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Weichselian glaciation of the Taymyr Peninsula, Siberia

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During recent years there has been a re-assessment of the glacial history of the Russian Arctic, from the Kola Peninsula in the west to the Lena Delta and beyond in the east (e.g. Svendsen *et al.* 1999). In this context work has been carried out on the northwestern and central parts of the Taymyr Peninsula (Figs 1 and 2). The present contribution is a summary of these results regarding the glacial and marine history of Taymyr, in chronological order, and with reference to previous Russian work. It should be noted that it does not cover the Putorana Plateau at the southern base of the peninsula.

The pre-Weichselian glacial and marine history

The maximum glaciation of the Taymyr Peninsula, i.e. when this whole northern region was covered by ice, probably took place during the Saalian Stage that ended at *c.* 125 ka BP. The deep isostatic depression of the land caused by the thick ice load led to widespread post-glacial marine inundation, sediments of which were deposited over large parts of Taymyr. Boreal molluscs in these marine sediments dating from the following Eemian (Kazantsevo) interglacial Stage indicate sea temperatures much warmer than present (*e.g.* Kind & Leonov 1982).

The Early Weichselian – the Weichselian glaciation maximum on Taymyr

The glacial geomorphology and drainage systems, the direction of glaciotectonic deformations and the provenance of crystalline erratic boulders indicate that the glaciations that affected the north-western and central Taymyr during the Weichselian were mainly caused by ice-sheet advance from the Kara Sea shelf. At one occasion the ice reached across the Byrranga Mountains and up to 250 km into the lowlands beyond. According to both the Russian literature (Andreyeva, 1978; Kind & Leonov 1982; Andreeva & Isaeva 1982), and more recent results (Siegert *et al.* 1999), the Weichselian maximum glaciation on Taymyr reached the Urdach (Fig. 3, stage I) and Sambesin (Fig. 3, stage II) ice-marginal zones and has been tentatively assigned to the Early Weichselian (Zyryankan). However, according to Astakhov (1998), the Early Weichselian ice sheet did not reach further south than the very prominent Dzhangoda-Syntabul-North Kokora (DSK) ice marginal zone (Fig. 3, stage III). This zone was interpreted by Andreeva & Isaeva (1982) and Isayeva (1984) both as a recessional moraine from the Early Weichselian and the maximum position of a Late Weichselian (Sartan) ice-sheet advance that extended well south of the Byrrangas. Further north, another distinct lobate ice-marginal zone was identified by Isayeva (1984), termed the Mokoritto (in the Pyasina River basin) – Upper Taymyr Ridge (Fig. 3, stage IV). This ridge was believed to date from an oscillation during the recession of a Late Weichselian ice sheet. Glacigenic sediments in some of these ice-marginal zones are still underlain by glacier ice, as demonstrated by Siegert *et al.* (1999) from Labaz Lake on the distal side of the Sambesin Moraine. Partly based on this evidence, they concluded that this advance occurred after the exceptionally warm Eemian interglacial, and most likely during the Early Weichselian Substage. Remnants of supposedly Early Weichselian glacier ice are also found under a melt-out till and soil cover in some Byrranga Mountain valleys. The presence of this ice is also indicated by distinct thermokarst landscapes just north of the mountains, clearly visible on satellite images.

Deglaciation from the Early Weichselian maximal position to the Byrranga Mountains

The ice recession from the Early Weichselian maximal position towards the Byrranga Mountains took place in a marine basin because glacio-isostatic depression of the land had allowed a marine inundation of the deglaciated area. This is clearly demonstrated from several localities where marine sediments occur in the Taymyr Lake basin (Fig. 3). Six of these sites have been investigated sedimentologically and a dating programme using both mollusc shells and sediments from the sections (26 ESR and 5 OSL dates) has yielded consistent ages of 95-70 ka BP. Radiocarbon dates from mollusc shells from the same localities have all given infinite ages. Delta sediments were eroded and buried by beach sediments, which occur at heights up to *c.* 100 m a.s.l. The most prominent of these delta sediments occur in the Ledyanaya River valley (Fig. 3, locality 5), the type locality for the 'Ledyanaya Gravel Event' (Möller *et al.* 1999a, b). Here, the topset beds reach 100-120 m a.s.l. and the marine basin into which the deltas prograded probably reached 90-100 m a.s.l. This high post-glacial marine limit, together with the huge accumulations of coarse sediments within the deltas, confirm the substantial glacio-isostatic depression and indicates a large flow of sediment-laden glacial meltwater southwards through the Byrranga moun-

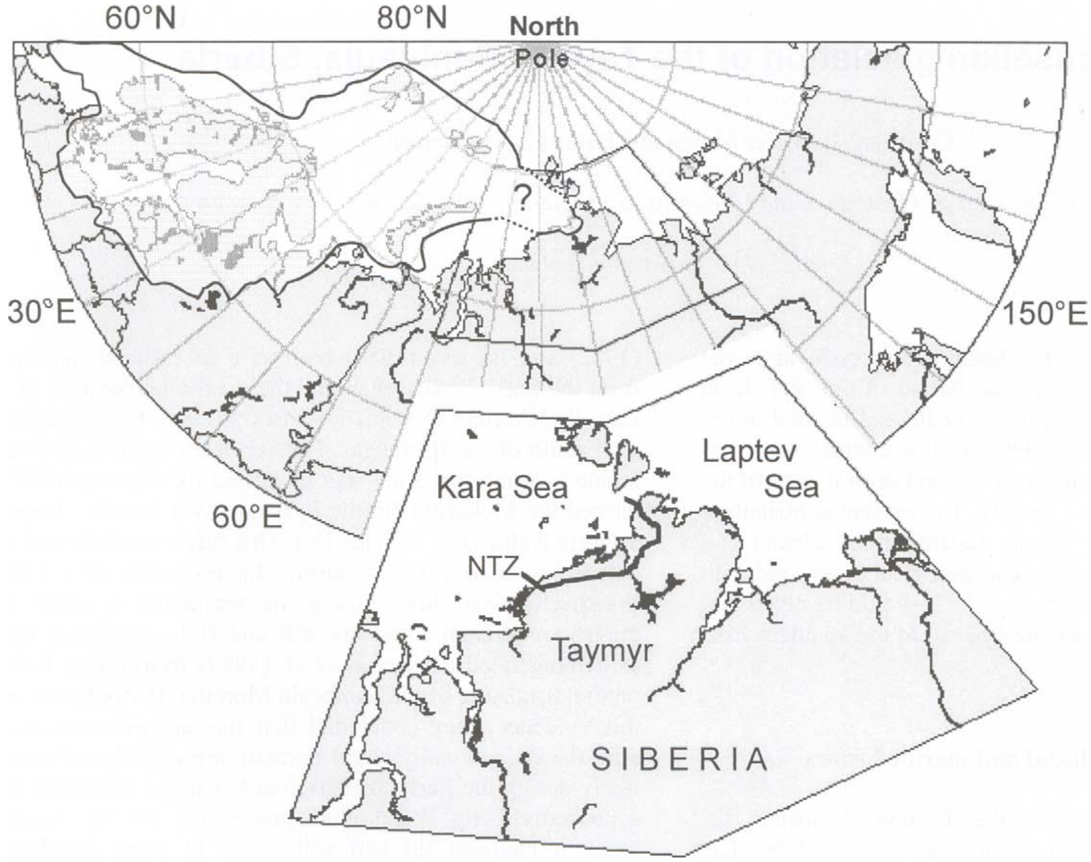

Fig. 1. Map of northern Eurasia and the Taymyr Peninsula (inset), showing the North Taymyr ice-marginal zone (NTZ), and the extent of the LGM glaciation based on the synthesis by Svendsen et al. (1999).

tain valleys and into the marine basin. This meltwater must have emanated from an ice front, which at that time stood along the northern slopes of the mountains (Fig. 3).

This marine event is probably the equivalent of the Karginsk Marine Transgression of Andreeva & Kind (1982), in its earliest phase radiocarbon-dated to 50-39 ka BP. However, these ^{14}C dates, from mollusc shells, were conventional and may well prove to be infinite if the AMS technique is used.

The marine basin, shown in Fig. 3, is a palaeogeographical reconstruction of the situation during the time of the 'Ledyanaya Gravel Event', constructed using shorelines of 100 m a.s.l. along the Byrranga Mountains (the authors' data) and 50 m at Khatanga Bay (Andreeva *et al.* 1982). The inundated areas to the south in this reconstruction are somewhat smaller than might be expected from the known distribution of subaquatic deglaciation sediments (*e.g.* Andreeva & Isaeva 1982; Siegert *et al.* 1999). This is because a substantial part of the regression must have already taken place when the ice front had retreated to the Byrrangas.

There are no signs of any glaciation reaching south of the Byrranga Mountains since this Early Weichselian deglaciation (*e.g.* Möller *et al.* 1999a). These mountains and the Taymyr Lake basin have thus been continuously ice free ever since, as illustrated by the sediment sequence (lacustrine/bog/aeolian sediments) at Cape Sabler, where the base has been radiocarbon-dated to >40 ka BP and continuous deposition to the Holocene is present (Kind & Leonov 1982; Pavlidis *et al.* 1997; Derevyagin *et al.* 1999; Möller *et al.* 1999a). Lake sediment successions from both the Taymyr Lake itself and from the adjacent Levinson-Lessing Lake (Ebel *et al.* 1999; Hahne & Melles 1999; Niessen *et al.* 1999) also indicate ice-free conditions since at least the Middle Weichselian.

Deglaciation of the Chelyuskin Peninsula

The Early Weichselian Kara Sea ice sheet also inundated the Chelyuskin Peninsula on northernmost Taymyr, where it flowed eastwards over the 350 m high Astrup- and Sverdrup Mountains. This conclusion is based on till and glaciotectonic deformations overlying and affecting Eemian interglacial marine sediments, and from the occurrence of Kara Sea crystalline erratics found on the hilltops (Möller *et al.* unpublished). In addition, the glacio-isostatic depression in this area resulted in post-glacial marine inundation, ESR dated to *c.* 95-80 ka BP and thus largely contemporaneous with that in the Taymyr Lake basin. The marine limit from this time lies between 65-80 m on Chelyuskin. Both the Eemian and Early Weichselian marine sediments here con-

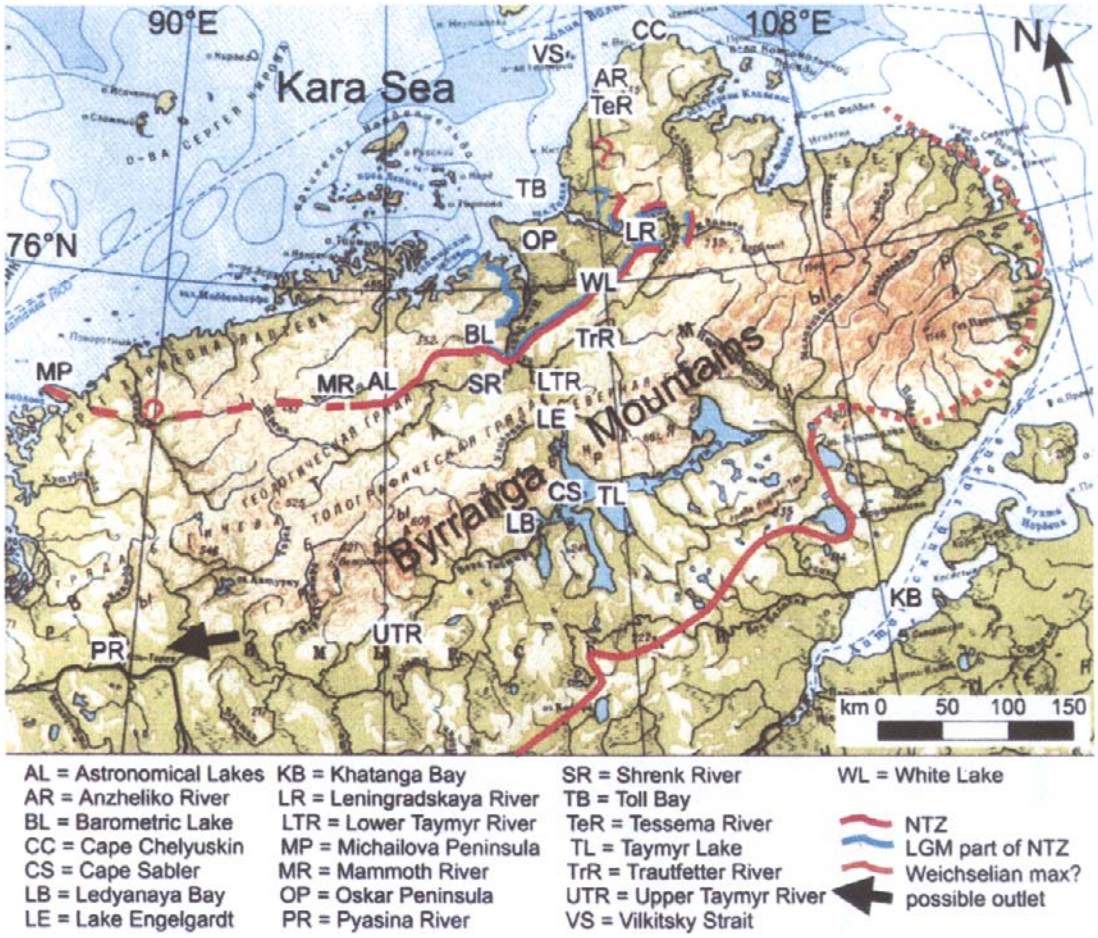

Fig. 2. The northern Taymyr Peninsula with geographical names mentioned in the text, together with the current authors' proposed outlines of the North Taymyr ice-marginal zone (NTZ) and the main ice-front position at the time of the Weichselian glaciation maximum. The Astrup- and Sverdrup mountains lie east of the Angelika River on the Chelyuskin Peninsula. The base map is 'Россия и сопредельные государства' Geodetic and Cartographic Federal Office of Russia, Moscow 1996, original scale 1:4,000,000.

tain shells of *Chlamys islandica,* which indicates considerably warmer water temperatures during the earlier parts of the Weichselian than later or even today.

The North Taymyr ice-marginal zone

The northwestwards retreat of the Early Weichselian ice front from the Byrranga Mountains seems to have proceeded largely by calving into a glacial lake filling the Shrenk-, Trautfetter- and part of the lower Taymyr river valleys and dammed towards the northwest by the ice itself. A new grounding line was reached on the northwestern sides of the Shrenk- and Trautfetter valleys, causing a temporary stillstand of the ice front which resulted in the formation of the North Taymyr ice-marginal zone, the NTZ (Figs. 2 and 4).

The NTZ is a complex of glacial, glaciofluvial and glaciolacustrine deposits, containing large amounts of re-deposited Quaternary marine sediments and also glacially-displaced, coal-bearing Cretaceous sands. It has now been dated for the first time and described in some detail by Alexanderson *et al.* (2001, 2002), but had already been broadly mapped and discussed by Kind & Leonov (1982). When the Kara Sea ice-sheet front stood at this ice-marginal zone it seems to have crossed the present coastline at the Michailova Peninsula at *c.* 75°N. The NTZ can then be followed first eastwards and then northwards for 700-750 km, mostly 80-100 km inland, and seems to re-cross the present coastline south of the Tessema River, around 77°N. It is best developed in its central parts, *c.* 100 km northeast and southwest, respectively, of where it is today cut through by the Taymyr River. The base of the NTZ (Alexanderson *et al.* 2001, 2002) is a series of ridges up to 100 m high and 2 km wide, mainly consisting of, or possibly only covered by, re-deposited marine silts. They are still ice-cored, but in most parts of the zone the present active layer only rarely reaches the ice-surface. Smaller ridges of both till and glaciofluvial material are superimposed onto the main ridges. They often surround lakes that originated as minor over-deepened glacial basins. Associated with the NTZ are deltas, abrasion terraces and shorelines corresponding to two generations of ice-dammed lakes, with shore-levels at between 140-120 m and at *c.* 80 m a.s.l. (Fig. 5). These lakes drained southwards into the Taymyr Lake basin, as recorded by current directions in fluvial sediment sequences along the Taymyr River valley

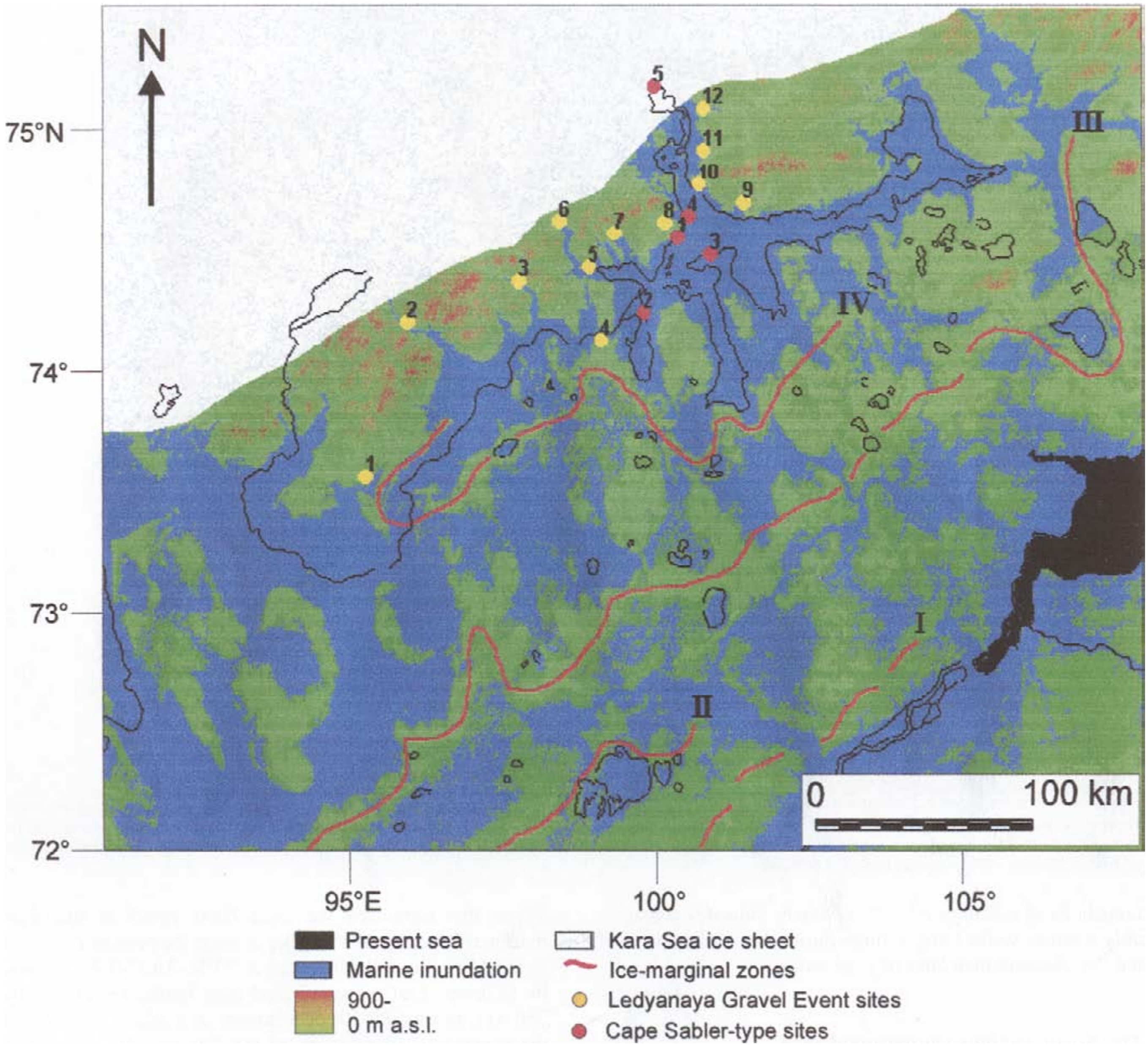

Fig. 3. Palaeogeographical reconstruction of the Taymyr Lake basin and the North-Siberian Lowland to the Khatanga Bay and Khatanga River, immediately following the Early Weichselian deglaciation of the area. The extent of the marine inundation is calculated using a GLOBE digital elevation model (GLOBE Task Team and others 1999; Hastings & Dunbar 1999) with a northern shoreline set at 100 m a.s.l. (the authors' data) and a southern shoreline at Khatanga Bay at c.50 m a.s.l. (Andreeva et al. 1982). The red lines I-IV indicate ice-marginal complexes, according to various authors in Kind & Leonov (1982). The yellow dots numbered 1-12 are localities with marine deltaic deposits from the Early Weichselian 'Ledyanaya Gravel Event', studied by the authors, with locality (5) Ledyanaya River, being the type locality. The red dots numbered 1-5 are localities with 'Cape Sabler-type' sediments, deposited between 40-10 ka BP. Locality (1) Cape Sabler, is the type locality.

where it passes through the Byrranga Mountains (today the river flows northwards). From the Taymyr Lake basin, the water continued either westwards to the south-eastern Kara Sea shelf (present watershed at *c.* 25 m) or eastwards to the Khatanga Bay and the Laptev Sea (present watershed *c.* 60 m). These courses depend on whether the Kara Sea shelf, and thus the continuation of the western outlet, was totally or only partially blocked by the ice sheet.

The Early Weichselian NTZ stage

The NTZ has three generations (Alexanderson *et al.*, 2001, 2002). The oldest is that formed as the ice front, largely through calving into its frontally dammed lake, had retreated northwestwards from its Byrranga still-stand position to the new grounding line. This stage is associated with the deepest glacial lake, reaching 140-120 m a.s.l. Two

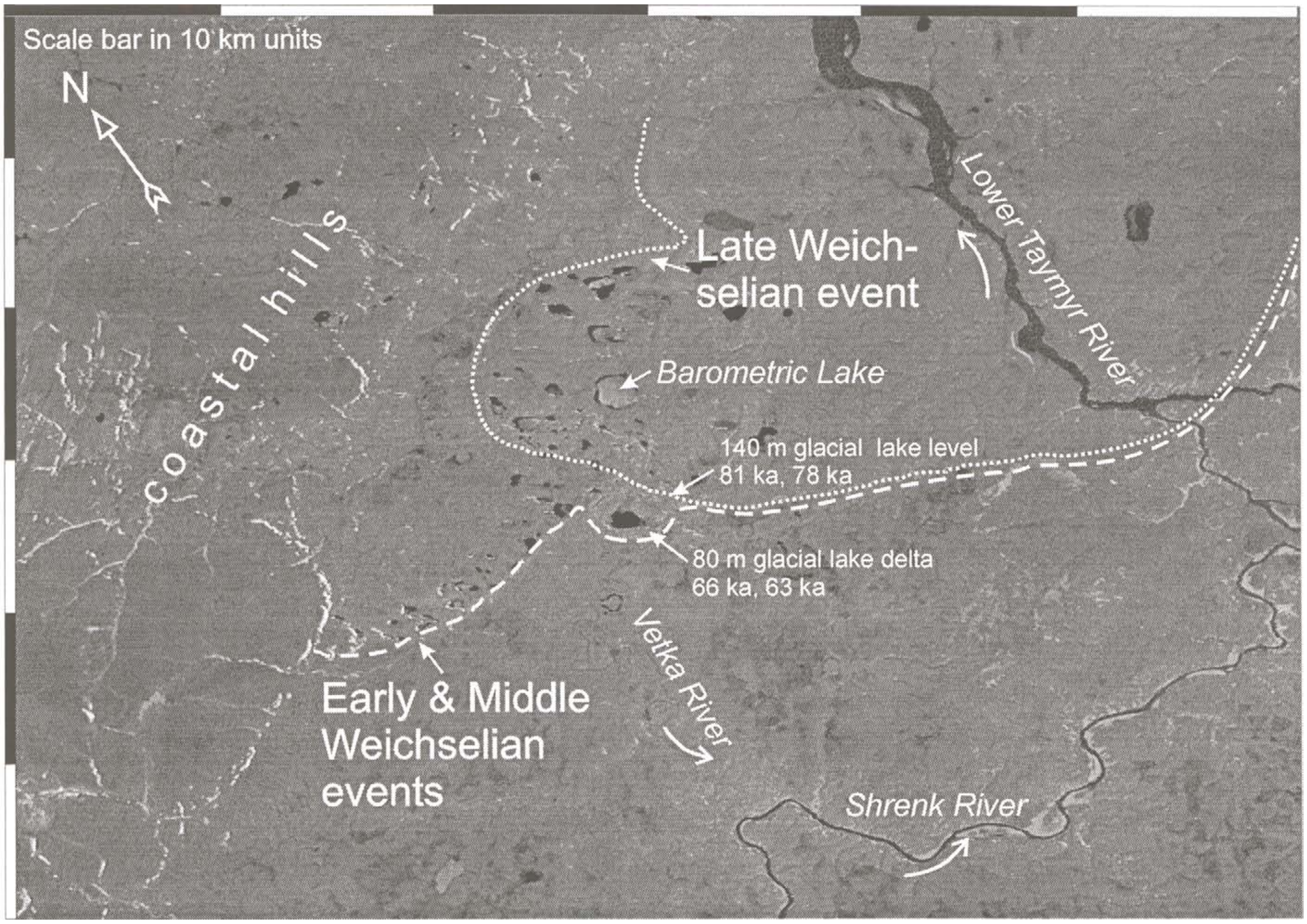

Fig. 4. Landsat image (no. 153/006, August 8th 1982) of the North Taymyr ice-marginal zone (NTZ) in the Barometric Lake area. Its outer (southern) limit is hatched. From the bedrock escarpment in the coastal hills, the oldest terminal moraine (hatched line; Early-Middle Weichselian events) stretches eastwards. In its central part it was also affected by the youngest ice-movement (Late Weichselian, LGM, dotted line). The smooth semi-circular western limit of the LGM ice-lobe indicates that this last glaciation advanced over deglaciated ground behind the older moraine and thus indicates a certain age difference between the two stages (>30 ka according to the dates presented herein). The younger glaciated area, inside the dotted line, where many slides expose buried glacier ice, looks much 'fresher' than the older areas. A dendritic erosional pattern inside the LGM lobe (visible in the upper right corner) is characteristic of extensive silty re-deposited marine sediments. The smoother surface outside (south of) the ice-marginal zone results from a cover of partly rhythmitic glaciolacustrine silts.

OSL dates from an ice-contact glaciofluvial sequence aggradated to the 140 m level gave ages of *c.* 80 ka BP, which combined with the ESR ages obtained for the 'Ledyanaya Gravel Event' indicate its relationship with the deglaciation process north-westwards from the Early Weichselian maximum stand south of the Byrrangas and the Taymyr Lake basin.

The Middle Weichselian NTZ stage

During the second NTZ generation, the ice front seems to have stood more or less at the same positions as during the older stage. This caused an overprinting on the previous morphology of a number of over-deepened lake basins and a new system of marginal moraine ridges, associated glacial-lake deltas and shorelines, valley fills, etc. The glacial lake was, however, shallower than the previous waterbody and reached only 80 m a.s.l. This lake has been OSL-dated at two localities. Two delta samples from one site in the Barometric Lake area gave it an age of *c.* 65 ka BP, and two dates from fluvial terrace deposits along the Mammoth River, connecting the ice front with the lake basin, gave *c.* 70-55 ka BP. This stage of glacial-lake sedimentation is further supported by three OSL dates of 60-55 ka BP, from glaciolacustrine rhythmites in the Taymyr Lake basin, just south of the Byrranga Mountains. As shown in Fig. 5, glacial damming in the north led also to a rising water level in the Taymyr Lake basin. The available dates thus indicate that an interval at least 10,000 years long occurred between the two oldest NTZ events.

Thick glaciolacustrine deposits are also found along the Kara Sea coast, from the Taymyr River mouth to north of the Leningradskaya River (the Tollia Bay glaciolacustrine

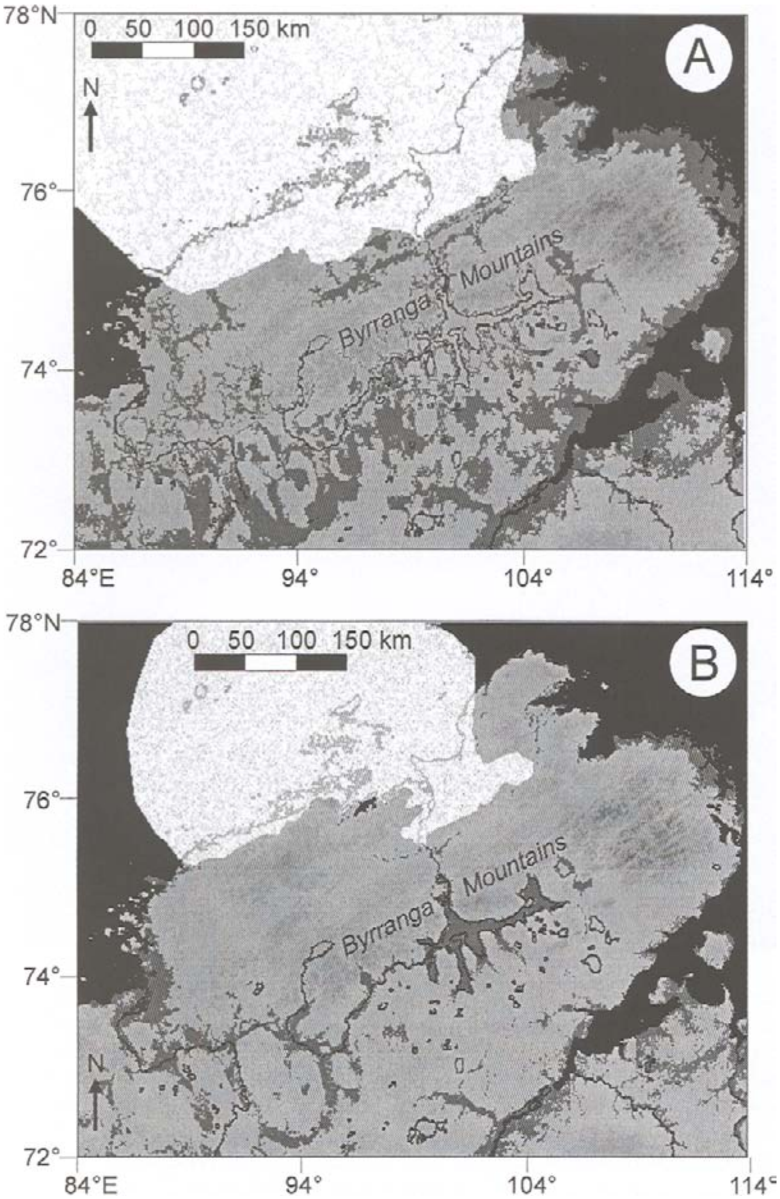

*Fig. 5. Drainage patterns and the possible extent of glacial lakes dammed by **(A)** Early-Middle Weichselian and **(B)** Late Weichselian ice sheets on the northwestern Taymyr Peninsula. The reconstructions are based on geological evidence for former lake levels and the GLOBE digital elevation model (GLOBE Task Team and others 1999). For the older lake stages, defined by shore-line data from north of the Byrranga Mountains, an approximate southward shoreline gradient of 0.25 m/km has been used. The level of the LGM lake has been estimated at 25 m a.s.l. (the present level of the watershed west of the Taymyr Lake basin), without any gradient since at that time the isostatic depression was probably very minor. The lakes extended via the present Taymyr River valley (Fig. 2 for geographical names), through the Byrrangas into the Taymyr Lake basin. From there the outlet was probably westwards, across the modern c. 25 m a.s.l. watershed to the Pyasina River and onwards to the southeastern Kara Sea shelf. Alternatively, it flowed south-eastwards into the Khatanga River basin and the Laptev Sea, but there the present watershed lies at c. 60-70 m a.s.l. Lack of field evidence from the tentative drainage-ways from the Taymyr Lake basin, and on isostatic gradients south of the Byrranga Mountains, still prevent a definite conclusion regarding the route the water actually took.*

Fig. 6. Remnant Late Weichselian (LGM) glacier ice under a melt-out till cover of only c. 0.5 m., near White Lake. Photograph by C. Hjort.

sediments'; Funder *et al.* 1999). They indicate damming between the present land and an ice front receding onto the Kara Sea shelf, after retreating from the NTZ. The OSL dates of *c.* 70 - 80 ka BP obtained seem to relate much of this sedimentation to the deglaciation after the Early Weichselian NTZ event (Funder *et al.* unpublished).

The Late Weichselian NTZ stage

During the third NTZ generation the Kara Sea ice sheet was much thinner than previously and inundated a much smaller area (Alexanderson *et al.*, 2001, 2002). Because it did not cross a 300-500 m high range of coastal hills (e.g. Fig. 4), which were overridden during the two previous stages, its thickness near the present coastline could not have been more than 500 m. Nonetheless, it penetrated 100 km inland, on a 150 km broad front centred along the lower Taymyr River valley and terminated at altitudes below 150 m a.s.l. Northeast of the valley the front abutted a system of bedrock cuestas, whilst to the southwest it was in contact with the pre-existing NTZ moraine and, in one case, formed an independent lobate moraine (Fig. 4). The area overridden by this ice sheet, the most recent to inundate the Taymyr Peninsula, is to a large extent covered by dislocated marine sediments, identifiable on satellite images by their dendritic erosional pattern. In a 5-10 km wide zone behind the former ice front, where the ice contained most debris, the landscape is patterned by a multitude of shallow slides, exposing remnant glacier ice under a melt-out till cover of only about 0.5 m. (Fig. 6). Further northwest (up-ice), there are fewer indications of the former overriding, probably the consequence of a cleaner and more rapidly melting ice. However, a boulder-lag on top of the glaciolacustrine sediments at the Kara Sea coast (Funder *et al.* 1999) may date from this glacial event.

This youngest ice sheet advance is pre-dated by two radiocarbon dates of mollusc shells *(Hiatella arctica, Astarte sp.)* of *c.* 20 ka BP, from glacially re-deposited marine silt sampled *c.* 2 km behind the former ice front position near White Lake (Alexanderson *et al.*, 2001, 2002). It is post-dated by a radiocarbon date of *c.* 12 ka BP from *in situ* terrestrial material from just inside the present coast on Oskar Peninsula (Bolshiyanov *et al.* 2000), and possibly also by organic material retrieved from the sea bottom off the coast in the Toll Bay. Here a radiocarbon date (a conventional bulk sample) has given *c.* 16 ka BP (Bolshiyanov *et al.* 1998). The glaciation thus dates from the Weichselian Last Glacial Maximum (LGM). This brief advance (8000 years or less) of a thin ice sheet onto the present land may have been of surge character, utilizing an easily deformable substratum. It is not yet clear whether it emanated from the growth of a regional ice cap on the very shallow, and for global eustatic reasons at that time, mostly dry shelf in the northeastern corner of the Kara Sea, or if it was connected to the west to ice centred near Novaya Zemlya.

No evidence of any glacial lake dammed by this LGM ice sheet have been found north of the Byrrangas and it is therefore thought that meltwater from this thin ice sheet mainly drained southwards via the Taymyr River valley into the Taymyr Lake basin (Fig. 5B, and Alexanderson *et al.*, 2001, 2002). Indications of an increasing sedimentation rate in the lake around 19 ka BP (Möller *et al.* 1999a, Möller *et al.* unpublished) suggest a causal connection with the meltwater input.

No raised marine shorelines dated to the LGM or thereafter have been found on Taymyr which is not surprising considering the thin, short-lived and thus isostatically insignificant ice and the extremely low eustatic sea level at the time, persisting into the Holocene.

Summary of results

The main results of this study of the glacial and marine history of the Taymyr Peninsula, summarized in Fig. 7, are as follows:

Three main phases of Weichselian glaciation of successively decreasing amplitude have been mapped (Figs. 2, 3 and 5) and dated. The most extensive glaciation dates from the Early Weichselian (culminating ≥100 ka BP), and a Middle Weichselian event of intermediate extent dates from *c.* 65 ka. The last and least extensive glaciation, contemporaneous with the Last Glacial Maximum (LGM), was short, lasted only 8000 years or less, culminated between 18 - 16 ka BP, and had largely disappeared from present onshore areas by 12 ka BP.

The ice sheets that covered the Taymyr Peninsula on all three occasions during the Weichselian emanated from the Kara Sea continental shelf, from which they advanced generally southeastwards across the land. At most, the ice-front reached some 400 km from the coast, leaving a series of more or less distinct zones of ice-marginal features south of the Taymyr Lake basin. In the south and east the ice-front reached the Laptev Sea drainage basin. No sign of any local Weichselian glaciation has been encountered and the only recorded glaciation that affected most of the Byrranga Mountains has been that of overriding Kara Sea ice. However, the higher easternmost part of the Byrrangas, not studied by the authors, may at times have acted as a local centre of glaciation. Today it still supports some minor cirque glaciers.

The Kara Sea ice sheets dammed large glacial lakes, filling the lake- and river basins both north and south of the Byrranga Mountains (Fig. 5) and, during the final stages of the different deglaciations, also lowland areas along the coast. The water from north of the mountains drained southwards along the Taymyr River valley (where today the water flows northwards) into the Taymyr Lake basin, and in most cases thereafter probably westwards to the Kara Sea shelf.

The glacio-isostatic depression of the Earth's crust, arising from the ice-load, led to substantial marine submergence of present land areas on Taymyr. Most

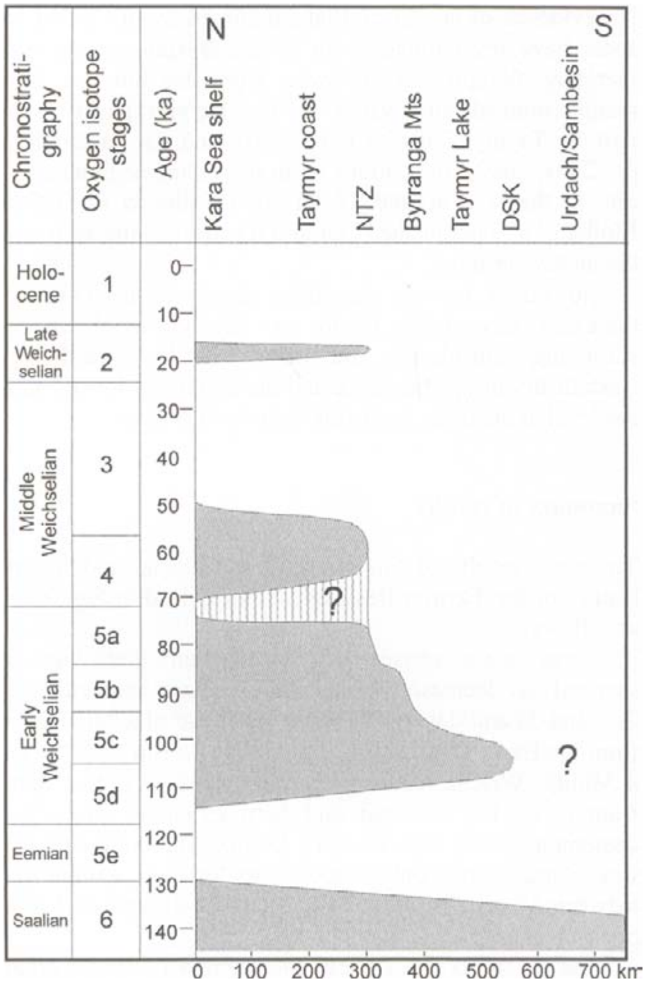

Fig. 7. Glaciation curve for the Taymyr Peninsula. The ice sheets, which originated on the Kara Sea shelf, advanced onto the peninsula from the N-NW. During the Saalian, the whole of Taymyr seems to have been ice-covered. The three Weichselian glaciations were of progressively decreasing amplitude (cf. Figs. 3 and 5). The maximum limit of the Early Weichselian glaciation is not precisely known but it did at least reach the Dzhangoda-Syntabul-North Kokora (DSK) ice marginal zone (stage III, Fig. 3). Two Early Weichselian retreat stages are illustrated on the northern side of the Byrranga Mountains, during the time of the 'Ledyanaya Gravel Event' (Fig. 3) and at the North Taymyr ice-marginal zone (NTZ; Fig. 5:A). The Middle Weichselian ice-front at the NTZ was roughly the same as that from the Early Weichselian (Fig. 5:A), whereas the Late Weichselian (LGM) ice-cover was considerably less extensive and thinner (Fig. 5:B).

widespread was probably the so-called Boreal Transgression during the early part of the Eemian (Kazantsevo) interglacial, mainly an isostatic effect of the preceding substantial Saalian glaciation. The Early Weichselian transgression, following on what in Siberia was the Weichselian maximum glaciation, reached *c.* 100 m above the present sea level. However, the short-lived, thin, and comparatively less extensive Late Weichselian ice cap, contemporaneous with the global eustatic sea level low around 18 ka BP, did not isostatically influence the land sufficiently to create any marine shorelines elevated above the present.

The concept of a maximum ice cover during the LGM, in which ice more or less totally covered the Eurasian Arctic during the Late Weichselian, for long advocated by some researchers (e.g. Grosswald 1998) and extensively used by climate modellers (e.g. Budd *et al.* 1998), is incorrect. If ever such large ice-sheets existed, and all at the same time, they certainly pre-dated the Weichselian.

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