Middle Pleistocene glaciations of the Russian North
Valery Astakhov*
Geological Faculty, St. Petersburg University, Universitetskaya 79, St. Petersburg 199034, Russia

Abstract

Geological data on the pre-Eemian glaciations of northern Russia, including the latest results by the Russian–Norwegian PECHORA project, are synthesized in order to present evidence for comparison with other early glaciations around the Arctic. The bulk of evidence indicates that Arctic and Subarctic regions of European Russia, of western and central Siberia during the Middle Pleistocene were at least 4 times covered by large ice sheets, which advanced mainly from the shelf ice domes, partly from Fennoscandia and the Putorana Plateau. Ice accumulations in the Ural Mountains were insignificant and did not form any noticeable ice dispersal centres. Unlike the classical glaciated areas, ice sheets of northern Russia acted mainly on a soft, perennially frozen substrate, which was heavily glacitectonised. The Middle Pleistocene ice sheets were much larger than the Weichselian ones. The Fennoscandian ice dispersal centre was most active in northern European Russia during the penultimate glaciation (OIS 6) when shelf-centred ice domes were relatively weaker. Larger continental ice sheets were formed in preceding ice ages, when Kara Sea ice dispersal centre dominated. The lowland ice sheets reached their maximum extent at different stages, from Cromerian Don glaciation in European Russia to OIS 8 in West Siberia. Therefore, the maximum ice limit is time-transgressive in northern Russia.

1. Introduction

The volume and extent of Middle Pleistocene ice sheets exceeded those of the Late Pleistocene by far, especially on the eastern flank of glaciated Eurasia (e.g. Ganeshin, 1973). Accordingly, their impact on the geological structure and environments of the Arctic and Subarctic regions was more profound. However, geological research within the QUEEN framework has largely been focused on the Late Pleistocene history of the Russian North. Only a few sections of Middle Pleistocene drift have been studied by QUEEN members on the Russian mainland. Hence the bulk of data discussed below is derived from Russian literature.

Over the last half-century various attempts have been made to synthesize data on Middle Pleistocene glaciations collected by hundreds of Russian researchers. The only work in which all Quaternary of the Russian Arctic and Subarctic is discussed, is the monumental volume by Sachs (1953). Another outstanding contribution is a stratigraphic monograph with a Quaternary map of European Russia by Yakovlev (1956). In the 1960–1970s the huge influx of data, especially from geological surveys, led to graphical generalisations in the form of synthetic Quaternary maps for the entire Soviet Union (Ganeshin, 1973) and separately for each of the super-regions of northern Eurasia such as the Russian Plain, the Urals, West and Central Siberia. These maps are principal sources of hard data about the size of former ice sheets obtained by generations of mapping geologists. Lately they were used to compile the digital map of Pleistocene ice limits as part of the INQUA project (Astakhov, 2003).

After Sachs and Yakovlev numerous articles and regional monographs were dealing with the Middle Pleistocene glacial deposits of the North in terms of stratigraphy (Arkhipov and Matveyeva, 1964; Lazukov, 1970; Zubakov, 1972; Yakhimovich et al., 1973; Kaplyanskaya and Tarnogradsky, 1974; Arkhipov et al., 1986, 1994; Velichko and Shick, 2001), lithology (Kuznetsova, 1971; Zemtsov, 1973a, b; Sukhorukova et al., 1987; Andreicheva, 1992; Andreicheva et al., 1997), palaeogeography and geomorphology (Isayeva, 1963; Troitsky, 1975; Arkhipov et al., 1976). Structural geological and sedimentological works are noticeably scarcer (e.g. Zakharov, 1968; Kaplyanskaya and Tarnogradsky, 1975; Astakhov et al., 1996). Rare attempts to reconstruct dimensions and flow patterns of the ice sheets were mostly based on till lithologies (Zubakov, 1972; Sukhorukova et al., 1987) and occasionally on glaciological considerations (Voronov, 1964).
The volume of existing data makes a comprehensive overview impossible for any journal paper. Hundreds of papers discussing various aspects of the pre-Weichselian glacial history from different standpoints cannot be reviewed here. My task is limited to briefly describing the most reliable geological results in pre-Weichselian glacial geology of northern Russia beyond the realm of Fennoscandian glaciations (Fig. 1) in order to present data for comparison and to highlight weak points that might be of interest for further research. A selection of key evidence in a diverse area ca 4.5 million km², although it might seem arbitrary, is actually scale-dependent. It is dictated by the author’s mapping experience, according to which superregional conclusions are derived mostly from examination of large geological features, whereas small details of geological structure often yield only results of local significance.

The questions of immediate concern will be (i) size and flow pattern of former ice sheets, (ii) possible correlations of ice advances within the QUEEN area.

2. General geological setting

Northern Russia as an area of inland glaciation is very different from the classical glaciated regions of northwestern Europe and North America. It is largely soft-rock flatland extending offshore as sedimentary basins of the Barents and Kara seas (Fig. 1). The weak substrate is responsible for the large thickness (up to 300–400 m) and predominantly fine-grained composition of the Quaternary cover. Only in the east looms the Putorana Plateau, up to 1600 asl, a major source of hard-rock clasts, built of horizontally layered dolerites.
and lavas. Other smaller sources of erratics are narrow Palaeozoic ranges of the Ural and Byrranga Mountains and low ridges of Timan, Novaya Zemlya and Pai-Hoi (Fig. 1). The rest of the area is underlain by Mesozoic and Cenozoic sand, clay, silt, opoka, diatomite and therefore is apt to produce few visually recognisable clasts. Consequently, the traditional method of reconstructing former glaciers by mapping boulder trains would inevitably point to the Central Siberian uplands and the smaller salients of folded Palaeozoic rocks as the only sources of moving ice. The seaward sloping sedimentary basins of the Pechora, West Siberian and North Siberian lowlands have generally been viewed as an arena of marine incursions from the Arctic Ocean.

The stratigraphic methods employed and conclusions obtained are different in two natural zones: (a) the Arctic with marine and glacial formations alternating, and (b) the Subarctic, where only terrestrial stratified sediments occur sandwiched between thick diamictons. These zones, being crossed by the Uralian Range, give four stratoregions to be discussed separately: two in European Russia and two in Siberia. In all regions 3 to 5 diamict sheets up to 60 m thick each are found in borehole profiles (Arkhipov, 1971; Zubakov, 1972; Lavrushin et al., 1989). Tills of the penultimate glaciation can be locally seen in exposures of the Arctic beneath Upper Pleistocene strata, whereas diamictic glaciations can be locally seen in exposures of the Arctic (Lavrushin et al., 1989). Tills of the penultimate glaciation are known just from boreholes.

The Middle Pleistocene till sheets gradually plunge northwards and get progressively more eroded in the high Arctic, especially on the sea floor (Fig. 2). The occurrence of pre-Weichselian tills is mantle-like: they can be found both in buried valleys at 300–350 m bsl (locations 14 and 15 in Fig. 1) and on plateaus 500–600 m asl (locations 11 and 13 in Fig. 1). The thickest accretions of Middle Pleistocene sediments, up to 200–300 m, are known from the areas of rougher sub-Quaternary relief along the Urals and Central Siberian Plateau, whereas the flat Timan Ridge and central West Siberian lowlands often bear a discontinuous cover of glacial deposits less than 50 m thick. Above the Arctic Circle the Middle Pleistocene sediments are either totally eroded or fill in deep depressions. The latter are normally obscured by the Weichselian glacial complex which is often glaciectonically stacked to attain 100 m in thickness (Fig. 2). The described regional structure reflects a lowland position of principal ice dispersal centers.

Since the 1950s many authors, based on the low content of pebbles, local occurrence of marine fossils and the old idea of montane ice dispersal centres, interpreted thick diamict sheets, partly or entirely, as glaciomarine formations (Sachs, 1953; Lazukov, 1970; Zubakov, 1972). However, sedimentological analysis of fine-grained Middle Pleistocene diamictons in their stratotype sections proved beyond any reasonable doubt that they were deposited by huge ice sheets that advanced southwards (Guslitser, 1973; Kaplyanskaya and Tarnogradsky, 1974, 1975). The pattern of ice pushed ridges (Fig. 1) and dispersal of lowland clasts also indicate ice streams diverging from lowlands to the adjacent highlands (Astakhov, 1974a, 1977), contrary to ice flows from the mountains predicted by the glaciomarine hypothesis. The distribution and thickness of glacial deposits, as well as the pattern of their imbricate accretions (Figs. 1 and 2), is in accordance with N–S directed ice advances from the shelf but is hardly explainable by ice dispersal from the highlands.

3. Size and flow pattern of ice sheets

3.1. European Russia

3.1.1. Ice sheets inferred from erratics

The ice limits in central European Russia since the XIX century have been attributed to activity of the Fennoscandian ice dispersal center, as suggested by the distinct boulder trains and configuration of the marginal formations. For the last half-century three major Middle Pleistocene ice advances called Oka, Dnieper (the maximum glaciation) and Moscow have been correlated with the Elster, Saale and Warthe glaciations of Central Europe (Yakovlev, 1956; Goretsky et al., 1982). In northern European Russia, however, influx of glacial ice from the northeast was acknowledged quite early (Ramsay, 1904). The contributions of individual ice domes were thoroughly discussed by Yakovlev (1956). Based on provenance of erratics in the European North, Yakovlev distinguished three major areas of ice sheet growth: (1) Fennoscandia, (2) Novaya Zemlya with the adjacent Barents Sea shelf and (3) the Urals.

The dark-grey Novaya Zemlya till is a thick, fine-grained diamicton with strong NE–SW or N–S fabrics. It is devoid of Fennoscandian erratics but contains some fragments of Novaya Zemlya pink and black limestones (Andreicheva, 1992). Large limestone blocks transported from the Kara Sea coast towards SW across the Pai-Hoi Range have been known for a long time (Voronov, 1951). Many authors also noted numerous boulders of foreign rocks scattered over flat-topped mountains of the Polar Urals up to 1000 m asl (Yakovlev, 1956). Fragments of western Uralian rocks occur
Fig. 2. Profiles of Quaternary formations on the Barents Sea coast (from Lavrushin et al., 1989, simplified). See Fig. 1 for location. Diamictions: 1—deep buried (pre-Holsteinian); 2—close to sea level (Saalian); 3—surficial (Weichselian); 4—stratified silt and clay; 5—sand; 6—borehole. Till sheets are g1 to g5 and marine formations are m1 to m5 (m5 is probably a glaciotectonic repetition of m4-F.A.); IIIh is a lacustrine formation with Likhvin-type pollen spectra according to Lavrushin et al. (1989).
east of the main watershed, limestone clasts from the low western piedmont being often found atop glacially smoothed hills 500–600 m high (Savelyev, 1966). According to Yakovlev (1956) ice streams directed from Novaya Zemlya to the SSW reached the Volga catchment area, where they coalesced with SE flowing Fennoscandian ice of the Dnieper glaciation to form the largest ice sheet of European Russia. This ice sheet was thought to have penetrated into the southern steppes by two huge ice streams forming the Dnieper Lobe in the Ukraine and the Don Lobe in southeastern Russia. In this model ice from northeastern sources covered practically all sedimentary basins of the Russian Plain north of 58° N.

The subsequent penultimate glaciation left the reddish brown till widely observable on the surface west of the Pechora. This till is unanimously correlated with the Moscow glacial complex of Central Russia. It contains numerous western erratics, including the characteristic nepheline syenite from the Kola Peninsula, and therefore must have been deposited by a Fennoscandian ice sheet. East of the Pechora the latter coalesced with ice streams originating from Novaya Zemlya and the Urals (Yakovlev, 1956; Potapenko, 1974; Lavrov et al., 1986; Andreicheva, 1992).

Individual ice domes are not easily identified by the erratic dispersal alone on which many authors rely heavily. A straightforward interpretation of statistics on pebble composition and orientation may be controversial. For example, south of 64° N till of western provenance have long been known on the Uralian piedmont. Heaps of boulders of Palaeozoic sedimentary rocks from the west occur even at the very foot of the highest range of the Northern Urals. However, farther to the west clasts of sedimentary rocks are mixed with central Uralian crystalline rocks, i.e. the percentage of Uralian clasts in the clayey basal till apparently increases westwards. Varsanofieva (1933) explained this paradox by ice of northern origin streaming along the Urals and fanning off westwards into the lowlands and eastwards into the mountains. North of 64° N, just west of the highest massif of the Peri-Polar Urals, clayey tills are even more enriched in Uralian erratics, which led to the idea of thick ice which presumably flowed westwards from ice domes positioned over the Urals (Yakovlev, 1956; Chernov, 1974). Pebble orientation and mineralogical composition of the till matrix were also used to suggest a separate Uralian ice dome (Kuznetsova, 1971; Andreicheva, 1992).

However, the question is not that simple. The most comprehensive work was done by Lavrov et al. (1986) who mapped the glacial topography and measured pebble composition in hundreds of till samples a quarter of a cubic meter each. The generalised results unambiguously show the persistent N–S and NE–SW dispersal of glacial clasts over the northeastern Russian Plain during the maximum Pleistocene glaciation (Fig. 3A), west–east direction for the till of the penultimate glaciation west of the Pechora and again N–S ice flow east of this river (Fig. 3B). The maps by Lavrov et al. (1986) offer no signs of a Uralian influence except at several locations with transverse fabric (Fig. 3B) reported by Kuznetsova (1971). The pebble content pattern and the main vector of till fabric points directly towards the NE across Pai-Hoi and Novaya Zemlya into the Kara Sea, without disturbance by ice flows from the Urals or from the Barents Sea.

3.1.2. Other evidence of ice dispersal

The signals from pebble composition and mineralogy of tills are often mixed. On the western carbonateous piedmont of the Northern Urals (63–61° N) Varsanofieva (1933) found that the clayey till of western provenance was covered in places by a clast-supported diamicton full of central Uralian erratics at 20 km west of the mountain front. Based on these data she suggested two glaciations: one in the form of a regional ice sheet which advanced along the Urals and a subsequent glaciation in the form of restricted piedmont ice flows from old alpine troughs. The situation is mirrored on the Siberian slope of the Peri-Polar and Northern Urals between 65° N and 62° N (Sirin, 1947; Ber, 1948), where a till of eastern (Siberian) provenance mantling the hills up to 500 masl is superposed by a cobbly diamicton of local (central Uralian) provenance. Sirin (1947) concurred with Varsanofieva to suggest two glaciations on the eastern slope: a maximum ice sheet which advanced from the West Siberia onto the Urals and a local glaciation centred in the Uralian axial zone of metamorphic rocks.

Thick sequences of lowland drift later found on both slopes of the mountain range amply confirm ice advances onto the Northern Urals from both NW and NE but reject local ice caps. The thickest clayey till at 500–600 m asl in the axial zone (Fig. 4A) contains fragments of black Carboniferous limestones picked up in the low piedmont some 20 km to the west (Astakhov, 1974a). The clayey till is capped by the 50 m high kame-like hummocks built of well-washed sand with small and roundish cobbles of central Uralian origin but obviously deposited by the same inland ice sheet, most probably of OIS 6. In contrast, younger local moraines filling alpine troughs higher than 600 m (Fig. 4A) consist of only clast-supported tills derived from metamorphic rocks. The Siberian slope of the Northern Urals, where no alpine moraines have been mapped, is in places covered by thick matrix-supported tills of eastern provenance (Fig. 4B), containing fragments of soft Mesozoic rocks of the West Siberian basin and the West Siberian mineralogical assemblage (Ryzhov, 1974).
Fig. 3. Pebble content and ice flow indicators in Middle Pleistocene tills of northeastern European Russia: A—maximum glaciation; B—penultimate glaciation. By Lavrov et al. (1986) with minor additions from Matveyeva (1967) and Gornostay (1990) for the Timan Ridge and from Astakhov (1974b), Ryzhov (1974), Astakhov et al. (1999) for the Urals. Isolines show volumetric content of pebble fraction 1–5 cm in till samples about a quarter of cubic meter each. Black wedges are long axes of pebbles. Arrows are other ice flow indicators: striae, boulder pavements, eskers, transport paths of erratics. Hatched are Palaeozoic salients of the Timan Ridge and Urals. Note the pebble content decreasing downglacier and increasing locally in the lee of the Timan Ridge at southwestern corner of Fig. 3A. Lowland erratics in basal tills (Fig. 4A) and esker orientation in Fig. 3B are at odds with fabrics of surficial diamicton measured by Kuznetsova (1971) in the upper Pechora area.

Fig. 4. Lowland tills on western (A) and eastern (B) slopes of the Northern Urals. A—river Telspos catchment, N 63° 50' / E 59° 0' (from Astakhov, 1974a); B—between rivers Manya and Mazapatya, N 62° 15' / E 59° 50' (from Ryzhov, 1974, simplified). 1—laminated fine sand and silt; 2—coarse sand with pebbles; 3—clast-supported diamicton of local provenance; 4—matrix-supported diamicton with lowland clasts; 5—borehole. Note kames of lowland glaciation undisturbed by Uralian glaciers in Fig. 4A.
In the lowlands no landforms testifying to ice flow from the Urals have ever been mapped (Fig. 1). Moreover, even on the western piedmont of the Northern Urals, 200–300 m asl, eskers and striae are oriented either N–S or even NW–SE (Astakhov, 1974b). This is quite compatible with ice flow directed towards the mountains and not with a Uralian ice dispersal centre.

The 90-m thick sequence of fine-grained Middle Pleistocene glacial sediments of a kame field found in the central metamorphic zone (Fig. 4) has evidently never been affected by any glaciers of montane origin. Similar kames built of fine sand are also known from the east of the central range (Ber, 1948). According to this author’s observations, in several places of the Northern Urals well-preserved kames are mantled by thin clast-supported diamicton full of fragments of Uralian quartzites and schists. This sediment, which is better be interpreted as ablation till, may well belong to the same ice advance. Thus, no second ice advance is needed to account for pebbles of Uralian provenance in the surficial diamict of the pediments. The crystalline pebbles mostly originate from mountains higher than 500 m and therefore are rare in the basal till but abundant in the ablation till, which was enriched in clasts from nunataks during the lowering of the ice surface. This agrees with the fact that the percentage of Uralian crystalline rocks in diamictons of the Pechora Basin is minimal in the oldest tills of thicker ice sheets, while thinning, might acquire reverse surface gradients forcing supraglacial boulders from Uralian nunataks to slide westwards. This could happen in the end of every ice age, thus adding to the volume of crystalline clasts already delivered to the lowlands by small alpine glaciers which probably acted prior to the main ice advances from the shelf. If the thin diamictons of Uralian provenance had been formed subglacially by westward ice flow, as Varsanoieva (1933), Kuznetsova (1971), Andreicheva (1992) and others suggested, there should have been abundant features of glacial erosion and deposition transverse to the longitudinal topography and structures of the Urals. Nothing of the kind has ever been detected by remote sensing or surface mapping. On the contrary, all large structural and geomorphic features suggest ice flow towards or parallel to the Urals. The NNE–SSW ice flow reflected in the clast distribution is also supported by large-scale striations across the Palaeozoic structures of the Timan Ridge (Fig. 3A).

The most reliable indicators of thick upslope flowing inland ice are large glaciotectonic disturbances which in places form arcuate ridges up to 250 km long (Astakhov et al., 1999). In the Pechora Basin such features are oriented in accordance with ice flow directions from NE and NW (Fig. 1). Huge rafts of soft Mesozoic rocks, including rock salt, have been incorporated into the till of northeastern provenance. The till of the penultimate glaciation contains large basalt blocks from Timan (Guslitser, 1973). In the peri-Timan area ice flow from the west is also clearly indicated by surficial ice-pushed features. For example, along the Arctic slope of the Timan Ridge a large allochthonous stack of westward dipping, imbricated slices of Mesozoic and Quaternary rocks, testifies to eastward glaciotectonic transport over a distance of some 40 km (Gornostay, 1990). Orientation of small glaciotectonic structures is more scattered.

In the Arctic zone ice flow features directed from lowlands into the mountains are abundant as well. A sand pit on Hanmei river near Labytnanghi on the eastern piedmont of the Polar Urals, examined during the PECHORA project expedition in 2000, displays Middle Pleistocene glaciofluvial gravels lying atop a very clayey till (Fig. 9). Surprisingly, these sediments contain mostly fragments of soft Mesozoic rocks from West Siberia but no clasts of resistant ultramafic rocks from the nearby Rai-Iz massif. Gravelly cross-beds all dip towards the Urals. Farther northwards the Late Pleistocene matrix-supported Sopkay moraines strike W–E, i.e. transverse to the Urals, reflecting an ice flow from the shelf (Astakhov, 1979). Even the youngest bouldery moraines on the northwestern tip of the Urals at 560 m asl show only ice push from the north, i.e. from the Kara Sea (Astakhov et al., 1999). The SE-facing arcuate ridges on the Siberian slope (Fig. 1), outlining a piedmont morainic apron south of the Arctic Circle (Astakhov, 1997), can hardly be of a Uralian origin, because they (i) occur only downglacier of old wide troughs crossing the narrow mountain range and (ii) do not have any symmetrical counterparts on the western, more humid slope. Therefore, the morainic apron of the eastern piedmont most likely originated from outlet glaciers that drained a Middle Pleistocene ice sheet of European Russia via Uralian through valleys to the SE. This suggestion agrees with the boulder trains of northwestern provenance traced across the Urals (Yakovlev, 1956).

For the interpretation of the ice sheet flow patterns it is crucial that the sedimentological evidence of lowland glacial advance into the Urals are in accord with the pattern of ice-pushed ridges and terminal moraines in the lowlands. Large ice-pushed ridges generally strike parallel to the Arctic shoreline and nowhere fringe the Uralian range except narrow morainic aprons along the
foot of the mountains south of 67°N (Astakhov, 1977, 1997; Astakhov et al., 1986). Where discrepancies exist between the lithological composition of the glacial deposits and the pattern of ice-pushed ridges, the latter should be taken as decisive evidence, because fresh large-scale geomorphic features can only be produced by the latest ice flows. The above mentioned horseshoe-shaped end moraines of the Kara ice sheet, shoved up-valley in the Polar Urals (Astakhov et al., 1999), consist of heaps of local boulders reoriented by ice push from the north. These and many other similar observations are good evidence that the Urals were generally overridden or bypassed by ice streams that originated north of the mountains, most likely on the western Kara shelf. The low and narrow mountain range of the Urals was not a major ice dispersal center either in the Late Pleistocene (Astakhov et al., 1999), or in pre-Eemian times of greater continental ice sheets.

3.1.3. Dominant ice dispersal centre

Thus, the available data indicate that during the Middle Pleistocene northern European Russia was the realm of a powerful inland ice that flowed from the NE up-slope and eroded mostly soft Meso-Cenozoic sediments to deposit unusually thick and clayey tills. Lateral erosion of the Ural Mountains by transit ice streams contributed a small amount of central Uralian clasts to the generally fine-grained drift. Although the main ice streams were basically directed to the south and southwest, inland ice also flowed laterally across the Urals, overriding their flat-topped mountains when the ice was over 1 km thick. When the European ice sheet was thinner, it could reach the Siberian slope of the Urals only in the form of outlet valley glaciers.

Karpukhin and Lavyov (1974) considered the Yakovlev’s Novaya Zemlya ice sheet too large and preferred to explain the NE–SW fabric in the Upper Volga area by a diverted flow of Fennoscandian ice. According to them traces of a Novaya Zemlya glaciation and erratics of NE provenance occur mainly east of river Severnaya Dvina. Immediately west of 50°E the drift limit turns almost straight south in accordance with the margin of Fennoscandian ice. For comparison, Velichko et al. (1977), based on the peculiar composition of the fine-grained Don till, suggest that even the huge Don Lobe on 52°N was produced by the northeastern ice dispersal centre!

The strong NNE–SSW orientation of various glacial features, persistent over thousands of kilometers from the Pai-Hoi Range on 68°N to the Upper Volga on 58°N, is truly amazing, especially compared to the radially diverging pattern of Fennoscandian ice flow. It seems impossible for a small elongated ice dome over the narrow Novaya Zemlya archipelago to produce the extensive ice streams which deflected the Fennoscandian ice. The lowland ice sheets of northeastern origin, which emanated such long strings of erratics and flow features, obviously were too thick to be obstructed by most ice advances from Fennoscandia.

Yakovlev (1956), who saw the difficulty, suggested an additional accumulation area on the adjacent Barents Sea shelf. However, no traces of ice flow from the NW onto the Russian mainland have been mapped for the maximum glaciation: anywhere east of 43°N all features are directed NE–SW or N–S. Features of W–E and NW–SE orientation and clasts of western provenance first appear in surficial tills of the penultimate (Vychegda = Moscow) glaciation, when the influence of the northeastern ice dispersal centre decreased (Matveyeva, 1967; Andreicheva, 1992; Andreicheva et al., 1997). This underlines the dominant position of the Kara Sea shelf as a major source of inland ice in northern European Russia throughout the Pleistocene. Only during the penultimate glaciation the shelf ice domes were overpowered by a Fennoscandian ice sheet which advanced across the Timan Ridge at right angles to the ice flow from the Kara Sea.

3.2. Siberia

3.2.1. Signatures of ice motion

East of the Urals the thickness of inland ice and its flow pattern are more controversial issues, especially for the West Siberian Plain. Historically there have always been competing hypotheses of large Middle Pleistocene glaciers versus concepts of thinner local ice sheets that were assumed to reflect the drier Siberian climates. The first paradigm is commonly maintained by practicing geologists, who observe ubiquitous glacial features in various areas and at various altitudes, whereas the second trend of thinking is largely motivated by general palaeogeographical considerations.

One of the main glaciation centres was inferred long ago from the pyroxene abundance in till matrix and the mafic rock fragments scattered over the Central Siberian Plateau built of Palaeozoic sedimentary formations, Triassic basalts and dolerites (Obruchev, 1931; Urvantsev, 1931; Sachs, 1953). Three morainic belts rich in dolerite boulders concentrically surround the Putorana Plateau (Isaev, 1963). In the east the Putorana ice coalesced with a small ice sheet of the Anabar Plateau. It is interesting that during the penultimate glaciation the easternmost Anabar ice sheet, similarly to the European situation, was overpowered by eastward ice flow from Putorana (Isaev and Isaeva, 1974). Ice flow from the High Arctic was inferred early basing on characteristic granite boulders transported onto the dolerite plateaus of Putorana from the Nordenskjold Archipelago and northern shores of the Taimyr Peninsula across the c. 400 m high Byrranga Mountains. The phenomenon was first thought to result from a reverse topographic gradient of the Ice Age (Urvantsev, 1931). Today it is
seen as evidence of an ice dome thicker than 2 km on the Kara Sea shelf. This Arctic ice sheet prevented the Putorana ice from flowing northwards (Andreyeva, 1978; Kind and Leonov, 1982).

The difference between glacial features of Central Siberia and West Siberia is striking. In Central Siberia U-shaped valleys, deeply cut into bedrock and in places barred by boulder-rich morainic arcs, radiate from the Putorana ice dispersal centre. They are accompanied by smoothed, striated, sometimes fluted and drumlinised surfaces, by occasional eskers and glaciofluvial fans (Isayeva, 1963; Arkhipov et al., 1976). There are such typical signatures of wet-based sliding as boulder pavements on the Yenissei (Troitsky, 1975).

On the contrary, eskers, flutes and marginal ridges are totally absent west of the Yenissei. They are replaced by the englacial glaciitectonic imbrications, kame fields and late glacial sandurs. Especially characteristics are thick fine-grained West Siberian tills with ubiquitous local and far-travelled blocks of soft sediments, including Quaternary and Palaeogene loose sands with local and far-travelled blocks of soft sediments, including Quaternary and Palaeogene loose sands with original lamination preserved. In many cases sedimentary rafts hundreds of meters long were transported over hundreds of kilometers (Shatsky, 1965; Zakharov, 1968; Kaplyanskaya and Tarnogradsky, 1974). The glaciitectonised structure of the glacial deposits, that is common for most sections of northern West Siberia, often precludes visual tracing of stratigraphic contacts. Such tills cannot have been deposited by lodgement, but most likely reflect the structure of dirty basal parts of huge stagnant ice sheets which slowly melted out in a degrading permafrost environment (Astakhov and Isayeva, 1988; Astakhov et al., 1996).

The wet-based versus dry-based features at the same latitudes in Siberia clearly point out to the difference between the downslope sliding over rigid bedrock in Central Siberia and slow glaciitectonic motion of the entire ice-permafrost couplet up slope in West Siberia. Especially suggestive are the huge composite imbrications and the lack of any ice retreat features. In West Siberia vast ice fields seem to have simultaneously lost mobility to decay for a very long time, being protected from beneath by thick permafrost (Astakhov et al., 1996). Masses of buried glacial ice are ubiquitous in the Upper Pleistocene tills of Arctic Siberia. Fossil ice may have even survived from Middle Pleistocene glaciations conserved in the West Siberian permafrost, as suggested by very thick massive ice sometimes found in deep boreholes.

The described combination of glacial features indicates large ice sheets that were somewhat sluggish due to the cold stored in the lithosphere over the entire Pleistocene. This accumulated cold is evident from numerous boreholes in West Siberia, which find a thick perennially frozen layer at 150–200 m from the surface even on 59–60° N, i.e. far south from the present-day continuous permafrost of the Arctic. Detached blocks and drag structures in glacial drift of the region suggest that the cold glaciers proceeded by involving into motion a 300–400 m layer of very unstable although frozen clayey substrate (Astakhov et al., 1996). This type of inland glaciation is dynamically different from other glaciated regions, which is also evident from the poor preservation of interglacial formations. Inter-till palaeo-sols, common in North America, have never been observed in West Siberia.

The ice flow pattern is hard to recognise in the West Siberian Plain, because the predominantly soft bedrock, consisting of Cretaceous and Palaeogene sand, silt, clay, opoka and diatomite provide neither streamlined features, nor enough clasts for statistical analysis. Before the onset of modern glacial sedimentology and glaciitectonic research in the 1970s the only ice flow indicators used for reconstructions were clasts of Uralian and Central Siberian crystalline rocks. Although already Obruchev (1931), basing on the configuration of the few known morainic chains, suggested a lowland ice dome on the Taz and Gydan peninsulas, subsequent mapping failed to find its material signatures, and ensuing overviews acknowledged only ice dispersal paths from the Urals and Central Siberian uplands (Sachs, 1953; Zarrina et al., 1961; Lazukov, 1970; Zubakov, 1972; Arkhipov et al., 1977). Nevertheless, Zemtsov (1973a, b), who interpreted the composition of several thousand boulders and mineralogical samples of till matrix, concluded that there was a central zone in the north of West Siberia with no fragments of Uralian rocks or central Siberian dolerites. Tills of the central zone contained mostly material of local Mesozoic and Cenozoic formations with admixture of Taimyr rocks. Zemtsov thought this zone to have been influenced by an additional ice dispersal centre on the Taimyr Peninsula, and he did not rule out a possibility of ice flow from a hypothetical lowland ice dome by Obruchev (1931). Also Kaplyanskaya and Tarnogradsky (1975) interpreted marine fossils found in diamictons of the Lower Yenissei area as signatures of ice flow from the Kara Sea.

### 3.2.2. Puzzling erratics

Again, as in European Russia, in West Siberia a discrepancy exists between the strong signatures of up slope ice flow from lowland ice domes (Astakhov, 1976, 1977) and the dominant petrographic and mineralogical composition of the glacial drift, which seemingly is evidence to the contrary. E.g. the most comprehensive study of till composition in West Siberia (Sukhorukova et al., 1987) reveals three major clastic provinces roughly coinciding with the earlier conclusions by Zemtsov (1973a, b): Central Siberian, Uralian and West Siberian (Fig. 6). Sukhorukova et al. (1987) maintain that these provinces reflect the relative
significance of three major ice dispersal paths: from the Putorana Plateau, from the Urals and from the Kara Sea shelf. First, this interpretation contradicts the pattern of ice-pushed features which everywhere only reflects ice flow directed upslope (Astakhov, 1977). Second, it is glaciologically impossible: there is no obstacles in the very low central West Siberian Plain that would prevent Uralian and Central Siberian ice streams from moving farther south beyond the mapped drift limit (Figs. 1 and 6). Especially strange is the sudden increase of Uralian clasts in the Ob tills south of 64°N, which made Sukhorukova et al. (1987) suggest an ice dome in the Northern Urals instead of the Polar Urals, as would follow from the general N–S ice transport (Sukhorukova et al., 1987). All these are should be characteristic of fluvial rather than glacial transport (Sukhorukova et al., 1987). The crucial indication of southbound flow of thick Middle Pleistocene ice in West Siberia is the system of arcuate ice-shoved imbrications of intricately disturbed soft rocks, often topographically expressed as hill–hole pairs. The system of the largest ice pushed ridges runs roughly parallel to the coast of the Arctic Ocean (Fig. 1). The largest zones of thrusted and tightly folded sediments are up to 200 km long and 20–25 km wide (Zakharov, 1968; Troitsky, 1975; Arkhipov et al., 1976; Astakhov, 1979; Astakhov et al., 1986). The disturbances may penetrate down to 400 m below the surface, which is probably the world record. The tectonic style of these structures indicates their deformation in a frozen state and is evidence of deep crumpling of soft substrate during ice movement (Astakhov et al., 1996). These structures, normally consisting of parautochtonous slices or detached blocks of local provenance, as a rule, occur far upglacier from the ice margin. Along the ice margin they are often replaced by huge rafts of far-travelled Mesozoic, Palaeogene and Quaternary sediments (the famous Yugan, Samarovo and Semeyka erratics of soft Jurassic and Paleogene rocks hundreds of meters long). They sometimes have been transported as far as 600 km downglacier (Shatsky, 1965; Kaplyanskaya and Tarnogradsky, 1974; Astakhov et al., 1986). The above facts imply a thickness of the West Siberian ice sheets in the order of kilometers, not hundreds of meters as was thought in the 1950–1960s (e.g. Lazukov, 1970; Zubakov, 1972).

Independent evidence of very thick Middle Pleistocene ice in West Siberia is provided by numerous glacial valleys with irregular bottom profiles that are buried by drift, in places 300–400 m thick (Arkhipov and Matveyeva, 1964; Zubakov, 1972; Arkhipov et al., 1976, 1994). These overdeepened, predominantly N–S striking valleys, never occur in the proglacial zone. Their glacial origin can be readily seen in the longitudinal profile of the Quaternary thickness across the drift limit based on numerous boreholes along the Ob and her left tributaries. In the periglacial area Pre-Quaternary bottom profiles, gently sloping parallel to the present-day fluvioglacial thalwegs, do not show any overdeepening (1–4 in Fig. 5). Immediately north of the maximum glaciation
limit the buried bottom of the Ob valley becomes very irregular, plunging deep below sea level (5, 6 in Fig. 5), which cannot be explained by normal fluvial processes.

The principal ice dome over the Kara Sea shelf and adjacent lowlands only got generally (although not unanimously) accepted after remote sensing had revealed the pattern of ice pushed ridges and after foreign erratics found in the mountains were considered (Astakhov, 1976, 1977, 1979). Lowland tills of Mesozoic provenance of the West Siberian Basin (Fig. 4B) and erratic boulders found high in the Urals indicate that above the Arctic Circle inland ice covered summits more than 1 km high, whereas at 62–63°N the trimline occurs at c. 500 m asl. In the western part of the Central Siberian Upland three till sheets with lowland erratics, 33 m thick altogether, were described on the table-like summit of a dolerite monadnock 618 asl at 150 km from the drift limit (location 13 in Fig. 1, Fainer et al., 1976).

The surface of the inland ice, which brought Mesozoic material from the northwest and deposited it atop the inselberg at loc. 13, Fig. 1, must have been higher than 700 m asl (Fainer et al., 1976) and at least 900 m upglacier in the Yenissei valley, south of loc. 9 (Fig. 1), where till of the maximum glaciation was found below sea level (Zubakov, 1972). These observations make the West Siberian ice sheet at least 500 m thick at 64°N at 150 km from the drift limit and c. 1000 m thick at 65°N, i.e. at 350 km upglacier from the margin of the maximum ice sheet (Fig. 6).

Voronov (1964), basing on empirical profiles of Antarctic and Greenland ice sheets and the known configuration of the drift limit in Siberia, calculated the maximum thickness of the West Siberian ice sheet as 3.5 km on the Yamal Peninsula. Judging by the above geological facts, this estimate seems to be realistic. To overpower and divert southwards ice streams from the Putorana Plateau, as evidenced by the foreign tills east of the Yenissei, the lowland ice dome must have been really thick and probably occupied the entire Kara Sea shelf.

4. Chronology of ice advances

4.1. European Russia

4.1.1. General stratigraphic framework

The modern chronological concepts of Middle Pleistocene glaciations in northern European Russia are
heavily dependent on the official stratigraphic scale of Central Russia, either directly, as in the Arkhangelsk Region of prevailing Fennoscandian glaciers, or in disguise of local stratigraphic labels, as in the Timan–Pechora–Vychegda Region of dominant ice advances from the northeast (Guslitser et al., 1986).

The stratigraphic cornerstones of central European Russia are classical interglacial formations of biogenic and limnic sediments at the Likhvin and Mikulino stratotypes, indicating climates warmer than the present. They were traditionally correlated to the Holsteinian and Eemian. The most continuous till sheet is poorly topographically expressed and for a long time has been associated with the Dnieper maximum of the Fennoscandian glaciation in the Ukraine, close to 48°C14N, and with the German Saale glaciation. Another, less extensive pre-Eemian glacial complex, mapped mainly north of 54°C14N by its distinct glacial topography, is attributed to the Moscow glaciation, presumably equivalent to the Warthe glaciation (Yakovlev, 1956; Goretsky et al., 1982). The till underlying the Likhvin marker horizon for a long time was thought to represent the oldest Oka (Elsterian) ice sheet of more limited extent (Table 1).

The most problematic was the third interglacial formation (Odintsovo, or Roslavl) found between two uppermost Middle Pleistocene tills. This sequence, showing a characteristic pollen profile with two deciduous peaks, is notably different from both Likhvin and Mikulino pollen successions. In formal stratigraphic schemes and in general maps of the Quaternary it was for many years placed between the Moscow and maximum Dnieper glaciations (Krasnov, 1971; Ganeshin, 1973), although there always were dissidents insisting on a much older age of the Roslavl strata.

This scheme with two separate Saalian glaciations was also applied to northern European Russia, where the Novaya Zemlya till was associated with the maximum Dnieper ice advance and the younger till containing Fennoscandian erratics—with the Moscow glaciation. The official regional stratigraphic scheme offers correlation units (climatostratigraphic horizons) replicating central Russian climatoliths (Guslitser et al., 1986). Several glacials and interglacials were distinguished from litho- and pollen stratigraphy in parallel with the old Central Russian stratigraphic scale, in which Saalian tills were separated by the very warm interglacial called Odintsovo (Roslavl) around Moscow and Rodionovo on the Pechora.

However, in the 1970s it was discovered that the till of the Don Lobe was older than the Dnieper till of the Ukraine (Velichko et al., 1977; Velichko and Faustova, 1986). The Don till is overlain by the Muchkap interglacial strata with two characteristic deciduous optima and with remains of typically Tiraspol (Cromer) rodents. A similar fauna was described from the stratotype sections of the Roslavl interglacial. This implied that the maximum glaciation on the Don was separated from the Dnieper till by at least two interglacials: Roslavl (Muchkap) and Likhvin. Thereby an intra-Saalian interglacial had to be abandoned (Shick, 1989). The new stratigraphy was proven beyond any reasonable doubt when sediments with the Likhvin (Russian Holsteinian) floras were found atop the Roslavl sequence (Biryukov et al., 1992). In the stratigraphic scheme of Central Russia, presently used by the Russian Geological Survey, no early Saalian till or overlying intra-Saalian interglacial formation (OIS 8 and 7) are mentioned. The only till sandwiched between the Likhvin and Mikulino formations is the Moscow glacial complex correlated with OIS 6 which presumably laterally merges with the Dnieper till of the Ukraine (Shick, 1989).

Still, there are researchers who accept the new pre-Holsteinian Don–Muchkap cycle but also insist on two separate glaciations (the Dnieper and Moscow) between
the Likhvin and Mikulino warm stages (e.g. Sudakova and Faustova, 1995). Recently an attempt to fill in the gap between the Moscow till and Likhvin strata has been undertaken by Velichko and Shick (2001). They suggest as climatochronological units 2 palaeosols and 2 loess units found directly on top of the Likhvin lacustrine formation with *Brasenia* flora (Table 1). In this new scheme they place the Dnieper glaciation at the beginning of OIS 6, implying that the maximum drift limit in the Ukraine is somewhat older than the Moscow till within the same ice age. The maximum glaciation of the eastern Russian Plain is firmly outlined by the Don Lobe (probably OIS 16) reaching south to the 50th parallel.

### 4.1.2. Stratigraphy in the Arctic

The modern stratigraphic scheme first did not affect the remote northern areas, where two Saalian tills (Pechora and Vychegda) were conventionally correlated with the Dnieper and Moscow glaciations. These tills are separated by a warm interglacial with two climatic optima described at Rodionovo as a counterpart of the Eemian sea, whereas the lower formation corresponds to unit m1 in the Lavrushin's profiles (Fig. 2). In some boreholes it is underlain by a diamicton. From the Kolva formation Gudina (1976) described an arctoboreal foraminifera with characteristic *Miliolinella pyriformis*, which she correlated with the Ob and Turukhan strata in West Siberia and with the marine Holsteinian. The latter correlation is at odds with palynological investigations which find Likhvin-type spectra stratigraphically higher than the Kolva formation (Fig. 2). In one borehole a diamicton was discovered at the base of the Kolva formation (Yakhimovich et al., 1973).

### 4.1.3. Stratigraphy in the Subarctic

Terrestrial interglacial sediments sandwiched between tills are known mainly from three natural exposures in the Pechora catchment area. The best studied is the Rodionovo section (2 in Fig. 1) with very compact, slated and slightly distorted peat up to 3.5 m thick contained in clay and silt within a sandy inter-till fluvial sequence. In the arboreal pollen spectra spruce, pine and birch are dominant with admixture of *Abies* and *Alnus* (Loseva and Duryagina, 1973). Two climatic optima were inferred based on a small admixture of deciduous tree pollen (Duryagina and Konovalenko, 1993), which led the referred authors correlate this sequence with the Odintsovo/Roslavl interglacial of Central Russia.

In the Kipiyevo section (3 in Fig. 1) lacustrine strata with a similar pollen assemblage also contain large *Unio* shells, thick coniferous logs with ‘formidable growth of tree-rings’ and nuts of *Ajuga reptans*, which now lives only in oak forests some 400 km to the south (Guslitser and Isaychev, 1983). The Kipiyevo interglacial strata are dissected by ice wedge-casts and overlain by sediments containing a late Middle Pleistocene assemblage of teeth of pied and grey lemming, similar to that found between the Likhvin lacustrine strata and the overlying till south of Moscow. The evolutionary level of the Kipiyevo lemmings is somewhat higher than in the Likhvin stratotype, which made Guslitser and Isaychev (1983) suggest a Moscow–Warthe age for this rather archaic
fauna. They also describe another find of similar rodent remains in the Akis section 6 km downstream of loc. 2, Fig. 1. At this site lemming teeth were collected from cross-bedded sand overlying the same Novaya Zemlya till as is at the base of the Kipiyevo sequence. The evolutionary level of the Akis lemmings is only slightly higher than in the Lower Saalian beds of the Likhvin section, again with no progressive Late Pleistocene morphotypes present. Guslitser and Isaychev (1983) relate the Kipiyevo interglacial to the Saale–Warthe interglacial (OIS 7) and the underlying till to the ‘early Saale’.

Recent dating attempts by the Russian–Norwegian PECHORA project confirm an OIS 6 age for the surficial till of the Subarctic zone. The dated section is located in present-day tundra on Seyda river, formally in the Arctic (4 in Fig. 1) but featuring only terrestrial sediments. A compact peat layer 1 m thick and 300 m long, with forest pollen spectra even richer than in Rodionovo, is contained in a thin sand sheet at the base of the 40 m thick stacked till sequence. The peat first yielded a finite radiocarbon date and was thought to represent the Middle Weichselian (Lodmashchelye section by Arslanov et al., 1987).

However, more detailed sampling of this sequence by J.I. Svendsen and M. Henriksen provided much older ages. An uninterrupted series of samples of the inter-till peat analysed for U/Th ratio in the laboratory of St. Petersburg University yielded ages of ca 200 ± 30 ka BP in the middle of the peat layer. Younger values obtained from the top and bottom of the peat are accounted for by postdepositional influx of younger uranium (analyst Yu. Kuznetsov). OSL dating on quartz particles in the peat produced ages of 180 ± 13, 185 ± 12 and 191 ± 37 ka, whereas the surrounding sand was dated to c. 144 ka (three datings) and once to 173 ± 75 ka. Glaciofluvial and glaciotectonised sands in the upper part of the overlying glacial complex sequences yielded OSL values of 148 ± 10, 149 ± 13, 152 ± 11, 156 ± 16, 160 ± 9 and 170 ± 13 (Table 3). Thus, there are two different sets of OSL dates: one is close to 150 ka and another is close to 200 ka. The consistency of the dates and the large measured dose rates, according to A. Murray, make these dates apparently reliable. The 50 ka difference in OSL ages of the two sets of samples probably means that a Late Saalian glacier picked up a peat layer ca 200 ka old and deposited it as a stratiform raft together with younger glaciofluvial sand. A Saalian age of this sequence is supported by OSL dates of 109 ± 8 from the top and 143 ± 12 ka from the bottom of the overlying aeolian sand. A Late Saalian OSL date of 152 ± 9 ka was also obtained from the sand between the peat and the upper till at Rodionovo (Table 3, sample by O. Maslenikova).

The age of the lower, ‘Novaya Zemlya’ till of the Pechora basin is less certain. Its correlation depends on the age of the Rodionovo interglacial. OIS 7 suggested by local geologists by comparison with the central Russian Odintsovo–Roslavl sequence (Guslitser et al., 1986) looks like a miscorrelation, because the Roslavl strata around Moscow are certainly pre-Likhvin, or pre-Holsteinian (see above).

4.1.4. How many ice advances?

This question heavily depends on the correlation of the rare interglacial sequences. It is interesting to compare the palaeontological characteristics of the Rodionovo formation with the Chirva interglacial strata known from boreholes in the south of the Subarctic zone (Vychegda catchment area) and correlated by pollen with the Likhvin interglacial (Duryagina and Konovalenko, 1993). These and other authors (Guslitser et al., 1986; Loseva et al., 1992; Andreicheva et al., 1997) presume that the Chirva predates the Rodionovo. However, both formations contain almost identical botanical taxa, including indicative Likhvin species Osmunda claytoniana and O. cinnamomea (Table 7 in Duryagina and Konovalenko, 1993). Both pollen
diagrams feature five zones and two climatic optima with an admixture of deciduous trees, both, unlike the older Visherka horizon, contain no Tertiary relics and only rare exotic (Balkan-Caucasus) elements such as Betula sect. Costatae, Picea sect. Omorica, P. sect. Strobus. The slightly richer floristic composition of the Chirva strata is easily explained by the more southerly position of the studied site. As mentioned above, the rodent assemblages above the Kipiyevoo (Rodionovo) strata are very similar to those found on top of the Likhvin type sequence. The only OSL date available from the base of the Rodionovo peat gave a fairly old value 334 ± 29 ka, more appropriate for OIS 9 or 11 than for OIS 7 (sample by O. Maslenikova, Table 3).

The most important is the stratigraphic position of the interglacial formations in borehole profiles of the Arctic zone (A, B and C in Fig. 1). Loseva et al. (1992) relate the pollen spectra of the terrestrial inter-till sequence in boreholes 8-y, 5-y, 3-y and 71 (Fig. 7) to the Chirva interglacial, but the marine formation at the same level in the SE boreholes 754 and 755 is correlated with the younger Rodionovo interglacial. Consequently, the overlying till in the NW boreholes is thought to be the Pechora till (OIS 8 in their correlation), but its lateral counterpart in the SE is referred to the younger Vychegda till (OIS 6) (Fig. 7). Neither the lithological composition of the tills, nor the landscape features support such a differentiation. In the profile described by Lavrushin et al. (1989) slightly farther to the east (A in Fig. 1) the lateral change from the Likhvin lacustrine formation to the marine formation m3 (Fig. 2), suggested by the authors, seems more logical.

The Chirva and Rodionovo interglacials have never been found in superposition (Figs. 2 and 8). Therefore, it appears that the uppermost Middle Pleistocene interglacial, the Rodionovo on the Pechora, is identical with
the Chirva interglacial of the Vychegda catchment area. Many interglacial sequences covered by the upper till in the Subarctic zone, and lying just below sea level in the Arctic, probably belong to the same interglacial interval, most likely represented by the marine formation with *Cyrtodaria angusta*. The *Cyrtodaria* strata are in places found up to 70 m asl (Zarkhidze, 1972), which gives a rough idea of the large isostatic depression caused by the thick preceding ice sheet.

In the compromise scheme by Velichko and Shick (2001), accepting the different Chirva and Rodionovo interglacials, the Pechora glaciation is not correlated anymore with the Dnieper or other maximum ice advance of Central Russia. Instead it is shifted downwards to OIS 10, probably in order to accommodate at OIS 12 another glaciation called the Pomus by Guslitser et al. (1986) (Table 1). This results in the correlation of the mighty Pechora glaciation of NE provenance with the thin Kaluga loess on top of the Likhvin stratotype sequence. However, the Pechora till, widely observed in many Subarctic sections and covered by the distinctly interglacial Rodionovo formation, is still the most salient feature of the northern drift. Therefore, it better correlates with a central Russian till covered by the Likhvin strata, the Oka till, which has been always thought as Elsterian in age. There is no lithostratigraphic evidence of a laterally consistent Pomus glacial complex.

Whether the Chirva/Rodionovo interglacial corresponds to OIS 9 or to OIS 11 is uncertain, but its stratigraphic position makes it the best candidate for correlation with the Russian Holsteinian, i.e. the Likhvin *s. stricto*. The preceding Visherka interglacial sequence, containing Tertiary relics such as *Liquidambar* and *Pterocarya* plus exotic *Tsuga* and *Ilex*, not known from younger interglacials, consequently would better correspond to the Roslavl/Muchkap strata overlying the Don till of the maximum glaciation, as suggested by Velichko and Shick (2001) (Table 1).

In this respect sections close to the glacial drift limit are of particular interest. The best picture of the geological structure of the Pechora–Volga interfluve area is given by the geotechnical drilling data described by Stepanov (1974, 1976). Two of his profiles crossing each other at right angles are presented in Fig. 8. The surficial till g3 correlated by Stepanov with the Dnieper glaciation is covered by only one interglacial alluvial formation of the modern valleys with fresh-water molluscs, rich diatom flora and characteristic Mikulino pollen spectra. A modern area of concentration of the
The interglacial formation between g3 and the underlying g2 till (Fig. 8) contains a flora similar to the Likhvin assemblage with indicator plants such as *Osmunda claytoniana*, *Pinus sect. Strobus*, *Picea sect. Omorica*, *Tilia tomentosa* which have a modern area of concentration in the western foothills of the Alps, according to L. Tyurina. The plant macrofossils identified by P.I. Dorofeyev are typical for the Singil floras of the Russian ‘Mindel-Riss’ (Stepanov, 1976). A single find of forest elephant *Palaeoloxodon* sp. is known from a similar sequence on Kolva river, tributary to the Kama river (Yakhimovich et al., 1973). The overlying g3 till should be the Uralian counterpart of the Vychegda till. The underlying dark-grey till g2, low in Uralian boulders, contains mostly clasts of sedimentary rocks and in this respect is not different from the Pechora till.

The lower inter-till formation (between g2 and g1) shows pollen spectra of mixed forests with very few pollen of *Carpinus*, *Corylus* and exotic trees. The high percentage of pyrite grains is typical for the oldest interglacial of the eastern Russian Plain (Stepanov, 1974). If the lower interglacial sequence, locally labeled the Solikamsk formation, can be correlated with the Roslavl/Muchkap strata, then the underlying...
overconsolidated g1 till (the Kama till of Stepanov) should be a counterpart of the Don till of southern Russia.

The alternative interpretation puts the Solikamsk interglacial into OIS 17–19 and the Kama till into OIS 20 (Zubakov, 1992), which makes the Kama till contemporaneous to the Mansi till of West Siberia presently attributed to the Matuyama chron (Volkova and Babushkin, 2000). If the latter interpretation is correct, then the maximum glaciation of northeastern Russia is represented by g2 till of Stepanov’s profile (Fig. 8). The limit of this maximum glaciation shown in the left lower corner of Fig. 1 was for many years attributed to the Dnieper (early Saalian) glaciation (Krasnov, 1971; Ganeshin, 1973) which later proved to be wrong (Velichko et al., 1977; Shick, 1989).

The correlation between the Arctic region of marine transgressions and the Upper Pechora–Vychegda catchments remains problematic. A formal comparison says that the three main glacial complexes underlying the Upper Pleistocene of the Arctic (Fig. 2) probably correspond to the three tills of the Pechora–Kama interfluve (Fig. 8). However, g1, g2 and g3 in both profiles are just diamicnt units numbered by this author and cannot be viewed as synchronous with similarly designated tills in the Arctic profiles. Actually, it is not easy to find in the Arctic Pleistocene counterparts to all warm intervals of the southern record. Two boreal transgressions are more or less satisfactorily reflected in the warm Mikulino and Likhvin floras of the south, whereas there is no evidence to synchronise the cool Kolva marine strata with the Visherka or Solikamsk interglacial formations with their exotic plant remains. It is possible that the Kolva interglacial is missing in the terrestrial record of the Subarctic zone. This question will stay open until more reliable means of long-distance correlation are found.

The above brief analysis of the available stratigraphic data allows to conclude that there are at least three readily recognisable glacial complexes and major pre-Weichselian ice advances in northeastern European Russia, which certainly does not preclude their subdivision into minor glacial stages. The fourth ice advance preceding the Kolva transgression in the Arctic might tentatively be correlated with the Kama till of the Pechora–Volga interfluve.

4.2. Siberia

4.2.1. General stratigraphic situation

The Siberian glacial chronology is more arbitrary due to the formidable size of the country and poor applicability of pollen analysis. Unfortunately the dominant boreal forests have a monotonous composition with practically no deciduous trees presently growing, except sparse lime in southwestern West Siberia. Therefore, in distinguishing interglacials one has to rely on N–S shifts of very broad biogeographical zones, which would demand hundreds of meticulously studied sections. In literature one can usually see generalisations of a continental scale based on a handful of sites and, which is even worse, with European labels attached to totally unrelated objects, i.e. atlantic terms applied to a non-atlantic environment. This certainly hinders development of an independent Siberian Pleistocene stratigraphy. Many geologists, exasperated by the difficulties encountered in Siberia, took to elaborating local stratigraphic scales by exclusively chronometric methods which normally should only be used for long-distance correlation. This poor practice, exemplified by the popular misuse of radiocarbon dating, led to corruption of the traditional stratigraphic nomenclature, which is not reliable anymore, being permanently reshuffled after each laboratory ‘discovery’ (Astakhov, 2001). To lesser degree the same happens with the Middle Pleistocene, although the limited number of available chronometric methods helps to keep the old stratigraphic terminology in a better shape.

Two stratigraphic markers, identified in key sections of the West Siberian basin, over several decades have been the cornerstones of glacial history and Quaternary mapping. These are the interglacial formations of the Kazantsevo transgression in the Arctic and the Tobol alluvium in central and southern West Siberia. The Kazantsevo formation consists mostly of shallow-water facies containing rich arctoboreal mollusc fauna with characteristic boreal species such as *Arctica islandica* indicating water temperatures 4–8 °C above the present-day Kara Sea temperature (Sachs, 1953; Troitsky, 1975). This formation is conventionally correlated with the Eemian strata of the Boreal transgression in European Russia. This correlation seems to be confirmed in Yenissei Siberia by several ESR dates on marine shells in the range 108–134 ka (Sukhorukova, 1999). The main drawback of this marker horizon is its being limited to the Arctic, where it is overlain by till and often badly glaciotectonised.

The marker significance of the Kazantsevo formation is somewhat diluted by the fact, that, as in European Russia, there are distinct traces of another boreal transgression. First, boreal mollusc shells and foraminifera have been locally found in Middle Pleistocene diamictons (Arkhipov and Matveyeva, 1964; Kaplyanskaya and Tarnogradsky, 1975). Second, there are intertill strata with rare boreal molluscs (Zubakov, 1972). Third, some Kazantsevo marine sequences contain shells of extinct species *Cyrtodaria jenisseae* (angusta) (Sachs, 1953; Kind and Leonov, 1982, see also discussion on Taimyr in Svendsen et al., this volume) and probably belong to earlier interglacials.

The Tobol strata are much better preserved in the area of their classic occurrence along the transverse Ob
and lower Irtysh, mostly between 62° N and 56° N, i.e. just within the drift limit and in the periglacial area. They are washed, diagonally bedded quartz sands with thick lenses of green-blush clayey silts, partly covered by till of the maximum glaciation. Literature on the Tobol strata is extensive, especially regarding palaeontological questions. A comprehensive overview of geological data is given in a collection of papers edited by Arkhipov (1975), and also in numerous works by palaeobotanists.

Pollen spectra, as always in Siberia, are not very characteristic. Sequences in the present taiga zone mainly show a predominance of arboreal Betula and rich herb assemblages with a minor coniferous component, which is common for the Siberian forest-steppe. Some successions reveal two coniferous peaks below and above the main forest-steppe phase. The interglacial nature of the formation is clear from abundant freshwater molluscs, especially Corbicula fluminalis (tibetensis) presently living only in Central Asia. However, a rather cool and relatively humid climate is indicated by the rich macrofossil flora with exotic aquatic ferns Azolla interglacialica, Selaginella selaginoides, Salvinia natans, etc. This assemblage, known as the ‘Flora of the Diagonal Sands’, is similar to the Singil flora of the Russian Plain and has for several decades been the main indicator of the so-called ‘Siberian Mindel-Riss’ and an argument for its correlation with the Likhvin and terrestrial Holsteinian. Later Azolla remains were also found in Upper Pleistocene sediments of the Lower Ob (Arkhipov et al., 1977).

The mammal fauna is the most controversial issue, probably due to the all-pervading redeposition of osteological material by the huge laterally migrating rivers. More frequent are finds of bones of the Tiraspol (Cromer) mammals. There is only one known site with forest fauna of the Singil type represented by Palaeoloxodon, Megaloceros, Bison, Eolaqurus, Arvicola, etc. In many places the ‘diagonal sands’ contain mammal species ranging from pre-Tiraspol to typical Late Pleistocene lemming faunas. The explanation is that the ‘diagonal sands’ may be deposited at the same topographic level by slow meandering rivers during different interglacials. The Tobol formation proper, according to Arkhipov (1975), chronologically ranges from the second half of Mindel to the Mindel-Riss interval, i.e. belongs to two interglacials.

This interpretation was supported by a wedge of glaciolacustrine varves (the Semeika formation) found in the middle of the Tobol formation on the Irtysh, where it is also overlain by till of the maximum Samarovo glaciation. The lower alluvial sequence, called the Talagaika formation, is thought to represent a pre-Holsteinian interglacial (Kaplyanskaya and Tarnogradsky, 1974). In the present stratigraphic scheme only the Corbicula sands between the Samarovo till and the Semeika varves are related to the Tobol climatostratigraphic horizon s.stricto (Volkova and Babushkin, 2000). Correlation of the Tobol horizon with the Holsteinian is apparently supported by TL dates of 300 ± 75 and 313 ± 80 ka and ESR date 306 ± 20 ka on a Corbicula shell. However, in the periglacial zone Corbicula shells yielded ESR ages 285, 219 and 174 ka (Arkhipov, 1989). Later the palaeomagnetic excursion Biwa-II-Semeika along with the ESR date of 396 ka were reported from the basal part of the Tobol alluvium with Corbicula shells (Volkova and Babushkin, 2000).

Anyway, there are two independent interglacial markers, one of marine and another of terrestrial origin that can be seen in West Siberian exposures. The Arctic marker, if identified correctly, should provide the upper boundary of the Middle Pleistocene tills. The Subarctic marker separates surficial Middle Pleistocene tills from pre-Holsteinian glacial events known only from glacial deposits of buried valleys.

4.2.2. Stratigraphy in the Arctic

The till overlying the Kazantsevo strata in most cases can be safely correlated with the Weichselian, the underlying till being related to OIS 6 (Svendsen et al., this volume). These ice advances are distinguished by their geographic distribution, because the post-Kazantsevo glaciation is limited to the Arctic, whereas the pre-Kazantsevo ice advance reached far beyond the Arctic Circle. The main problem is that in many cases either marine strata with a boreal fauna are older than the Kazantsevo s. stricto, or the Eemian interglacial is represented by non-marine facies. The first case is known from the Pukovo section in the Yenisei valley (loc. 9 in Fig. 1), where marine strata with interglacial pollen spectra and rare finds of a boreal fauna, including Arctica islandica, are sandwiched between two tills well beyond the limit of Late Pleistocene glaciation (Zubakov, 1972). Troitsky (1975), who insisted on the Eemian age of this marine formation, had therefore to extend the Weichselian ice limit along the Yenisei as far south as 64°N, which is refuted by periglacial evidence (Astakhov et al., 1986). A similar situation is in the central part of the West Siberian basin close to the Arctic Circle, but well beyond the currently accepted Weichselian ice limit (Svendsen et al., this volume). In the Samburg borehole a thick marine formation with an arctoboreal fauna was found beneath a Middle Pleistocene till (Zubakov, 1972).

Non-marine Eemian is found on the Lower Ob, where two main stratigraphic concepts have been competing. The classical concept relates most of surficial diamictons and varved sequences to glacial or glaciomarine formations of the Middle Pleistocene (Lazukov, 1970; Zubakov, 1972). According to Zubakov, this interpretation is based on pollen spectra characteristic of southern taiga found in sand infills incised into the thick varved
rhythmite at the Pyak-Yaha section of the southern bank of the Ob in the present forest-tundra (Fig. 9). Only thin lenses of diamict and gravel materials which sometimes occur on the surface suggest a Late Pleistocene glaciation (Lazukov, 1970). In contrast, the concept of the 'young stratigraphy', based mostly on sparse radiocarbon dates obtained in different sections, ascribes a Late Pleistocene age to all units of stratified and non-stratified drift observed in natural sections. In the latter scheme the Kazantsevo marker is represented by sand with boreal foraminifera identified in boreholes just below sea level (Arkhipov et al., 1977). This concept is currently accepted in the official stratigraphic scheme (Volkova and Babushkin, 2000).

Arkhipov et al. (1994), applying their radiocarbon-based 'young stratigraphy' to the entire Arctic Pleistocene, suggest a Holsteinian age for another interglacial formation at 100–200 m bsl, the so-called 'Ob marine strata'. This older interglacial formation, underlain by only one till, contains an assemblage of arctoboreal foraminifera of 'Miliolinella pyriformis zone'. The thick diamicitic sequence positioned between the two interglacial marine formations in this scheme belongs to OIS 6–8. Arkhipov et al. (1994) offer TL-dates on core samples of 153 ± 15 ka for their 'Kazantsevo formation' and 246 ± 23, 306 ± 26, 366 ± 31, 370 ± 31 ka for the 'Ob strata'.

The latest results from the Russian–Norwegian PECHORA project clearly refute the 'young stratigraphy'. Weichselian tills and related glaciolacustrine sediments are found only on the northern bank of the Ob river (Fig. 9). The fluvial or deltaic sands with forest pollen spectra incised into the thick varved sequence of the southern bank yielded four OSL dates of 125 to 138 ka (samples 115, 116, 133 and 134, Pyak-Yaha, in Table 3), together with non-finite radiocarbon dates supporting an Eemian age of these sands. Glaciofluvial sands beneath the varved sequence, as well as on high
interfluvcs of the Uralian piedmont, are OSL dated to c. 200 ka (samples 119 and 120 Pichuguy-Yaha in Table 3), which is consistent with a Middle Pleistocene age of the last ice advance on the Arctic Circle (Fig. 9). The underlying Middle Pleistocene till and terrestrial sand with peat are stratigraphically above the Arkhipov’s ‘Kazantsevo’ with TL-date of 153 ka, which means that the TL method underestimates the age, as compared to OSL dating. The better reliability of OSL datings has been independently confirmed by U/Th dating of the Seyda peat and by the above pollen data. Therefore, the sand with boreal foraminifera below sea level, is most likely Middle Pleistocene, probably Holsteinian.

Consequently, the deep lying Ob interglacial formation must be pre-Holsteinian, similar to the Kolva formation of the Pechora Basin with the same foraminifera assemblage (Gudina, 1976). This implies that the thickest (more than 100 m) till sequence, sandwiched between two interglacial marine formations, is not Saalian but older. Another important implication is that, accepting the traditional correlation of the Ob strata with the Tobol alluvium, the latter must be pre-Holsteinian. However, it is possible that the Tobol alluvium corresponds in the Arctic to the first marine formation with boreal foraminifera lying just bsl, i.e. to the ‘Kazantsevo strata’ by Arkhipov et al. (1977, 1994). In this case the lower marine formation, the Ob strata, may correlate with the Talagaika or even older interglacial deposits of the south (see below).

Middle Pleistocene tills of the eastern glaciated Arctic are poorly studied. The thick fine-grained diamictons directly underlying the Kazantsevo marine strata with boreal fauna were related to the marine or glaciomarine Sanchugovka formation with a sparse, predominantly Arctic fauna (Sachs, 1953; Lazukov, 1970; Zubakov, 1972) until Kaplyanskaya and Tarnogradsky (1975) thoroughly investigated the type section and found that the formation consisted of basal tills with rafts of marine sediments. The diamictons contain not only an Arctic fauna, but also shells of boreal and Cretaceous molluscs. The Sanchugovka till is believed to represent OIS 6, although Arkhipov (1989) thinks that below sea level there are real marine strata with Arctic foraminifera of OIS 7 underlain by tills of OIS 8.

One of the rare sections in which two interglacial marine formation are separated by the Murukta till can be seen is Novorybaynoye at the mouth of Khatanga river (10 in Fig. 1). The upper marine unit, which is not covered by till, is commonly interpreted as a deposit of the Eemian transgression, whereas the lower marine formation, containing foraminifera of the Milolimella pyriformis zone, and in another section farther to the west also Cyrtodaria angusta, is thought to represent the Siberian equivalent of the Holsteinian. The alternative stratigraphic model suggests an Eemian age for the lower marine unit and a mid-Weichselian age for the upper marine formation (Kind and Leonov, 1982). The latter interpretation is not only palaeontologically dubious, it is also at odds with the latest results of the QUEEN program which do not support a Late Pleistocene glaciation that far east (Svendsen et al., 2004). The traditional interpretation of this sequence in which the earlier transgression is thought to be Holsteinian (e.g. Gudina, 1976) suggests a Saalian age for the Murukta till, which agrees well with its widespread occurrence in Central Siberia.

4.2.3. Stratigraphy in the Subarctic

Best identifiable in this zone is the Samarovo till of the maximum glaciation named after the settlement close to the Irtysh mouth, where the famous thick sequence of stacked tills and Palaeogene opoka rafts has long been known (Shatsky, 1965). The additional diamict unit on top of the Samarovo till north of the Irtysh mouth is thought to represent the penultimate Taz glaciation. The Samarovo till, resting on the Tobol alluvium, is getting thinner upstream and disappears south of the Semeika village (5 in Fig. 1). North of this point a couple of additional tills beneath the Tobol formation are known from boreholes. The lowermost interglacial formation (the Talagaika alluvium) north of 63° N is overlain by a double diamict formation up to 70 m thick called the Shaitan till which is thought to correspond to the Semeika glaciolacustrine clay on the Irtysh (Volkova and Babushkin, 2000). The lowermost till (the Mansi till) is found beneath the Talagaika interglacial at the bottom of a drill well north of the drift limit on the Irtysh (Arkhipov, 1989).

There are two main problems with the till count in this zone. The first is connected with the Taz glaciation which is thought to predate the Eemian and deposit a till of limited distribution on top of the Samarovo glacial complex. Originally the Taz till was mapped in the upper reaches of river Taz, where it is separated from the underlying Samarovo strata by sands with ambiguous palaeontological characteristics. Later such a till was distinguished all over West Siberia. Although no interglacial formation with abundant organics has ever been found between the Samarovo and Taz till, the alleged Shirta interglacial, called ‘interstadial’ by more cautious geologists, persists in the regional stratigraphic schemes (Volkova and Babushkin, 2000). Interglacial organics are in general rare in Siberian inter-till formations. This led Lazukov (1970) to suggest that all till sheets along the Ob river are deposited by the maximum Samarovo glaciation, whereas (Arkhipov 1989; Arkhipov et al., 1978) tried to subdivide this sequence by means of thermoluminescence dating (A in Fig. 10).

According to Arkhipov the upper sand and silt in Kormuzhikhantka section on the Belogorye Upland
(loc. 6 in Fig. 1) is Eemian, and the overlying soft diamicton is therefore an Early Weichselian till (Fig. 10A). The till below the Eemian TL values belongs to the Taz glaciation of OIS 6, and the till next downwards—to the Samarovo glaciation of OIS 8. The lowermost till in this sequence is related to the Late Shaitan glaciation of OIS 10–12 (Arkhipov, 1989). This correlation does not contradict the latest PECHORA results in the Arctic Ob area. However, taking into account the too young TL dates in the Arctic zone, this lowermost till might be even older. As to the uppermost Kormuzhikhantka till, this soft, mantle-like diamicton, very low on pebbles, without structures of ice flow or shear planes at the base, is neither traceable regionally, nor associated with other glacigenic sediments. Therefore, it should be better viewed as a solifluction bed, or a flowtill derived from residual Middle Pleistocene ice, but not as a signature of a Late Pleistocene ice advance (Zolnikov, 1990). The latter interpretation fits the PECHORA data indicating no Late Pleistocene glaciation on the Ob along the Arctic Circle (Fig. 9).

Another problem is the correlation of the Ob-Irtysh ice advances with the Central Siberian events. As was pointed out, south of the Late Pleistocene ice limit on the Yenissei there are two tills separated by a marine formation with rare boreal shells (loc. 9 in Fig. 1). Zubakov (1972) relates the upper till to the last Middle Pleistocene glacial event called the Yenissei glaciation, OIS 6. This event is supposed to be identical with the Taz glaciation of West Siberia. Isayeva (1963) acknowledged this till as a counterpart of her second (Nizhnyaya Tunguska) belt of end moraines running around the Putorana Plateau between the drift limit and the Late Pleistocene Onyoka moraines. The Nizhnyaya Tunguska moraines in the northeast merge with the Murukta moraines, which in the stratigraphic scheme of Central Siberia are positioned above the Eemian level (Isayeva et al., 1986). This seems to be a miscorrelation because, according to the QUEEN results, the Early Weichselian maximum is represented by the youngest belt of the Onyoka moraines sensu Isayeva (1963) (see Taimyr discussion in Svendsen et al., this volume). Therefore, both Yenissei and Murukta tills should belong to OIS 6.

The till underlying the Pupkovo marine strata (loc. 9 in Fig. 1) is traditionally correlated with the Samarovo glaciation of OIS 8, which is thought to have reached the drift limit also on the Yenissei (Zubakov, 1972). However, it is more likely that the earlier boreal transgression, as on the Pechora and Ob, relates to the Holsteinian or OIS 11, thus making the lower till in the
Yenissei bluffs Elsterian in age. The official stratigraphic scheme keeps all these strata in the Bakhta superhorizon (Volkova and Babushkin, 2000) exemplified by the Bakhtinsky Yar section (B in Fig. 10, loc. 8 in Fig. 1). There is no indications of warm paleoclimates in the inter-till sediments traditionally correlated with the ‘Shirta interglacial’ (or interstadial) (Arkhipov and Matveyeva, 1964). This sequence is a rare case of the lower till overlying interglacial alluvium with a bone of *Alces latifrons*. The latter is characteristic of the Tiraspol (Cromer) mammalian complex (Arkhipov and Matveyeva, 1964; Arkhipov, 1975), which implies that the lower till in the Yenissei sections might well be Elsterian. Upstream of Bakhtinsky Yar a thicker till formation was found below the Bakhta strata in a borehole reaching 342 bsl. This so-called Lebed till is the lowermost member of the official stratigraphic scheme of Central Siberia (Isayeva et al., 1986).

Another key section is Khakhalevsky Yar close to the drift limit (C in Fig. 10, loc. 7 in Fig. 1). It represents the Turukhan alluvium (Arkhipov and Matveyeva, 1964), or Panteleyeva formation (Zubakov, 1972), sandwiched between two tills. The coarse channel alluvium overlying the lower till grades upwards into floodplain silts with gyttja and peat lenses, changing farther upwards into proglacial varves distorted by the maximum ice advance. The succession is capped by till and glaciofluvial sand. Pollen spectra of the channel alluvium show an upward increase of pollen of coniferous forests with predominance of *Picea* and *Pinus sibirica*. In the floodplain silts they are gradually replaced by *Betula* dominated parklands with abundant herbs, Ericaceae and *Selaginella selaginoides* (Levina, 1964). By these and other similar spectra the Turukhan alluvium is correlated with the Tobol alluvium of the Ob and Irtishy (Arkhipov, 1975). However, pollen spectra of the preceding Talagaika interglacial are not much different. Therefore, it cannot be excluded that the maximum glaciation on the Yenissei correlates not with OIS 8, as suggested by Arkhipov for the Samarovo glaciation, but with the preceding cold stages OIS 10 or 12.

The latter option is even more likely for the Central Siberian Upland, where the poorly preserved tills of the maximum glaciation are in a stark contrast with the inner belt of topographically expressive Nizhnyaya Tunguska moraines (Isayeva, 1963). There are authors who correlate the maximum glaciation limit of the eastern Central Siberia with the thick sequence of diamictons and stratified drift found by boreholes at 240 m bsl and lower on the bottom of the overdeepened Yenissei valley at Lebed (loc. 14 in Fig. 1). By its position under the sedimentary complex of the maximum Yenissei glaciation the Lebed double till sequence is similar to the Shaitan tills on the Ob (Volkova and Babushkin, 2000). However, the Lebed tills might even be pre-Elsterian in age.

4.2.4. How many ice advances?

The most pressing stratigraphic problem concerns the age of the two surficial tills—the Taz and Samarovo—overlying the Tobol horizon. They are traditionally related to OIS 6 and 8 correspondingly (Table 2). The alternative that both belong to OIS 6 is unlikely, because glacial landforms are not known atop of the Samarovo till covered by loess-like silts up to 15 thick. If the Tobol horizon proves to be pre-Holsteinian, and real interglacial landforms are found between the Taz and Samarovo tills, then the Taz till may relate to the Saalian (OIS 6) and the Samarovo till to the Elsterian.

The latter option was considered by Arkhipov based on TL and ESR datings. He concluded that the Tobol formation *s. stricto* might be pre-Holsteinian and therefore the Samarovo glaciation might be Elsterian. However, this alternative would upset the traditional correlation pattern and therefore not desirable for the time being (Arkhipov, 1989). Anyway, the great thickness of the tills underlying the penultimate interglacial in all major buried valleys suggests that Elsterian or earlier ice sheets of West Siberia were very large. It is quite possible that several ice advances are still hidden in the 70–100 m thick diamicic sequences of the buried valleys, where no good interglacial formations have been distinguished so far. The latest results of deep coring in Arctic West Siberia show that assemblages of arctoboreal foraminifera (previously perceived as the Holsteinian ‘zone of Milolina pyriformis’) occur at three different stratigraphic levels (Volkova and Babushkin, 2000). This makes correlation of the Arctic tills with the terrestrial record in the south even more difficult.

The above data allow to infer four major pre-Eemian ice advances in the Siberian record (Table 2). The oldest Mansi till reflects a more restricted ice sheet. In the present official stratigraphic scheme of West Siberia (Volkova and Babushkin, 2000) this ice advance is related to the Matuyama chron of reverse polarity, i.e. is thought to be older than 700 ka, although Arkhipov (1989) preferred to place it at OIS 18. The thickest Shaitan tills separated by stratified drift with Arctic foraminifera are certainly pre-Holsteinian but within the Brunhes chron, their more precise correlation with the European record being premature. The correlation with OIS 12–16 suggested by Arkhipov (Table 2) is only based on very old and therefore hardly reliable TL dates. The maximum glaciation (OIS 8, or 10, or 12) probably produced the thickest (up to 3.5 km) ice sheet that grew over the Kara Sea shelf and eventually overrode nearby mountain ranges up to an altitude of 1 km. The last Middle Pleistocene ice sheet called the Taz (or Yenissei, or Murukta), judging by the fresh glacial landforms, was formed in OIS 6. It was thick enough to cover almost the same area as the maximum glaciation and flow southwards over the low mountains.
5. Conclusions

(1) The huge ice sheets, much larger than the Weichselian ones, at least 4 times covered the Russian mainland and adjacent shelves prior to the Eemian.

(2) The main centre of ice accumulation was the Kara Sea shelf, additional sources of inland ice being Fennoscandia and the Barents Sea shelf in European Russia, and the Putorana Plateau in Siberia. The Ural Mountains played mostly the passive role of an orographic barrier in the ice flow pattern.

(3) The extent and geological work of the coalesced ice sheets imply an Antarctic type of glaciation with ice thickness up to 3.5 km. Unlike Antarctic and most of North Atlantic ice sheets, North Russian continental glaciers acted on predominantly soft and perennially frozen substrate, which was deeply affected by pervading glaciectonism.

(4) The thickest tills are found beneath interglacial formations similar to the Holsteinian, suggesting that the most extensive ice sheets are pre-Saalian not only in European Russia, but probably also in Siberia.

(5) During the maximum (Cromerian) glaciation and subsequent ice ages (OIS 16 to 10) the influence of the Fennoscandian ice dome was limited in northern European Russia. The Fennoscandian ice sheet, however, culminated during the penultimate glaciation (OIS 6), when shelf sources of inland ice were less powerful than in pre-Holsteinian times.

(6) The drift limit in Northern Russia is time-transgressive, being certainly pre-Holsteinian in northeastern Europe, probably OIS 8 in West Siberia and getting older east of the Yenissei.

(7) There are several unsolved questions concerning correlation of the marine transgressions with terrestrial interglacial events. The reliability of the correlation of Russian pre-Eemian interglacials with their western European counterparts noticeably decreases northwards and eastwards partly because of the insufficient data available, and also due to the fading biotic signal of the climatic fluctuations.

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