistocene in age (Astakhov 2013). The genus *Cyrtodaria* contains only two extant species, *C. kurriana* and *C. siliqua* (MolluscaBase 2021), while all other species are now extinct. Sachs (1951) identified *C. jensenseae* and supposed that the species represents a transitional or annectant form between the Pliocene *C. angusta* and modern *C. siliqua*. The differences between *C. angusta*, *C. jensenseae* and *C. siliqua*, along with their simultaneous occurrence at the same stratigraphical level, have been confirmed by subsequent investigations (Merklin *et al.* 1979; Krylov *et al.* 2014). Prior to this, *C. jensenseae* and *C. siliqua* were considered as the same species (Troitsky 1966) and referred to as *C. jensenseae*, while

Table 1. Age and correlation of sedimentary formations and related periods described in this paper, with MIS, classic chronostratigraphy of the West Siberia, and predecessors' schemes.

Series, subseries	MIS	MIS age intervals (ka)	Sedimentary formations in the present paper	Sedimentary formations by Sachs (1953), Volkova (1958)	Sedimentary formations by Zubakov (1972)	Revised chronostratigraphical units of the West Siberia (Astakhov 2013)	NW European stage equivalents (Fennoscandian glaciations)
Holocene	1	14–	Present day alluvium and lacustrine	Present day alluvium and lacustrine	Present day alluvium and lacustrine	Holocene	Holocene
Late Pleistocene	2	29–14	1st river terrace	1st river terrace	1st river terrace		Late Weichselian
	3	57–29	2nd river terrace	Karginsky marine; 2nd river terrace	2nd river terrace		Middle Weichselian
	4–5d	115–57	Yermakovo/Kara glacial	Zyryanka glacial	Yermakovo glacial	Zyryanka	Early Weichselian
	5e	130–115	Karginsky/Payuta marine (upper marine)	Kazantsevo marine; Kheta marine	Kazantsevo marine	Karginsky	Eemian
Middle Pleistocene	6	191–130	Taz glacial	Sanchugovka marine and glacimarine	Yenisei glacial	Taz	Late Saalian
	7	243–191	Kheta marine (lower marine) Solenaya alluvium	Messo alluvial	Pupkovo marine	Kazantsevo	Wacken/Dömnitz
	8	301–243	Samarovo glacial	Till of maximal glaciation	Bakhta glacial	Samarovo	Early Saalian

some researchers suggest that *C. jensseae* and *C. angusta* are the same species (Astakhov 2006, 2013; Alexanderson *et al.* 2014; Möller *et al.* 2019). Therefore, we consider it necessary to re-examine all sites with reported finds of species from the genus *Cyrtodaria* (Volkova 1958; Lavrushin 1959; Zemtsov 1967; Zubakov 1972; Bidgiev *et al.* 1981; Gusev *et al.* 2012; Fig. 1B, C).

We undertook field investigations in 2016 and 2017 in the Bolshaya Kheta and Tanama river basins (Figs 1B, 2, 3, 4) as part of the state geological mapping by the Russian Geological Research Institute. The focuses of this paper are the facies analysis, palaeontological characteristics, age determinations, stratigraphy and correlation of the marine sediments, especially the formation we interpret to be of Middle Pleistocene rather than Late Pleistocene age. Preliminary OSL ages have been previously published in the Map of Quaternary deposits (Nazarov *et al.* 2018) and in a recent article in a Russian geological journal (Nazarov *et al.* 2020).

Study area and background

River bluffs composed of sand, silt and clay with abundant *in situ* molluscs are exposed along a ~100-km stretch of the Bolshaya Kheta River (Fig. 2). Earlier investigators have developed a common general stratigraphical scheme for the exposed strata (Fig. 3A), despite disagreements concerning the age and genesis of the Quaternary deposits (Zagorskaya *et al.* 1965;

Slobodin *et al.* 1967; Zemtsov 1967). In addition to boreal-Arctic and Arctic species currently living in the Kara Sea, other molluscan species such as the extinct *Cyrtodaria jensseae* and boreal *Limecola balthica*, *Mytilus edulis* and *Arctica islandica* have been found here. The marine strata have been classified as the Kazantsevo Formation (Zagorskaya *et al.* 1965; Slobodin *et al.* 1967; Zemtsov 1967), or sub-divided into the Sanchugovka, Kazantsevo and Kheta beds (Volkova 1958). Until now, all researchers have suggested a Late Pleistocene age for marine sediments exposed along the Bolshaya Kheta River. However, this is an interpretation we will challenge in this paper.

Material and methods

Fieldwork and palaeontological analysis

We studied surficial deposits using satellite images and during fieldwork. We cleared exposed sections of vegetation and allochthonous deposits as widely as possible, in order to trace contacts between beds, carry out detailed descriptions of sedimentary structures, and collect samples. In this paper, we use the terminology of Reineck & Singh (1980) to describe the sedimentary structures. Precise locations and elevations were determined using a hand-held GPS and altimeter, which measured relative heights above mean sea level (a.s.l.) with 0.5-m precision.

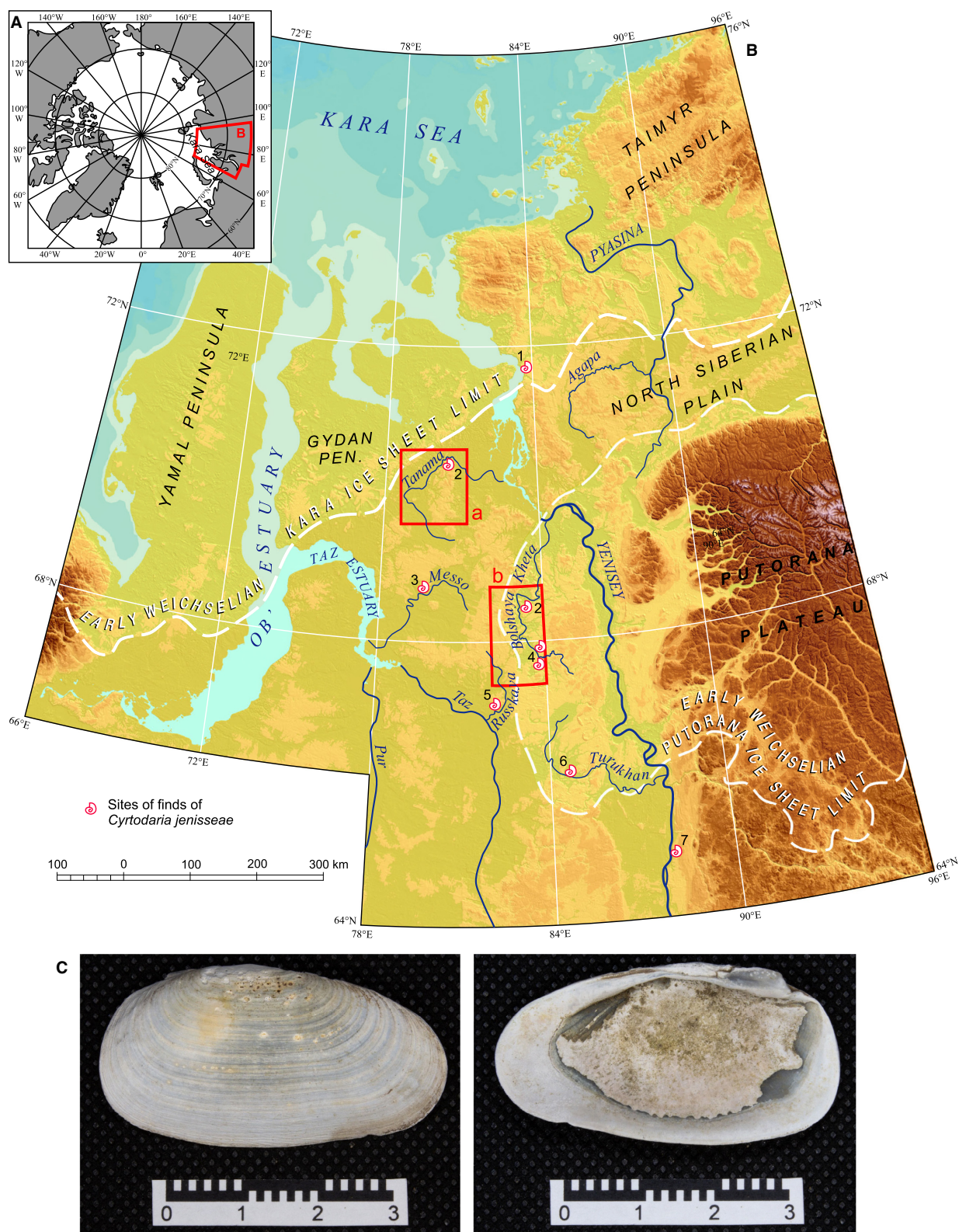


Fig. 1. A. Circumpolar map of the Northern Hemisphere. Red line shows map margins of B. B. Digital elevation model of the West Siberian Arctic and adjacent areas. Quadrangles mark the present study areas: a = Tanama River (Fig. 4A); b = Bolshaya Kheta River (Fig. 2). Numbers show sites where *Cyrtodaria jensiseae* molluscs have been found, by different authors: 1 = Gusev *et al.* (2012); 2 = the present study; 3 = Bidgiev *et al.* (1981); 4 = Volkova (1958); 5 = Zemtsov (1967); 6 = Lavrushin (1959); 7 = Zubakov (1972). Area of Early Weichselian ice sheets is lightened (Nazarov *et al.* 2016, 2018). C. *Cyrtodaria jensiseae* specimen from site 7254 (Fig. 2). Scale bars are 3 cm long.

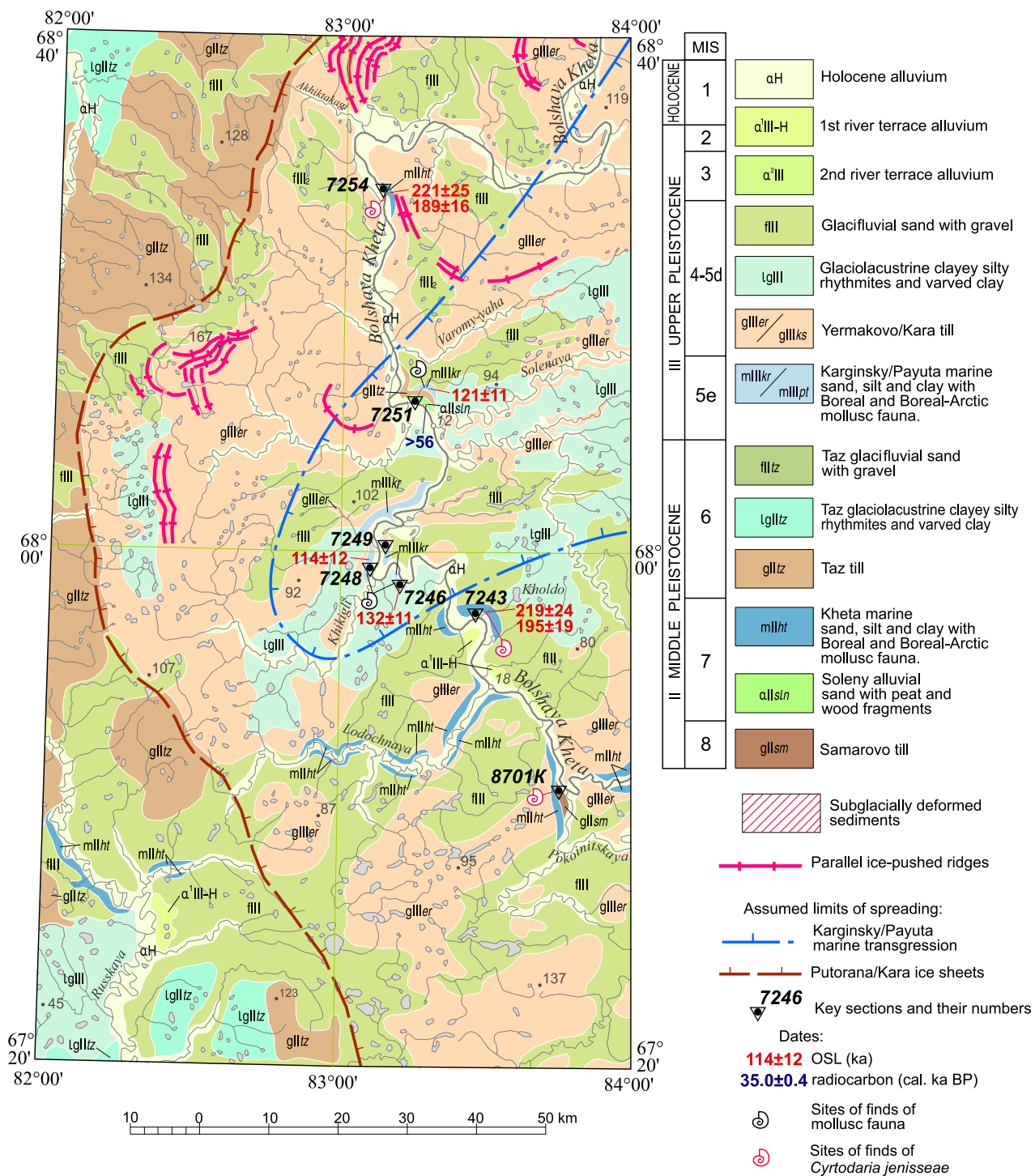


Fig. 2. Quaternary map of the middle Bolshaya Kheta River and adjacent areas. For location see Fig. 1B (box b).

In order to obtain *in situ* faunal remains, mainly comprising marine molluscs, we washed large volumes (2–10 buckets) of sediment from cleared section walls through 1–4 mm mesh sieves. We also collected shells from the river bank and slumped deposits. The source of

molluscs – *in situ* or collected – is marked in the text and in Fig. 5. Species identification was carried out in the Zoological Institute of the Russian Academy of Sciences (St. Petersburg). To identify molluscs of the genus *Cyrtodaria*, primary descriptions and papers with the

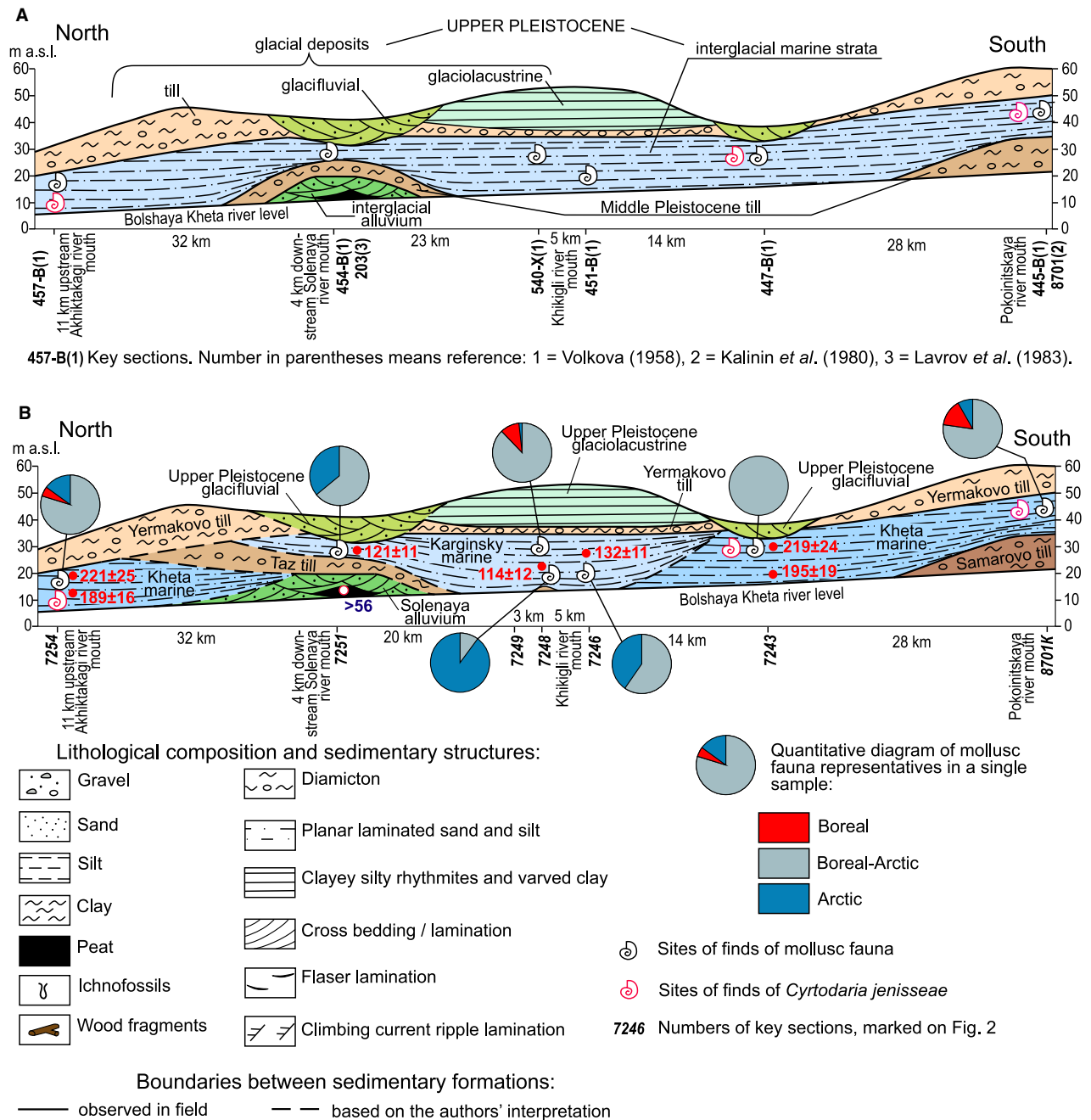


Fig. 3. Summary stratigraphical profiles along the middle Bolshaya Kheta River. A. According to previous data. B. According to this paper. Horizontal scale is approximate. See also the legends in Fig. 2.

first images of shells were used (Spengler 1793; Nyst & Westendorp 1839; Dunker 1861; Tryon 1874; Dall 1920; MacNeil 1957).

OSL dating

We obtained 14 OSL ages (Table 2) measured on both quartz and K-rich feldspar using multi-grain aliquots. One of the main assumptions in OSL dating is that the

sample was well bleached at burial. If this assumption is untrue, then multi-grain measurements are likely to overestimate the true burial age. Quartz and feldspar are known to have very different bleaching rates, where quartz bleaches more than one order of magnitude faster than feldspar (Godfrey-Smith et al. 1988; Thomsen et al. 2008). Therefore, if the quartz and feldspar ages are comparable to each other, it is likely that quartz was indeed well bleached at burial (Murray et al. 2012).

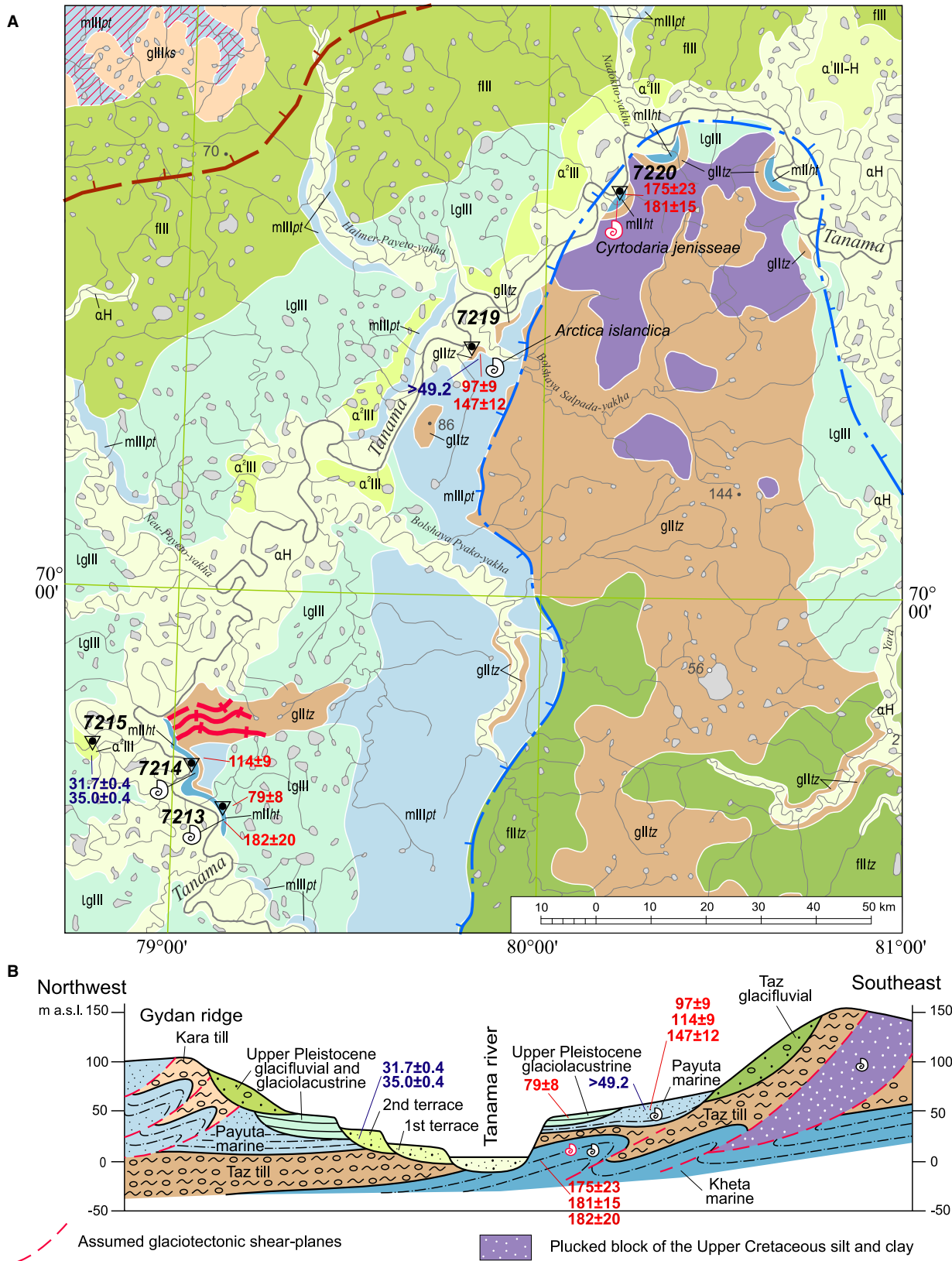


Fig. 4. A. Quaternary map of the middle Tanama River and adjacent areas. B. Summary stratigraphical profile of the middle Tanama River and adjacent areas. See legends in Figs 2, 3.

Marine formation		Karginsky and Payuta, Upper Pleistocene										Kheta, Middle Pleistocene																			
Area		Bolshaya Kheta					Tanama					Bolshaya Kheta					Tanama														
Site		Khikigili					Solenaya River			Malaya Salpada		Kholdo			Akhihtakagi			Olenyi Rogi													
Section's number		7246		7248			540-X		7251	454-B		7219			8701K 445-B		7243		447-B		7254		458-B		7220		7213		7214		
Reference		1		1			2		1	2		1			2		1		2		1		2		1		1		1		
Sample's number		112		113		119/6		119/9		119/10		119/12		119/16		135		34-35		sd		sd		542		sd		202		234/1	
Height above river level		sd		20-21		5-6		sd		21		24		9		119/9		25		10		119/10		27		12		119/12		31	
Altitude*		sd		20-21		5-6		sd		21		24		9		119/9		25		10		119/10		27		12		119/12		31	
boreal	Cyrtodaria jenisseae																														
	Arctica islandica																														
	Ariadnaria insignis																														
	Buccinum undatum																														
	Chirona hameri																														
	Cyrtodaria siliqua																														
	Limicola balthica																														
	Mytilus edulis																														
	Neptunea despecta																														
	Admete viridula																														
boreal-arte	Amauropsis islandica																														
	Ariadnaria borealis																														
	Astarte arctica																														
	Astarte borealis																														
	Astarte crebricostata																														
	Astarte crenata																														
	Astarte elliptica																														
	Astarte montagui																														
	Aximopsida orbiculata																														
	Boreocingula castanea																														
Arctic	Buccinum scalariforme																														
	Buccinum terraenovae																														
	Ciliatocardium ciliatum																														
	Colus islandicus																														
	Colus pubescens																														
	Cryptonatica affinis																														
	Curtitoma incisula																														
	Curtitoma inflata																														
	Curtitoma tenuicostata																														
	Cylchna alba																														
Arctic	Ennucula tenuis																														
	Frigidoalvania cruenta																														
	Hiatella arctica												</																		

*sd - sample is collected from slumped deposits

Taxons

-  - Gastropoda
-  - Bivalvia
-  - Crustacea

Amount of specimens in samples

is marked by numbrs (the present data) or reflected by letters (Volkova 1958):

S - sporadic
R - rare
P - predominate
O - often
A - abundant

References:

1 - the present paper
2 - Volkova (1958)

Fig. 5. Mollusc species collected from marine sediments.

Table 2. Optically stimulated luminescence (OSL) summary for quartz and K-feldspar (KF) extracts. Depth is the current burial depth, w.c. is the saturated water content and *n* is the number of aliquots included in the dose estimation. The equivalent doses are estimated using the arithmetic mean. The feldspar ages (IR₅₀ and pIRIR₂₉₀) have not been corrected for residual doses or for anomalous fading.

Stratigraphical position	Locality	Field no.	Lab. no.	Depth (m)	w.c. (%)	Sand size fraction (µm)	<i>n</i>	Specific activity (Bq kg ⁻¹)			Equivalent dose (Gy)			Dose rate (Gy ka ⁻¹)		OSL age (ka)	
								²³⁸ U	²²⁶ Ra	²³² Th	⁴⁰ K	QuartzOSL	KF: IR ₅₀ pIRIR ₂₉₀	KF: IR ₅₀ pIRIR ₂₉₀	OSL age (ka)	KF: IR ₅₀ pIRIR ₂₉₀	QuartzOSL
Glaciolacust., Up. Pleist.	Tanama River	7213-173	RGI-332	20	21	180–250	18	30±5	24.2±0.5	22.1±0.4	593±28	167±14	–	2.11±0.10	–	–	79±8
			Riso 212501			180–250	3					–	234±11 418±33	3.05±0.12	–	77±5 137±13	–
Payuta interglacial, Upper		7214-189	RGI-374	20	25	180–250	16	15±3	10.2±0.2	11.3±0.3	665±31	213±11	–	1.87±0.09	–	–	114±9
			Riso 212503			180–250	3					–	242±28 406±59	2.81±0.11	–	86±11 145±22	–
Pleistocene		7219-223	RGI-191	22	23	180–250	19	8±2	5.6±0.2	4.9±0.2	364±17	154±9	–	1.05±0.04	–	–	147±12
			Riso 212504			180–250	3					–	156±12 262±8	1.99±0.09	–	79±7 132±8	–
		7219-226	RGI-384	16	26	180–250	19	9±2	8.0±0.2	9.0±0.2	370±18	110±8	–	1.13±0.05	–	–	97±9
			Riso 212505			180–250	3					–	142±6 312±10	2.07±0.09	–	69±4 151±9	–
Karginsky interglacial, Upper	Bolshaya Kheta River	7246-115	RGI-159	27	20	90–180	19	–	13.1±0.6	12.4±0.4	674±22	275±18	–	2.08±0.07	–	–	132±11
			Riso 212506			180–250	3					–	272±4 433±29	2.97±0.11	–	92±4 146±12	–
Pleistocene		7248-139	RGI-162	25	27	90–180	23	9±2	10.5±0.3	10.1±0.2	621±29	201±17	–	1.77±0.07	–	–	114±12
			Riso 212507			90–180	3					–	281±14 419±11	2.40±0.10	–	117±8 175±10	–
		7251-554	RGI-160	12	31	90–180	21	–	15.3±0.7	15.2±0.5	710±27	249±18	–	2.06±0.07	–	–	121±11
			Riso 212508			180–250	3					–	276±9 411±18	2.95±0.11	–	94±5 139±9	–

(continued)

Table 2. (continued)

Stratigraphical position	Locality	Field no.	Lab. no.	Depth (m)	w.c. (%)	Sand size fraction (μm)	n	Specific activity (Bq kg^{-1})			Equivalent dose (Gy)		Dose rate (Gy ka^{-1})		OSL age (ka)	
								^{238}U	^{226}Ra	^{232}Th	^{40}K	QuartzOSL	KF: IR ₅₀	KF: IR ₅₀	QuartzOSL	KF: IR ₅₀
Kheta interglacial, Middle Pleistocene	Tanama River	7213-172	RGI-331	22	32	180–250	27	15 $\pm$ 3	15.6 $\pm$ 0.3	17.2 $\pm$ 0.3	571 $\pm$ 27	309 $\pm$ 28	–	1.69 $\pm$ 0.08	–	182 $\pm$ 20
			Riso 212502			180–250	3					–	264 $\pm$ 47	2.63 $\pm$ 0.10	100 $\pm$ 19	–
		7220-249	RGI-192	28	26	180–250	19	7 $\pm$ 2	7.0 $\pm$ 0.2	7.3 $\pm$ 0.2	479 $\pm$ 22	241 $\pm$ 15	549 $\pm$ 34	1.33 $\pm$ 0.05	–	181 $\pm$ 15
			Riso 212509			180–250	3					–	306 $\pm$ 12	2.27 $\pm$ 0.09	135 $\pm$ 8	–
		7220-253	RGI-213	12	23	180–250	24	13 $\pm$ 2	9.4 $\pm$ 0.2	9.3 $\pm$ 0.2	422 $\pm$ 20	230 $\pm$ 28	667 $\pm$ 23	1.32 $\pm$ 0.05	–	175 $\pm$ 23
Bolshaya Kheta River		7243-516	Riso 212510			180–250	3					–	302 $\pm$ 10	2.25 $\pm$ 0.09	134 $\pm$ 7	–
			RGI-164	8	33	90–180	20	10 $\pm$ 2	11.5 $\pm$ 0.3	12.2 $\pm$ 0.3	682 $\pm$ 32	418 $\pm$ 41	636 $\pm$ 52	1.91 $\pm$ 0.07	–	219 $\pm$ 24
		7243-519	Riso 212511			90–180	3					–	421 $\pm$ 10	2.55 $\pm$ 0.11	165 $\pm$ 8	–
			RGI-158	22	21	180–250	19	17 $\pm$ 3	13.9 $\pm$ 0.3	16.1 $\pm$ 0.3	651 $\pm$ 31	393 $\pm$ 31	697 $\pm$ 48	2.02 $\pm$ 0.08	–	195 $\pm$ 19
		7254-144	Riso 212512			180–250	3					–	434 $\pm$ 42	2.96 $\pm$ 0.12	147 $\pm$ 16	–
			RGI-163	15	26	180–250	23	17 $\pm$ 4	10.6 $\pm$ 0.3	8.9 $\pm$ 0.3	593 $\pm$ 27	317 $\pm$ 20	834 $\pm$ 33	1.68 $\pm$ 0.06	–	189 $\pm$ 16
		7254-152	Riso 212513			90–180	3					–	374 $\pm$ 29	2.35 $\pm$ 0.10	159 $\pm$ 14	–
			RGI-161	12	27	180–250	21	11 $\pm$ 2	11.5 $\pm$ 0.3	9.9 $\pm$ 0.2	599 $\pm$ 28	377 $\pm$ 37	743 $\pm$ 73	1.71 $\pm$ 0.07	–	221 $\pm$ 25
			Riso 212514			180–250	3					–	487 $\pm$ 19	2.64 $\pm$ 0.11	184 $\pm$ 10	–
												–	839 $\pm$ 94	–	317 $\pm$ 38	–

The samples were collected from sedimentary sections in the study area using opaque PVC tubes hammered into freshly exposed outcrops. Sample preparation and gamma spectrometry, as well as OSL measurements of some of the quartz aliquots from every sample, were conducted at the OSL Laboratory of the Russian Geological Research Institute (St. Petersburg, Russia). Feldspar OSL measurements and the rest of the quartz OSL measurements were undertaken at the Nordic Center for Luminescence Research (Roskilde, Denmark). The samples were prepared by standard methods (Wintle 1997), with sand-sized quartz and K-feldspar grains selected from the 180–250 μm and 90–180 μm fractions.

The OSL measurements were conducted using Risø TL/OSL Readers (Bøtter-Jensen *et al.* 2010) on stainless steel discs (quartz) or cups (K-feldspar). The equivalent dose (D_e) measurements in quartz followed the single aliquot regenerative-dose (SAR) protocol (Murray & Wintle 2000, 2003). K-rich feldspar D_e measurements were made using the post-infrared infrared stimulated luminescence (pIRIR₂₉₀) SAR protocol (Thiel *et al.* 2011). Test doses used in the pIRIR₂₉₀ protocol were 40–80% of the D_e in accordance with Yi *et al.* (2016). For quartz, the OSL signal was summed over the initial 0.32 s, and the signal from the subsequent 0.8 s was deducted (early background subtraction, EBG). The pIRIR₂₉₀ and IR₅₀ equivalent doses in K-feldspar were obtained by summing the first 0.8 s and by deducting the last 10 s of the total measured interval (late background subtraction, LBG). Average D_e values were calculated using the arithmetic mean. All uncertainties are given at 1 σ (68% confidence interval).

Two acceptance criteria were applied to exclude inadequate D_e values from the data. Firstly, quartz aliquots with D_e uncertainties higher than 30% were rejected. Secondly, we excluded outliers lying out of the range between the lower quartile minus 1.5 times the interquartile range and the upper quartile plus 1.5 times the interquartile range. Only three quartz aliquots failed to meet the standard criteria based on recycling ratio and recuperation. Nevertheless, these aliquots were not rejected, since there is no observable effect of applying these criteria to final D_e values (Thomsen *et al.* 2016). No feldspar aliquots were rejected because all of them met all the acceptance criteria.

To obtain environmental dose rates, the activities of ^{238}U , ^{226}Ra , ^{232}Th and ^{40}K were measured using high-resolution gamma spectrometry (Murray *et al.* 1987) with a high-purity germanium (HPGe) radiation detector Canberra BE3825. These activities were converted to infinite matrix dose rates using the conversion factors of Guérin *et al.* (2011). Samples were sealed by wax in plastic cups and kept for at least 20 days before measurement to allow ^{222}Rn to reach equilibrium with its parent ^{226}Ra . Cosmic ray dose rates were calculated

following Prescott & Hutton (1994) using present-day burial depths. For the calculations of total dose rates, it was assumed that the sediments were fully saturated by water throughout the burial period. The internal beta dose rates in K-feldspar were calculated based on an expected K concentration of $12.5 \pm 0.5\%$ (Huntley & Baril 1997) and a Rb concentration of 400 ± 100 ppm (Huntley & Hancock 2001).

Figure S1 shows three representative quartz natural OSL stimulation curves. An OSL stimulation curve from Risø calibration quartz is also shown (Hansen *et al.* 2015), which is known to be dominated by the fast component (Jain *et al.* 2003; Singarayer & Bailey 2003). The fast component is the preferred OSL dating signal because it is most easily reset and stable over geological time scales (Murray & Wintle 2000). About 40% of the measured aliquots appear to have a significant medium component, which is of potential concern since the medium component is more difficult to bleach, may have stability issues, and can lead to inaccurate dose estimates as a result (Bailey 2003; Choi *et al.* 2003; Jain *et al.* 2003). To maximize the fast component contribution of the cumulative signal, we use early background subtraction (EBG, Ballarini *et al.* 2007). By fitting individual natural OSL curves using three exponential decaying components, we find that the fast component comprises $88 \pm 2\%$ ($n = 32$) of the OSL signal in the chosen summation interval on average. If we had instead used late background subtraction (LBG, i.e. the first 0.32 s and the final 0.8 s of stimulation), the fast component would comprise $79 \pm 3\%$. For all aliquots, the average dose ratio of LBG to EBG is 0.87 ± 0.02 ($n = 14$ samples). We find that there is no significant difference in decay shape between individual natural and corresponding regenerated OSL signals.

The inset to Fig. S1 shows the dose response curves for the three aliquots illustrated in the main graph. The dose response curves from these samples are fitted using a saturating exponential function with a linear component or a sum of two exponential functions. Murray *et al.* (2008) reported a similar behaviour for their samples (with independent age control) extracted from a deposit on the Seyda River in the Pechora Lowland, Russia, and concluded that their results obtained from the high dose linear region of the laboratory dose response curve were accurate. Figure S2 demonstrates a typical K-feldspar pIRIR₂₉₀ decay curve from the natural signal and the dose-response curve of the same aliquot.

Dose recovery tests were undertaken for both quartz (Fig. S3) and K-feldspar (Fig. S4). Quartz aliquots were bleached twice at room temperature for 100 s using blue LEDs. A pause of 10 000 s was inserted between stimulations (Murray & Wintle 2003). The dose recovery ratios for given doses of 9, 232 and 418 Gy were satisfactory (i.e. consistent with unity $\pm 10\%$, although they appear to increase with given dose (i.e. at 418 Gy it is 1.14 ± 0.05 , $n = 6$)). The pIRIR₂₉₀ and IR₅₀ dose

recovery ratios for K-feldspar were measured after bleaching 12 aliquots of sample 7220-249 for 4 h in a Höhle SOL2 solar simulator. Six aliquots were used to measure the residual dose, which was 42 ± 3 and 8.7 ± 0.9 Gy for pIRIR₂₉₀ and IR₅₀, respectively. The remaining six aliquots were sorted into two groups of three, which were given *in situ* beta doses of 271 and 542 Gy, respectively, and subsequently measured using the pIRIR₂₉₀ protocol. The dose recovery ratios (after subtraction of the relevant residual doses) are shown in Fig. S4. While the dose recovery ratios for the IR₅₀ signal are consistently poor (~ 0.73), they are satisfactory for the pIRIR₂₉₀ signal for doses of 271 and 542 Gy.

To measure the hard-to-bleach IRSL signal in K-feldspar, we bleached six aliquots from each of the five samples for 4 or 48 h in a Höhle SOL2 solar simulator, then measured the residual doses. The IR₅₀ and pIRIR₂₉₀ residual doses are plotted against the corresponding D_e values for each sample in Fig. S5. For these samples, the residual dose is constant as a function of the natural dose and the residual doses are estimated as simple averages of all results, e.g. 4.1 ± 0.4 and 24.4 ± 0.7 Gy for IR₅₀ and pIRIR₂₉₀ after 48 h bleaching, respectively (Fig. S5B). Note that these residual doses have not been subtracted from the measured natural feldspar dose.

OSL burial ages are derived by dividing the average equivalent doses by the total dose rates (Table 2).

Radiocarbon dating

Four new ¹⁴C ages have been obtained from the Bolshaya Kheta and Tanama River valleys (Table 3). Plant detritus, wood fragments and peat were picked by hand from more than 0.5 m depth in cleared section walls. Elemental carbon was produced by pyrolysis from the extracted organic fraction. Lithium carbide, obtained from the coal, was decomposed with water to produce acetylene, which was then transformed to benzene. Radiocarbon in the benzene samples was measured on the liquid scintillation spectrometer 'Quantulus 1220'. All samples were

dated in the Laboratory of Geomorphological and Paleogeographical Research of Polar Regions and Ocean, Institute of Earth Science, St. Petersburg University. The calibration of radiocarbon dates was performed using the Calib v. 8.2 software and IntCal20 calibration curve (Reimer *et al.* 2020; Stuiver *et al.* 2020).

Results

Stratigraphy along the Bolshaya Kheta River

In this section, we present our results from the key sites mentioned above. The general stratigraphical sequence from bottom to top (Table 1) includes the Middle Pleistocene Samarovo till, Solenaya alluvium, Kheta marine formation and Taz till, and the Upper Pleistocene Karginsky marine formation and Yermakovo glacial complex. The Yermakovo glacial complex comprises till, glaciolacustrine and glaci-fluvial deposits.

Pre-Kheta units. – The oldest exposed Quaternary deposits were described by V. V. Komarov (Kalinin *et al.* 1980) near the Pokoinitskaya River mouth (site 8701K in Figs 2, 3; latitude 67.68°N, longitude 83.78°E). The base of the section is composed of grey silty-sandy diamicton with pebbles and boulders of mainly Putorana traps (Siberian traps) volcanic rocks, attaining a visible thickness of up to 12 m. The rock type suggests that clasts were transported by glaciers from the neighbouring Putorana plateau. The diamicton contains numerous intraclasts of fine-grained sand with mollusc shell fragments. V. V. Komarov correlated the diamicton with the Middle Pleistocene Bakhta till (Table 1), which forms hummocks and ridges of moraine south of 66°N. The presence of marine mollusc shell fragments has led some researchers to assume that the deposits represent glaciomarine facies of the Sanchugovka beds (Table 1; Volkova 1958; Zemtsov 1967). We correlate the diamicton to the Middle Pleistocene Samarovo till (MIS 8), since it is overlain by the Kheta marine formation.

Table 3. Radiocarbon ages. The dating was conducted by the Laboratory of Geomorphological and Paleogeographical Research of Polar Regions and Ocean, Institute of Earth Science, St. Petersburg State University. Calibration of radiocarbon dates was performed using Calib v. 8.2 software and IntCal20 calibration curve (Reimer *et al.* 2020; Stuiver *et al.* 2020)

Field no.	Lab. no.	Stratigraphical position	Material	Conventional date (a BP)	Calibrated age (cal. a BP; median probability)	Calibrated age range (cal. a BP; 1σ)	Calibrated age range (cal. a BP; 2σ)
7251-163	LU-8989	Solenaya alluvium	Wood fragment from peat	$\geq 56\ 640$	–	–	–
7215-202	LU-8513	2nd alluvial terrace	Plant detritus	$31\ 040 \pm 350$	$35\ 420 \pm 388$	$35\ 081\text{--}35\ 920$	$34\ 683\text{--}36\ 119$
7215-203	LU-8514	2nd alluvial terrace	Plant detritus	$27\ 690 \pm 390$	$31\ 695 \pm 497$	$31\ 204\text{--}31\ 979$	$31\ 100\text{--}32\ 377$
7219-233	LU-8516	Payuta marine	Wood fragment	$\geq 45\ 530$	–	–	–

Another stratigraphical unit, Solenaya alluvium, was identified on the right side of the Bolshaya Kheta River, 4 km downstream from the Solenaya tributary (7251 in Figs 2, 3B; 68.19°N, 83.23°E). The exposed bluff is 1.2 km long, faces southwards, and is located 32–35 m above the river, which lies about 12 m a.s.l. at this location (Fig. 6A). The base of the section comprises 8 m of light grey medium-grained sand with large-scale planar cross and trough cross-bedding (Fig. 6A). The thickness of cross-bedding sets ranges from 0.1 to 0.5 m. Smaller trough-like channels, up to several centimetres deep, occur at the base of some cross-bedding sets. Large spruce trunks and peat fragments have been observed in the lower parts of the sandy beds. Trunks are up to 20 cm in diameter, contain well-preserved twigs and roots, and have not been rounded, which suggests they have not been transported far. Large blocks of peat were found in the lower parts of sand beds halfway along the bluff, where a block of peat up to 30 m long and 0.6 m thick was extracted (Fig. 6B). The peat is very compact, contains thin (up to 1 cm) seams of bluish-grey silt, and its top is located at 16 m a.s.l. Bluish-grey silt, up to several tens of cm thick, has been uncovered below the peat. The sedimentary structures suggest that the sand represents alluvium deposited within a river channel. The peat yielded a non-finite radiocarbon age of $\geq 56\,640$ years, representing the only known site of exposed Middle Pleistocene peat within the West Siberian Arctic. At 24 m a.s.l., the alluvial sand is overlain by the Taz till (Fig. 6C).

The same sand with silty laminae and plant detritus has been uncovered in several boreholes located 30–40 km to the southwest and northeast from site 7251, where pine, spruce, birch and larch seeds were also identified (Slobodin *et al.* 1967; Arkhipov *et al.* 1980). This floral composition is characteristic of coniferous arboreal vegetation, which can now be found several hundred kilometres to the south of our study site. By contrast, the study site is now covered only by treeless ground-hugging tundra vegetation. The sand is overlain by a silty clay with boreal marine foraminifers, probably representing the Kheta marine formation.

These sediments were initially referred to as the Messo alluvial beds (Table 1; Sachs 1953; Volkova 1958) and subsequently as Middle Pleistocene alluvium (Lavrov *et al.* 1983). We propose the name ‘Solenaya alluvium’ for these undoubtedly interglacial terrestrial sediments and correlate them with MIS 7, although their age is poorly constrained and they could potentially be older.

Kheta marine formation. – We propose the name ‘Kheta marine formation’ after the former ‘Kheta beds’ by Volkova (1958) for the lower silty-sandy strata with an abundant molluscan fauna. We studied this unit at sites 7243 and 7254 in the field (Figs 2, 3B), and also include a short description of site 8701K. The base of the marine strata is below river level across much of the study area,

except near the Pokoinitskaya River mouth (site 8701K on Figs 2, 3B). Here, V. V. Komarov (Kalinin *et al.* 1980) described an erosional contact between the marine formation and the underlying Samarovo till.

Site 7243 (Figs 2, 3B) is located on the right bank of the river, downstream from the mouth of the Kholdo creek (67.92°N, 83.45°E), where the river level is 17 m a.s.l. (Fig. 7A). The river bluff is about 1.3 km long, up to 35 m high, and faces southwards. The section is exposed in terrain on the right side of the river valley, reaching a surface altitude of about 65–70 m a.s.l.

The base of the cleaned section is located about 28 m a.s.l. and consists of greyish silty fine-grained sand and silt, with 1–2 mm thick laminae and climbing-ripple cross-lamination. Around 1 m above the bottom, the sediments conformably change to yellow-grey fine-grained sand with rare rounded clay clasts and flaser bedding, up to 2–2.5 m thick (Fig. 7B). The sand (sample number 7243-519) yielded an OSL age of 195 ± 19 ka at 30.3 m a.s.l. (Table 2).

The sand is overlain by a unit consisting mainly of greyish planar parallel-laminated clayey silt and fine-grained sand, with an uneven contact at the base but without any evidence for an unconformity (Fig. 7C, D). The unit is up to 20 m thick and makes up the bulk of the river bluff, with an irregular bed thickness ranging from several mm to a few cm. Contacts between the beds are uneven and the sandy beds sometimes display flaser bedding. The whole unit is intensely bioturbated and dominated by vertical domichnia burrows (*Diplocraterion*) up to 20 cm deep (Fig. 7C; Collinson *et al.* 2006). Rhythmite sets, which are up to 50 cm thick and consist of tens of clayey and silty beds, are visible on cleared section walls (Fig. 7D). The thickest beds in some sets are clay beds, while in others the thickest beds are composed of silt. The unit contains numerous mollusc and crustacean shells of boreal-Arctic species, including *in-situ* *Macoma calcarea*, *Hiattella arctica*, *Balanus* sp. and *Mya* sp., as well as slumped *Ennucula tenuis* and *Astarte borealis*. In some places, several shells form aggregates. Volkova (1958) collected typical *Cyrtodaria jensenseae* and several other species from this stratigraphical level (Fig. 5). The sediments (sample number 7243-516) yielded an OSL age of 219 ± 24 ka at 44.3 m a.s.l. (Table 2), suggesting an MIS 7 age. The sedimentary structures and faunal composition suggest that the sediments accumulated in a littoral environment and we interpret the rhythmites to represent tidal bedding. The top of the Kheta formation is eroded at about 45 m a.s.l., as described below.

Site 7254 (Figs 2, 3B) is located on the right bank of the river around 11 km upstream of the Akhik-takagi tributary (68.47°N, 83.12°E), where the river lies 6 m a.s.l. The river bluff is 900 m long, 16–27 m high and faces southwestwards. The river valley cuts through a series of hummocky moraines reaching up to 124 m a.s.l.



Fig. 6. Site 7251 along the Bolshaya Kheta River (Solenaya River; Figs 2, 3B). **A.** Stratigraphical profile of the section. See legends in Figs 2, 3. Boxes show panels B–F. 121±11 gives OSL age and >56 shows radiocarbon age. **B.** Block of the Middle Pleistocene peat at the base of alluvium. **C.** Light grey alluvial sand at the base of the clearing, near the man and the spade. It is covered by grey-brown banded or (pseudo)laminated basal till with sandy intraclast of spheroidal shape, with rare pebbles and boulders. The upper part of the photograph shows bluish-grey clayey silt with numerous mollusc shells. **D.** Assimilation zone of glaciodynamic contact between alluvial sand and the basal till. **E.** Sandy spheroidal intraclast within the till. In the left and right parts of the photograph, near elongated margins of the intraclast, quarter folds are visible inside the till (marked by thin white arrows). **F.** The bottom of clayey silt with scattered mollusc shells, with discontinuous layers of fine-grained sand.

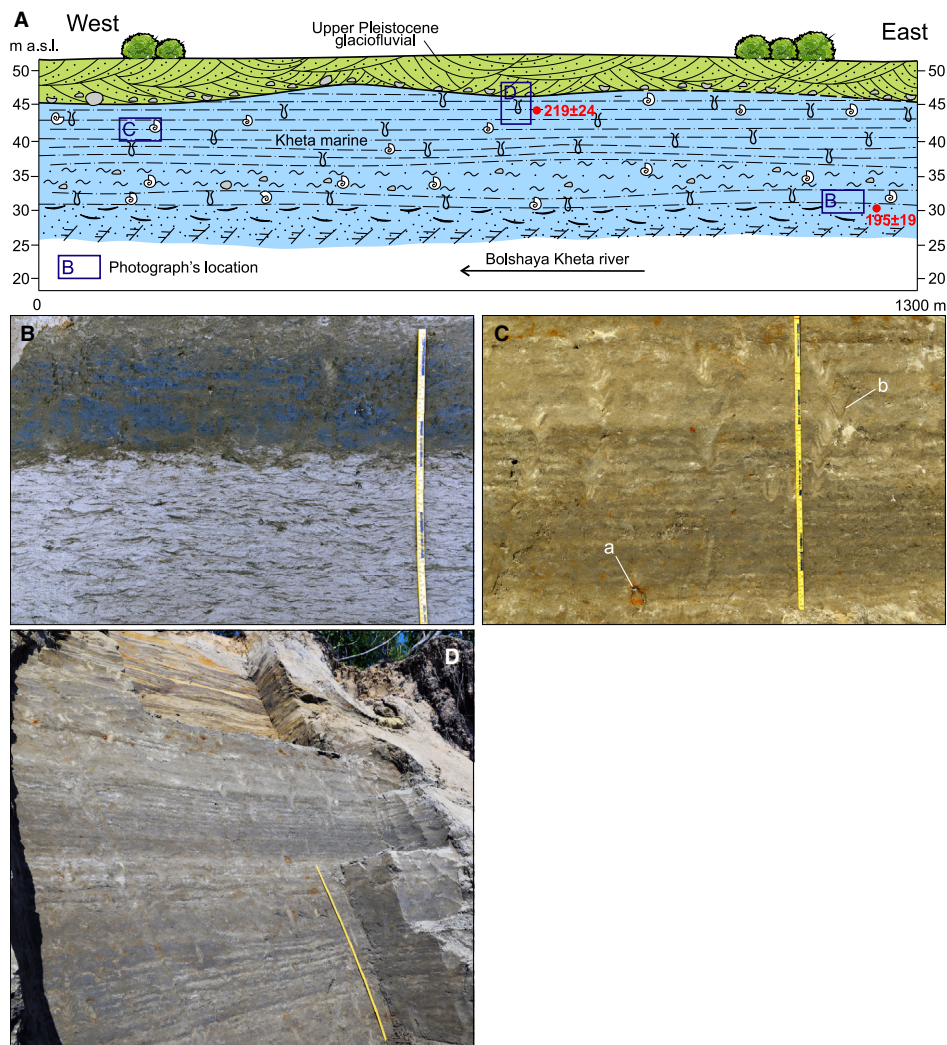


Fig. 7. Section 7243 along the Bolshaya Kheta River (Figs 2, 3B). A. Stratigraphical profile. Legends in Figs 2, 3. Boxes show panels B–D and numbers give OSL ages. B. Fine-grained sand with rare clay gravel and flaser lamination. C. Planar parallel-laminated clayey silt and fine-grained sand with mollusc shells (a) and U-shaped *Diplocraterion* trace fossils (b). D. Rhythmic sets of planar laminated clayey silt and fine-grained sand up to 50 cm thick.

The entire formation consists of grey and yellow-grey fine-grained sand interbedded with silt, from the lowermost clearing at 14 m a.s.l. to the uppermost at 21 m a.s.l. (Fig. 8A). The thicknesses of individual beds range from 1 to 10 cm and the contacts between them are both sharp and gradual. Nonetheless, the beds can be traced for tens of metres along the section wall. Most primary sedimentary structures have been destroyed by intense bioturbation, with only some troughs filled with light grey sand up to 5 cm deep above silty beds being clearly visible (Fig. 8B). The troughs have a heterogeneous distribution within planar parallel beds, suggesting a tidal environment.

Numerous iron-stained molluscs and mollusc burrows are observed throughout the entire succession. We collected *in situ* boreal-Arctic species, including *Astarte*

montagui, *Astarte elliptica*, *Macoma calcarea*, *Mya pseudoarenaria*, *Amauropsis islandica*, *Hiatella arctica*, *Ciliatocardium ciliatum*, *Axinopsida orbiculata*, *Yoldiella lenticula*, *Solariella obscura* and *Boreocingula castanea*, as well as the Arctic species *Portlandia arctica*, *Serripes groenlandicus*, *Cylichnoides validus* and *Laona quadrata*.

On the river bank and slumped slope, we collected the boreal species *Cyrtodaria siliqua*, boreal-Arctic species *Mya truncata*, *Plicifusus kroeyeri*, *Admete viridula*, *Musculus niger*, *Cryptonatica affinis*, *Curtitoma tenuicostata*, *Balanus* sp., *Solariella obscura*, *Neptunea* sp., *Ariadnaria borealis* and *Buccinum terraenovae*, Arctic species *Euspira tenuistriata*, and the diagnostic *Cyrtodaria jensseae*.

We obtained two OSL dates from this unit, 189 ± 16 and 221 ± 25 ka at 15 and 18.2 m a.s.l., respectively



Fig. 8. Site 7254 along the Bolshaya Kheta River (Figs 2, 3B). A. Kheta marine sand and silt, covered by silty-clayey diamicton of the Yermakovo basal till. The contact is marked by dashed line. B. Wavy parallel-laminated fine-grained sand and silt with numerous bioturbations, mollusc shells and troughs cut up to 5 cm deep into silt beds and filled with light-grey sand (marked by thin white arrows). C. Shear-banded glaciotectionally deformed contact zone between till and underlying sand, with clay clasts and shell fragments.

(sample numbers 7254-144 and 7254-152, Table 2). The formation is overlain by shear-banded Upper Pleistocene Yermakovo till.

Marine sediments, located in a similar stratigraphical position and containing a comparable fauna to those described at our 7243 and 7254 sites, were studied by V. V. Komarov (Kalinin *et al.* 1980) on the left bank of the Pokoinitskaya River at section 8701K (Figs 2, 3B). The eroded top of the Samarovo till is covered by a 17-m-thick unit of planar parallel-laminated and planar cross-bedded sandy-silty sediments, with silt layers containing plant detritus. Whole valves and fragments of marine mollusc shells occur in the sands, including the boreal species *Arctica islandica*, *Mytilus edulis* and *Limecola balthica*, and the boreal-Arctic species *Ciliatocardium ciliatum*, *Astarte borealis*, *Macoma calcarea*, *Mya truncata* and *Cyrtodaria jensenseae* (Volkova 1958). V. V. Komarov correlated these marine sediments with the Upper Pleistocene Kazantsevo Formation (Kalinin *et al.* 1980). However, due to the presence of *Cyrtodaria jensenseae* and their stratigraphical position, we correlate these sediments with our Kheta Formation. The

formation is overlain by a dark-grey clayey diamicton comprising the Upper Pleistocene Yermakovo till at 50 m a.s.l. Therefore, facies changes typical for a regressive sequence are observed. Most of the formation is represented by littoral sandy sediments, which are very uniform in character and structure across a distance of 65 km between sites 7243 and 7254.

Taz till. – We observed this till of the last Middle Pleistocene glaciation only at site 7251 on the Bolshaya Kheta River, near the Solenaya River mouth (Figs 2, 3B). This till separates the interglacial deposits of the Middle Pleistocene Solenaya alluvium from the Upper Pleistocene Karginsky marine beds.

At 24 m a.s.l., the alluvial sand is unconformably overlain by brownish and greyish-brown sandy-silty diamicton with scattered pebbles, boulders and sandy intraclasts (Fig. 6C). A pronounced assimilation zone of glaciodynamic contact, up to 0.4 m thick, has been observed at the base of the diamicton (Fig. 6D). This zone, with substrate cannibalization and drag folds, contains sand of the underlying alluvial formation,

which has been stretched into discontinuous bands or (pseudo) layers by the slow movement of debris-charged glacier ice. A large sandy intraclast, more than 3 m in length, was uncovered in the middle part of the diamicton. The intraclast has a spheroidal shape and consists of plucked blocks and folded sand, with remnants of primary sedimentary structures. There are quarter folds within the diamicton along the intraclast contact (Fig. 6E), which are typical for dynamometamorphic mylonites (Trouw *et al.* 2010) and glacially deformed materials (van der Wateren *et al.* 2000). These folds are situated just outside of the opposite elongated margins of the intraclast, forming by rotation of the sandy block due to ice layers travelling at contrasting velocities. The basal ice layers, characterized by more intense friction with underlying rocks, moved at a slower velocity compared to the upper layers. The assumed ice-flow direction is from the NW based on numerous measurements of drag folds and lineations. The diamicton, up to 5 m thick, is unconformably overlain by silt and clay of the Karginsky marine formation.

Karginsky marine formation. – We studied this unit at two field sites. Site 7251 (Figs 2, 3B) is located near the Solenaya River mouth and is the only site where the base of the Karginsky marine strata can be observed. At this location, the top of the Taz till is apparently eroded, with the overlying bluish-grey-brown clayey silts with numerous scattered mollusc shells of the Karginsky marine formation unconformably overlying the till at 29 m a.s.l. (Fig. 6A). The silt is massive, but discontinuous layers of grey fine-grained sand are observed in all beds (Fig. 6F). The sand layers are up to a few cm thick with thin planar parallel lamination, but trace fossils such as burrows protrude through the silt. The silt gradationally passes upwards into bluish-grey fine-grained sand with planar parallel lamination and ripple cross-lamination due to increasing thickness of the sandy layers, with layers of grey silt up to a few cm thick. We obtained an OSL age of 121 ± 11 ka from the sand (sample number 7251-554, Table 2).

In the downstream part of the section, the silt with intraformational unconformity is overlain by sand interlaminated with silt, with trough cross-lamination at the base. In silty beds of the marine sediments, boreal-Arctic mollusc species were collected (*in situ*) and identified, including *Macoma calcarea*, *Hiatella arctica*, *Lyonsia arenosa*, *Astarte montagui* and *Axinopsida orbiculata*, as well as the Arctic species *Portlandia arctica*, *Cylichnoides densistriatus* and *Obesotoma starobogatovi*. Volkova (1958) collected boreal *Limecola balthica* and several other species from the upper part of this unit (Fig. 5). The top of the marine sediments is eroded at 35–43 m a.s.l.

The Khikigli site includes three sections (7246, 7248 and 7249 in Figs 2, 3B) on both sides of the Bolshaya Kheta River, ranging from 6 km upstream to 2–3 km

downstream from the mouth of the Khikigli tributary (Fig. 9A). Section 7248 (67.97°N, 83.11°E) is the most spectacular and complete, while the other two sites were used to add further details concerning the compositions of the different formations. The bluff is 1.3 km long, cuts higher topography up to 86 m a.s.l., and faces south-eastwards. The height of the bluff decreases from 54 m in the upstream part to 42 m in the downstream part, where the river is located at 14 m a.s.l.

At the base of the section, at about 5000 m in Fig. 9A, yellowish-grey silty sand was uncovered. Aqueous sedimentary structures were not observed in the sand, with only rare thin lenses of grey fine-grained sand. The lenses are discontinuous, 2–20 cm long and sometimes disrupted by a few mm-scale normal faults. The upper contact of the sand is erosional, with a 20-cm-deep pit infilled by the overlying marine silty clay. We were not able to clear more of this lower part of the section, therefore the processes leading to formation of the sand remain uncertain. It is possible that it is a subaerial deposit deformed by cryogenic processes.

The sand is overlain by a 4-m-thick, greyish-brown, compact silty clay with layers (up to 6 cm) of grey fine-grained sand with internal planar parallel-lamination (Fig. 9B). The beds are less than a few metres long. Numerous mollusc shells are scattered in the clay and the contacts of sandy beds are disrupted by bioturbation. At 22 m a.s.l., there is a gradual transition to fine-grained sand with beds of silty clay ranging from a few mm to 20 cm thick, decreasing in thickness upwards. The sand is grey and light grey, while the silty clay is bluish-grey or bluish brown. Sedimentary structures are represented by flaser bedding, planar or wavy parallel-lamination, and small-scale trough cross-lamination (Fig. 9C, D). The depths of the troughs rarely exceed a few cm, with a width of several tens of cm. Many of the large flasers are composed of fine-grained plant detritus and numerous mollusc shells are scattered in the sediments. Beds with inclined parallel-lamination and clayey gravel eroded from underlying layers occur in this part.

The sandy part is characterized by a speckled appearance due to traces of marine faunal activity, including numerous burrows and trackways. Their depth, thickness, shape and orientation are very variable, but their size rarely exceeds a few centimetres. We were fortunate to observe trace fossils in 3D in the field due to scouring by wind (Fig. 9E, F). According to P. A. Beznosov (Institute of Geology, Rep. Komi Scientific Centre, Urals Branch of Russian Academy of Science, Syktyvkar), the trace fossils are represented by *Psilonichnus* isp., *Skolithos* isp., *Arenicolites* isp., cf. *Spirophyton* (*Zoophycos*) isp. and cf. *Thalassinoides* isp., which are generally characteristic of the *Psilonichnus* and *Skolithos* ichnofacies.

We collected (*in situ*) boreal *Limecola balthica*, boreal-Arctic *Astarte montagui*, *Astarte arctica*, *Astarte crenata*, *Hiatella arctica*, *Macoma calcarea*, *Lyonsia arenosa*,

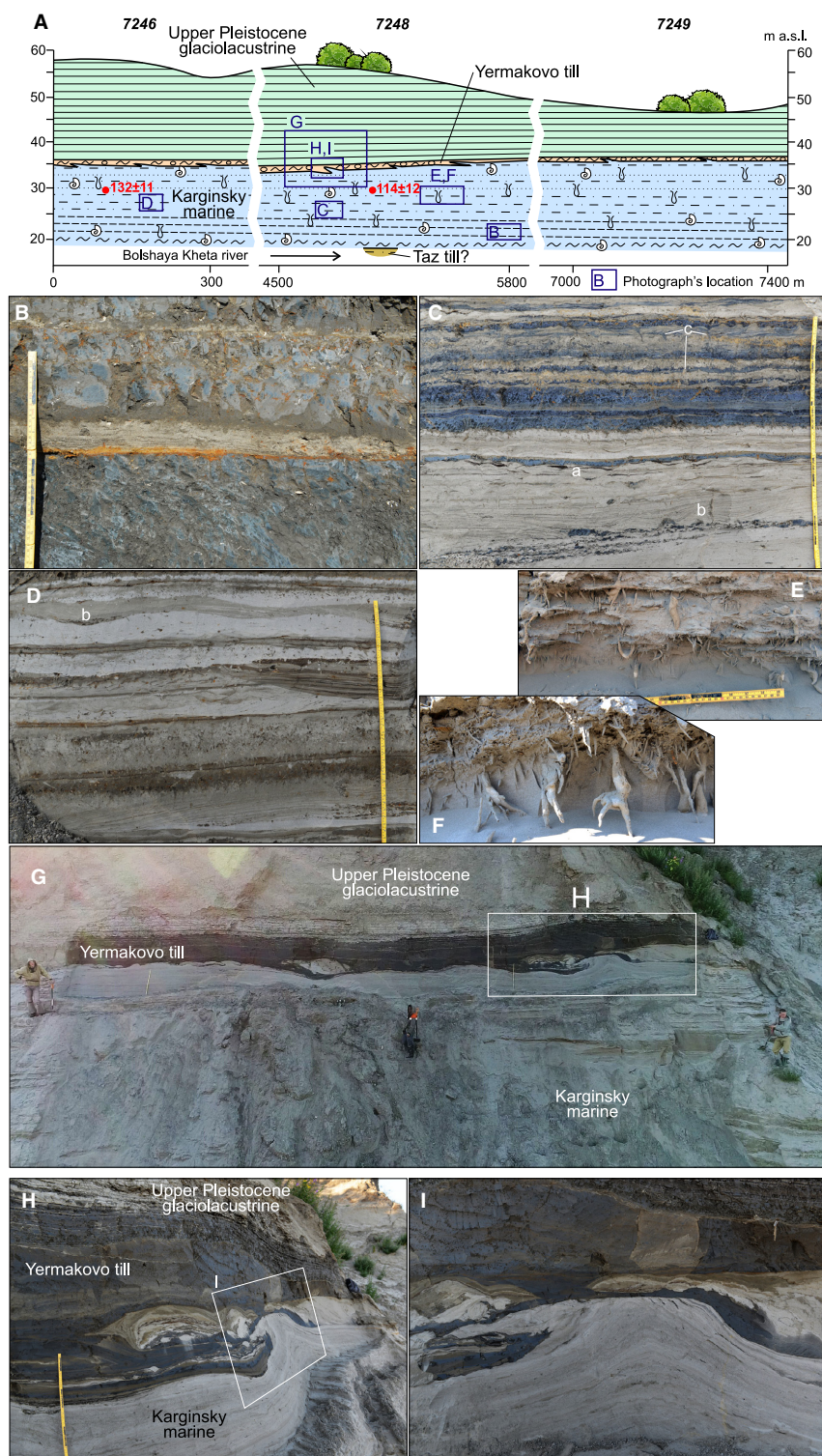


Fig. 9. The Khikigli site along the Bolshaya Kheta River (7246, 7248, 7249 in Figs 2, 3B). **A.** Stratigraphical profile of three sections. Legend is given in Figs 2, 3. Boxes show panels B–I, black numbers represent key sections and red numbers – OSL ages. **B.** Silty clay with beds of fine-grained sand with fine planar parallel-lamination, numerous mollusc shells and bioturbations. **C.** Sand with planar, wavy, flaser (a), small-scale trough cross-lamination (b) and traces of marine faunal activity (c). **D.** The same sand as in Fig. 6C, but with deeper troughs (b) and clayey gravel in the lower bed. **E, F.** Scoured trace fossils. **G.** General view of the section 7248. Note glaciodynamic contact at the bottom of basal till. **H.** Basal till with detaching rafts of underlying sand (cannibalization), which partly stretched into boudinage structures. The till is covered by glaciolacustrine varved clay and clayey-silty rhythmites. **I.** Close-up of folded and cannibalized marine sand underlying the basal till. Structures of incorporated sandy intraclasts in the till.

Musculus discors, *Amauropsis islandica*, *Ennucula tenuis*, *Axinopsida orbiculata* and *Frigidoalvania cruenta*, and Arctic *Portlandia arctica*, *Colus sabini*, *Obesotoma starobogatovi*, *Cylichnoides scalptus*, *Cylichnoides densistriatus* and *Batharca glacialis*. On the river bank and slope, we collected the boreal species *Cyrtodaria siliqua* and Arctic species *Colus sabini* and *Cyrtodaria kurriana*.

The sedimentary structures indicate a tidal depositional environment for the entire unit, an interpretation supported by the trace fossils and coarsening upward trend, characteristic of a marine regressive sequence.

Two OSL ages, 132 ± 11 and 114 ± 12 ka (sample numbers 7246-115 and 7248-139, respectively), were obtained from the sandy part of the sequence (Table 2). The dates, as well as the relatively warm water molluscan fauna, suggest a correlation with the Karginsky marine formation and thus MIS 5e. Previously, the type section at Karginsky Cape on the Lower Yenisey River yielded six OSL ages in the range 117–97 ka (Nazarov & Henriksen 2010) and four IRSI ages in the range 119–93 ka (Gusev *et al.* 2019). At 31 m a.s.l., the marine sediments are overlain by the Yermakovo till (see below).

Yermakovo glacial complex. – The Yermakovo glacial complex is the sedimentological product of an ice sheet, which spread from the Putorana plateau during Early Weichselian time. The ice sheet crossed the Yenisey River between the mouths of the Turukhan and Bolshaya Kheta rivers (Figs 1B, 2), while its marginal landforms are observed to the west of the Bolshaya Kheta River. Till, glaciolacustrine and glaciifluvial deposits of the Yermakovo glacial complex comprise the upper part of all the sedimentological sections along the Bolshaya Kheta River. It is important to note that the Putorana ice sheet did not connect and interact with the Kara ice sheet, which advanced into northern Siberia from the Kara Sea shelf (Fig. 1B; Nazarov *et al.* 2016).

We observed the Yermakovo till at two sites: site 7254 and the Khikigli site. At site 7254 (21 m a.s.l.; Figs 2, 3B), the Kheta marine sediments are overlain by greyish-brown clayey-silty diamicton, with a pseudo-stratified or massive structure and scattered pebbles (Fig. 8A). The contact zone between the underlying sand and diamicton is represented by a layer, up to 0.4 m thick, consisting of thin (1–10 mm) wavy discontinuous laminae, numerous clay clasts and shell fragments derived from the underlying sand (Fig. 8C). The visible thickness of the diamicton is about 2 m. The composition of the diamicton, along with the shear zone at its base, demonstrate that the diamicton is a basal till.

At the Khikigli site, sections 7246, 7248, 7249 (Figs 2, 3B), the Karginsky marine sediments are overlain by a greyish-brown sandy-silty diamicton up to 0.8 m thick (Fig. 9A, G). The contact between the units is represented by a sharp unconformity at 31 m a.s.l. The shear zone along the contact contains numerous intraclasts indicating substrate cannibalization. Underlying sands

are intruded into the diamicton as overturned drag folds, diapirs and flame-like structures (Fig. 9H). Within the diamicton, cannibalized stratified rafts are broken into sandy intraclasts, which are partly stretched into shear lenses, discontinuous layers and boudins. There are also numerous reverse faults and fragments of clay and mollusc valves in the shear zone.

These features demonstrate a glaciotectonic origin for the contact between the marine sediments and the diamicton, which is undoubtedly the Late Pleistocene Yermakovo till. The key point is that both shearing and folding indicate an ice-flow direction towards the west-southwest. Similar glaciotectonic features and structural orientations are found in all three sections 7246, 7248 and 7249 (Figs 2, 3B, 9A), across a distance of >7 km. The diamicton is capped by a clayey glaciolacustrine rhythmite up to 8 m in thickness (Fig. 9H), which was not influenced by the underlying glaciotectonics.

According to V. V. Komarov (Kalinin *et al.* 1980), the interglacial marine sediments (see above) at site 8701K (Figs 2, 3B) are capped by a dark-grey clayey diamicton (up to 4 m thick) of the Upper Pleistocene Yermakovo till, with rare pebbles and boulders of Siberian trap basalts.

Glaciifluvial deposits of the Yermakovo glacial complex have been described from sites 7243 and 7251. At site 7243 (Figs 2, 3B), the upper parts of the Kheta marine sediments have been eroded and are unconformably overlain by yellow-grey medium-grained sand with trough cross-bedding (Fig. 7A). The troughs are up to 10 cm deep. The sand contains scattered pebbles and gravel lenses, along with seams and thin lenses of clayey silt, indicative of a periodically stagnant water regime. At site 7251 (Figs 2, 3B), sands with trough cross-bedding, planar and flaser lamination, and rare silty layers fill an incised channel that cuts into the Karginsky marine sediments, with a pronounced erosional lag at the base (Fig. 6A).

Stratigraphy along the Tanama River

We observed a very comparable stratigraphical sequence along the Tanama River (Figs 1B, 4) to the Bolshaya Kheta River, except that the youngest Yermakovo till is missing. We provide a brief stratigraphical description below.

Kheta marine formation. – At sites 7213, 7214 and 7220 (Fig. 4A), the bases of the exposures are composed of clayey silt and sand with an abundant marine molluscan fauna, including *Cyrtodaria jensisseae*. We obtained OSL ages of 182 ± 20 , 181 ± 15 and 175 ± 23 ka at sites 7213 and 7220 (sample numbers 7213-172, 7220-249 and 7220-253, respectively Table 2).

Taz till. – The Taz basal till, represented by a clayey diamicton with scattered pebbles, overlies the Kheta

marine beds at sites 7213 and 7214. This diamicton also forms the base of the section at site 7219 (Fig. 4). At site 7220, a huge block of Upper Cretaceous silt and clay, up to 60 m thick and more than 100 km² in area, has been thrust on top of the marine beds by glaciotectonics (Nazarov *et al.* 2018).

Payuta marine formation. – Marine sand and silt containing numerous *Arctica islandica*, a characteristic boreal species, unconformably overlie the Taz till. We obtained OSL ages of 147 ± 12 , 114 ± 9 and 97 ± 9 ka from the sand (sample numbers 7219-223, 7214-189 and 7219-226, respectively) and an infinite radiocarbon age of ≥ 49 210 years BP from a wood fragment (Fig. 4, sites 7214 and 7219, Tables 2 and 3). These sediments correspond to the Payuta marine formation, with its type section exposed at the Taz estuary (Fig. 1; Nazarov 2007), and can be correlated with MIS 5e (Table 1). The marine formation forms a well-pronounced regional flatland at altitudes of 60–70 m, separated from higher moraines by long gentle slopes. In many places there are distinct and laterally persistent slope breaks along the 70 m contour, reflecting a sharp change in slope gradient and taking on the appearance of strandlines. This area of flat topography stretches from the Ob' estuary northeastwards to the Northern Siberian Plain (Nazarov *et al.* 2016, 2018) and can be interpreted as a marine terrace.

Kara glacial complex. – The Early Weichselian Kara ice sheet did not cross the Tanama River (Fig. 1B). Therefore, the Payuta marine beds are covered by till only further to the northwest (to the left in Fig. 4B). Along the river, the Payuta marine beds are covered by glaciolacustrine rhythmites and varved clay with an OSL age of 79 ± 8 ka (sample number 7213-173, section 7213, Fig. 4, Table 2), and glaciifluvial sandy sediments.

Postglacial sediments. – Postglacial sediments comprise a second river terrace alluvium, with radiocarbon ages of $35\,420 \pm 388$ and $31\,695 \pm 497$ cal. a BP, and are incised into the underlying glaciolacustrine sediments (section 7215, Fig. 4).

Discussion

Are there two marine interglacial formations exposed in West Siberia?

Over the course of the last century, many researchers have been in agreement that there are two marine formations with a boreal molluscan fauna exposed in West Siberia – the Kazantsevo and Karginsky horizons (Table 1, Sachs 1953). Up until the 2000s, both of these formations were believed to be Late Pleistocene in age. Numerous modern studies of type localities near Cape Karginsky on the Lower Yenisey and in other regions of the West Siberian

Arctic and Taimyr Peninsula, along with the acquisition of OSL and electron spin resonance (ESR) ages, revealed that the Karginsky marine formation can be correlated with the MIS 5e interglacial (Astakhov 2006; Astakhov & Nazarov 2010; Nazarov & Henriksen 2010; Nazarov *et al.* 2018; Möller *et al.* 2019), but not with MIS 3 as previously assumed (Sachs 1953; Table 1). However, the age of the older Kazantsevo Formation remains disputed and unresolved. Are there two exposed marine formations of different ages, or is there only one described under two different names? New IR-OSL ages within MIS 5a, obtained from sand containing a marine molluscan fauna within the type locality on the right bank of the Lower Yenisey (Gusev *et al.* 2016), could not definitively answer this question, since the stratigraphical relationship between tills and the dated marine sand was not determined. A strong line of evidence to suggest that the two marine formations are of different ages lies in the discovery of the diagnostic boreal mollusc species *Cyrtodaria jensenseae* within the Kazantsevo marine sediments, along with its absence from the Karginsky beds (Sachs 1953).

In the Bolshaya Kheta River valley, the marine formation is sandwiched between Middle and Upper Pleistocene till beds (Fig. 3A). Based on stratigraphy, OSL ages and molluscan fauna, we have for the first time definitively determined that the Kazantsevo Formation/Kheta beds and the Karginsky/Payuta formations comprise two distinct marine formations of different ages.

We observed both marine formations in a continuous stratigraphical succession, separated by the Taz till, only at site 7214 on the Tanama River. We did not find the two marine formations in the same location at any of the sites on the Bolshaya Kheta River; therefore, the stratigraphical profile given in Fig. 3B shows our interpretation only.

The ratio of the IR₅₀ to quartz ages is 0.77 ± 0.04 ($n = 14$), i.e. the IR₅₀ ages are on average ~24% younger than the quartz ages. This is not surprising, since it is well established that the IR₅₀ signal from feldspar is known to suffer from anomalous fading (Spooner 1994). However, the pIRIR₂₉₀ signal from K-feldspar has been argued to be stable (Buylaert *et al.* 2012), with a ratio of the pIRIR₂₉₀ ages to quartz of 1.39 ± 0.07 ($n = 14$) in our samples. We show the pIRIR₂₉₀ ages as a function of the quartz ages in Fig. 10, where it is clear the pIRIR₂₉₀ ages overestimate those from quartz across the entire time interval investigated here. This possibly indicates that the pIRIR₂₉₀ signal wasn't completely bleached at burial, in contrast to the quartz signal. As a result, we consider the quartz ages as the most reliable.

All seven OSL ages, obtained from quartz measurements of the Kheta marine sediments, are around 200 ka and correlate with the MIS 7 interglacial. The results from feldspar OSL dating confirm that quartz is well bleached, giving us confidence in our quartz OSL ages. The OSL dating results support our hypothesis that the

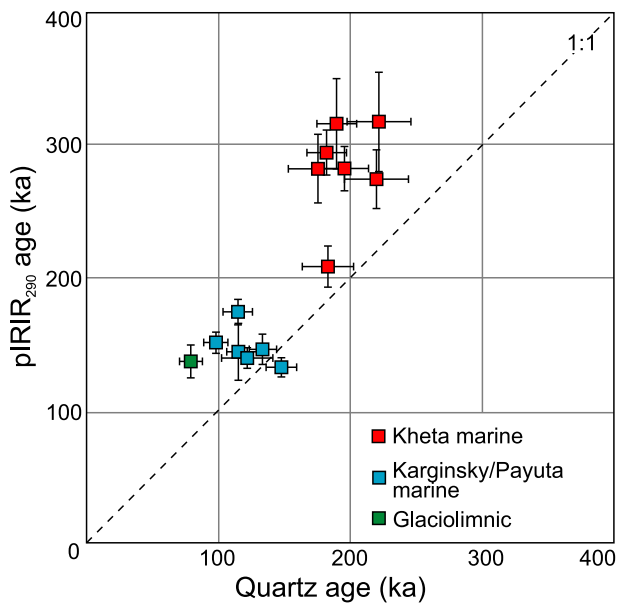


Fig. 10. pIRIR₂₉₀ ages shown as a function of quartz ages. The dashed line indicates the 1:1 line.

Kheta marine formation was deposited during a Middle Pleistocene interglacial boreal marine transgression.

Three quartz OSL ages from the Karginsky marine formation on the Bolshaya Kheta River range from 132 ± 11 to 114 ± 12 ka (Table 2), which mostly correlate with MIS 5e. However, OSL ages from the Payuta Formation along the Tanama River occupy a comparatively wider age range, spanning 147 ± 12 to 97 ± 9 ka. Furthermore, 16 OSL ages ranging from 166 ± 9 to 96 ± 5 ka, with a mean of 135 ka, have been obtained from Payuta marine sediments at several sites along the Taz estuary (Nazarov 2007; Astakhov & Nazarov 2010). Therefore, we can correlate both the Karginsky and Payuta marine formations with MIS 5e based on OSL dating and stratigraphy.

A characteristic feature of the Kheta marine sediments is the presence of the extinct species *Cyrtodaria jensiseae* (Fig. 1C), which is absent from the Karginsky/Payuta marine formations.

These results conform with stratigraphical and geochronological data from the east of the study area. Möller *et al.* (2019) described evidence for distinct Middle Pleistocene and Late Pleistocene interglacial marine transgressions across the Taimyr Peninsula, which can be correlated with MIS 7 and MIS 5e, respectively, based on OSL, IRSL and ESR ages.

How far did the interglacial marine transgressions penetrate inland?

The Karginsky/Payuta transgression. – The Karginsky and Payuta marine sediments have been observed at many sites from the Ob' estuary to the North Siberian

Plain (Fig. 11; Nazarov 2007; Nazarov & Henriksen 2010; Nazarov *et al.* 2016, 2018). The marine formation is overlain by different strata at different locations, depending on whether the region was affected by advancing ice sheets (Fig. 4B). Within the limits of the Early Weichselian Kara and Putorana ice-sheet advances, the marine sediments are covered by the Kara or Yermakovo till. In the Bolshaya Kheta River basin, the sediments are locally distributed and probably accumulated within a broad shallow marine embayment, which extended far into West Siberia from the northeast. Shallow marine facies at the base of the formation have been observed at 30 m a.s.l. at the Solenaya River site (Figs 3B, 11A). The base of the formation dips southwards at a shallow gradient below river level, since the base of the exposed section at the Khikigli site is composed of the same clayey-silty facies as at the Solenaya River site. The top of the Karginsky Formation has been eroded along the Bolshaya Kheta River section and its visible thickness is barely more than 20 m.

In contrast, beyond the Early Weichselian ice-sheet limits such as in the Tanama River basin, the marine sediments comprise a vast area of flat topography at 60–70 m a.s.l., which can be traced from the Ob' estuary to the North Siberian Plain (Fig. 11, Nazarov *et al.* 2016, 2018). The altitudes above current sea level indicate the magnitude of glacial isostatic crustal rebound after the last Middle Pleistocene (Taz) glaciation.

The Kheta transgression. – The Pupkovo site at $\sim 65^\circ\text{N}$ on the right bank of the Yenisey River represents the southernmost site where marine sediments yield U/Th ages of 233 or 170 ka, characteristic of the Kheta Formation (Zubakov 1972; Fig. 1B, site 7). We plotted the distribution of sites believed to include Kheta marine sediments on a map (Fig. 11) and outlined an area (dark blue dashed lines) that could potentially be covered by the sea during MIS 7. The upper part of the marine formation has been removed by glacial erosion at all sites, but the uppermost preserved portion of the formation is found at 50 m a.s.l. Therefore, glacial isostatic subsidence of at least 50 m occurred within the area beneath the Samarovo ice sheet, prior to the subsequent Kheta interglacial marine transgression.

How warm were interglacial environments?

Boreal molluscan fauna from both marine formations are indicative of summer water temperatures ranging from $+3$ to $+13^\circ\text{C}$ and winter temperatures of -1.6°C at a water depth of about 20 m. This temperature regime is comparable to the present-day White Sea where these mollusc species live today (Dobrovolskiy & Zalogin 1982), which is situated outside of the Arctic Circle and almost 2000 km westward of the study area. By comparison, the nearby Kara Sea is characterized by maximum summer temperatures of $+6^\circ\text{C}$ in the

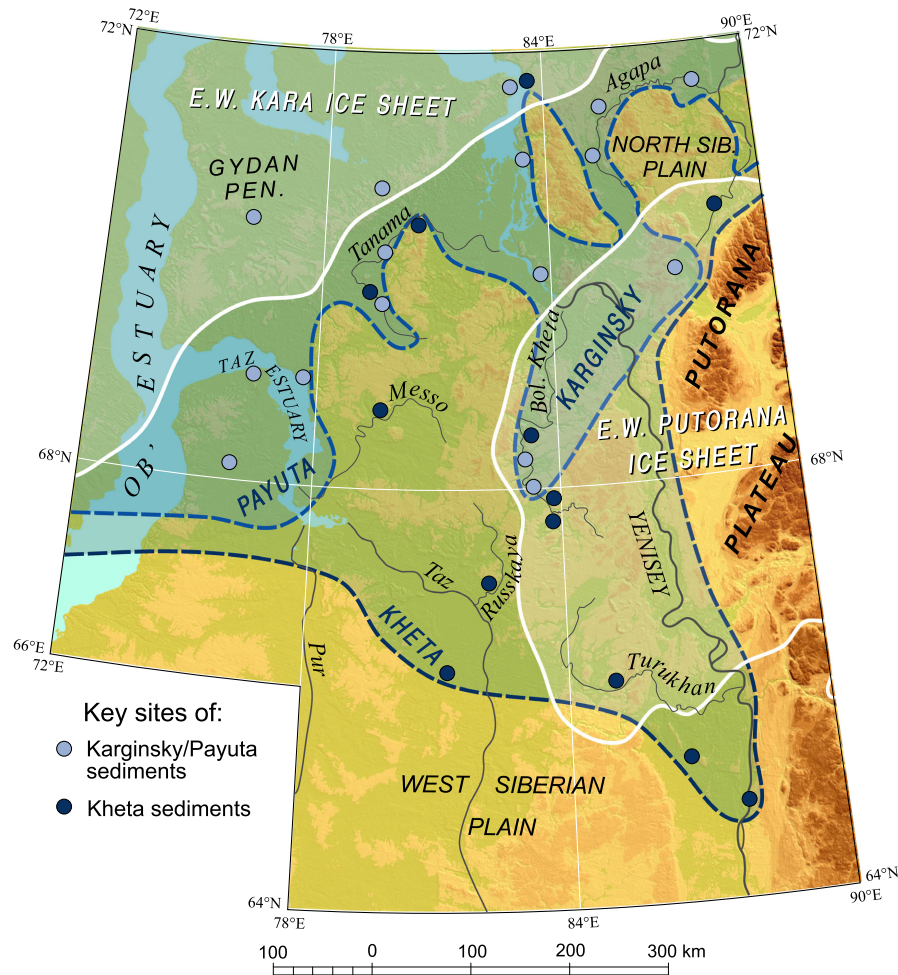


Fig. 11. Reconstruction of the Middle and Late Pleistocene interglacial transgressions. Dashed lines show assumed limits of interglacial marine transgressions: Kheta (dark blue line, MIS 7) and Karginsky/Payuta (light blue line, MIS 5e). White solid lines show assumed limits of the Early Weichselian Kara and Putorana ice sheets. Limits of the Middle Pleistocene ice sheets are south of the map margin.

southwestern part and $+2^{\circ}\text{C}$ in the northeast, with a mean winter temperature of -1.7°C (Dobrovolskiy & Zalogin 1982). The climate of West Siberia during the MIS 7 and MIS 5e interglacials was clearly significantly warmer than at present. Furthermore, the boreal molluscan assemblages suggest that warm Atlantic waters penetrated much further eastwards compared to today.

The Solenaya alluvium, containing fossilized peat and coniferous tree trunks, underlies the Kheta Formation. We propose that these sediments accumulated in a river basin draining northwards, after the Samarov ice-sheet dam broke and northward river drainage resumed, but before shallow marine waters transgressed inland from the northeast to deposit the Kheta Formation. Plant remains in the alluvium indicate an extensive coverage of taiga forest, in contrast to the treeless tundra of today, suggesting a much warmer climate than at present. These findings suggest that the climate of West Siberia during MIS 7 was at least as warm as during MIS 5e.

Conclusions

In the Bolshaya Kheta and Tanama river basins, the base of the exposed section comprises marine sand with silty layers and a boreal molluscan fauna, which we term the Kheta marine formation (Figs 2, 3B, 4). The extinct mollusc *Cyrtodaria jennisseeae* is a diagnostic species of this formation and is not found within the overlying Upper Pleistocene sediments in the study area. We therefore conclude that the Kheta marine formation is of Middle Pleistocene age and can be correlated with the MIS 7 interglacial. The Kheta marine formation is overlain by Middle or Upper Pleistocene glacial deposits, or by Upper Pleistocene marine sediments.

A younger marine formation occurs higher in the Quaternary succession of West Siberia, which can be correlated with the Karginsky marine formation along the Bolshaya Kheta River and the Payuta marine formation along the Tanama River (Figs 2, 3B, 4). Based

on OSL ages, this marine formation is Upper Pleistocene in age and can be correlated with the MIS 5e interglacial. Numerous specimens of the warm-water mollusc *Arctica islandica* were defined at one site on the Tanama River. Along the Bolshaya Kheta River, the Karginsky marine formation is overlain by the Upper Pleistocene Yermakovo glacial deposits. Beyond the limits of the Early Weichselian ice sheets, the Payuta marine sediments comprise a vast area of flat topography at altitudes of 60–70 m a.s.l., stretching from the Ob' estuary to the North Siberian Plain.

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Data availability statement. – Data available on request from the authors.

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Supporting Information

Additional Supporting Information to this article is available at <http://www.boreas.dk>.

Fig. S1. Representative normalized and background subtracted quartz natural OSL curves. Also shown is an OSL stimulation curve from a sample known to be fast-component dominated (Cal Q). The inset shows the dose response curves for the three aliquots shown in the main graph. The open symbols show the recycling values.

Fig. S2. Typical K-feldspar pIRIR₂₉₀ decay curve from the natural signal of a single aliquot from the sample 7220-253. The inset shows a typical K-feldspar

dose-response curve of the same aliquot (the open symbol represents the recycling value).

Fig. S3. Dose recovery results for quartz samples. Quartz aliquots were bleached twice at room temperature for 100 s using blue LEDs. A pause of 10 000 s was inserted between stimulations. Then 14 aliquots of 7 different samples, 6 aliquots of sample 7213-172 and 6 aliquots of sample 7243-516 were given doses of 9, 232 and 418 Gy, respectively. Also shown is the 1:1 line (full) as well as the $\pm 10\%$ lines (dashed).

Fig. S4. Dose recovery results for K-rich feldspar aliquots from sample 7220-249. Aliquots were bleached for 4 h in a daylight simulator before doses of 271 and 542 Gy were given. The dose recovery ratio (corrected for residual dose) is given next to each point.

Fig. S5. IR₅₀ and pIRIR₂₉₀ residual doses measured after bleaching in a Hönlé SOL2 solar simulator for 4 h (A) and 48 h (B) vs. their corresponding D_e values for five samples (7219-223, 7213-173, 7248-139, 7220-249 and 7254-152). Each data point is an average of three aliquots. Simple averages are used to estimate hard-to-bleach residual doses.