Ice-free interval corresponding to Marine Isotope Stages 4 and 3 at the Last Glacial Maximum position at Kileshino, Valdaj Upland, Russia

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Abstract. Radiocarbon and optically stimulated luminescence dates, together with bio- and lithostratigraphical data, revealed an interval of ice-free conditions between 72.2 OSL and 33.8 cal ^{14}C ka BP at the Kileshino site (Valdaj Upland, Russia), corresponding to Marine Isotope Stages (MIS) 4 and 3. Limnic sedimentation conditions occurred at the Kileshino site between 57.5 OSL and 33.8 cal ^{14}C ka BP, corresponding to MIS 3 'megainterstadial' in European Russia (Oerel to Hengelo interstadials in Central Europe). During the last glaciation, a sedimentary unit of laminated silt and sand of fluvial origin was redeposited at that site due to expansion of the Scandinavian Ice Sheet (SIS). This unit expresses fluvial sedimentation conditions NW of Kileshino between 72.2 and 40.8 OSL ka. All dates together suggest that the Kileshino site was ice-free between 72.2 OSL and 33.8 cal ^{14}C ka BP. The sedimentary unit of laminated silt and sand was redeposited at the Kileshino site during the last SIS not before 33.8 cal ^{14}C ka BP, according to previous studies, possibly at its maximum extent between 19.1 cal ^{14}C BP and 18 OSL ka. Only one till, younger than 72.2 ka, was found from the Kileshino outcrop. It can be concluded that the SIS reached this area only once during the last 72.2 ka – in the late Valdaj (Weichselian), after 33.8 cal ^{14}C ka BP. The expansion of the SIS to the study area between 115 and 58 ka could be neither proved nor disproved as there is no chronological information about the time between 115 and 72.2 ka.

Key words: Scandinavian Ice Sheet, Last Glacial Maximum, Marine Isotope Stage, MIS, late Valdaj, Weichselian.

INTRODUCTION

The extent and timing of the Scandinavian Ice Sheet (SIS) during the Valdaj (also spelt Valdai or Valday) (Weichselian) cold stages have been investigated previously by many authors. In the NW part of European Russia, however, especially in the area of Valdaj, the chronological data are still insufficient and further studies are required.

Contradictory opinions exist regarding the advance of the SIS to the NW part of European Russia during the Valdaj cold stage. Some studies claim that the area was covered by the SIS twice: (1) in the early or middle (Marine Isotope Stage (MIS) 4), and (2) the late Valdaj (Zarrina 1991; Arslanov 1993). Other studies, however, state that the SIS advanced to the NW part of European Russia only during the late Valdaj, while in the early/middle Valdaj the margin of the SIS did not reach beyond the Baltic Sea Depression and Russian Karelia (Chebotareva & Makarycheva 1982; Velichko et al. 2004, 2011). The extent and timing of the SIS during the Last Glacial Maximum (LGM) in different areas have been estimated by many authors (Larsen et al. 1999; Lunkka et al. 2001; Rinterknecht et al. 2007, 2008; Wysota et al. 2009; Marks 2010; Guobyte & Satkunas 2011; Lasberg & Kalm 2013). Yet, the timing of the LGM has not been suggested in the region close to the Valdaj Upland and the extent of the LGM has been modelled based on glacial landforms and geomorphology (Ehlers & Gibbard 2004; Kalm 2012). Thus, it is essential to have more chronological proof to confirm the modelled position.

Previously, several authors (Vigdorchik et al. 1974; Zubakov 1974; Malakhovskij & Spiridonova 1981; Arslanov 1987) have published radiocarbon dates from the Kileshino site in the Valdaj Upland. Chronological data together with sedimentology have been summarized by Zarrina (1991) and palynological analysis has been made by Giterman et al. (1975).

The aim of the current study is to define ice-free intervals in the Kileshino outcrop based on bio- and lithostratigraphical data, radiocarbon and optically stimulated luminescence (OSL) dates and to interpret the timing of glacial sediments found from the outcrop. In addition, we intend to check the interpretations based only on palynological data (Giterman et al. 1975) using modern dating methods.

STUDY AREA

The study site is located in the central part of the Valdaj Upland (western part of the Russian Plain), on the East European Platform in the Tver region of Russia. The outcrop of Kileshino (56.88033°N, 33.45834°E) is located near Kileshino village on the left bank of the Sizhina River, ca 4 km north of the town of Selizharovo and 10 km east of Lake Volgo (Fig. 1). The area around the outcrop is plain and several 1 m high boulders are found in the surroundings. The study site (~215 m a.s.l.) lies close to the margin of the modelled last SIS during its maximum extent (Kalm 2012). The Valdaj Upland area is generally a slightly hilly plain with average elevations from 150 to 250 m a.s.l. and the highest point of 346.9 m a.s.l. near the town of Vyshnij Volochek. The southern part of the Valdaj Upland appears to be the main watershed between the drainages of the Caspian and Baltic seas on the East European Platform.

MATERIAL AND METHODS

Field work and sampling were performed at the Kileshino outcrop in the autumn of 2011. The outcrop was described, sampled and photographed in the field. Detailed sedimentological studies were carried out and five main sedimentary units and 19 lithofacies were distinguished. The lithofacies classification used in Fig. 2 is modified from Eyles et al. (1983) and Krüger & Kjær (1999); sediment colour was identified according to Munsell's colour system chart (Munsell Color 1998).

Samples for dating were taken below the till for determining the age of the last SIS advance and the ages of sedimentary units. Four samples for OSL dating of fluvial and limnic sediments from depths of 268–258, 231–158, 141–111 and 80–78 cm (Fig. 2) were collected in plastic tubes and sent to the Laboratory of Chronology, University of Helsinki, for age estimation. The samples were measured by the Risø TL-DA-12 reader and equivalent doses were estimated using a single-aliquot regenerative-dose protocol (Murray & Wintle 2000). Six samples for radiocarbon dating by the accelerator mass spectrometry (AMS) method were taken from depths of 545, 375–365, 355–350, 310–295, 273–268 and 258–252 cm (Fig. 2) and examined in detail in order to define terrestrial and aquatic plant macrofossils for each sample before dating. The main purpose of this determination was to minimize the age overestimations, because the aquatic macrofossils have a 'reservoir effect' compared to macrofossils of terrestrial origin (Hua 2009), but also some general conclusions about climate were made based on the identified species. Samples for macrofossil analyses were washed under tap water through a sieve with a 0.25 mm mesh. Plant remains were picked out under an Olympus SZ61 stereomicroscope. Identification was done under a Nikon SMZ800 low-power stereomicroscope using the keys of Katz et al. (1965, 1977) and Schoch et al. (1988) and the reference collection of seeds and fruits of the Laboratory of Geoarchaeology and Ancient Technology at the Institute of History in Tallinn.

The AMS ages were determined in the Beta Analytic Radiocarbon Dating Laboratory, Florida, USA. The dates were calibrated with 1σ uncertainty using the IntCal09 calibration curve (Reimer et al. 2009) and the OxCal v.4.1 program (Bronk Ramsey 2009).

RESULTS AND INTERPRETATIONS

Lithostratigraphy

The outcrop opens up 545 cm of sediments. Based on sediment lithology and dating, five main sedimentary units were determined (Fig. 2).

Sedimentary unit 1 (SU1) comprises two layers of laminated silt and sand. The bottommost layer (545–469 cm) is fine-layered laminated silt and sand (colour 10YR/4/2 – dark greyish-brown) containing some finely disseminated organic layers. It is overlain by a layer of sediments of the same type (469–379 cm) but different colour (2.5YR/5/2 – weak red). At a depth of 399–379 cm the sediments are massive, not stratified. Sediments of SU1 refer to rhythmic deposition of varved clay under periglacial conditions. One ^{14}C AMS sample was taken from the bottommost section of this unit.

Sedimentary unit 2 (SU2) has a transitional basal contact with SU1. The bottommost layer (379–273 cm) is fine-layered silt with gyttja and plant macrofossils (7.5YR/3/1 – very dark grey). The upper part of SU2 consists of three thin layers: a layer of compressed, finely laminated peat with silt (273–268 cm; 10YR/2/1 – black) interchanges to laminated fine sand with a diffused peat layer (268–258 cm; 10YR/5/3 – brown) and to a well-decomposed peat layer (2.5YR/2.5/2 – very dusky red) at a depth of 258–252 cm. All three topmost layers of SU2 have transitional lower and upper bedding surfaces. The unit SU2 indicates the change in sedimentation conditions, as rhythmic flood-plain sediments in the lower part change to typical limnic sediments in the upper part. Altogether, six ^{14}C AMS samples were taken from the lower, central and top parts of this unit.

Sedimentary unit 3 (SU3) shows rhythmic sedimentation – laminated silt and sand layers typical of fluvial sedimentation systems interchange throughout the unit. The 252–231 cm interval of stratified brown (7.5YR/5/2; 7.5YR/4/2) silt and sand is overlain by sediments of the same type but of different colour

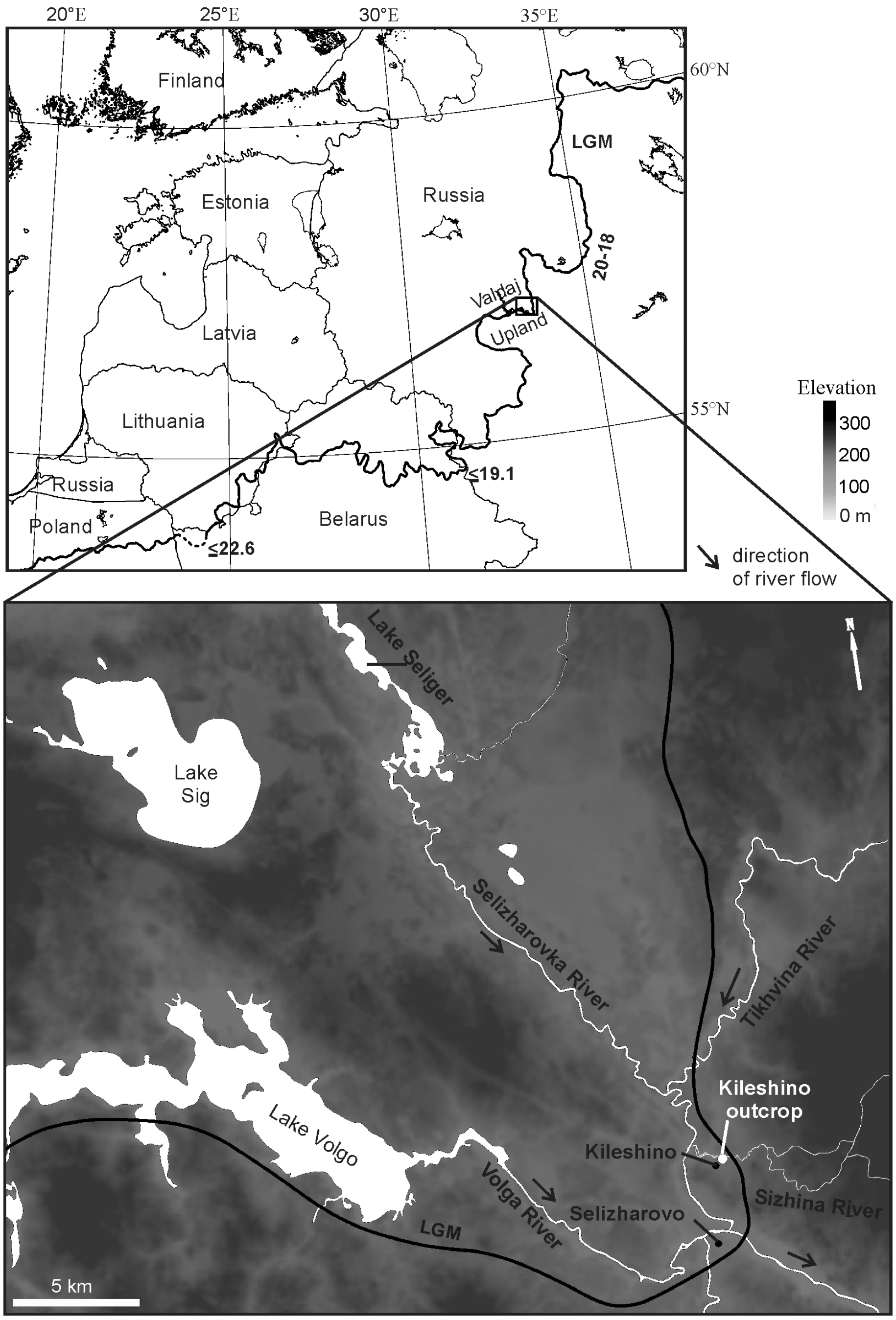

Fig. 1. Location of the Kileshino outcrop. Last Glacial Maximum (LGM) ages are based on Lasberg & Kalm (2013) and Demidov et al. (2006).

(5YR/3/3 – dark reddish-brown to 10YR/5/4 – yellowish-brown) with some organic layers inside (231–158 cm). The next layer (158–141 cm) is massive, reddish-grey (5YR/5/2) silt with diffused organics, overlain by an interval (141–111 cm) of varicoloured (5YR/4/4 – reddish-brown and 10YR/6/4 – light yellowish-brown), deformed and stratified silt and medium sand. The layer at a depth of 111–91 cm is greyish-brown (10YR/4/2 – dark greyish-brown in the lower part; 10YR/5/2 – greyish-brown in the upper part), massive and blockish silt containing some gravel. It is covered by a dark yellowish-brown (10YR/4/6), massive silt layer (91–80 cm) overlain by a thin layer of light brownish-grey (10YR/6/2), loose and massive fine sand (80–78 cm). Layers in SU3 are

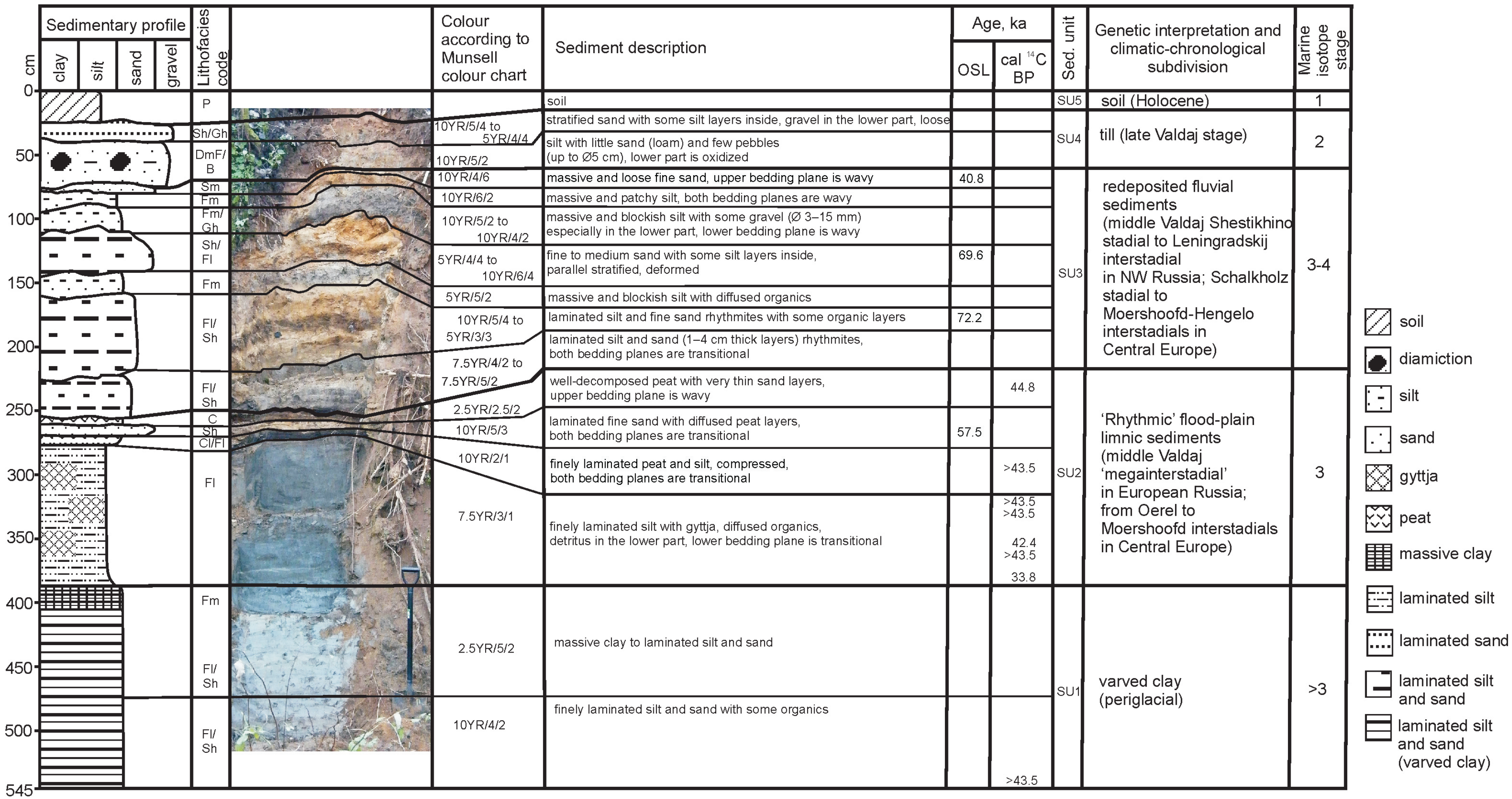

Fig. 2. Description of the Kileshino outcrop with main sedimentary units and genetic interpretation. Climatic-chronological subdivisions are according to Velichko et al. (2011).

contorted and their bedding planes are mostly wavy, which indicates that they were deformed after deposition.

Sedimentary unit 4 (SU4) comprises a layer of greyish-brown (10YR/5/2) loam with pebbles up to 5 cm in diameter at a depth of 78–40 cm, overlain (40–23 cm) by brown (10YR/5/4 – yellowish-brown to 5YR/4/4 – reddish-brown), loose and stratified sand with gravel in its lower part. The unit SU4 refers to a glacial environment as it comprises sediments of different grain sizes from silt to pebbles (till) and gravel without apparent organics.

The topmost sedimentary unit (SU5) from the interval 23–0 cm is brownish silty soil.

Ages and climate-chronological interpretations of sedimentary units

Climate-chronological interpretations for all sedimentary units were made based on four OSL and six ^{14}C AMS age estimations from different depths (Tables 1 and 2) and identified plant macrofossils (Table 3).

It was possible to obtain only one infinite AMS ^{14}C age from SU1 (Fig. 2). The terrestrial macrofossil (*Betula alba*) was estimated to be older than 43.5 ^{14}C ka BP, which is close to the maximum age that can be determined by the radiocarbon dating method. Based on

Table 1. ^{14}C ages

Lab. No.	Sample No.	Depth, cm	^{14}C BP, ka	Cal ^{14}C BP (1σ), ka	Median of cal age, ka	Origin of plant macrofossils
Beta-315232	KIL-1	258–252	41.11 ± 0.42	44.46–45.12	44.8	Terrestrial
Beta-315234	KIL-2	273–268	> 43.5	–	–	Terrestrial
Beta-315236	KIL-3	310–295	> 43.5	–	–	Terrestrial
Beta-315237	KIL-3-2	310–295	> 43.5	–	–	Aquatic
Beta-315238	KIL-4	355–350	37.85 ± 0.33	42.15–42.69	42.4	Terrestrial
Beta-315239	KIL-4-2	355–350	> 43.5	–	–	Aquatic
Beta-315240	KIL-5	375–365	29.12 ± 0.17	33.38–34.41	33.8	Terrestrial
Beta-315241	KIL-6	545	> 43.5	–	–	Terrestrial

Table 2. OSL ages

Lab. No.	Sample No.	Depth, cm	Dose rate, Gy ka^{-1}	Dose, Gy	Age, ka
Hel-TL04251	KIL 1	80–78	2.109 ± 0.253	86.0 ± 9.9	40.8 ± 6.9
Hel-TL04252	KIL 2	141–111	1.914 ± 0.277	133.2 ± 14.1	69.6 ± 12.7
Hel-TL04253	KIL 3	231–158	1.962 ± 0.248	141.7 ± 14.8	72.2 ± 12.1
Hel-TL04254	KIL 4	268–258	1.884 ± 0.320	108.3 ± 15.4	57.5 ± 12.9

Table 3. Identified and dated plant macrofossils

^{14}C sample No.	Depth, cm	Determined species of plant macrofossils	Origin of plant macrofossils
KIL-1	258–252	*Schoenoplectus lacustris*	Terrestrial
	258–252	*Nuphar lutea*	Aquatic
KIL-2	273–268	*Schoenoplectus lacustris*	Terrestrial
	273–268	*Najas marina*	Aquatic
	273–268	*Carex vesicaria*	Terrestrial
KIL-3	310–295	*Schoenoplectus lacustris*, *Betula pubescens*	Terrestrial
KIL-3-2	310–295	*Najas marina*	Aquatic
KIL-4	355–350	*Betula alba*, *Populus tremula*	Terrestrial
KIL-4-2	355–350	*Najas marina*	Aquatic
KIL-5	375–365	*Salix* sp., *Betula alba*, *Carex vesicaria*	Terrestrial
KIL-6	545	*Betula alba*	Terrestrial

one radiocarbon date (>43.5 ^{14}C ka BP), we assume that SU1 was deposited before the late Valdaj and not later than 43.5 ^{14}C ka BP. Furthermore, the genesis of the sediments (varved clay) indicates cold conditions typical of late glacial periods and ages from the sedimentary unit above (SU2) show that the study site was ice-free during MIS 3. We concluded that SU1 was deposited in the peripheral zone of the SIS margin earlier than MIS 3.

Four AMS ^{14}C dates from SU2 yielded the age of >43.5 ^{14}C ka BP for terrestrial and aquatic macrofossils (Table 1, Fig. 2). Three AMS dates of terrestrial macrofossils were between 33.8 and 44.8 cal ^{14}C ka BP. Also one OSL age, 57.5 ± 12.9 ka, was determined from that unit (Table 2, Fig. 2). Thus, the ages from SU2 vary from 57.5 OSL to 33.8 cal ^{14}C ka BP. Some identified plant macrofossils (*Betula alba*, *Betula pubescens*, *Populus tremula*, *Salix* sp.) are cold-tolerating species that are native and abundant throughout northern Europe and indicate that during SU2 the climate was similar to the nowadays one, which implies ice-free conditions (Table 3). Plant macrofossils (*Najas marina*, *Carex vesicaria*, *Schoenoplectus lacustris*, *Nuphar lutea*) that typically inhabit wet areas like lakes, ponds and swamps were also found from SU2. Furthermore, *Najas marina*, *Schoenoplectus lacustris* and *Nuphar lutea* from the upper part of SU2 indicate that the water level was lowering.

Based on dates, identified plant macrofossils and the genesis of sediments, SU2 corresponds to the middle Valdaj (MIS 3) 'megainterstadial' in European Russia (from Oerel to Hengelo interstadials in Central Europe) (Arslanov 1993; Velichko et al. 2011). The MIS 3 'megainterstadial' is characterized by alternating warm and cool phases and, based on the age interval of SU2, the sediments from the Krasnogorskij interstadial (Oerel–Glinde interstadials in Central Europe) to the Leningradskij interstadial (Moershoofd–Hengelo interstadials in Central Europe) are present (Velichko et al. 2011).

Three OSL ages determined from SU3 resulted in inconsistent ages compared to SU2 (Table 2, Fig. 2). The unit SU3 should be younger than the unit below according to the superposition principle, but OSL samples yielded the ages of 72.2 ± 12.9, 69.6 ± 12.7 and 40.8 ± 6.9, which are older than the ages from SU2. Unfortunately there was no material for ^{14}C AMS dating of SU2 for age comparisons. Because dates from SU3 are inconsistent with other ages below and considering also the fact that layers are contorted, we have a reason to conclude that the whole unit was replaced and moved to the Kileshino site by the last SIS advance. The sediments of SU3 are fluvial in origin and, based on the dates from SU3, we suggest that the lower part of SU3 corresponds to the middle Valdaj Shestikhino stadial (Schalkholz stadial in Central Europe) and the upper part to the middle Valdaj Leningradskij interstadial in European Russia (Moershoofd–Hengelo interstadials in Central Europe) (Velichko et al. 2011). No dates from SU4 or above are available, and thus the age of till found from SU4 is not older than 33.8 cal ^{14}C ka BP, which is the youngest age estimated from the organics in rhythmic flood-plain sediments under till and sands, and corresponds to the late Valdaj glaciation.

To sum up, the age range of 72.2 OSL to 33.8 cal ^{14}C ka BP obtained from our outcrop shows that the SIS did not reach the Kileshino site during MIS 4 between 72.2 and 58 OSL ka. Yet, there is no chronological information about the time between 115 and 72.2 OSL ka in our outcrop.

DISCUSSION

Radiocarbon dates taken below till at the Kileshino site ranged between >43.5 and 33.8 cal ^{14}C ka BP, indicating the existence of ice-free conditions. Previously, several wood samples have been dated by the radiocarbon dating method that yielded ages between 53.5 OSL and 43.2 cal ^{14}C ka BP (Arslanov 1987), which also supports our findings. However, there is a contradiction in regard to the lithology when comparing our results with previous work. We have interpreted the one till present at Kileshino to be late Valdaj in age, while Zarrina (1991) considered it to be of middle Valdaj age. A possible explanation could be that there are two tills present at the Kileshino site and Zarrina (1991) refers to the lower till, while the description of the upper part of the outcrop between middle Valdaj till and soil is absent. Nevertheless, the discrepancy between our data and the age of the lower till remains. This can be explained by misinterpretation of this sediment, which could actually be some other sediment. Also Zarrina (1991) doubted the glacial origin of the sedimentary unit interpreted as till, because she described it as 'atypical facies variations' of till (clayey with some boulders). Data from the areas adjacent to the study site (Arkhangelsk region, Karelia and Vologda area) support the idea that the uppermost till found at the Kileshino site is late Valdaj in age. None of the outcrop sections or boreholes of that region contain early Valdaj till of SIS origin (Demidov et al. 2004) and recent studies as well claim that during the Valdaj glaciation the study area was overridden by the SIS only once, in the late Valdaj (Velichko et al. 2004, 2011).

Sedimentary unit 1 (SU1) at our study site was possibly deposited in the periglacial area and on the basis of our chronological data, earlier than MIS 3, while the SIS did not override the Kileshino site. Supposing that a middle (MIS 4) Valdaj glaciation occurred in European Russia as some authors have suggested, and SU1 was deposited at that time, no hiatus existed in the outcrop between SU1 and SU2. The reason is that during the MIS 3 'megainterstadial' in European Russia (Oerel to Moershoofd interstadials in Central Europe) the water level of the ice-dammed lake in front of the SIS margin dropped and SU2 was formed as the lake changed to a typical non-glacial shallow lake and the deposition of peat started. But if SU1 is considered to be older than MIS 4 (coeval with MIS 6 Moscow stage in European Russia; late Saalian in Central Europe), sediments of MIS 5e Mikulino interglacial in European Russia (Eemian interglacial in Central Europe) are absent from the Kileshino outcrop. This contradicts the results of Giterman et al. (1975) who, on the basis of palynological analysis, assigned the sediments under peat at the Kileshino site to the Mikulino interglacial. However, no chronological data were available at that time to prove it. Our radiocarbon and OSL dates do not support this conclusion as SU2 is younger than the Mikulino interglacial and SU1 is described as periglacial sediments.

Sedimentary unit 3 (SU3) presumably redeposited at the Kileshino site in the course of the advance of late Valdaj glaciers, since a fast-flowing NW–SE directed ice-stream corridor existed in that area (Demidov et al. 2006). Nevertheless, dates from SU3 (if they are reliable) still exhibit an ice-free time at Kileshino during MIS 4 and 3 at the same time as the area to the NW of Kileshino was ice-free, relying on the fact that the general direction of the last SIS advance was from NW to SE. The upper part of SU3 could refer to the 'atypical till' described by Zarrina (1991), because her description of the lithology together with the dates is similar to our data.

Sedimentary unit 4 (SU4), which represents late Valdaj till, could have been deposited by debris ice. It has been assumed that the long and thin lobes of fast-flowing ice streams between the Gulf of Finland and the LGM position in the study area became detached from the SIS during deglaciation (Demidov et al. 2006). Unfortunately, the late Valdaj age has not been dated directly and based on our dates from the outcrop, it can only be concluded that the last SIS reached the Kileshino site not before 33.8 cal ^{14}C ka BP. Previous works suggest that the SIS reached its maximum position in the Vologda area at 18 OSL ka (Lunkka et al. 2001), in Russian Karelia not before 17 OSL ka (Larsen et al. 1999) and in NE Belarus not before 19.1 cal ^{14}C BP (Zimenkov 1989). Thus, the last SIS reached the Kileshino site presumably between ca 19.1 cal ^{14}C BP and 18 OSL ka. This corresponds well with 20–18 ka, which has also been suggested as the LGM age in NW Russia (Demidov et al. 2006).

CONCLUSIONS

- According to our chronological data, the SIS reached the Kileshino site only once during the last 72.2 OSL ka – in the late Valdaj, after 33.8 cal ^{14}C ka BP and presumably between 19.1 cal ^{14}C BP and 18 OSL ka.
- Based on the dated sediments, limnic sedimentation conditions existed at the Kileshino site during MIS 3, between 57.5 OSL and 33.8 cal ^{14}C ka BP, which corresponds to the middle Valdaj 'megainterstadial' in European Russia (Oerel to Hengelo interstadials in Central Europe).
- To the NW of Kileshino, fluvial sedimentation conditions occurred during 72.2–40.8 OSL ka on the basis of our chronological data.
- According to our interpretation that SU3 was redeposited by the advancing SIS at the Kileshino site and together with available dates from SU2, which express the ages in situ, we conclude that ice-free conditions existed during 72.2 OSL–33.8 cal ^{14}C ka BP at that site.

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MIS 4-3 jäävabad intervallid viimase jäätumise maksimumlevikupiiril Kilešinos Valdai kõrgustikul Venemaal

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Käesoleva uuringu tulemused näitavad, et ajavahemikul 72 200–33 800 kalendriaastat tagasi, mis vastab neljandale ja kolmandale merelisele isotoopstaadiumile (MIS 4 ning MIS 3), oli viimase Skandinaavia jäätumise maksimumlevikupiiril olev Kilešino jäävaba. Dateeringutest ilmnevad järvelised sedimentatsioonitingimused Kilešinos ajavahemikul 57 500–33 800 kalendriaastat tagasi, mis vastab MIS 3 megainterstadiaalile Venemaa Euroopa-osas (Oereli kuni Hengelo interstadiaal Kesk-Euroopas). Skandinaavia mandriliustik kandis oma viimasel pealetungil Kilešinosse vooluveelise settekompleksi, mille moodustavad vaheldumisi aleuriidi- ja liivakihid. Settekompleks ise väljendab vooluveelisi settetingimusi Kilešinost loode pool ajavahemikul 72 200–40 800 aastat tagasi. Kõiki dateeringuid arvesse võttes järeldub, et Kilešino oli viimase Skandinaavia jäätumise ajal jäävaba ajavahemikul 72 200–33 800 kalendriaastat tagasi ja aleuriidi-liivakihtidega settekompleks transporditi uuringualale hiljem kui 33 800 kalendriaastat tagasi, lähtudes aga varasematest töödest tõenäoliselt liustiku maksimumlevikul ajavahemikul umbes 19 100–18 000 aastat tagasi. Kilešinost leiti ainult üks noorem kui 72 200 aastat vana moreenkiht ja sellest järeldub, et Skandinaavia mandriliustik jõudis uuringualale ainult ühe korra viimase 72 200 aasta jooksul: Hilis-Valdais (Weichsel) hiljem kui 33 800 kalendriaastat tagasi. Skandinaavia mandriliustiku laienemine uuringualale ajavahemikul 115 000–58 000 aastat tagasi ei leidnud kinnitust ega ümberlükkamist, kuna ajavahemiku 115 000 kuni 72 200 aastat tagasi kohta puuduvad kronoloogilised andmed.