Ice advance-retreat sediment successions along the Logata River, Taymyr Peninsula, Arctic Siberia

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Cover Picture: Mammoth tusk (Bernhardson 2012)

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Abstract: A number of sites were investigated in river sections along the Logata River on the Taymyr Peninsula, Russia, and its adjacent areas to shed more light on the glaciation history over the last glacial cycles. The sediments exposed at the investigated sites are correlated and put into a local stratigraphic scheme divided into five main units. *Unit 1* is positioned lowest in the stratigraphy and consists of greyish yellow sand with gravel horizons made up of shale. The poor exposure of the unit obstructs any attempt to interpret the depositional environment of the unit. *Unit 2* is a matrix-supported silty clayey diamicton with glaciotectonic lamination and sand boudins; it is interpreted as a subglacial traction till deposited from NE. *Unit 3* consists of intercalated massive and laminated beds of silt and clay with a varying abundance of marine molluscs and drop clasts (IRD). The unit is interpreted as deposited in an off-shore glaciomarine depositional environment. *Unit 4* is made up of sorted sediments, primarily sand, but also coarser and finer sediments. Organic detritus is common in the unit. *Unit 4* is interpreted as a fluvial depositional environment of a meandering river. *Unit 5* is the uppermost unit in the local stratigraphic scheme and contains properties typical of so called ice complex deposits; it consists of sorted sediments of silt and sand with peat inclusions and an abundance of ground ice. Organic detritus and mega fauna fossils are common in the unit. All sites examined in detail were sampled for radiocarbon, OSL and ESR dating. All radiocarbon datings (13) on mollusc shells and organic macro remains yield infinite ages, while the results from the ESR and OSL datings are still pending. All units together suggest a full glacial-deglaciation cycle with a Kara Sea ice sheet advancing and retreating within a marine basin, and with an isostatically driven regression thereafter, ending with a terrestrial environment. The most probable timing is the Early Weichselian, as described for central and north Taymyr in Möller et al. (2011, in: Ehlers et al., *Developments in Quaternary Science* 15, 373-384).

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Isframstötar och isreträtter längs Logatafloden, Tajmyrhalvön, arktiska Sibirien — en sedimentologisk och stratigrafisk studie

MARTIN BERNHARDSON

Sammanfattning: Ett antal flodskärningar undersöktes längs Logatafloden och dess omkringliggande områden på Tajmyrhalvön, Ryssland, för att öka förståelsen för de senaste glaciationscyklerna i Sibirien och ryska Arktis. De exponerade sedimenten vid lokalerna uppvisade distinkta attribut som gjorde det möjligt att korrelera sedimenten vid de olika lokalerna med varandra och upprätta en lokal litostratigrafi för området, uppdelat i fem olika enheter. *Enhet 1* är den lägst belägna enheten och utgörs av grågul sand med grushorisonter bestående av skiffer. Enheten var dåligt exponerad och på grund av detta gick det inte att avgöra sedimentens depositionsmiljö. *Enhet 2* är en matrix-stödd siltig lerig diamikt med glacialtektonisk stratifiering och inneslutningar av sandiga så kallade "boudins". Enheten tolkas som en basalmorän deponerad av en glaciär som rörde sig från nordost mot sydväst. *Enhet 3* består av silt och lera i omväxlande massiva och laminerade bäddar. Bäddarna innehåller marina mollusker och är ställvis rik på grus- och stenpartiklar, tolkade som dropstenar från drivande is. Enheten antas representera en glacimarin depositionsmiljö. *Enhet 4* består av sorterade sediment, främst sand, men även finare och grövre sediment avsatta i rippel-skiktade, planskiktade och trågkorsskiktade bäddar. Organiskt material är vanligt förekommande i enheten. *Enhet 4* tolkas som en fluvial depositionsmiljö, närmare bestämt en meandrande flod. *Enhet 5* är den högst belägna enheten i den lokala stratigrafin och uppvisar typiska egenskaper av så kallade iskomplexavlagringar. Enheten består av sorterat material av silt och sand, med ett rikligt innehåll av organiskt material, och är rik på torvinneslutningar och innesluten markis. Enheten innehåller även fossil av mega-fauna, t.ex. mammut och stäppbison.

Ett antal prover togs från lokalerna för OSL-, ESR- och AMS ^{14}C-dateringar. Samtliga AMS ^{14}C-dateringar (13) gav infinit ålder (>45 000 – 48 000 år) medan ESR- och OSL-dateringarna ännu inte är färdiganalyserade. Samtliga enheter sedda i sin helhet kan tolkas som avsatta i succession under en isframstöt-deglacationscykel när en Karahavsis avancerade från norr med en marin bassäng framför sig. Under deglaciationen skedde en isostatiskt driven regression, dvs. havet grundade upp, och efterföljdes av en terrestrisk depositionsmiljö. Den mest troliga tidsställningen för isframstöten är tidig Weichsel, vilket skulle vara i linje med den utveckling som beskrivits för centrala och norra Tajmyr, summerad av Möller et al. (2011, i: Ehlers et al., *Developments in Quaternary Science* 15, 373-384).

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Abbreviations

AMS	**Accelerator Mass Spectrometry**
APEX	**Arctic Palaeoclimate and its Extremes**
ASTER	**Advanced Spaceborne Thermal Emission and Reflection Radiometer**
BSIS	**Barents Sea Ice Sheet**
DEM	**Digital Elevation Model**
ESR	**Electron Spin Resonance**
GCM	**Global Circulation Model**
GPS	**Global Positioning System**
IMZ	**Ice Marginal Zone**
IRD	**Ice Rafted Debris**
IRDi	**Ice Rafted Debris index**
KSIS	**Kara Sea Ice Sheet**
LGM	**Last Glacial Maximum**
MIS	**Marine Isotope Stage**
MPS	**Maximum Particle Size**
OSL	**Optically Stimulated Luminescence**
PECHORA	**Palaeoenvironment and Climatic History of the Russian Arctic**
QUEEN	**Quaternary Environment of the Eurasian North**
SIS	**Scandinavian Ice Sheet**
UT IMZ	**Upper Taymyr Ice Marginal Zone**
WGS	**World Geodetic System**

1   Introduction

1.1   Scientific significance

The debate concerning global warming has been going on for some years now, and has not only involved the scientific community but also the media in general. What has not been highlighted so often is that some parts of the Earth are more susceptible to these climate changes than others. The Arctic is an important player in the global climate due to its quick response to climate changes, as the reduction of sea ice the last years is evident of (Thiede et al. 2004). Regardless of this the palaeoclimate of the Arctic has been rather unexplored except for the last few decades.

Research programmes like QUEEN (Quaternary Environment of the Eurasian North), PECHORA (Palaeoenvironment and Climatic History of the Russian Arctic) and APEX (Arctic Palaeoclimate and its Extremes) have promoted cooperation between members of the scientific community that previously were divided by political and linguistic barriers (Svendsen et al. 2004; Thiede et al. 2004; Astakhov & Nazarov 2010). The outcome of these programmes has led to paradigm shifts concerning the spatial and temporal distribution of the Eurasian Ice Sheet (Svendsen et al. 2004). Many uncertainties still remain and further research is thus essential to be able to create more accurate ice sheet reconstructions. Arctic Russia and Siberia are especially problematic areas, and there exist a number of conflicting reconstructions of the Eurasian Ice Sheet over these areas for the last glacial cycle (Svendsen et al. 2004). One might wonder why this is important; with the on-going debate concerning global warming and GCMs (Global Circulation Model) indicating climate change with severe impact on the human population in some parts of the world (IPCC 2007) it is of great importance to understand how the climate fluctuated in the past. This is due to the fact that the current GCMs are based on previous research and paradigms of climate change and glacial-interglacial cycles that with the present knowledge are either exaggerated or underestimated as is discussed in reviews and summaries as of, for example, Svendsen et al. (2004). If the assumptions that are made in the models are incorrect then the results can hardly be deemed trustworthy.

1.2   Aim and scope of the study

During the summer of 2012 an international research expedition conducted field work on the Taymyr Peninsula in Siberia, Russia. The expedition was a subproject within the APEX programme. The aim of the expedition can be divided into two parts; the first one aims to shed more light on the glaciation history of the Taymyr Peninsula over the last glacial cycles, while the other aims to expand our knowledge of the environmental changes in Late Pleistocene and Holocene fauna and flora. The areas that were examined in more detail were situated along the

Lukthak, Logata, and Upper Taymyr Rivers within the Taymyr River drainage system, going through Lake Taymyr and out into the Kara Sea, and in the end of the field season, one visit to the Novorybnoe site situated along the Khatanga River, draining towards the Laptev Sea (Fig. 1). This thesis will concern the sites examined by expedition members from the Department of Geology, Lund University, Sweden, along the Logata River and its adjacent areas.

The aim of this thesis is to present the sections mapped from the Logata River and its surroundings and discuss them in the context of earlier research concerning Arctic Russia and Siberia, as to further increase our understanding of the glaciation history of this area.

1.3   Background

1.3.1 Glaciation history

Arctic Russia and Siberia cover a vast area and have been prone to an intricate interaction between not just one, but three major ice sheets; the Kara Sea Ice Sheet (KSIS), the Barents Sea Ice Sheet (BSIS) and the Scandinavian Ice Sheet (SIS) (Kjær et al. 2006). When these ice sheets merged they created the Eurasian Ice Sheet. The theories concerning the temporal and spatial distribution of these ice sheets during the last glacial cycles have changed during the last decades (Svendsen et al. 2004; Möller et al. 2011; Astakhov 2013). The manner of their initiation, especially concerning the KSIS and BSIS, has been explained by a number of different models. Saks (1953) suggested that ice caps formed over mountainous areas (for example the Ural and Byrranga Mountains) and subsequently expanded over the lower lying areas. This scenario was later challenged by a theory advocating the thickening of sea ice that later grounded on the continental shelves as the origin of the KSIS and BSIS (Grosswald 1980, 1998; Kind & Leonov 1982). The most recent paradigm to this date suggests that the two previous ones mentioned might not contradict one another and instead may be combined (Möller et al. 2006; Ingólfsson et al. 2008; Möller et al. 2008; Möller et al. 2011). The importance of nucleation areas for local ice caps that subsequently expanded over the continental shelves and initiated the formation of the Kara Sea Ice Sheet is stressed for areas such as Cape Chelyuskin (Möller et al. 2008) and Severnaya Zemlya (Möller et al. 2006, 2007; Ingólfsson et al. 2008). The support for these claims are indications of ice flow directions that contradict ice flows that should have been created by a Kara Sea ice sheet centred over the shelf. Still, just a number of local ice caps cannot explain the isostatic depression that the raised beaches in the adjacent terrestrial environment suggest. Also, numerous features indicating upslope ice flow from the low coastlands towards the elevated uplands have been identified through remote sensing during the last 40 years
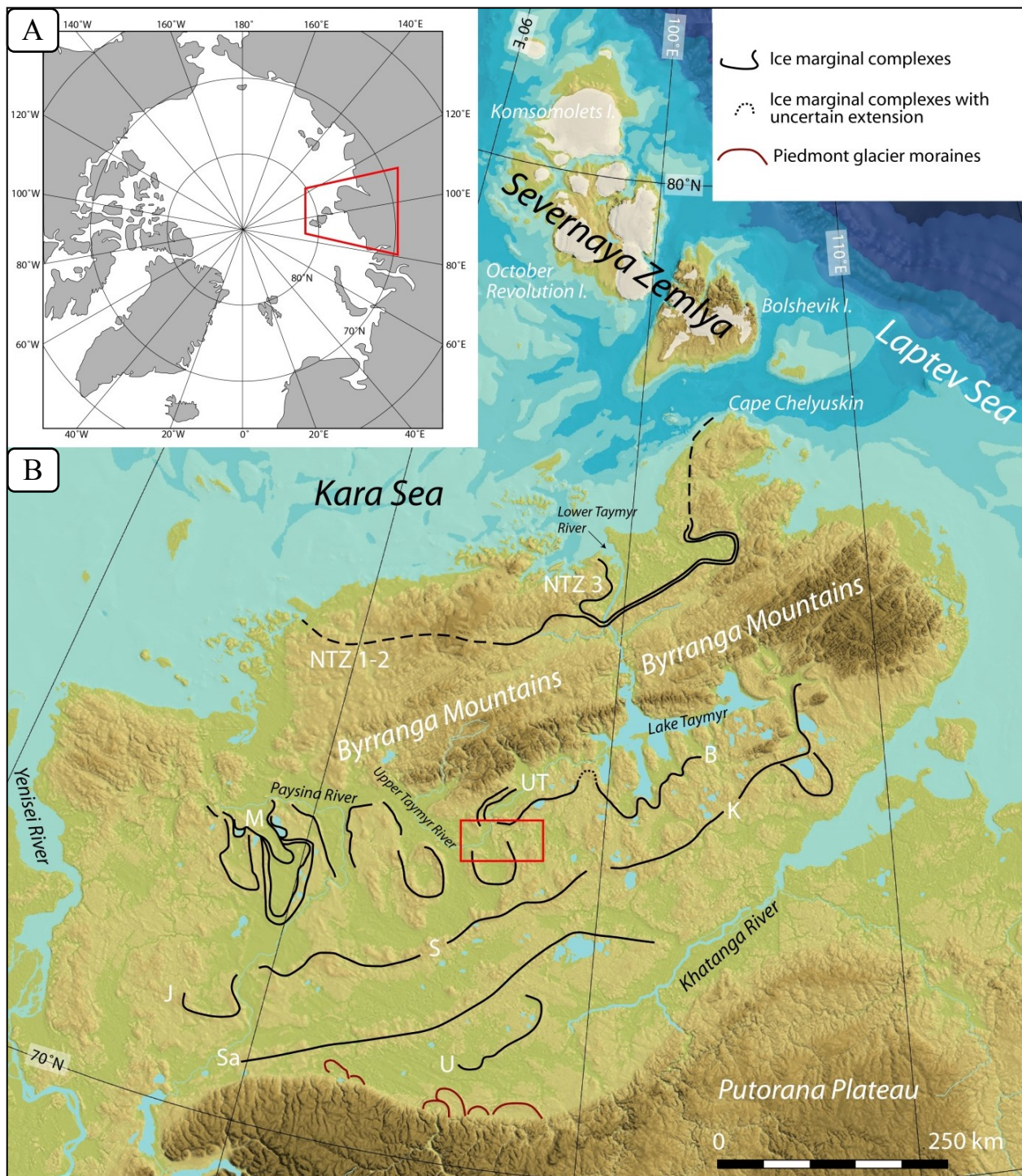
Fig. 1. A) Map centred over the North Pole with the extension of Fig. B marked by the red trapezoid. B) Map of the Taymyr Peninsula. Note the generally low topography of the peninsula. Major exceptions are the Byrranga Mountains and the Putorana Plateau. The red rectangle encompasses the study sites in the proximity of the Logata River, their locations shown in more detail in Fig. 3B. The letters mark the different ice-marginal complexes present on the Taymyr Peninsula, using the terminology of Kind & Leonov (1982): M, Mokoritto; UT, Upper Taymyr; B, Baikuronyora; J, Jangoda; S, Syntabul; K, Severokokorsk; Sa, Sampesa; U, Urdachsk. The North Taymyr ice-marginal zone (NTZ) was investigated in more detail by Alexanderson et al. (2001, 2002).The extent of the formations has been reinterpreted by Möller & Sallaba (2010) as is displayed by the lines drawn in this figure (modified from Möller et al. 2011). The ice-marginal complexes marked by the black lines are thought to have a Weichselian origin except for the Sampesa (Sa) and Urdachsk (U) moraines which are thought to possibly be of a Saalian origin (Möller et al. 2011). Svendsen et al. (2004) suggested that the J-S-B line reflects the maximum extent of the KSIS during the Weichselian. This is challenged by Möller et al. (2011) who highlight that the work by Möller & Sallaba (2010) points out that these moraine ridges do not match each other geomorphologically, making the J-S-K line a more plausible candidate for the maximum extent of the Weichselian glaciation.

(Astakhov 2013).

It is not only the formation of the ice sheets that made up the Eurasian Ice Sheet that has been questioned through time, but also their spatial and temporal distribution (Svendsen et al. 2004 and references therein). It is especially for the later part of the Weichselian and the LGM where opinions differ concerning northwestern Siberia and the Taymyr Peninsula. Grosswald (1980, 1998) and Grosswald & Hughes (2002) advocate an extensive ice sheet expansion during the LGM, while others suggest a much more limited glaciation during the same time period (e.g. Möller et al. 1999; Alexanderson et al. 2001, 2002; Svendsen et al. 2004; Möller et al. 2006; Möller et al. 2008; Ingólfsson et al. 2008). As was highlighted by Möller et al. (1999) most scientists agree that large parts of the Taymyr Peninsula have been glaciated, but no consensus has been reached so far when it comes to the source of this glaciation as well as when the last major glaciation occurred. As stated in Svendsen et al. (2004) the opinion of the members of the QUEEN programme is that three major glaciations affected Arctic Russia and Siberia during the Weichselian; during the Early Weichselian (100-80 kyr BP), the Middle Weichselian (60-50 kyr BP) and the Late Weichselian (25-15 kyr BP) with extensive deglaciations in between. The expansion of these ice sheets blocked the drainage paths of the rivers that drained into the Arctic Sea (Mangerud et al. 2004; Svendsen et al. 2004). This caused redirected flow of these rivers southwards and the formation of a large number of glacial lakes along the ice margin.

Looking at the larger picture of the Eurasian Ice Sheet during this time frame there seems to be a phase-antiphase behaviour through time, with a progressively larger ice sheet over Scandinavia during the Weichselian for each glaciation, while the opposite applied for Arctic Russia and Siberia (cf. Svendsen et al. 2004).

There exist very few findings that the Taymyr Peninsula was glaciated during the Late Weichselian. The Severnaya Zemlya archipelago in the northeastern edge of the Kara Sea shows signs of having been ice-free during the LGM (Möller et al. 2006), and as mentioned earlier in the text this archipelago is thought to have been an important nucleation area for the initiation of the formation of the KSIS (Möller et al. 2006; Möller et al. 2007; Ingólfsson et al. 2008). Still, there are signs that the northwestern part of the Taymyr Peninsula was overridden by a glacier at this time (Alexanderson et al. 2001, 2002). The ice that inundated the northern edge of the Taymyr Peninsula was probably less than 500 m thick due to its inability to cross certain topographic obstacles (Möller et al. 2011).

The Early Weichselian glaciation was as previously stated much more extensive than the subsequent glaciations for Arctic Russia and Siberia (Svendsen et al. 2004). For example, it was only at this time during the Weichselian that the KSIS crossed the Byrranga Mountains, suggesting that the ice must have been more than 1000 m thick when it crossed the northwestern coast of the Taymyr Peninsula. However, the glaciation of the Taymyr Peninsula and adjacent areas during the Early Weichselian is dwarfed in comparison to the glaciation that occurred during the Late Saalian (160-130 kyr BP). A summary of the spatial and temporal extension of the ice sheets over the Taymyr Peninsula and other areas affected by the Eurasian Ice Sheet can be seen in Fig. 2.

South of the Byrranga Mountains for some 250 km there exist a number of moraine-ridge complexes (Kind & Leonov 1982). Möller et al. (2011) state that these moraine-ridge complexes show clear signs of having been created at marginal positions of the KSIS when examining the provenance of crystalline erratic boulders, the glacial geomorphology and the direction of glaciotectonic deformation. However, opinions differ concerning which glaciation event that the different ridges can be tied to (cf. Andreeva & Isaeva 1982; Kind & Leonov 1982; Svendsen et al. 2004).

The southern part of the Taymyr Peninsula has been the target of thorough investigations by Russian scientists (Astakhov 2013). There exist some problems with these investigations when put into a modern scientific context. The practice from Soviet times to use approved stratigraphic schemes, where mapped sections are put into these already established schemes without any facies descriptions, obstructs any attempt to reinterpret the sedimentary units. Also, many researchers have correlated their own investigated sites in Siberia with the stratigraphical units in this scheme, without critically questioning the validity of the chronology for the different units. This is highly problematic since some of these units have been related to different marine isotope stages without having been scrutinized by geochronometric dating methods. Other units have been determined by conventional radiocarbon dates that with more modern methods would be deemed infinite. Two marine formations that have turned out to be especially problematic are the Karginsky and Kazantsevo formations. The Karginsky formation has been related due to finite conventional radiocarbon dates to MIS 3 (Middle Weichselian), while the Kazantsevo formation has been related to MIS 5e (Eemian) (Kind & Leonov 1982). The chronology of these two formations has been heavily scrutinized the last few years (Astakhov & Nazarov 2010; Astakhov 2011, 2013). For example, Karginsky sediments that contain a foraminifer fauna suggesting a warmer sea than at present (Kind & Leonov 1982), have in spite of this been linked to the cool MIS 3 (Astakhov 2013). ESR dates on marine shells from Karginsky sediments (Arkhipov 1990), as well as OSL dates (Nazarov et al. 2009) from the same sequence, have, however, yielded ages of 121.9-111 kyr BP, indicating an age closer to early MIS 5 than MIS 3. More recent examination by Astakhov & Nazarov (2010) as well as Astakhov & Mangerud (2005, 2007) of borehole sediments from the Lower
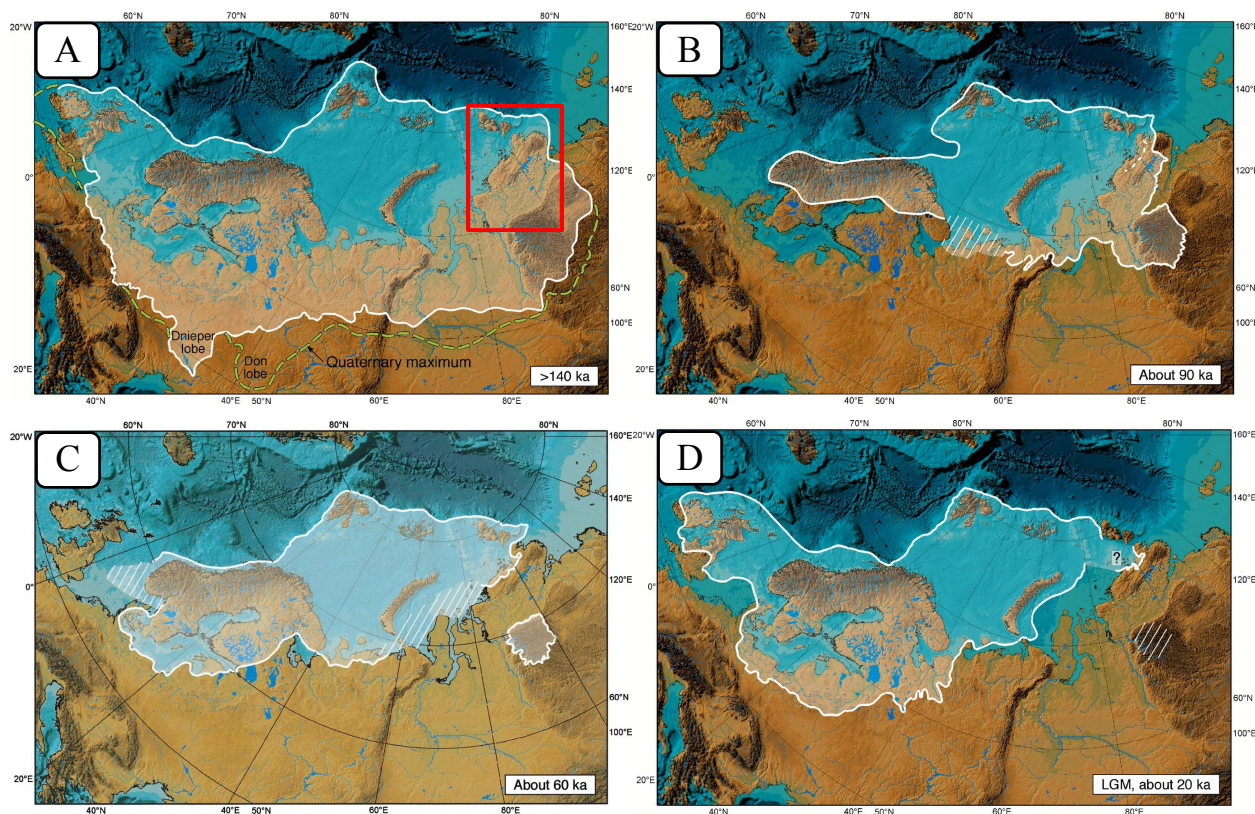
Fig. 2. Reconstructions of the Late Saalian and three Weichselian glaciations according to the QUEEN members as displayed by Svendsen et al. (2004). Note that it was only during the Saalian and Early Weichselian glaciations that the KSIS crossed the Byrranga Mountains and passed the area where the Logata River is situated today as indicated in (A) and (B). Some glaciers and ice sheets that were present at this time (e.g. the Alps, Iceland etc.) are not displayed in the figure. The hatched fields display uncertainties in the ice sheet's extent (all figures from Svendsen et al. 2004). The red rectangle highlights the Taymyr Peninsula and adjacent areas visible in Fig. 1B.

A) The Late Saalian glaciation (160-130 kyr BP) was the largest of the four glaciations. Note the large extension of the ice sheet both in Europe and Siberia at the same time. This is in stark contrast with the ice sheet dynamics during the Weichselian glaciations, where there was a phase-antiphase behaviour in the ice sheet's extent between Europe and Siberia.

B) The Early Weichselian glaciation (100-80 kyr BP). The Eurasian Ice Sheet is smallest over Fennoscandia during this glaciation while the ice sheet had its largest extension for Arctic Russia and Siberia during this time of the Weichselian. The KSIS is thought to have joined the local ice caps over the Putorana Plateau and Anabar Uplands during this glaciation. The dashed line highlights the retreat stage of the NTZ ca. 80 kyr BP.

C) The Middle Weichselian glaciation (60-50 kyr BP) had a much more limited extension over Siberia, and the Taymyr Peninsula in particular, during this time. There was still a local ice cap over the Putorana Plateau, although it did not merge with the KSIS.

D) The Late Weichselian glaciation (25-15 kyr BP). The impact of the KSIS on the Taymyr Peninsula is very limited during this glaciation as is evident of the map. Only the northern part of the peninsula was affected as reported in Alexanderson et al. (2001, 2002).

Ob River, where dating of peat overlying the Kazantsevo formation have yielded dates of Eemian age, suggests that Kazantsevo is older than previously has been thought. Also, Astakhov (2013) states that the presence of shells from the extinct mollusc *Cyrtodaria angusta* makes it more plausible that the Kazantsevo represents a time span of MIS 7 age rather than MIS 5e. Of course this is inconvenient when some till formations owe their chronology to their stratigraphic relationship to these two formations. The Murukta diamictons were previously thought to have originated during the Early Weichselian. However, in the southern part of the Taymyr Peninsula these diamictons are superimposed by marine Karginsky sediments (Kind & Leonov 1982), suggesting that their age is older than the Eemian if the revised age for Karginsky is used, placing it at least around MIS 6 (Astakhov 2013). The problem with the age of the Kazantsevo formation is further highlighted by Šnejder (1989) who described sediments from the Serebryanka River valley that was assumed to be of Kazantsevo age, although the sediments never were dated. The full extent of the problematic nature of the Russian approved stratigraphic scheme for the Upper Pleistocene is thoroughly summarized by Astakhov (2001). Astakhov stresses that sedimentological
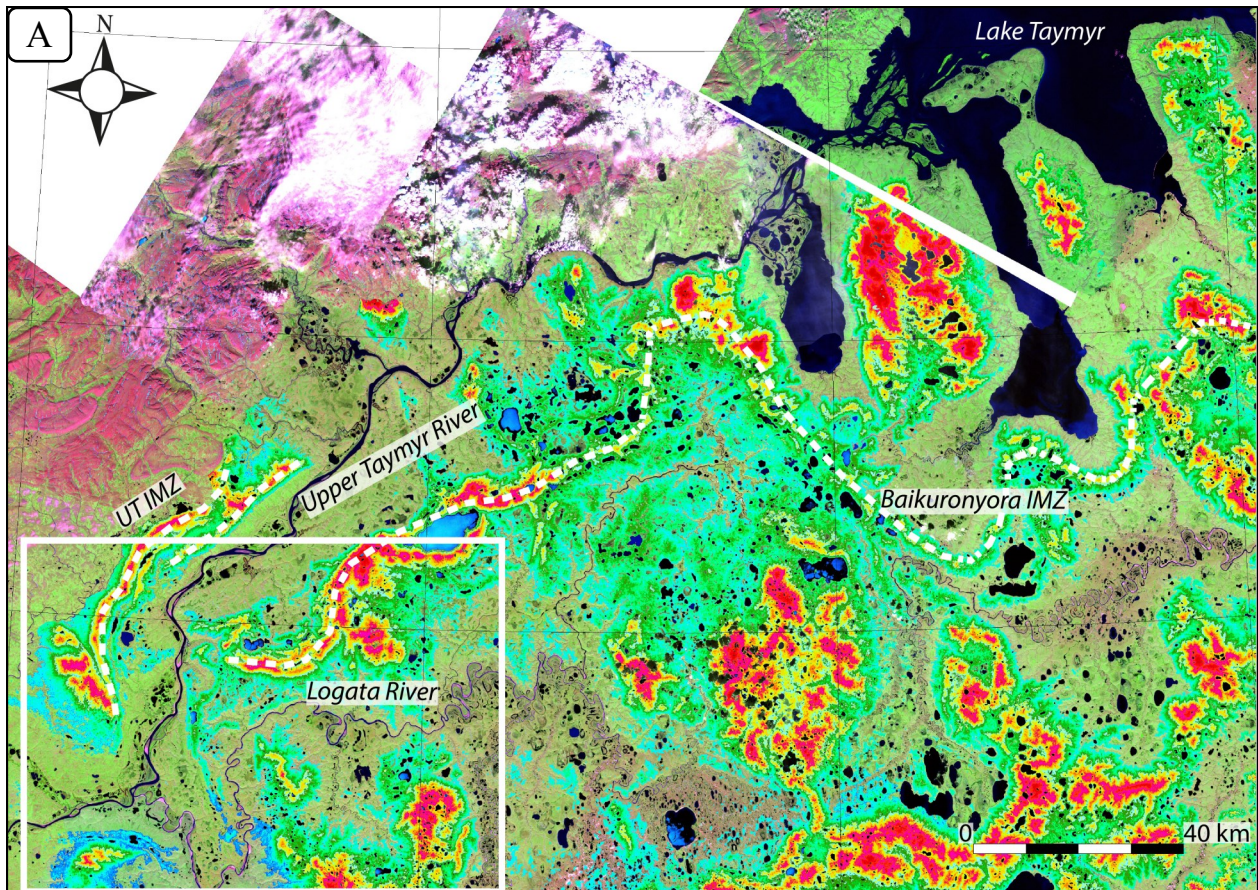
Fig. 3. A) DEM of the UT IMZ (Upper Taymyr Ice Marginal Zone) and its adjacent areas. The dashed white lines mark the UT IMZ in the Taymyr River valley and its continuation in the Baikuronyora IMZ south of Lake Taymyr. Note the lobate pattern in the southward extensions of the bays of Lake Taymyr. The white rectangle indicates the magnified area in Fig. 3B. Blue colours represent an elevation of 30-70 m a.s.l., yellow and orange colours 120-150 m a.s.l. and red colours an elevation of 170-300 m a.s.l. For a detailed legend of the elevation see Appendix 1. The DEM is constructed from ASTER satellite data (see Möller & Sallaba (2010) for explanation).

misinterpretations and indiscriminate use of untrustworthy radiocarbon dates are the two main reasons why the previously approved stratigraphic scheme should be considered obsolete and no longer of any use.

A different approach to investigate the climate fluctuations of northern Siberia, and the Taymyr Peninsula in particular, were employed by Jørgensen et al. (2012) who used a combination of ancient sedimentary DNA with more traditional methods of macrofossil and pollen analysis. Their results suggest that the Taymyr Peninsula experienced only very small climatological changes during the Late Pleistocene as indicated by a stable vegetation cover for this time period. This contest the paradigm of an extensive LGM ice sheet for Siberia as previously have been proposed by some scientists (e.g. Grosswald 1980, 1998; Grosswald & Hughes 2002).

Further data contradicting an extensive LGM ice sheet for Siberia and Arctic Russia can be found in Mangerud et al. (2008). A number of ^{10}Be exposure dates show that the extent of glaciers in the Polar Urals did not extend any noticeable distance compared to

their present distribution. This is in agreement with the ice sheet reconstructions by members of the QUEEN programme (Svendsen et al. 2004) and is explained with low precipitation rates during the LGM in Siberia. If there is not enough precipitation then the glaciers cannot grow (Holden 2008). On a greater scale the low precipitation can be linked to the phase-antiphase behaviour of the Eurasian Ice Sheet during the Weichselian (Svendsen et al. 2004). The successively larger ice sheet over Scandinavia would inhibit precipitation from reaching Arctic Russia and Siberia, explaining the progressively smaller extension of the KSIS and BSIS. Also, the Ural Mountains do not seem to have formed any ice dispersal centres worthy of mentioning during the earlier parts of the Pleistocene either (Astakhov 2004).

A striking feature of Siberia is the lack of many landforms usually associated with glaciers, such as lodgement tills, drumlins, eskers, flutes etc. (Astakhov 2013). All of these landforms have in common that they are connected with glaciers with a warm-based thermal regime, suggesting that the glaciers that have affected Siberia predominantly were cold-based in
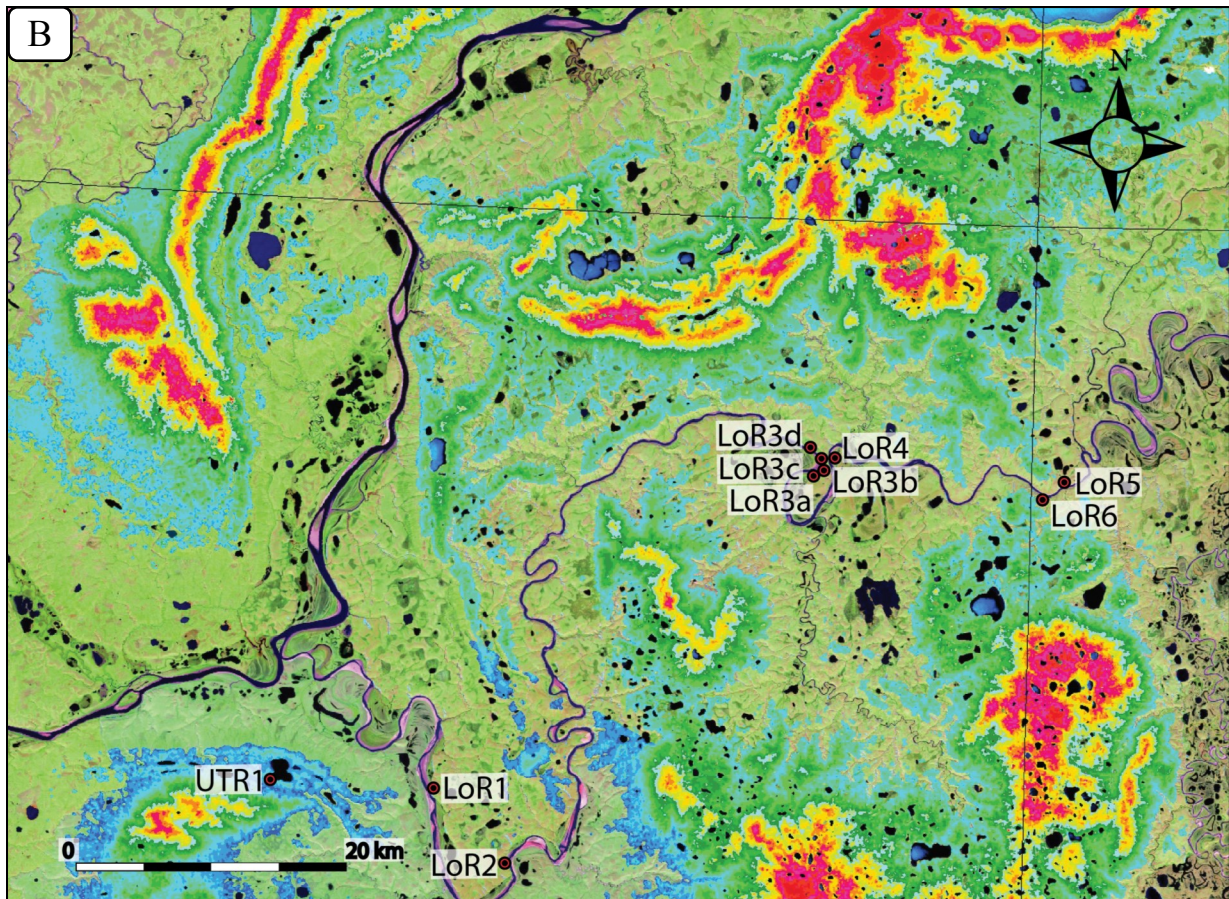
Fig. 3. B) DEM of the Logata River and parts of the Upper Taymyr River with the position of the study sites. The ridge complexes north of the study sites along Logata River belong to the UT IMZ and Baikuronyora IMZ, as seen in Fig. 1, thus placing the sites in a former ice-marginal area. Note the abundance of thermokarst lakes in the pictures.

nature. Astakhov (2013) further highlights that the perennially frozen substrate of the Russian north behaved differently than the substrate in many Atlantic environments. This obstructs any attempt to make direct correlations between Northern Europe and Siberia. The abundant permafrost covering large parts of Arctic Russia and Siberia suggests that the glaciers advanced predominantly by englacial sliding across thrust-planes (cf. Benn & Evans 2010) or as proposed by Astakhov et al. (1996) by movement over a deforming bed composed of a frozen clayey substrate with a high water content since the water could still exist in a liquid state and thus keep its plastic properties.

1.3.2 Geological setting

Within the Taymyr fold area three zones can be distinguished; North-, Central- and South-Taymyr (Vernikovsky 1997). The South-Taymyr zone, including the Byrranga Mountains and the Taymyr Lake basin, consists predominantly of sedimentary rocks with a Palaeozoic origin with dolerite dikes and sills. The two other zones consist mainly of Precambrian rocks, and the basin just north of the Byrranga Mountains consists of sandstones, carbonates, volcanics, shales and a few granites of Neoproterozoic to Palaeozoic origin. These rocks are predominantly covered by Mesozoic-Cenozoic deposits, partly unconsolidated.

1.3.3 Study area

The Taymyr Peninsula is situated in the northern part of Russia and covers a vast area of 400 000 km^2 and is fringed by the Kara Sea and the Laptev Sea in the north and the Putorana Plateau in the south (Fig. 1). Large parts of the peninsula consist of lowlands, with the exception of the Byrranga Mountains that run across the peninsula from the northeast towards the southwest. The highest point on the Taymyr Peninsula is situated 1 146 m a.s.l. (above sea level).

The Logata River is a tributary to the Upper Taymyr River situated south of the Byrranga Mountains on the Taymyr Peninsula (Fig. 1). The Upper Taymyr River terminates in Lake Taymyr and is the largest river entering the catchment area of the lake. As can be seen in Fig. 3 the Logata River cuts through a number of ice-marginal complexes, making it ideal for the aim of the project to resolve the glaciation history of this part of the Taymyr Peninsula over the last glacial cycles. The ice-marginal

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complexes in question seem to belong to the Upper Taymyr Ice Marginal Zone (UT IMZ) and in extension the Baikuronyora IMZ (Fig. 1). Earlier investigations summarized by Kind & Leonov (1982) state the presence of sediments that have been interpreted as tills, glaciolacustrine, marine, lacustrine and aeolian sediments.

2 Methods

2.1 Information gathering and mapping

The Taymyr Peninsula is a vast area and any attempts to make regional mapping of the glacial morphology may seem daunting. Mapping of areas of interest has been performed using Landsat images in conjunction with ASTER satellite digital elevation data (Möller & Sallaba 2010).

Thanks to the earlier work of Russian scientists (e.g. Kind & Leonov 1982) many of the intricate and detailed sections are already identified, facilitating the choice of sites for field work. The principal mean of transportation between the study sites was with zodiacs along the river systems. This thesis only concerns the study sites along the Logata River and its adjacent areas, their geographical positions visible in Fig. 3B. During the transportation of equipment and personnel into the field by helicopter, an aerial surveillance was undertaken for spotting any good sections for more detailed investigations.

The geographical positions of the investigated sites were determined with a GPS (Garmin GPSMAP® 60CSx) with an average accuracy of ± 5 m and utilising the WGS 84 datum.

2.2 Stratigraphical and geochronological investigations

The sediments of interest were mainly exposed along riversides and lakeshores. The selected sites were documented and analysed concerning their stratigraphy and facies composition. All sites logged in detail were subject to geochronological investigations. Samples were taken for accelerator mass spectrometry radiocarbon (AMS ^{14}C), optically stimulated luminescence (OSL) and electron spin resonance (ESR) dating. This thesis will only utilise AMS ^{14}C datings performed at Lund University, Sweden, as OSL and ESR results are not yet available. Since all the radiocarbon datings yielded infinite ages no calibration of the dates was needed. All types of organic material were collected for radiocarbon dating, while sediment with sand sized grains was sampled for OSL dating and mollusc shells and enclosing sediment for ESR dating. All sections were excavated in a predominantly vertical manner, cleaned and documented in two-dimensional section drawings at 1:20 scale, using standardized lithofacies codes for sediment discrimination (Table 1). Due to the shifting cohesiveness of the sediments and the presence of permafrost the sections were excavated and cleaned in a number of subsections, overlapping with one another, creating a staircase pattern. The height of the sections over the river was determined with a SILVA clinometer. The strike and dip of some beds were determined by measuring with a SILVA compass. The magnetic declination in the area is 16°E and all measurements have been adjusted accordingly. The river's elevation over sea level was determined from topographical maps and the height of the sections over the river was added to calculate the correct elevation of the sections with an estimated error of ±5 m. The section drawings were digitized and colourized (Fig. 4) in Adobe Illustrator CS4, CS5 and CS6. Photographs taken during field investigations were used during the digitalization process to add further details to the logs in conjunction with the field notes. The data from the clast fabric analysis was evaluated according to the eigenvalue method (Mark 1973) and was processed in STEREONET for Windows©, thus calculating the eigenvalues for the clasts as well as plotting the resulting values graphically. The normalized eigenvector (V_1) was adjusted due to the magnetic declination of 16°E.

Since samples retrieved for OSL and ESR dating will not be used in this thesis the theory behind these dating methods will only be described briefly. OSL dating is based on the assumption that sediment grains exposed to sunlight under transport lose trapped electrons, trapped during radioactive decay in their environmental setting before the new transport phase (Walker 2005). Their "geological clock" will then be reset. At deposition the exposure to sunlight is shut off and the process restarts; adjacent material containing radioactive isotopes, or themselves containing these isotopes, produce low levels of radiation resulting in electrons getting released and subsequently trapped in 'spaces' in the sampled material. The longer the sampled sediment is exposed to this radiation, the more electrons get trapped. When the sediment, naturally or forced to in the laboratory, is exposed to a light source the trapped electrons are released, causing a light emission. By measuring this light emission it is possible to determine when the sediment last was exposed to sunlight, most often the time of deposition (Walker 2005). OSL dating is usually used in the time span of 200-150 000 yr BP, even though it is possible to use for younger or older ages (cf. Walker 2005).

ESR dating is similar to OSL dating in that it measures trapped electrons, although the methods employed are different. The sample, usually mollusc shells embedded in sediment, is after burial exposed to high frequency electromagnetic radiation in a magnetic field, where the magnetic field is changed until the electrons start to resonate at a certain frequency, displaying the number of trapped electrons (Walker 2005). These are subsequently used to determine the age since electron trapping in the material started. Walker (2005) states that the trapped electrons are not emptied during ESR dating contrary to OSL

Table 1.
Lithofacies codes modified from Eyles et al. (1983).

Lithofacies codes	Lithofacies type description: Grain size, texture, structure, construction
D(Si)ms(s)	Diamicton, Silty, matrix-supported, stratified, sheared
CoG(m)	Cobbles & Gravel, massive
SGcm	Sandy Gravel, clast-supported, massive
Sr(A)	Sand, type-A ripple-laminated
Sr(B)	Sand, type-B ripple-laminated
Srtc(A)	Sand, type-A ripple trough cross-laminated
Srtc(B)	Sand, type-B ripple trough cross-laminated
Spp	Sand, planar parallel-laminated
Spc	Sand, planar cross-laminated
Stc	Sand, trough cross-laminated
Sm	Sand, massive
Sm(ic)	Sand, massive, intraclast
Sl(ic)	Sand, laminated, intraclast
Sil	Silt, laminated
Sim	Silt, massive
SiC(def)	Silty Clay, (deformed)
Si/Cl	Silt/Clay, laminated
SiCl	Silty Clay, laminated
SiCm(d)	Silty Clay, massive, (dropstones)
CSil	Clayey Silt, laminated
Cl	Clay, laminated
C(l)/m	Clay, diffuse lamination, massive
Cm	Clay, massive
Cm(d)	Clay, massive, (dropstones)

dating, making it possible to make several measurements on the same sample. ESR dating has the major strength that it is usable on a number of different materials (Rink 1997). Its primary dating span is between 40 000-200 000 yr BP, i.e. past the limit of radiocarbon dating and for a much wider time span.

2.2.1 Radiocarbon dating

^{14}C is the rarest of the three types of isotopes of carbon, the others being ^{12}C and ^{13}C (Walker 2005). Put simple, one in a million million carbon atoms consists of ^{14}C. ^{12}C is the most naturally occurring isotope and 98.9% of the world's carbon atoms are ^{12}C. ^{13}C stands for around 1.1%. What sets ^{14}C apart from the other isotopes, other than its rarity, is that it is an unstable isotope that decays into the stable isotope ^{14}N of nitrogen. ^{14}C atoms form high up in the atmosphere due to the influx of cosmic ray neutrons that react with nitrogen, releasing a proton that in turn reacts with carbon to form ^{14}C. The carbon oxidises and forms $^{14}CO_2$ that disperses globally with other forms of carbon dioxide and enters the global carbon cycle. Later this carbon enters the biosphere due to the photosynthesis of plants and the subsequent ingestion of these plants by animals.

There is an interaction between the oceans and the atmosphere, often leading to an uptake of CO_2 by the oceans, making the carbon dioxide available for the marine biosphere (Walker 2005). Since ^{14}C is unstable it starts to decay after it has entered the biosphere. However, as long as an organism is alive it continues to receive an input of atmospheric ^{14}C, keeping the two spheres in isotopic equilibrium with one another. When an organism dies it no longer has any contact with the atmospheric carbon and the isotopic equilibrium is lost. By comparing the present level of ^{14}C in organic matter with the residual ^{14}C in the sampled tissue in question, an age can be determined for when the organism died. ^{14}C decays with a half-life of around 5730 years. It is possible to measure up to eight half-lives before the remaining concentration is too low to be of any use, making radiocarbon dating useful up to ages of ca. 45 000 years. Older organic matter is termed as being of infinite age, in contrast to the finite age of the measureable samples.

Although radiocarbon dating certainly is useful, one should be aware of the existence of a number of sources of errors that might influence the age of the dated sample. The one that perhaps is the hardest to anticipate is contamination of the sample by older or younger organic material (Walker 2005). Even small amounts of foreign organic material can displace the age of a sample by several thousand years. Contamination can occur at several different stages; prior to the sampling, during the field sampling and even in the laboratory. Other sources of errors are long-term variations in ^{14}C production, the marine reservoir effect and isotopic fractionation. One of the early assumptions in radiocarbon dating was that the concentration of ^{14}C in the atmosphere has been fairly stable over time, this however does not seem to be the case. This fluctuation of the production of ^{14}C is known as the De Vries effect. The marine reservoir effect is caused by the fact that the ocean and the atmosphere is not in an isotopic equilibrium. Different depths of the oceans get an input of ^{14}C at different times, thus meaning that in some cases the ^{14}C has already begun to decay for some time before it is available to the local biosphere. This has the consequence that the organic material has an apparent age that can be displaced hundreds and even thousands of years from its true age. Isotopic fractionation is due to that the terrestrial and aquatic biospheres
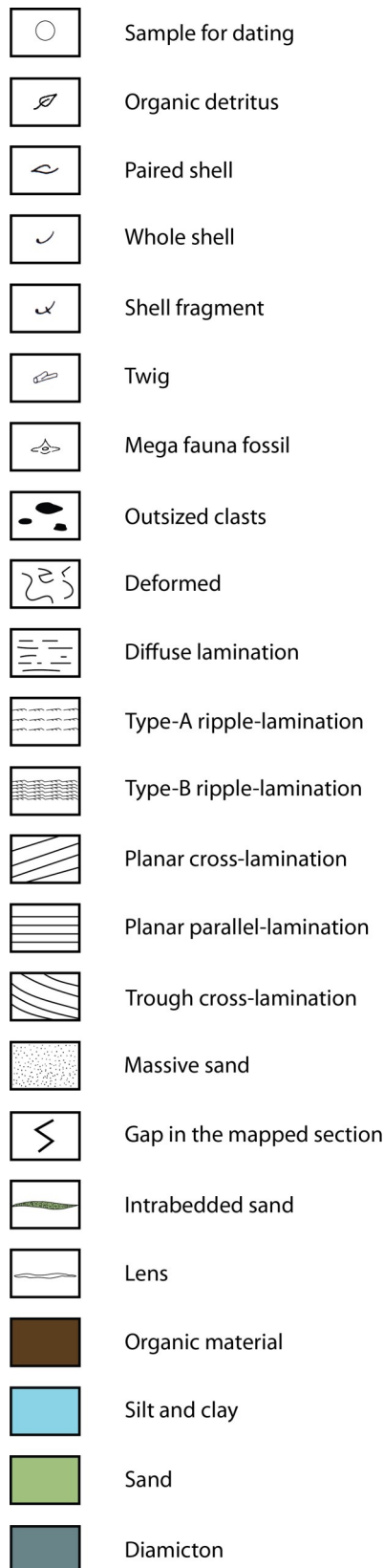
Symbol	Description
○	Sample for dating
⬭	Organic detritus
⌒	Paired shell
⌣	Whole shell
⌣	Shell fragment
⬭	Twig
⬥	Mega fauna fossil
••	Outsized clasts
⟩ट⟨	Deformed
≡≡	Diffuse lamination
⁓⁓	Type-A ripple-lamination
≈≈	Type-B ripple-lamination
⧄	Planar cross-lamination
≡	Planar parallel-lamination
⧅	Trough cross-lamination
⣿	Massive sand
⟨	Gap in the mapped section
⬬	Intrabedded sand
⌇	Lens
■	Organic material
■	Silt and clay
■	Sand
■	Diamicton

Fig. 4. Legend to sediment colours and structures, as used in the logs in Fig. 5.

favour different isotopes of carbon during uptake. For example, terrestrial plants have a tendency to prefer the lighter isotopes and the tissue of the plants thus has a lower concentration of ^{14}C than the atmosphere. This makes it appear older than it actually is. All of the above mentioned issues are well known and precautions are taken during dating to avoid contamination. There exist calibration methods that take into account the different error sources and it is possible to get an accurate age when these methods are employed (cf. Walker 2005).

3   Results

3.1   The Upper Taymyr Ice Marginal Zone

All field investigated sites along the Logata River and its adjacent areas are situated in distal direction, i.e. south of but quite adjacent, to the Upper Taymyr Ice Marginal Zone (UT IMZ; Figs. 1 and 3). The UT IMZ is the northernmost ridge complex of those positioned south of the Byrranga Mountains (Fig. 1). The general trend of the ridge complexes is from northeast to southwest, but with second-order lobate planforms towards southeast. This is particularly evident from the configuration of the UT IMZ (Fig. 3); a prominent lobe runs down the Upper Taymyr River valley from Taymyr Lake southwest-wards, the western arm ending ca. 10 km north of the Logata River outflow into Taymyr River, whereas the eastern arm forms two lobate structures north of the Logata River. The ridges in the close proximity of the investigated sites are roughly 150-230 m high, 0.3-15 km wide and sometimes form secondary ridge-trough cross sections, i.e. multicrested ridge complexes with the intraridge depressions often marked by series of smaller or larger lakes. As many ridge complexes have revealed the presence of fossil ice (Kind & Leonov 1982), this could explain the distribution of trough lakes and their formation due to thermokarst processes.

3.2   Sediment units

Taken together, all sediments exposed at the investigated sites are correlated and put into a local stratigraphic scheme divided into five main units. The units are as follow:

Unit 1: The lowermost unit. It consists of greyish yellow sand with gravel horizons made up of shale.
Unit 2: A matrix-supported silty clayey diamicton superimposed on Unit 1. Intraclasts of sand and clay are common as well as intrabedded sand beds, derived from the underlying Unit 1, giving the unit a stratified appearance.
Unit 3: Consists primarily of sorted sediments of silt and clay. The unit contains both massive and laminated beds with a shifting abundance of outsized clasts and marine molluscs throughout the unit.
Unit 4: Overlies Unit 3. The contact between the units is visible at LoR 3b where Unit 4 cuts Unit 3 in a

Table 2. Dating results.

Locality	Sample no	Altitude m a.s.l.	Dated material	Lab no	^{14}C yr BP	ESR pending	OSL pending
Upper Taymyr River 1 (72.8-74 m a.s.l.)	UTR 1:1	73.6				X	
(N73° 06.813'; E95° 47.808')	UTR 1:2a	73.8	Shell, whole *Hiatella arctica*	LuS 10389	>48000		
	UTR 1:2b	73.1				X	
Logata River 1 (22-24.1 m a.s.l.)	LoR 1:1a	23.7	Shell, whole *Hiatella arctica*	LuS 10377	>48000		
(N73° 06.577'; E96° 09.367')	LoR 1:1b	22.3				X	
Logata River 2 (18.1-33 m a.s.l.)	LoR 2:1	27.6				X	
(N73° 03.733'; E96° 20.492')	LoR 2:2	26.4				X	
	LoR 2:3	26.8	Shell, whole *Hiatella arctica*	LuS 10378	>48000		
	LoR 2:4	22.0				X	
	LoR 2:5	21.7	Shell, whole *Hiatella arctica*	LuS 10379	>45000		
Logata River 3a (30.9-42 m a.s.l.)	LoR 3a:1	34.2	Leaves of *Salix* and *Dryas*	LuS 10380	48200 -3000/+4000		
(N73° 19.956'; E97° 0.866')	LoR 3a:2	33.7	Leaves of *Salix*	LuS 10381	>48000		
	LoR 3a:3	31.7	Plant detritus	LuS 10382	>48000		
	LoR 3a:4	31.3					X
	LoR 3a:5	32.9					X
Logata River 3b (23.2-29.6 m a.s.l.)	LoR 3b:1	29.2					X
(N73° 20.278'; E97° 1.290')							
Logata River 3c (27.4-33.4 m a.s.l.)	LoR 3c:1	31.8	Wood, 2-5 mm ø	LuS 10383	>48000		
(N73° 20.723'; E97° 0.462')	LoR 3c:2	31.2	Twigs, 2-4 mm ø	LuS 10384	>48000		
	LoR 3c:3	28.1	Twigs, 3 mm ø. *Dryas* and *Salix* leaves	LuS 10385	>48000		
	LoR 3c:4	32.9					X
	LoR 3c:5	30.0					X
	LoR 3c:6	27.7					X
Logata River 3d (ca. 25 m a.s.l.)	LoR 3d:1	25	Shell, *Macoma balthica*	LuS 10386	>47000		
(N73° 21.015'; E96° 58.462')							
Logata River 4 (23-24.5 m a.s.l.)	LoR 4:1	24.1	Shell, whole *Hiatella arctica*	LuS 10387	>46500		
(N73° 20.470'; E97° 01.924')							
Logata River 6 (50.8-55 m a.s.l.)	LoR 6:1	54.1					X
(N73° 19.139'; E97° 32.471')	LoR 6:2	51.8					X
	LoR 6:3	50.8					X
	LoR 6:4	53.5	Shell, fragment	LuS 10388	>48000		

Upper Taymyr River 1

m

75.0

74.0

Cm(d)
U3

73.0

72.0

Clay | Silt | f m c | f m c | Cobbles
Sand | Gravel

○ UTR 1:2a ^{14}C: >48000 ^{14}C yr BP
○ UTR 1:1 ESR
MPS 30 cm
○ UTR 1:2b ESR

Logata River 1

m

24.0

U3
SiCm(d)

23.0

22.0

Clay | Silt | f m c | f m c | Cobbles
Sand | Gravel

○ LoR 1:1a ^{14}C: >48000 ^{14}C yr BP

MPS 15 cm

○ LoR 1:1b ESR

Logata River 3a

m

42.0

U5

41.0

34.0   Srtc(A)
Sil
Srtc(A)
Spp
Srtc(A)
33.0   Spp
Srtc(A)
SGcm
Spp
32.0
U4
Srtc(B)
31.0

30.0

Clay | Silt | f m c | f m c | Cobbles
Sand | Gravel

○ LoR 3a:1 ^{14}C: 48200 -3000/+4000 ^{14}C yr BP
○ LoR 3a:2 ^{14}C: >48000 ^{14}C yr BP
○ LoR 3a:5 OSL

284°/28°
○ LoR 3a:3 ^{14}C: >48000 ^{14}C yr BP
○ LoR3a:4 OSL

Logata River 2

m

33.0   Sil
Cm
Sil
Cm(d)
Sil
32.0   Cm(d)
CSil
Cm(d)
Cl
Cm(d)

31.0

Cl
30.0

29.0   U3

CSil
28.0   Cl

SiCm(d)
27.0

C(l)/m
26.0

25.0

24.0

SiCm(d)
23.0

SiCm(d)
22.0
U3
SiC(def)
21.0

SiCl
20.0

Si/Cl

19.0

Si/Cl

18.0

Clay | Silt | f m c | f m c | Cobbles
Sand | Gravel

MPS 6 cm
MPS 3 cm
MPS 4 cm

○ LoR 2:1 ESR
MPS 12 cm
○ LoR 2:3 ^{14}C: >48000 ^{14}C yr BP
○ LoR 2:2 ESR
MPS 3 cm

MPS 10 cm

○ LoR 2:4 ESR
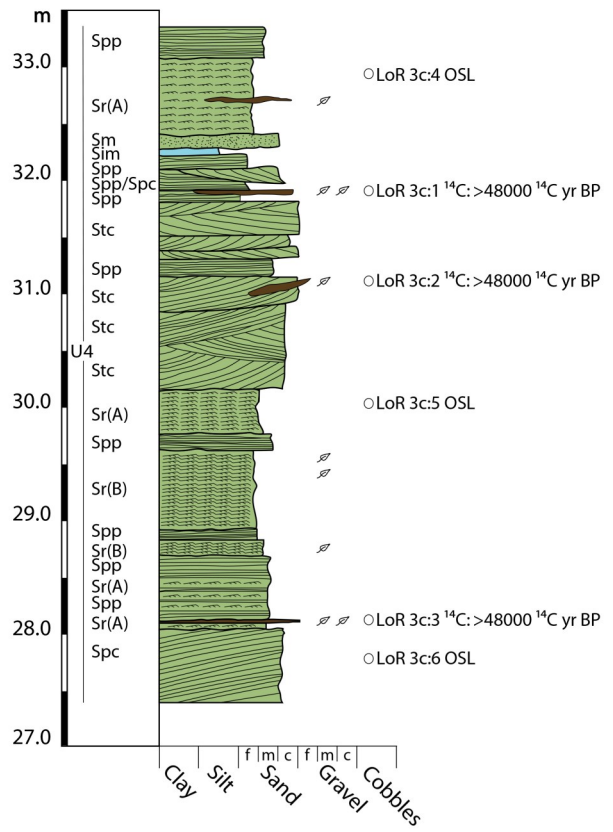○ LoR 2:5 ^{14}C: >45000 ^{14}C yr BP
MPS 15 cm

Fig. 5. Two-dimensional section drawings of the investigated sections. The elevation is in m a.s.l. and the units of the local stratigraphic scheme are displayed on the vertical axis (U1-U5). Sediment colours and structures are explained in Fig. 4, while the lithofacies codes are according to Table 1.
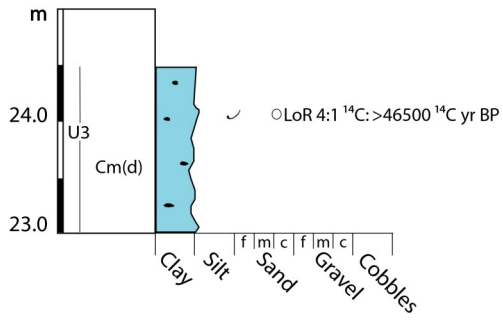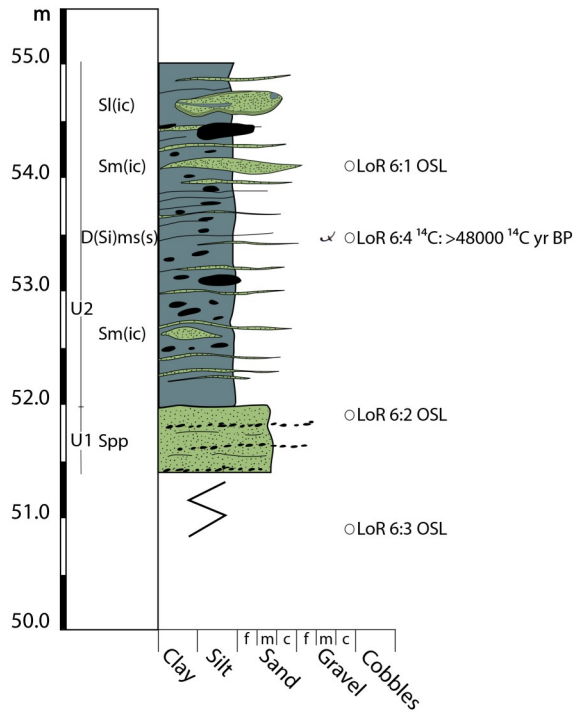
16
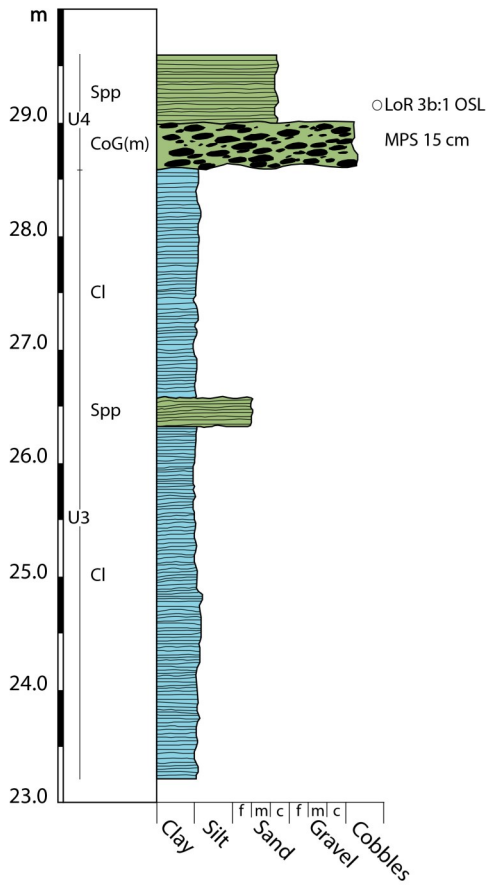
Logata River 3b

Logata River 3c
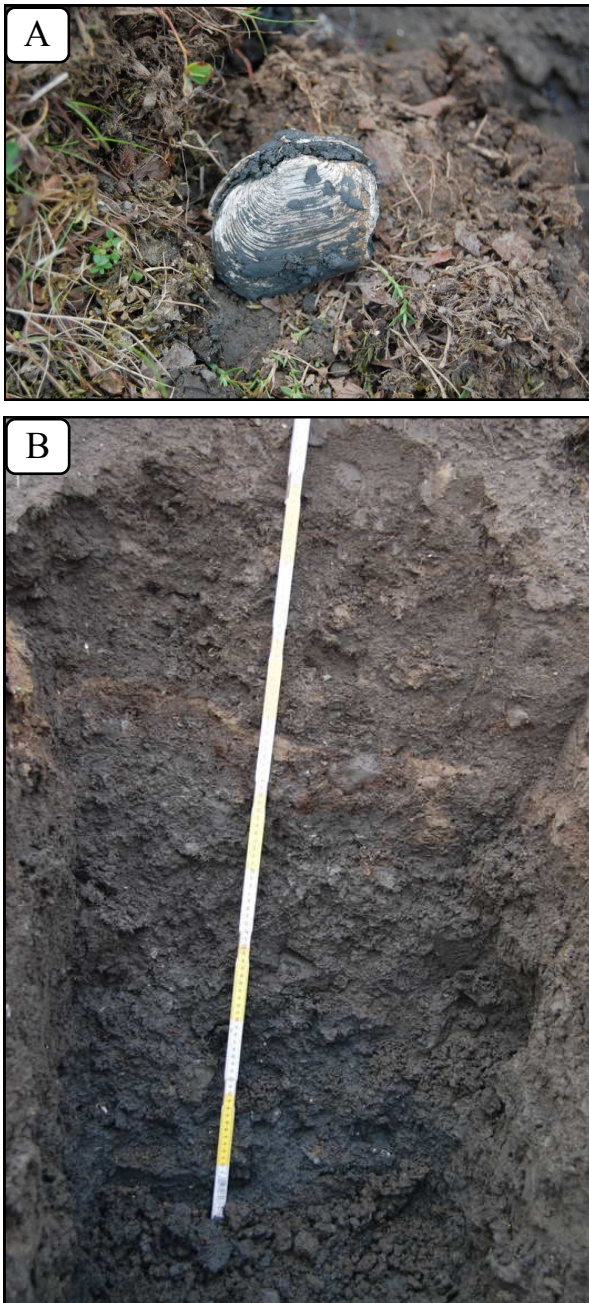
Logata River 4

Logata River 6

Fig. 6. Site UTR 1. A) A paired shell of *Mya truncata* found in the section. B) Overview of the logged section (pictures courtesy of Anjar).

discordant manner. The unit consists of sorted sediments, mainly sand. Both coarser and finer sediments are present as well. Organic detritus is common in the unit.

Unit 5: The uppermost unit. It belongs to the so called ice complex deposits. The unit consists mostly of sorted sediments of silt and sand with an abundance of ice and peat inclusions. Organic detritus and mega fauna fossils are present in the unit as well.

3.3   Investigated sites

All investigated sites are situated close to the riverside of the Logata River except of site Upper Taymyr River

1. Site positions are shown in Fig. 3B. Retrieved radio-carbon ages (all infinite) are shown in Table 2 and all logged sequences are shown in Fig. 5.

3.3.1 Upper Taymyr River 1

The site Upper Taymyr River 1 (UTR 1: N 73°6.813'; E 95°47.808') is situated some kilometres from the Upper Taymyr River at the flank of one of three prominent ridges forming a slightly arched east to west-trending structure, the highest point of the northernmost ridge at 91 m a.s.l. The ridges are ca. 15-20 km long and ca. 20 m high above their internal depressions.

Sediment description. – The crest-lines and upper slopes of the ridges are marked by at least 1 m thick deposits of well sorted gravel with mollusc shells. Only a small section could be excavated at the north-exposed base of the southernmost ridge close to a small lake situated in one of the depressions at 70 m a.s.l. (Fig. 3B). Redeposited coarse sediment along the lakeshores is rich in shells, primarily *Hiatella arctica*. The ca. 1 m high section (Fig. 5) showed massive greyish black clay (Fig. 6B) rich in outsized clasts with a MPS (Maximum Particle Size) of 30 cm. The clay contains paired shells of *Hiatella arctica* as well as a paired shell of *Mya truncata* (Fig. 6A). Along the lakeshore are numerous boulders with sizes of up to 1 meter in diameter and with visible striations on them. Shells were collected for ESR and radiocarbon dating. The radiocarbon dating from the site give an infinite age (>48 000 ^{14}C yr BP) while the ESR dating is still pending.

Interpretation. – The planform and size of the ridges enclosing site UTR 1 could indicate that these are ice-marginal zone moraines of an older generation than the UT IMZ. The ridge crests and upper slopes covered by beach gravel suggest that the moraine ridges were most probably formed in a subaqueous environment with a marine level at >91 m a.s.l. and that the capping beach sediments were formed during the following shore regression. Since the clay at the foot of one of the ridges at site UTR 1 contains *Hiatella arctica* and *Mya truncata*, being saltwater clams (Hanström & Dahl 1963; Dance 1974), one can assume that the clay is marine in nature. The presence of striated clasts in the clay, suggests that they are ice rafted debris (dropstones), released from drifting icebergs. The depositional environment would thus more specifically be glaciomarine and the sediments exposed in section UTR 1 is placed into Unit 3.

3.3.2 Logata River 1

Site Logata River 1 (LoR 1: N 73°6.577'; E 96°9.367') is a landslide with poor sediment exposure, but a small section (2 m), starting at ca. 22 m a.s.l. was cleared and logged (Fig. 5).
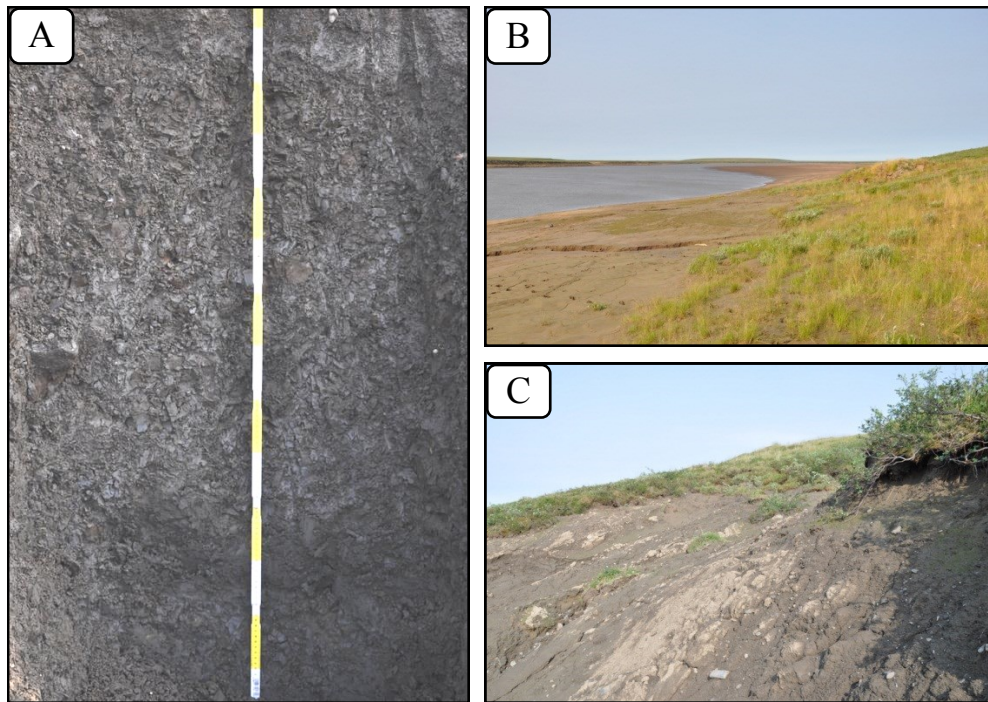
Fig. 7. Site LoR 1. A) Part of the logged section. B) The Logata River as seen from the riverside. C) Part of the landslide that was excavated and logged at LoR 1. Note the presence of outsized clasts.

Sediment description. – The exposed sediment is a massive silty clay (Fig. 7) with numerously occurring outsized clasts with a MPS of 15 cm. A few unpaired *Hiatella arctica* were found in the section, sampled for ESR and radiocarbon dating. The ESR dating is still pending while the radiocarbon dating yield an age of >48 000 ^{14}C yr BP and is thus infinite.

Interpretation. – The occurrence of *Hiatella arctica* suggests that the silty clay was deposited in a marine environment. The presence of dropstones indicates that a glacier was situated in the proximity of the site, hence suggesting that the depositional environment of the sediments in the section was glaciomarine. As is evident of these features the site (LoR 1) is very similar in appearance to UTR 1, and because of this the sediments in the section are classified as belonging to Unit 3 of the local stratigraphic scheme.

3.3.3 Logata River 2

Logata River 2 (LoR 2: N 73°3.733'; E 96°20.492') is a prominent river bluff (Fig. 8), the section being ca. 15 m high and starting at ca. 18 m a.s.l. The section was cleared in step-wise manner and logged continuously except for a gap of 2 m where sediments were impossible to be cleaned in a satisfactory way (Fig. 5). Marine mollusc shells derived from erosion of the river bluff were abundant on the riverside (Fig. 8D).

Sediment description. – The sediment sequence displays a varying silt to clay content from bottom to top, some beds being laminated and others massive. Outsized clasts are present in many beds, in some at

such frequency that the sediment is diamictic in character. Shells of marine molluscs in different conditions, mostly of *Hiatella arctica* but also other species such as *Astarte borealis*, were found in some beds. Samples were taken for radiocarbon dating as well as ESR dating. Two radiocarbon datings yield ages of >45000 and >48000 ^{14}C yr BP, respectively, i.e. infinite ages. ESR datings still pending.

In more detail; the lower part of the sequence is made up of finely laminated silt and clay (bed thickness 2-10 mm), interbedded with some few fine sand lamina (Fig. 8B). No shells were found at this level. The stratified silty clay changes upwards into massive silty clay, though the lower part showing deformed primary lamination. The massive clay is more or less rich in outsized clasts with a diameter of 1-15 cm giving it a diamictic character. The massive clay shows tendencies of having a diced structure. Marine molluscs occur both as shell fragments and as half shells and paired shells of *Hiatella arctica*.

Further up in the section after the gap between ca. 24 and 25.5 m the silty clay is diffusely stratified to massive. Outsized clasts are abundant as well as shells of *Hiatella arctica* and *Astarte borealis*. It ends with a ca. 40 cm thick bed of massive silty clay rich in outsized clasts (Fig. 8F). Above this comes a close to 4 m thick succession of more clayey, finely laminated sediment, clay beds being 1-3 cm thick and silt lamina 2-10 mm thick, intercalated with a few mm-thick fine sand lamina. Outsized clasts are rare, occurring only in a narrow band at ca. 28.5 m. The topmost ca. 1.5 m consist of alternating beds of laminated silt and massive clay, the latter diamictic in appearance due to the large presence of outsized clasts. The MPS in these
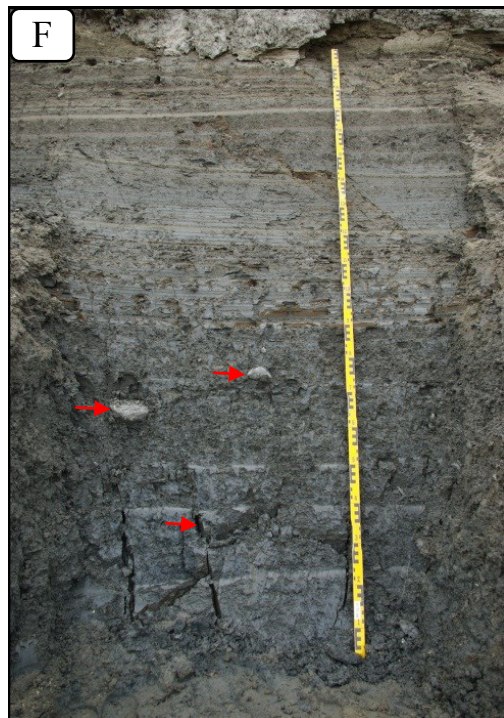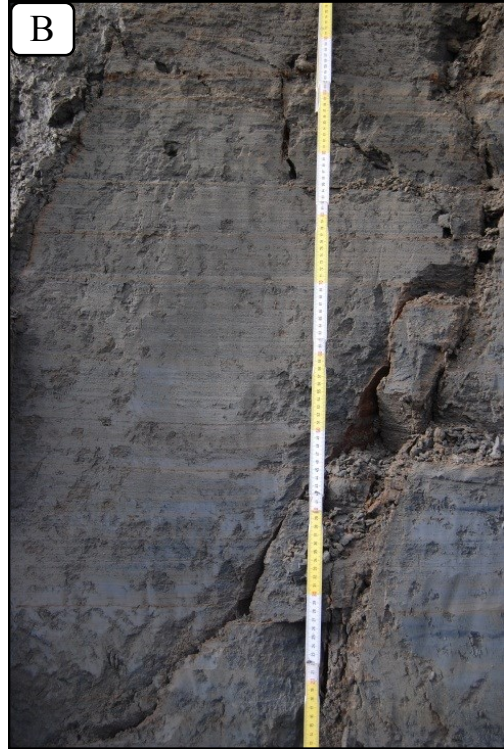
beds range from 3-6 cm. the general trend is that the clasts are only present in the more massive beds. This applies to the presence of shells and shell fragments as well.

Interpretation. – The presence of ice rafted debris (IRD), preferentially in the massive to vaguely laminated clay beds, as well as the occurrence of shells from *Hiatella arctica* and *Astarte borealis* suggest a glaciomarine depositional environment, since *Astarte borealis* and *Hiatella arctica* favour a cold habitat (Dance 1974). The whole sediment sequence is thus classified as belonging to Unit 3 of the local stratigraphic scheme.

The sediments most probably reflect an off-shore environment with deposition from suspension settling, thus explaining the abundance of silt and clay in the section. The lamination in some of the beds might be due to a higher depositional rate than in the massive clay, the interbedding between silt and clay reflecting short-term shift in sediment input at the site. This could also explain the absence of shells from these beds, since a too fast depositional rate is unfavourable for macrofauna colonisation (Ó Cofaigh & Dowdeswell 2001). An alternative explanation could be fluctuations in the salinity of the water. Many molluscs are sensitive to changes in salinity (Hanström & Dahl 1963) and the absence of molluscs over certain intervals could thus indicate periods of freshening of the water basin, in turn suggesting strong inflow of meltwater from a receding glacier. The absence of molluscs also go hand in hand with the increase of silt/clay lamination and vice versa; a more saline environment inhibits the formation of laminated beds as it promotes flocculation of the fine sediments and cause clay aggregates to be deposited at the same velocities as coarser sediment particles (Ó Cofaigh & Dowdeswell 2001).

High frequency of drop clasts correlates to the absence of lamination and suggests periods of higher iceberg discharge during deposition of massive clay. However, IRD is not totally absent from the laminated parts. If these are deposited during shorter events of high sediment input, then a more constant IRDi flux will be "diluted" in a larger sediment volume as it goes down in frequency.

It is worth mentioning that Ó Cofaigh & Dowdeswell (2001) summarized different theories concerning the formation of glaciomarine laminated/non-laminated sediments as some of their sediment descriptions show large similarities with the sediments at site LoR 2. One of the settings they describe is a high-latitude ice-distal glaciomarine

setting. The change between more massive beds, rich in shells and IRD, and laminated beds devoid of the same, is explained by temperature fluctuations that influence meltwater discharges, such as turbid meltwater plumes, as well as the presence of shorefast sea ice. The presence of sea ice would inhibit iceberg rafting and this would explain the lack of dropstones. The sea ice would also be unfavourable for the macrofauna and favours suspension settling. This would create an environment suitable for the deposition of the laminated beds. Of the abovementioned theories the one proposed by Ó Cofaigh & Dowdeswell (2001) seems to be the most plausible one.

3.3.4 Logata River 3

The Logata River 3 sites were chosen along a ca. 4 km long outer bend of a meander loop, along which sediments were more or less well exposed in ca. 25 m high river bluffs (Fig. 9D) above river level at ca. 20 m a.s.l. Three subsites were chosen for sediment logging, all at their top covered by Unit 5 sediments, which is "ice complex" sediment rich in peat just below the ground surface (Fig. 9C). However, ice complex sediment is only indicated in the log of site LoR 3a (Fig. 5). Ice complexes often consist of silt to fine sand sediments rich in organic material and with a high content of ground ice, the latter occurring both as syngenetical horizontal ice lenses and more vertical ice wedge polygonal systems (Schirrmeister et al. 2011). The sedimentology and formation of ice complex sediment sequences along Logata River is outside of this study (will be part of Kenneth Andersen's PhD thesis work) but it is worth mentioning that fossils of extinct mega fauna, like mammoth (*Mammuthus primigenius*) were abundant along the riversides between the Logata 3 sites (Fig. 9A), and at the LoR 3d site (not in Fig. 5; sediment from this subsite were only logged over the ice complex part, Fig. 9C), a quite coherent *in situ* steppe bison (*Bison priscus*) skeleton was encountered, frozen into the sediments (Fig. 9B). No datings from the ice complex sediments and its mega fauna remains are yet performed, but comparative sediments from the Lake Taymyr basin to the north are usually in the age range of 40-10 cal kyr BP (Möller et al. 2011; Jørgensen et al. 2012).

The riversides between the Logata 3 sites are lined with large and often striated clasts, some of boulder sizes up to 1-1.5 m, clast sizes nowhere encountered in exposed sediment. Kind & Leonov (1982) describe the occurrence of till at the base of this river bend which, unfortunately, could not be confirmed, in spite of frenetic reconnaissance.

Fig. 8 (Page 20)*.* Site LoR 2. A) Overview picture of the investigated site. The upper part of the logged section is visible in the picture. B) Close-up view of the lowermost bed of laminated silt/clay. C) Overview of the beds under the gap in the log. D) Collection of some of the shells that were found along the riverside of the site (Fig. D courtesy of Anjar). E) Overview of the laminated clay ca. 30 m a.s.l. F) Overview of three different beds at ca. 26-28 m a.s.l. Laminated clay at the top with occasional sand lenses, followed by a massive silty clay bed with outsized clasts. The latter are marked by red arrows. Underlying this bed is a diffusely laminated/massive clay bed.
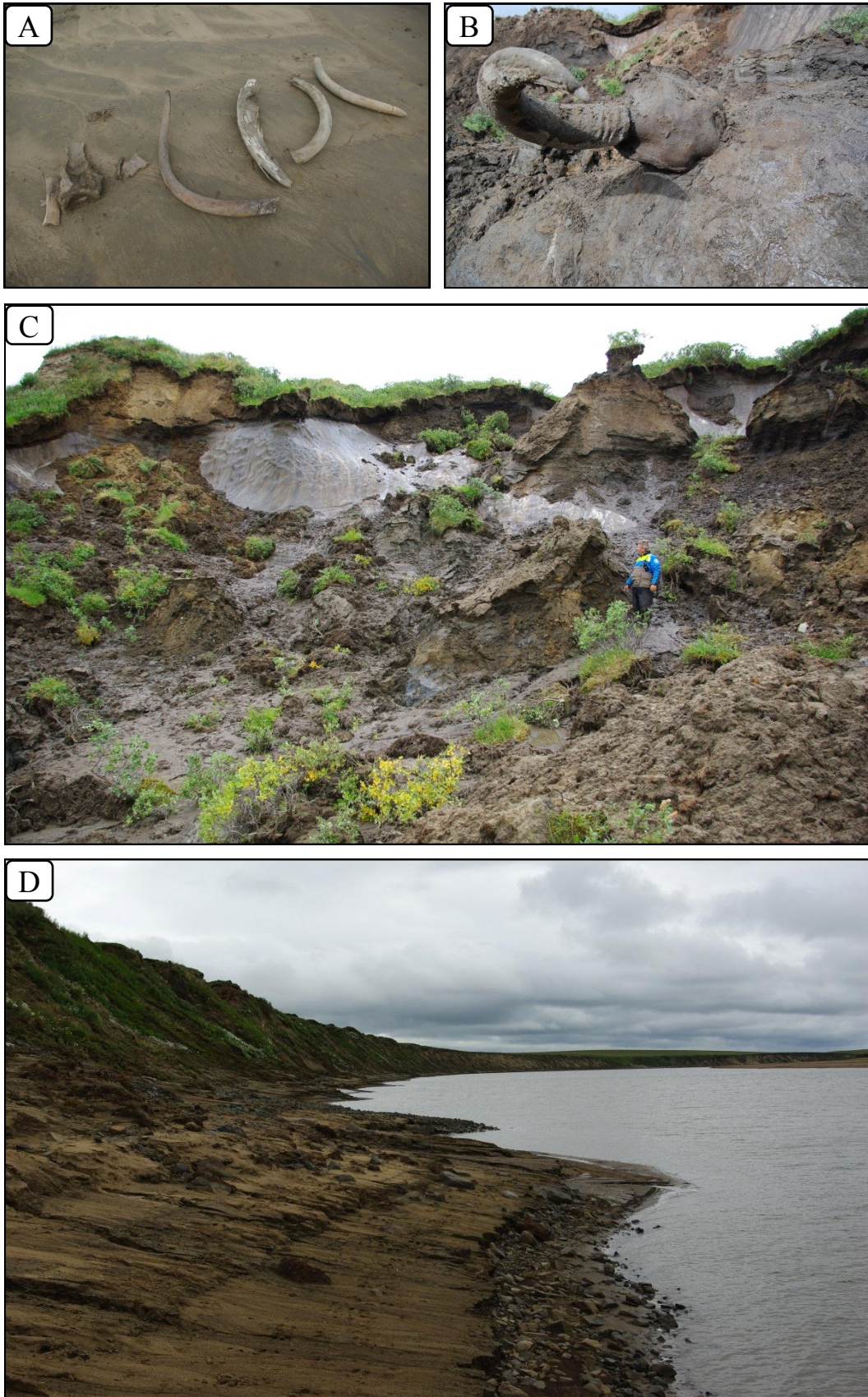
Fig. 9. A) Some of the mega fauna fossils found on the riverside at the Logata River 3 sites, mainly mammoth tusks. B) A steppe bison (*Bison priscus*) cranium still stuck in the frozen sediments seen in (C). C) Picture displaying the abundance of ground ice just below the soil surface at site LoR 3d. Unit 5 is visible at the top of the site (person in the picture for scale). D) Picture of the Logata River meander bend with the LoR 3 sites, facing upstream.
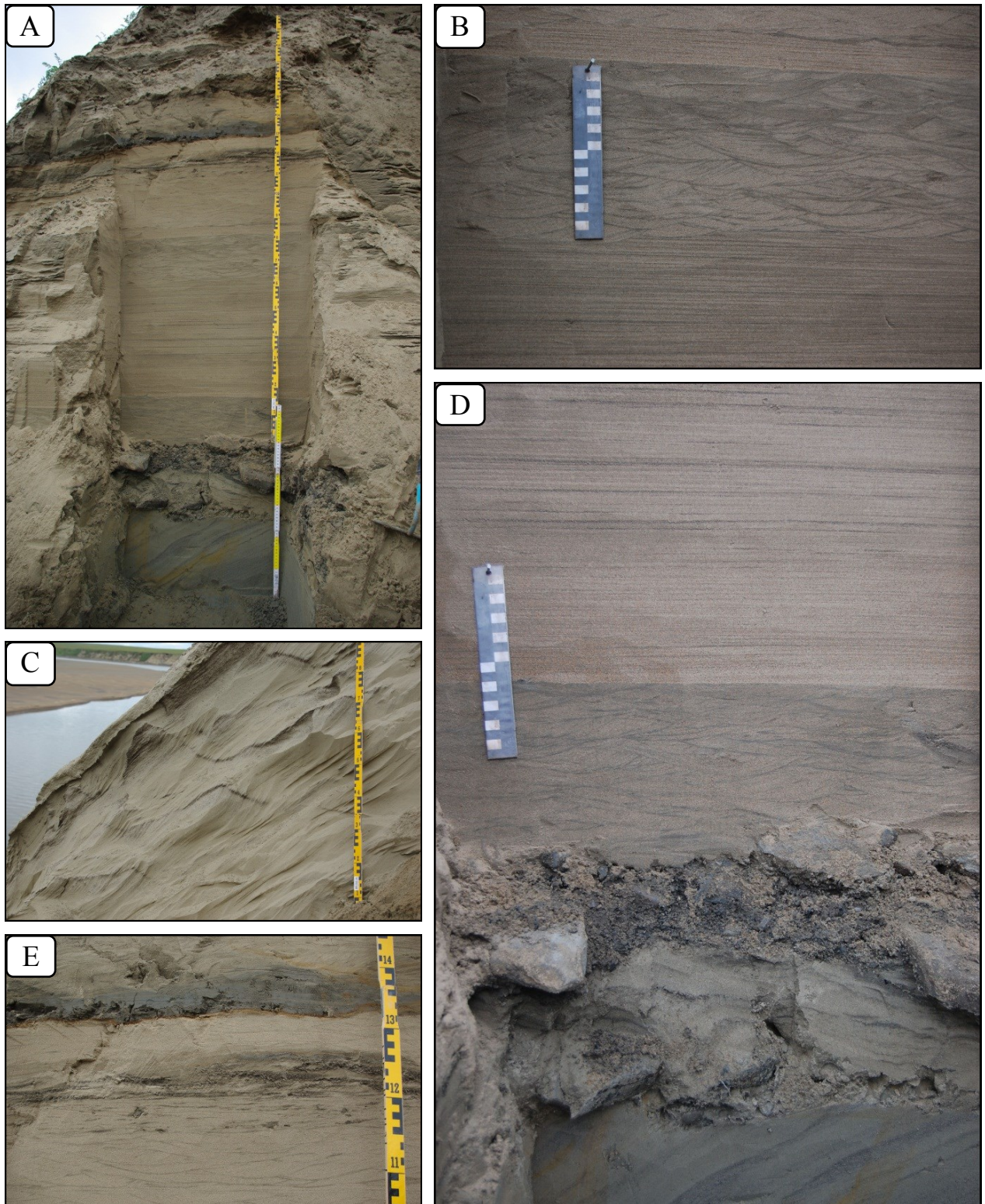
Fig. 10. Site LoR 3a. A) Overview of the upper part of the section. In the lower part is an erosional unconformity, below which the sediments are block-faulted towards the left. B) Sand bed with trough cross-laminated type-A ripples, positioned between two beds of planar parallel-laminated sand (33.3 m a.s.l). Note the scour-like contact between the two lower beds. C) The lowermost bed consisting of within a fault-block dipping type-B ripple trough cross-laminated fine sand with organic detritus in their lamina. D) Close-up view of the massive sandy cobble and gravel bed at the erosional unconformity and its overlying adjacent beds. E) Close-up view of the upper part of the logged section. Note the rip-up clasts and the laminated silt bed.

3.3.5 Logata River 3a

Logata River 3a (LoR 3a: N 73°19.956'; E 97°0.866') was possible to clean and log from ca. 11 m above the river, the logged sediment sequence starting at 31 m a.s.l. and with a gap between the ice complex and the underlying sorted sediments (Fig. 5).

Sediment description. – Most of the beds at site LoR 3a consist of fine sand with the exception of a silt bed near the top of the section as well as a gravel to cobble bed positioned lower in the stratigraphy (Fig. 10A). There seems to be erosive contacts between almost all the beds in the section. The whole sediment sequence below the ice complex sediments is classified as belonging to Unit 4 of the local stratigraphic scheme.

The lowermost part of the sequence consists of a succession of type-B ripple trough cross-laminated fine sand. There is an abundant occurrence of organic macro remains within ripple lamina, and especially concentrated at trough bottom (Fig. 10C). Later lab sieving of the sediments for extracting material for radiocarbon dating showed that most macro remains were thin twigs and rootlets, though quite a substantial part was clearly identifiable *Dryas* leaves. The sequence is not in its original place of deposition; the bedding planes dip ca. 28° towards WNW, suggesting block tilting in this direction.

The lower part of the sediment sequence is cut in a discordant manner, the erosional contact marked by a bed of cobble and gravel (Fig. 10D). Above this coarse-grained bed come alternating beds of type-A ripple trough-cross laminated fine sand and slightly coarser planar parallel-laminated sand (Fig. 10D). Bed shifts are often marked by erosional events; ripple troughs cut down into Spp beds and the base of Spp sets cut the crest tops of underlying ripple sets. The ripple bedsets at ca. 33.7 m a.s.l. contain small rip-up clasts with a diameter of 5-15 mm composed of silt, the silt clasts with thin internal organic-rich lamina (Fig. 10E). The logged sequence ends with a laminated silt bed and a ripple trough-cross laminated fine sand rich in organic material (Fig. 10E).

Samples were taken for radiocarbon and OSL dating, the latter still pending. Two radiocarbon ages are clearly infinite, both yielding ages of >48000 ^{14}C yr BP, whereas one dating suggests an age of 48200 ^{14}C yr BP (-3000/+4000), which probably also should be regarded as an infinite age.

Interpretation. – The ripple morphology of the sediments suggests a fluvial environment with changing flow velocities (Collinson et al. 2006). The occurrence of organic material throughout most of the section suggests an available vegetation cover in the proximity of the site during most of the sedimentation history. The block tilting of the lower part of the logged sequence is interpreted as a river-bank failure at a certain stage of gradual sediment accretion, after which sediment deposition continued
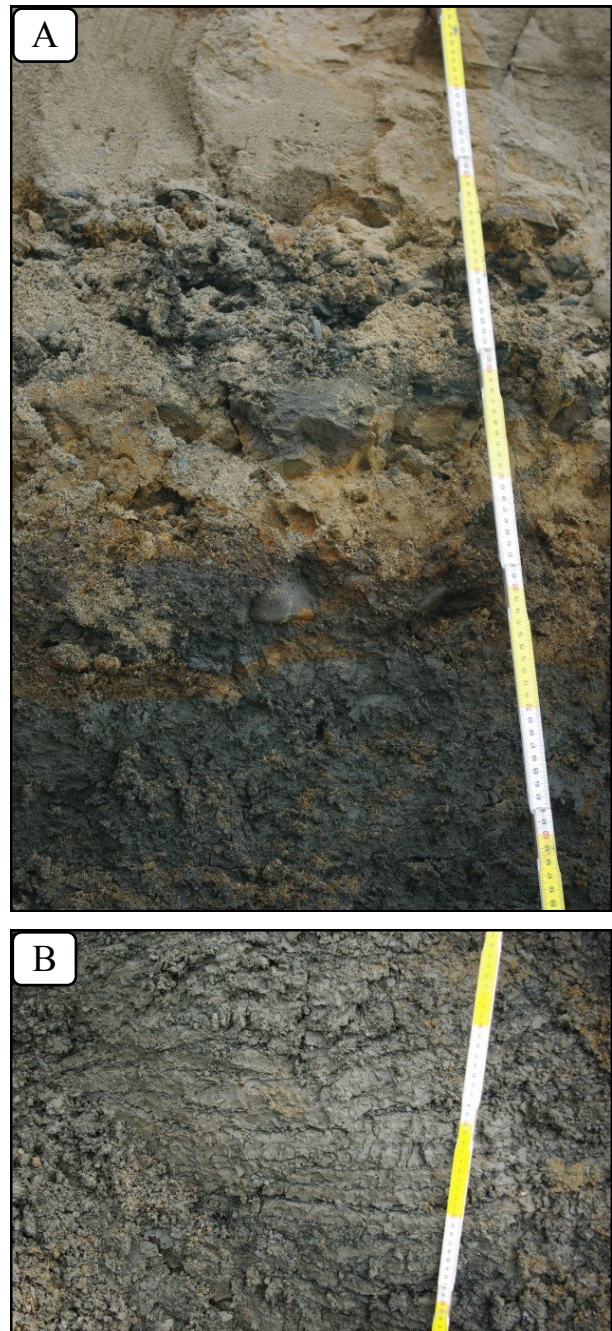
Fig. 11. Site LoR 3b. A) Close-up view of the three upper-most beds of the section; clay at the base is cut by an erosive unconformity above which is an erosional lag and planar parallel-laminated sand. B) Part of the laminated clay at the base of the section.

after a period of erosion on top of the slumped sediment sequence, the bank failure and the following erosion and deposition forming an event bed (Collinson et al. 2006). This would also explain the absence of organic material in the beds directly superimposed on this bed since the area probably was disturbed and terrestrial vegetation was suppressed for some time. There most likely exists a hiatus of unknown extent between the beds below and above the erosional unconformity. The bed of laminated silt

suggests a more low-energy depositional environment with low flow velocities prevailing during the deposition of this bed, possibly as flood-plain deposits (Nichols 1999).

The rip-up clasts embedded in ripple-laminated sets reflect erosion, transport and deposition of such flood-plain deposits from further upstream, the rounded character of the intraclasts suggesting some transported distance before emplacement (Nichols 1999).

3.3.6 Logata River 3b

Logata River 3b (LoR 3b: N 73°20.278'; E 97°1.290') is situated around 639 m downstream from LoR 3a. A 6.5 m high river section, starting at ca. 3 m above river level at 23 m a.s.l., was cleaned and logged (Fig. 5).

Sediment description. – The lower part of the section consists of laminated clay with greyish clay in 1-3 cm thick beds, separated by 1-2 mm thick lamina of even finer-grained black clay (Fig. 11B). The clay unit is interbedded with a 25 cm thick bed of planar parallel-laminated sand. No dropstones or molluscs were encountered in the clay sequence. In spite of this, the clay is classified as belonging to Unit 3 of the local stratigraphic scheme based on the fact that the same type of laminated clay was encountered at site LoR 3d, here continuing upwards into silty clay with dropstones and mollusc shells. However, the sediments exposed at the base of site LoR 3d were not possible to clean and log in a meaningful way more than to sample shells for dating (see below).

The clay sequence is discordantly cut on top of which is a ca. 35 cm thick bed of clast-supported cobble gravel with a MPS of 15 cm (Fig. 11A). The cobble gravel bed is in turn overlain by a thick succession of planar parallel-laminated and ripple-laminated sand, continuing upwards to the covering ice complex deposits (Unit 5). The sandy sediments at the site were wearyingly unstable and after several slump events, only 0.6 m were eventually logged. An OSL sample was retrieved from this bed, the age of which is still pending. The sediments above the clay sequence are correlated with the same sediments as exposed at site LoR 3a and classified as belonging to Unit 4 of the local stratigraphic scheme.

Interpretation. – The absence of shells in the laminated clay might suggest a lacustrine depositional environment. However, a single *Macoma balthica* shell, radiocarbon dated to be of infinite age (>47000 ^{14}C yr BP), at site LoR 3d, approximately 2 km away, with clay of similar type suggests that the clay is marine and thus should be correlated with marine clay beds at other sites (Unit 3). If this assumption is correct then one might expect an off-shore environment with mainly deposition from suspension settling, with a large meltwater input and very reduced ice-berg

rafting. The interbedded sand bed might be due to deposition from an occasionally occurring turbidity current (Nichols 1999). The *Macoma balthica* shell found at site LoR 3d was very close to the sediment face and thus not suitable for ESR dating.

The cobble gravel bed above the erosional unconformity most probably marks substantial erosion and change to a terrestrial-fluvial environment in which sediment of Unit 4 was deposited. There might be a substantial temporal hiatus between this bed and the one it superimposes (Unit 3).

3.3.7 Logata River 3c

The Logata River 3c (LoR 3c) site is located 935 m downstream of Logata River 3b (N 73°20.723'; E 97°0.462'). A 6 m high river section, starting at ca. 7 m above river level at 27.5 m a.s.l. was cleaned and logged (Fig. 5).

Sediment description. – The section consists primarily of alternating beds of ripple-laminated sand and trough cross-laminated coarser sand with the presence of planar parallel-laminated beds as well (Fig. 12B). It is common throughout the section with organic detritus in the ripple-lamination. As can be seen in the log (Fig. 5) a number of beds and lenses of organic material are also present in the section, mostly small twigs with a diameter of 2-5 mm, but also identifiable *Dryas* and *Salix* leaves (Fig. 12C, D). The upper part of the section shows clear signs of oxidation. Other secondary structures are visible in the section, like an ice wedge cast in planar parallel-laminated sand at 31.3 m a.s.l. (Fig. 12A). The upper part of the trough cross-laminated beds shows clear three dimensional bedforms while further down the section they are more obscure. Samples were taken for OSL (3) and radiocarbon dating (3); all radiocarbon samples give infinite ages >48000 ^{14}C yr BP while the OSL datings are still pending.

Below the section towards the riverside, clay similar to the one mapped at LoR 3b is exposed. The boulders on the riverside suggest that a diamicton might be present at the bottom of the site.

Interpretation. – The flow regime has obviously been shifting at the site through time, with higher flow velocities that enabled the three-dimensional dune migration in deeper channel position, ripple migration further up on the channel slope and deposition of silt beds at low flow velocities. Just like in section LoR 3a, the abundance of organic detritus throughout the section suggests existence of vegetation growing around the site during deposition. The grain size of the sediments suggests a distal depositional environment and the change from one bed of structures to another and then back again, in agreement with a meandering river system with development of point-bar sediment sequences (Nichols 1999). The finer deposits in the section could be overbank sediments washed in due to
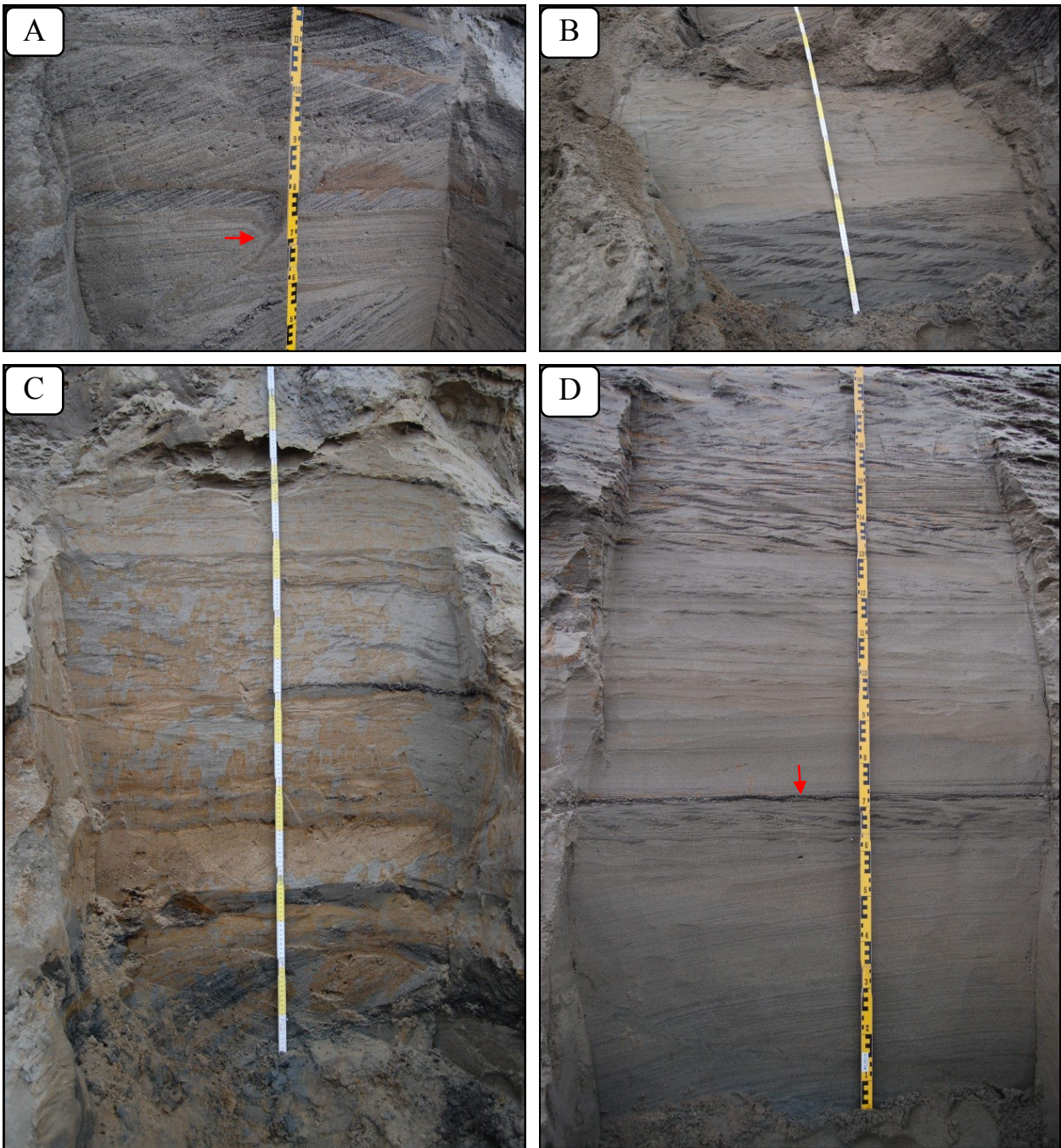
Fig. 12. Site LoR 3c. A) Close-up view of the trough cross-laminated sand as well as the planar parallel-laminated bed with an ice wedge cast (marked by the red arrow). B) Close-up view of the three beds underlying the trough cross-laminated sand (30.2 m a.s.l.). Note the abundance of organic material in the type-B ripples. C) Close-up view of the uppermost part of the section. Oxidation is visible in the beds and lenses of organic material are present. D) Photo of the lowermost part of the section. Note the thin organic bed running through the unit (marked by the red arrow).

occasional flooding of the area and the change of the structures in the sandy sediments might be due to bar migration as well as migration of the thalweg in the river system. The dunes in the section might very well reflect a deposition in the thalweg of the river where the flow velocity is at its highest.

The ice wedge cast in the section indicate syndepositional formation and presence of permafrost over periodically drained depositional surfaces, the wedge ice melting during later submergence,

cast formation and continued fluvial deposition. The sediments at the site are correlated with the fluvial sediments exposed at sites LoR 3a and LoR 3b and thus classified as belonging to Unit 4 of the local stratigraphic scheme.

3.3.8 Logata River 4

The Logata River 4 (LoR 4) section (N 73°20.470'; E 97°1.924') is situated close to the LoR 3b site (500 m to the northeast), on the other side of the meander
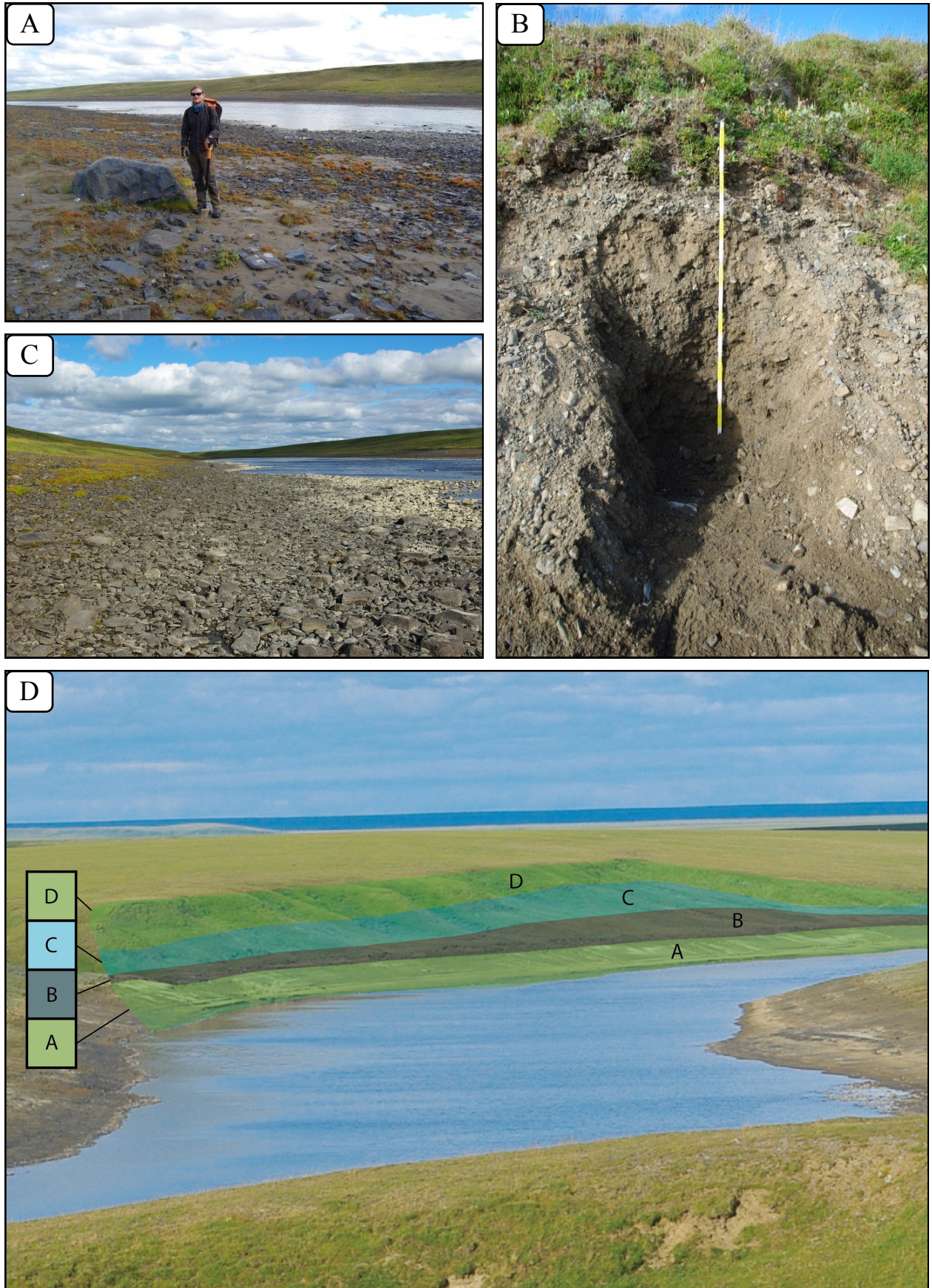
Fig. 13. Site LoR 5. A) Overview of the northern riverside along the Logata River. Note the size of the boulders (Fig. A courtesy of Anjar). B) The uppermost Unit D at the site. C) The riverside below the high-water mark. Note the with boulders heavily armoured beach, suggesting the presence of a diamicton in the local stratigraphy. D) Overview of the northern valley side of the Logata River with the suggested position of units A-D.

peninsula, as shown in Fig. 3B. A small section (1.5 m) was cleaned and logged, starting at 23 m a.s.l., ca. 3 m above the river level.

Sediment description. – The river section consists at its base of massive greyish black clay (Fig. 5), similar to the one found at LoR 3b. However, the clay here contains dispersed clasts, 1-2 cm in diameter. Weathered-out shells mainly of small *Macoma balthica* were frequent on the beach surface below the section. A whole *Hiatella arctica* on the section surface was sampled for radiocarbon dating, giving an infinite age (>46500 ^{14}C yr BP). The river bluff exposes further up sandy sediments as in all LoR 3 sites, indicating the same basal stratigraphy here. These sediments were, however, not logged as the LoR 4 site was only sampled during a quick stop during transport to a new base camp.

Interpretation. – The occurrence of saltwater clams (Hanström & Dahl 1963; Dance 1974) strongly suggests that the clay is of a glaciomarine origin, an interpretation further strengthened by the occurrence of IRD in the clay. The LoR 4 site also strengthens the environmental interpretation of the lower part of the nearby LoR 3b site, at which no clear marine indicator was found. The marine clay at site LoR 4 is thus correlated to the clays exposed at sites LoR 3b and LoR 3d classified as belonging to Unit 3 of the local stratigraphic scheme. The abundance of *Macoma balthica* at site LoR 4 indicates that the depositional environment here was shallower compared to the other sites with Unit 3 sediments (Hanström & Dahl 1963).

3.3.9 Logata River 5

The site Logata River 5 (LoR 5: N 73°19.777'; E 97°34.907') is the northern river bank of the Logata River, from ca. 25 m a.s.l. and up to the plateau (at ca. 60 m a.s.l.). The sediments are only exposed in small windows and a complete and continuous stratigraphy could not be excavated. However, based on the small exposed outcrops along the valley side, a schematic stratigraphy could be constructed, comprising four stratigraphic units (A-D, Fig. 13D).

Sediment description. – Unit A, exposed at the high water mark along the river, is a greyish-yellow sand (Fig. 13D). According to Kind & Leonov (1982) a till should be exposed above this sand, with drag fold at the contact to the sand. No such till could be located, but the slope above the Unit A sand host large boulders, and a boulder source must be located nearby; the low-water river beach beneath the high-water mark is heavily armoured with boulders (Fig. 13C), some in sizes up toward 2 m in diameter and many of them striated and some bullet-shaped (Fig. 13A). The non-located till is designated Unit B. Further up-slope, grey clay with drop clasts and shell fragments is exposed in

a small slump scar, designated Unit C. The topmost sediment (Unit D) is a coarse-grained gravelly sand to sandy gravel, ca. 3 m thick. (Fig. 13B).

Interpretation. – Standing alone, this site does not offer much possibilities of interpretation. However, the "lost till" is exposed on the opposite river bank ca. 2 km downstream (see below, site Logata 6), as is the underlying sand (Unit A). On stratigraphic correlation of similarities, Unit C at the Logata 5 site is classified as belonging to Unit 3 (glaciomarine) of the local stratigraphic scheme and the coarse sediments on top of these (Unit D) are classified as belonging to Unit 4 (fluvial setting) of the local stratigraphic scheme. If correct, Unit 4 is here much more coarse-grained than at other described localities, possibly reflecting a more proximal position.

3.3.10 Logata River 6

The Logata River 6 site (LoR 6) is a large slump in the southern valley side, positioned ca. 150 m south of the river (N 73°19.139'; E 97°32.471'). The back wall of the slump, being ca. 50 m wide, is situated at the plateau edge at ca. 65 m a.s.l. Mobilized sediments at the base of the back wall and lying on sloping permafrost were extremely unstable; in spite of this it was possible to get access to a small part of it and clean and log a 3.5 m high section, displaying at the base a sand unit, on top of which is a diamicton continuing to the plateau edge/surface (Fig. 5).

Sediment description. – At the bottom of the section a greyish yellow sand with gravel horizons of shale is poorly exposed. If the sand here is in its original position or rafted/thrusted could not be determined in the field. Sand with a similar appearance is exposed further down the valley side, ca. 150 m east of the slump in a steep slope. Two OSL samples were taken from the sand, one directly beneath the contact to the overlying diamicton in the logged section, and one at the site further away; results from these are pending. The basal sand is classified as belonging to Unit 1 of the local stratigraphic scheme, that is the lowermost recognized stratigraphic unit and it is believed that it correlates to Unit A across the river   at site LoR 5.

With a sharp contact to the Unit 1 sand is a matrix-supported silty clayey diamicton, rich in clasts, and is classified as belonging to Unit 2 of the local stratigraphic scheme. The diamicton is partly stratified in its appearance as it is intrabedded with numerous sand beds, from a few mm up to 5 cm in thickness and with lengths between 0.5-1.5 m (Fig. 14B). Yellowish sand also forms a number of lenticular to more stretched out intraclasts in the section, 5-20 cm thick and 30-80 cm long (Fig. 14A, C). One of the larger intraclasts has an internal primary lamination that conforms to its outer form (Fig. 14A). In addition to this are frequent occurrences of smaller intraclasts of clay, both massive red brown clay with diameters of
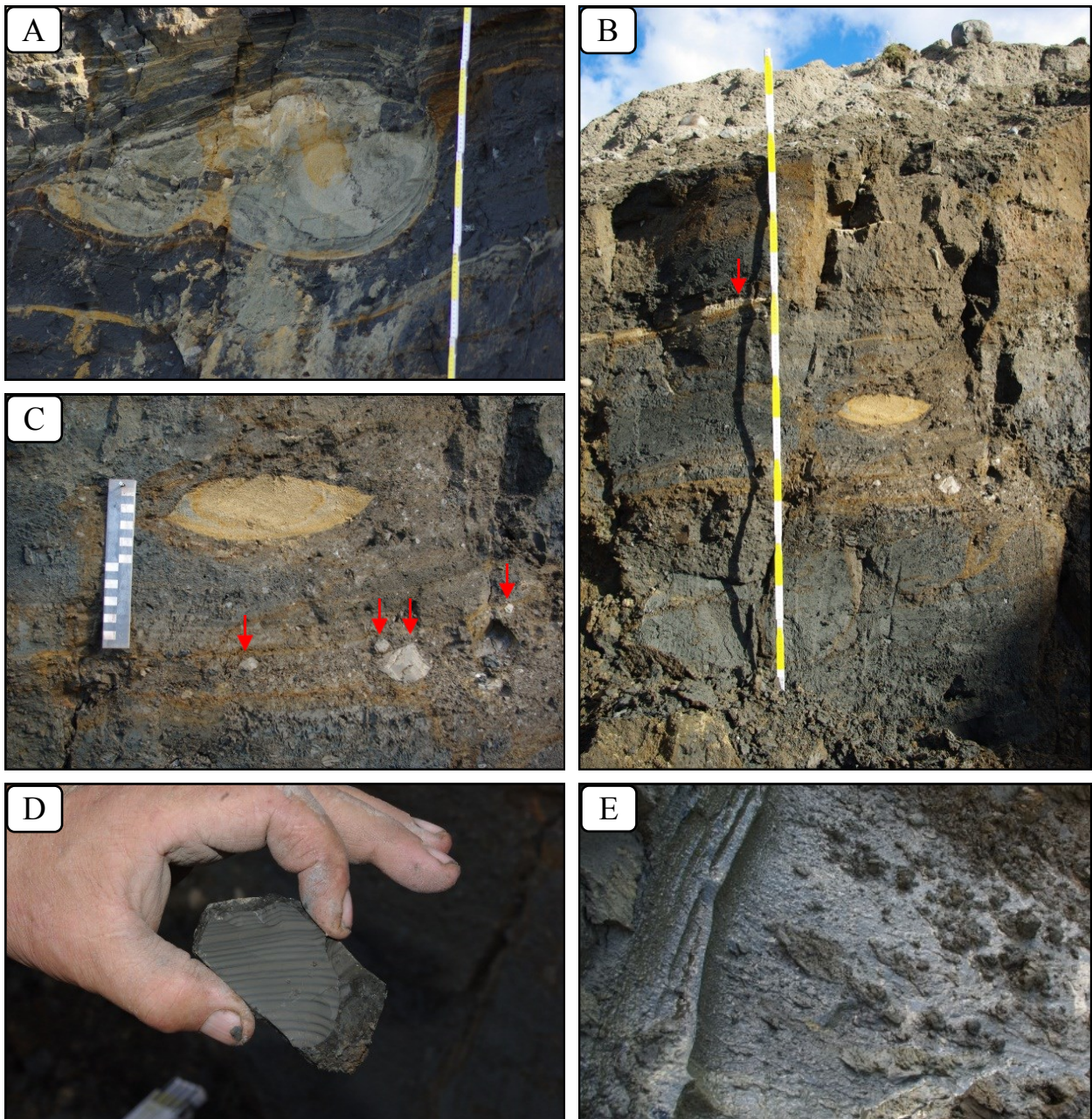
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Fig. 14. Site LoR 6. A) Sand intraclast with its internal primary lamination conforming to its outer form. B) Overview of the upper part of the logged section. Red arrow marks one of the intrabedded sand beds that are common throughout the section, giving the diamicton its partly stratified appearance. C) Close-up view of the sand intraclast (boudin) in picture B. Note the more angular intraclasts of clay, indicated by red arrows. D) Close-up view of one of the clay intraclasts found throughout the section with its primary lamination still intact. E) The active slumping was quite noticeable during the mapping of the section.

1-5 cm and greyish black, finely laminated (2-5 mm) clay (Fig. 14C). As is shown in Fig. 14D, many of these intraclasts have retained their primary sedimentary structures. A single mollusc shell fragment of unknown species was extracted from slumped diamicton.

A clast fabric analysis was performed in the diamicton in the eastern part of the slump back wall. Due to the tight time schedule of the expedition, and especially the lack of clasts with an acceptable a-axis to b-axis ratio (2:1), the measured clasts did not yield high enough numbers to give what usually is regarded as a statistically sufficient dataset (n=25). Still, the measured clasts are plotted in a stereonet (Fig. 15), after being adjusted for magnetic declination of the area. In spite of few measurements (n=17), it reveals a unimodal fabric shape with a fairly strong long-axis clustering (S_1=0.694) towards NE (V_1=49°/4°), suggesting a stress from this direction.

A sample for OSL-dating was taken from one of the sand intraclasts within the diamicton, the result pending. The retrieved mollusc shell has been radiocarbon dated, giving an infinite age (>48000 ^{14}C yr BP).
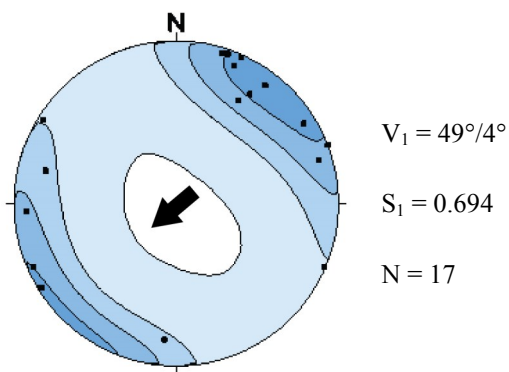
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$V_1 = 49°/4°$

$S_1 = 0.694$

$N = 17$

Fig. 15. Clast fabric data from the diamicton in site LoR 6. Clast long axis orientations (n=17) are plotted on Schmidt equal-area lower-hemisphere projection and contoured according to Kamb with a 2σ interval. The normalized eigenvalue (S_1) and eigenvector (V_1) were evaluated according to the eigenvalue method of Mark (1973) and was processed in STEREONET for Windows©. The N-value signifies the number of measured clasts. The V_1-value was adjusted due to the magnetic declination of 16°E for the area. The arrow marks the estimated stress direction.

Interpretation. – The limited access to the greyish yellow sand (Unit 1) obstructs any attempt to interpret the depositional environment of this unit, although its position in the local stratigraphic scheme suggests it is the oldest encountered along Logata River. The rounded, close to streamlined forms of some of the sand intraclasts suggest deformation of these due to difference in rheological strength between these and the matrix of the enclosing diamicton (cf. Benn & Evans 2010). Due to their distinct forms the sand intraclasts in Unit 2 are interpreted as tectonic boudins. The thinner and longer sand intrabeds, giving the diamicton a stratified appearance, are not interpreted as primarily deposited, but also these formed due to shearing of sand inclusions into a tectonic lamination. Thus the sand boudins and the sand intrabeds are probably due to cannibalization of the underlying Unit 1. The source of the finely laminated clay clasts in the Unit 2 diamicton is not known. The contact to and the interaction with the underlying Unit 1 suggest a subglacial origin of the diamicton and it is interpreted as a subglacial traction till in the definition of Evans et al. (2006) and Benn & Evans (2010). The clast fabric analysis suggests an ice flow direction during its emplacement from northeast.

3.3.11 Summary of sediment descriptions and interpretations

Unit 1: The lowermost Unit 1 sand is present at sites LoR 5 and LoR 6. It is the oldest sedimentary unit in the local stratigraphic scheme. Due to the poor exposure it is hard to determine a depositional environment for the sand. Two samples for OSL dating were retrieved from the unit, the results still pending.

Unit 2: Unit 2 is a matrix-supported silty clayey diamicton well exposed at site LoR 6, and indicated to be present at sites LoR 5 and LoR 3. The diamicton is stratified in its appearance with numerous sand intrabeds. The diamicton also contains rounded intraclasts of yellowish sand, interpreted as tectonic boudins, as well as more angular, massive red brown clay and greyish black finely laminated clay intraclasts. The sandy intrabeds are probably rafted and sheared material from Unit 1 and can thus, together with the sand boudins, be regarded as be due to cannibalization of the underlying Unit 1. These overall characteristics make the unit interpreted as a subglacial traction till in the sense of Evans et al. (2006) and Benn & Evans (2010). The clast fabric suggests an ice movement from northeast during deposition of the till. Two samples were retrieved from the unit, one for OSL dating of one of the sand intraclasts and one for radiocarbon dating of a mollusc shell. Result for the former is still pending, while the radiocarbon dating gives an infinite age (>48000 ^{14}C yr BP).

Unit 3: The unit was encountered at the sites UTR 1, LoR 1, LoR 2, LoR 3b, LoR 3d, LoR 4 and LoR 5. It consists of massive and laminated beds of silt and clay with a varying abundance of marine molluscs and outsized clasts. As is discussed in the interpretation of the different sections containing the unit, it most probably represents a glaciomarine depositional environment as primarily indicated by the presence of IRD as well as the presence of colder-water molluscs.

If the laminated beds of silt and clay are not due to a higher sedimentation rate but rather a decreased salinity concentration this could hint towards episodes of fresh water influx, perhaps due to meltwater pulses from the proglacial lakes that formed in Arctic Russia and Siberia in conjunction with the different ice advances during the last glaciations (Mangerud et al. 2004). It is beyond the scope of this study to identify suitable palaeo-lakes that could have been the source of this potential fresh water influx. The meltwater influx could also be of a more direct glacial source in combination with a calmer depositional environment as is summarized by Ó Cofaigh & Dowdeswell (2001). Molluscs for ESR (6) and radiocarbon (6) dating were sampled from the unit (Table 2). The age of the ESR datings are still pending while the radiocarbon datings yield in excess of 45-48 ^{14}C kyr BP, i.e. infinite ages.

Unit 4: Unit 4 is present at the sites LoR 3a, LoR 3b, LoR 3c and LoR 5. The unit is made up of sorted sediments, mainly sand but also coarser and finer sediments. Organic detritus of a terrestrial origin is common throughout the unit. As is stated in the interpretation of the sections containing Unit 4 sediment, this unit represents a fluvial depositional environment. No transitional off-shore/shore-face sedimentation phase from the marine Unit 3 was identified, which would seem logical in a local

stratigraphic scheme. Evidence of Unit 4 being fluvial is that no marine molluscs were found and the organic detritus that is present in the unit mainly consists of peat, twigs and other terrestrial sources. Even though this might be washed in material from a faraway source, its high abundance and the lack of marine organisms still speak in favour of a fluvial environment. Also, the absence of wave-ripples further supports a fluvial interpretation (Nichols 1999). The erosive contact and lag deposit between Unit 3 and 4 at site LoR 3b suggests a major hiatus.

The grain size distribution from the majority of the sites with Unit 4 sediment advocates a quite distal fluvial environment (Nichols 1999), and the back and forth changes between different bedforms suggest a meandering river. This is in agreement with the current meandering behaviour of the Logata River as is visible in Fig. 3. Since the gradient at large controls if a river will meander or not (Nichols 1999), one might assume that if no major changes in gradient has taken place since the deposition of the sediment then the river should behave quite similar to today during emplacement of Unit 4. The grain size of the sediments favours a meandering river more than a braided one since braided rivers usually have coarser sediments than meandering rivers (Miall 1996). Also, the presence of vegetation would have an inhibiting effect on the formation of a braided river, and as mentioned previously there is terrestrial detritus present in many of the beds. This reflects a vegetation cover in the proximity of the fluvial environment. Six samples for OSL dating were retrieved from the unit, results still pending. Six radiocarbon datings are made on plant remains, five of which are of >48000 ^{14}C yr BP (i.e. infinite) and one giving an age of 48200 ^{14}C yr BP (-3000/+4000). The latter should likely be regarded as of an infinite age as well.

Unit 5: The unit is present at all the LoR 3 sites, forming the uppermost unit in the river sections. It consists of ice complex deposits mostly made up of sorted sediments of silt and sand, rich in organic material, with an abundance of ice and peat inclusions. Extinct mega fauna remains were abundant along the riverside of the LoR 3 sites, most likely deriving from Unit 5. A skeleton of steppe bison (*Bison priscus*) was encountered in an *in situ* position frozen into the sediments at site LoR 3d. No datings of the sediments or fossils of Unit 5 are yet performed.

4   Discussion

4.1   A reconstruction of environmental change over time

The stratigraphic framework erected for the exposed sediments along the Logata River suggests a glaciation-deglaciation sedimentation sequence and environmental change. A major ice advance over older sediments of unknown origin (Unit 1) is indicated

from the Unit 2 diamicton. This ice expansion seems to have been from northeast towards southwest and deposited the till (Unit 2) that is exposed at LoR 6. This ice advance might have created the UT IMZ, as well as the ridge complex to the south around site UTR 1. If this is correct then the UT IMZ is likely younger than the other ridge complex and displays a recessional stage of the glaciation. It is not possible to judge if the southern ridge complex marks the maximum extension of this glacial advance, or if it terminated further south along some of the other mapped ice-marginal zones (Fig. 1). The ice sheet subsequently retreated, leaving a land isostatically depressed; consequently the area was inundated by the sea at ice-margin recession, creating an off-shore marine environment into which Unit 3 silts and clays were deposited, primarily from suspension settling. The proximity to the retreating ice margin is indicated from varying frequencies and fluxes of IRD, deposited into the finer sediments. Storm events and sediment-loaded meltwater from the ice margin might also have caused periodic influxes of coarser material.

At continued ice margin retreat, the isostatic adjustment should have caused the off-shore environment to move towards a shore-face and foreshore depositional setting. However, the studied sections do not give a clear sedimentary record of such a gradual uplift sequence other than a significant IRD decrease in the uppermost levels of Unit 3 and possibly a more fresh-water dominated environment, as indicated from the laminated and close to mollusc-free clay underlying Unit 4 at LoR 3b. Thus, exactly how progressive this environmental change was is difficult to determine, since the only contact found between Unit 3 and 4 (at LoR 3b) is erosive, where clast-supported coarse sediment drape this contact and represents a hiatus in the stratigraphy between the off-shore marine environment and the fluvial environment of Unit 4. The only sign of a shore regression is the presence of beach gravels on top of the ridges at UTR 1.

The marine environment was eventually substituted by a fluvial depositional environment and deposition of Unit 4 sediments. The presence of terrestrial organic detritus in the sediments reflects a vegetation cover in the proximity of the fluvial environment of the meandering river. This would suggest that enough time has passed for primary succession to form a suitable soil cover for vegetation in the area.

With time the fluvial environment changed into a subaerial one in which the ice complex started to form. According to Schirrmeister et al. (2011) the formation of ice complexes in Siberia was favoured by long-term stable conditions of a cold climate in conjunction with the absence of large ice sheets and glaciers in the proximity of the area. Also, Schirrmeister et al. (2011) summarize that field data from East Siberia shows that the ice complexes in those areas formed between the Early and Late

Weichselian. The stratigraphic successions along Logata River and the infinite ages received from organic remains within Units 3 and 4 show that this area, situated south of the Byrranga Mountains, was not covered by an ice sheet during the LGM, but so far do not exclude ice coverage during the Middle Weichselian (MIS 4).

4.2 Correlation with present glaciation models

The ice sheet that deposited the till (Unit 2) at site LoR 6 probably originated from the Kara Sea and crossed over the Byrranga Mountains on its way further south. With the present paradigm concerning the glaciation history of the Taymyr Peninsula (cf. Svendsen et al. 2004), and the infinite ages of the radiocarbon datings, there are two primary candidates for what glaciation event that deposited the till; the Late Saalian (160-130 kyr BP) and the Early Weichselian glaciation (100-80 kyr BP). One might hypothesize that the till is due to a local glaciation from the Byrranga Mountains. This does not seem likely when consulting the glacial reconstruction model by the QUEEN members (Fig. 2). Also, Hjort et al. (2004) and Möller et al. (2011) summarize that there are no findings that support a local glaciation of the Byrranga Mountains during the Weichselian. Also, based on the glacial stratigraphy and dating, Hjort et al. (2004) and Möller et al. (2011) conclude that a Middle Weichselian Kara Sea ice sheet advance did not make it over the Byrranga Mountains, but terminated at the North Taymyr Ice-Marginal Zone (NTZ 1-2, Fig. 1)

If the assumed time frames are correct this would give Unit 2 either a Saalian or an Early Weichselian age. Unit 3 and Unit 4 would thus correlate either to the Late Saalian and its transition into the Eemian, or the Early Weichselian. If Unit 2 should be of a Late Saalian/Eemian age, then the Early Weichselian glaciation visible in Fig. 2B must have had a basal regime that allowed the preservation of the older deposited sediment, like abundant permafrost and/or a cold-based glacier. As mentioned earlier, this is in agreement with the description of Astakhov (2013), mentioning of the lack of those many landforms that should be common as a result of a warm-based thermal regime of an ice sheet. If this alternative is correct, then the Early Weichselian glaciation and the subsequent deglaciation over the area must either have left very few traces or have been extensively eroded away. A strong indication that the marine sediments of Unit 3 are not from a Saalian/Eemian transition is the total absence of a boreal mollusc assemblage, taken as typical for marking Eemian/Kazantsevo strata (=Karginsky in the chronostratigraphic nomenclature of Astakhov (2013)).

Another, and more probable scenario – as hopefully will be verified when OSL and ESR ages come from Unit 3 strata – is that the maximum extent (termination) of the Early Weichselian glaciation is situated at the J-S-B line (Fig. 1) (cf. Svendsen et al. 2004), or at the J-S-K line (cf. Möller et al. 2011). Then the two ridge complexes on either side of the Logata River (UTR 1 versus LoR sites) should be due to halts or re-advances during an Early Weichselian glaciation. It would be quite natural to link the Unit 2 till to these ridge complexes, making an Early Weichselian origin a very plausible scenario. Developing this scenario further, Unit 3 could be linked to the marine inundation described by Möller et al. (1999) for the Early Weichselian. Their field work supports a marine inundation of Central Taymyr south of the Byrranga Mountains following the Early Weichselian glaciation, creating a marine basin with water depths as high as 100 m above present sea level. As is evident from the logged sediment successions (Fig. 5), all glaciomarine sediments are positioned below such an elevation. Their findings also support a substantial input of meltwater from the north into the marine basin during this part of the Weichselian, possibly explaining the laminated beds in Unit 3. This is however just speculations since neither the OSL nor the ESR datings are yet available. Nevertheless, the sediments in the sections show a picture of a landscape that still bears the signs of at least one glacial-interglacial cycle.

5 Conclusions

- A number of sites were investigated along the Logata River, south of the Byrranga Mountains, and its adjacent areas. The mapped sediments are correlated and placed in a local stratigraphic scheme, divided into five main sedimentary units.
- A number of samples were retrieved from the units for ESR, OSL and radiocarbon dating. All radiocarbon datings give infinite ages, while the results from the other samples are still pending.
- Unit 1 is the lowermost unit in the local stratigraphic scheme. It consists of greyish yellow sand with gravel horizons of shale. The poor exposure of the unit makes it hard to determine a depositional environment for the sand.
- Unit 2 is a matrix-supported silty clayey diamicton. Intraclasts of sand and clay are common as well as intrabedded sand beds, giving the unit a stratified appearance. Sand intraclasts are interpreted as glaciotectonic boudins. The unit as a whole is interpreted as a subglacial traction till, emplaced from NE as indicated from a clast fabric analysis. If linked to the glacial history proposed by Svendsen et al. (2004) this unit would be of a Late Saalian (160-130 kyr BP) or an Early Weichselian (100-80 kyr BP) age

and deposited by a Kara Sea emanating ice sheet (KSIS).

- Unit 3 consists mainly of sorted sediments of silt and clay in massive or laminated beds with a varying abundance of outsized clasts and marine molluscs. Unit 3 represents an off-shore glaciomarine depositional environment as is evident by the presence of IRD and marine molluscs. The time frame for deposition of the unit could either be the Saalian/Eemian transition or, more probably, in the Early Weichselian. The latter scenario is suggested by the absence of boreal molluscs. Later OSL and ESR datings will confirm which scenario is correct.

- Unit 4 consists of sorted sediments, primarily of sand with the presence of both coarser and finer sediments. Organic material is common throughout the unit. The unit is interpreted to represent a fluvial depositional environment, more specifically that of a meandering river. In the context of the glaciation history of the Taymyr Peninsula this unit most likely has an Early/Middle Weichselian origin.

- Unit 5 is the uppermost unit and consists of so called ice complex deposits. The unit is mostly made up of sorted sediments of silt and sand, rich in organic material, and with an abundance of ice and peat inclusions. Extinct mega fauna remains are present in the unit as well. The unit is correlated to the Cape Sabler-type deposits around Lake Taymyr, where it usually give ages between 40-10 kyr BP (Jørgensen et al. 2012).

- The local stratigraphic scheme supports a glaciation-deglaciation cycle with an isostatically driven regression; the most probable timing of this is the Early Weichselian as summarized for central and northern Taymyr in Möller et al. (2011).

6   Acknowledgements

7   References

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8 Appendix 1

**Legend of Heights
in m (AMSL)**

Compiled from Aster DEM

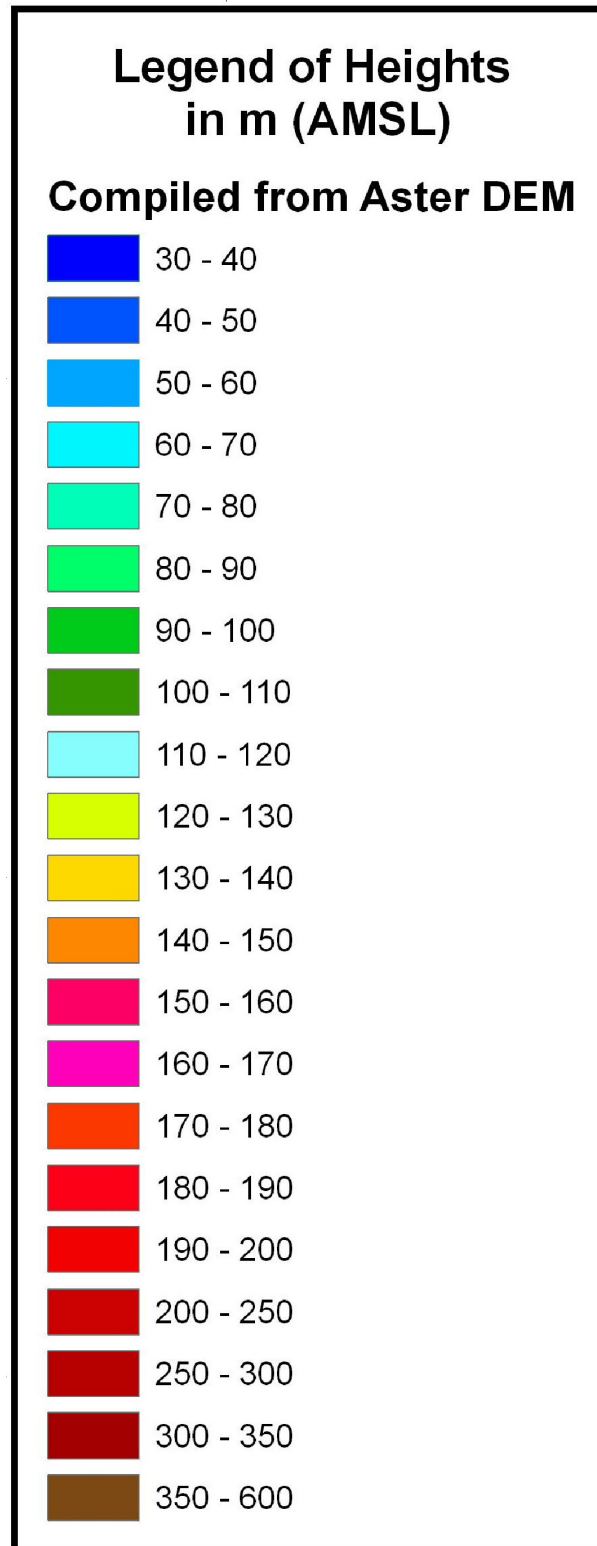|	
▮	30 - 40
▮	40 - 50
▮	50 - 60
▮	60 - 70
▮	70 - 80
▮	80 - 90
▮	90 - 100
▮	100 - 110
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▮	140 - 150
▮	150 - 160
▮	160 - 170
▮	170 - 180
▮	180 - 190
▮	190 - 200
▮	200 - 250
▮	250 - 300
▮	300 - 350
▮	350 - 600

Fig. A1. Detailed legend (colour coding) of the elevation as shown in the DEMs of Figs. 3A and 3B.

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