Quaternary Glaciations – Extent and Chronology
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Glaciations of the East European Plain - distribution and chronology

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The East European Plain is one of the regions which were repeatedly subjected to the expansion of large continental ice sheets. A notion of three ice sheets expanding successively into European Russia developed in the 1930s. They are known as the Oka, Dnieper and Valdai glaciations and were tentatively correlated with Mindel, Riss, and Würm of the Alpine region. Since then views on the number of glaciations and on the periodicity of glacial events has undergone a considerable revision (Fig. 1). Biostratigraphical and lithostratigraphical evidence suggest that first strong cooling which might have resulted in glaciation occurred as early as 2.4 to 1.8 million years ago (Frenzel, 1967; Grichuk, 1981), although no glacial deposits dating from this interval have been found. Vast ice sheets expanded into the European part of Russia for the first time beginning with the Brunhes Epoch. They are

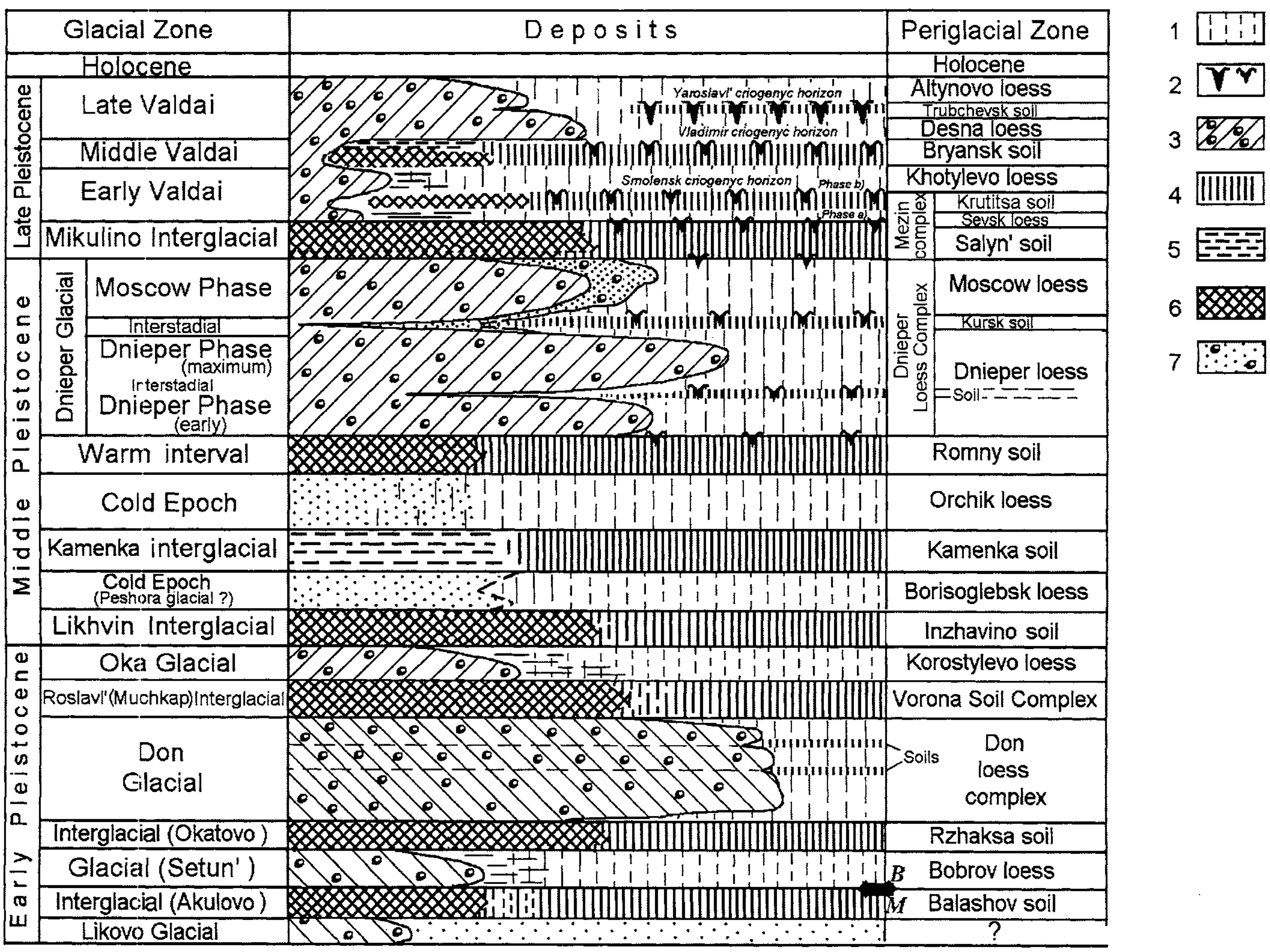

Fig. 1. Correlation between glacial and periglacial stratigraphy.

1 – loess,
2 – frost deformations,
3 – till,
4 – fossil soil,
5 – lacustrine deposits,
6 – peat deposits,
7 – glaciofluvial deposits.

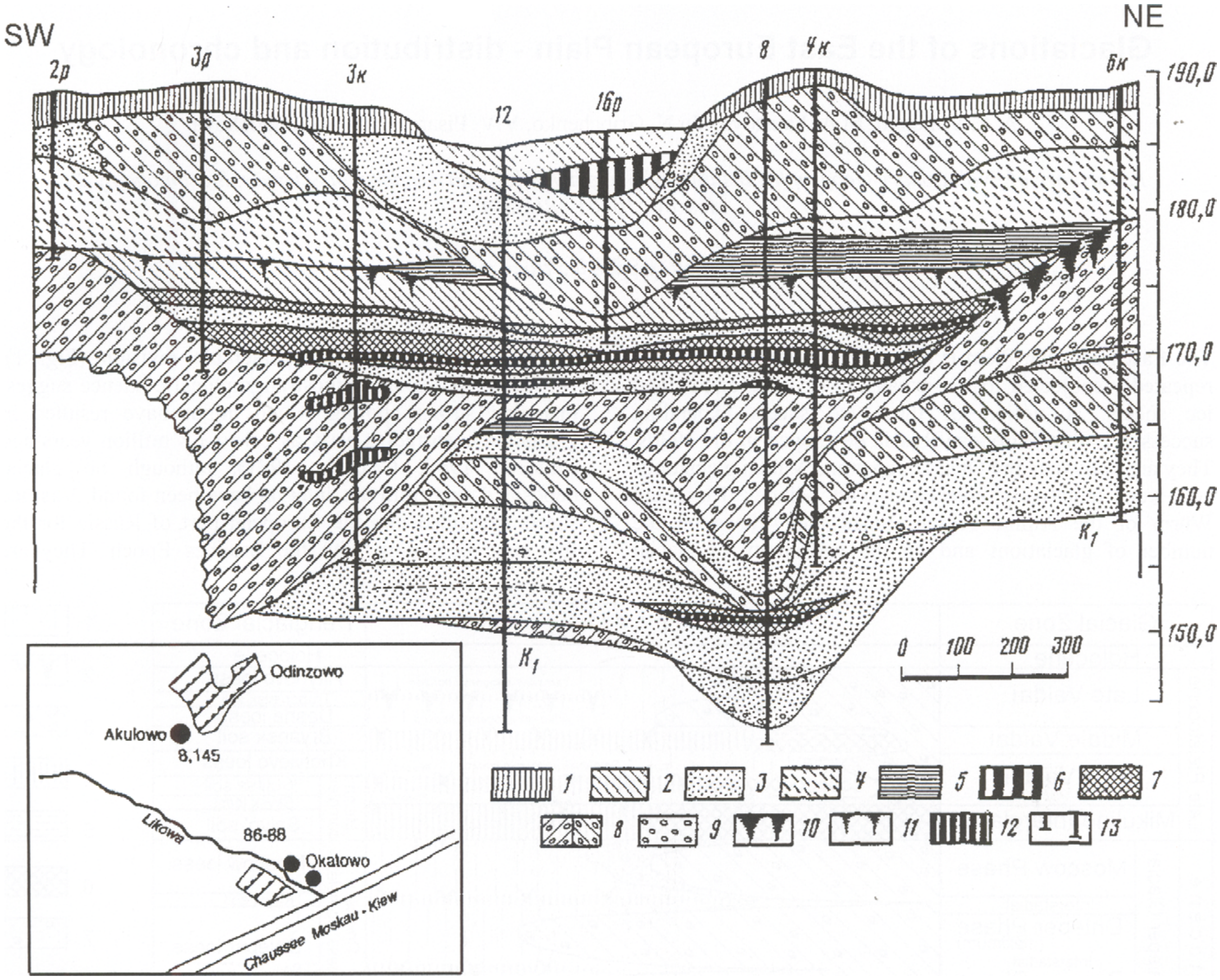

Fig. 2. Longtitudinal section of the Akulovo site.
1 - cover loam, 2 - lacustrine loam, 3 - sand, 4 - sandy loam, 5 - clay, 6 - peat, 7 - gyttja, 8 - diamicton (till), 9 - gravel and pebble, 10 - fossil soils, 11 - weakly comminuted fossil soils, 12 - detached blocks, 13 - boreholes.

associated with the Tiraspolian (faunal) period that corresponds to the 'Cromerian Complex' Stage in the Western European chronostratigraphy.

Likovo Glaciation

The oldest glaciation is correlated conventionally with 'glacial a' of the 'Cromerian Complex'; it expanded as far south as the latitude of Moscow. The so-called 'Likovo' till, attributed to this ice sheet, was only discovered in the 1980s, after members of the Geological Survey of the Central Regions of the East European Plain had thoroughly examined many boreholes in the Moscow region (Fig. 2). It has not yet been found elsewhere (Maudina *et al.*, 1985). Boreholes west of Moscow, near the western margin of the town of Odintsovo (Akulovo village) penetrated the till near the base of the Quaternary sequence. It is represented by black or greenish, dark grey loam including abundant gravel and small pebbles of sedimentary rocks (predominantly flint and limestone). Crystalline (augitite and rosé fine-grained granite with a grain size less than 1-2 mm) gravel is only occasionally found. No rocks of certain Scandinavian origin are recorded in any of the sections. The heavy-mineral composition is typically garnet-disthene-tourmaline. In the Don drainage basin, this cryochron (cold stage) is probably represented by the loess unit exposed in the Troitskoye section beneath the oldest soil. The fossil fauna of the latter is dominated by the ground squirrel *Citellus* (Krasnenkov *et al.*, 1997). The Troitskoye fauna's antiquity is suggested by presence of *Prolagurus pannonicus* KORM. and the abundance of European vole *Pitymis hintoni* KRETZOI (Agadjanian, 1992). A similar

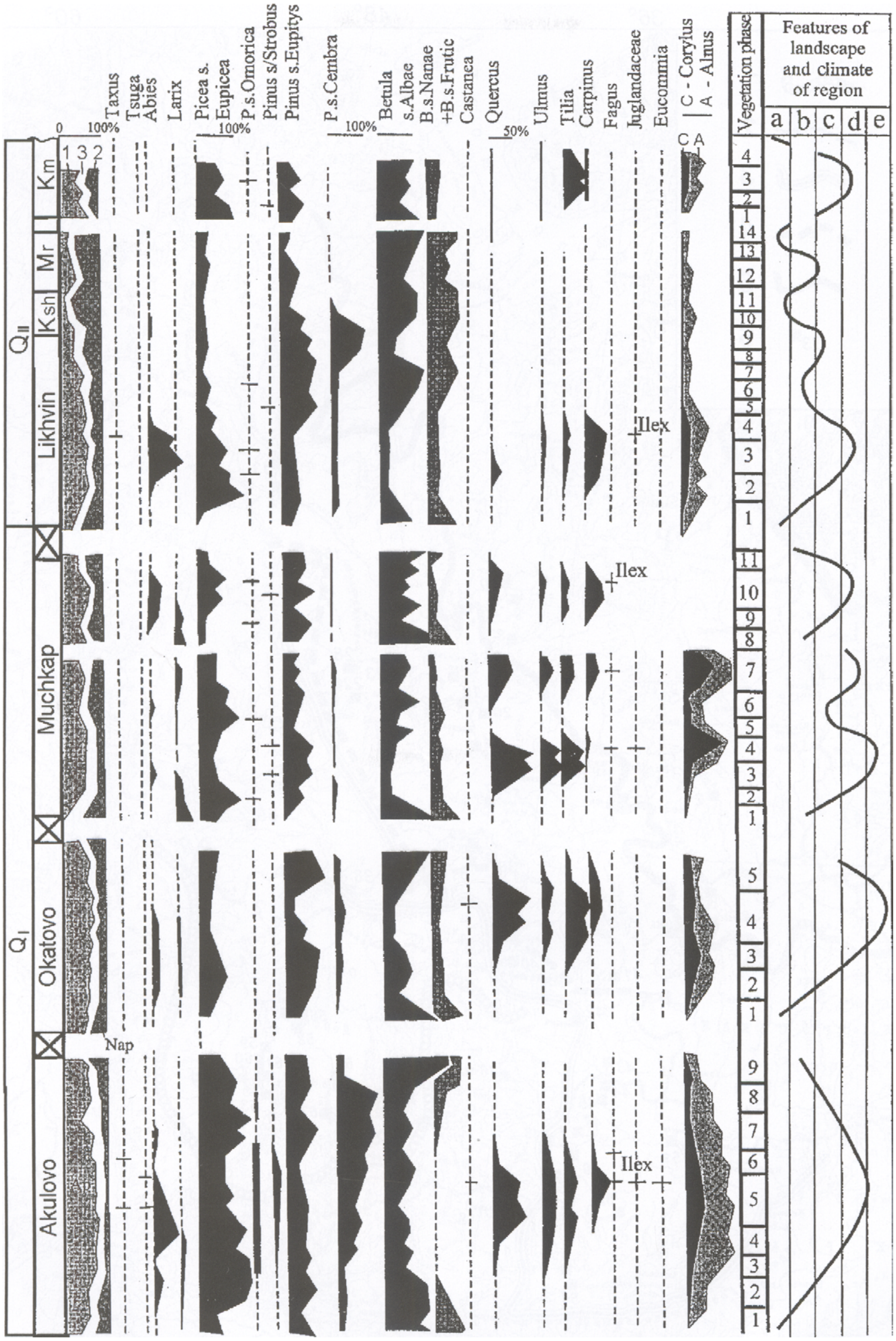

Fig. 3. Composite pollen diagram of the Lower- and Middle Pleistocene deposits in the northern and western Moscow region. General composition: 1 – AP, 2 – NAP, 3 – Spores; a - periglacial forest-steppe, b - tundra and forest-tundra, c - coniferous and deciduous forests, d - coniferous-broad-leaved forests, e - broad-leaved forests. Indices: Ksh – Kosha Interstadial, Mr - Maryno Interstadial, Km – Kamenka Interglacial.

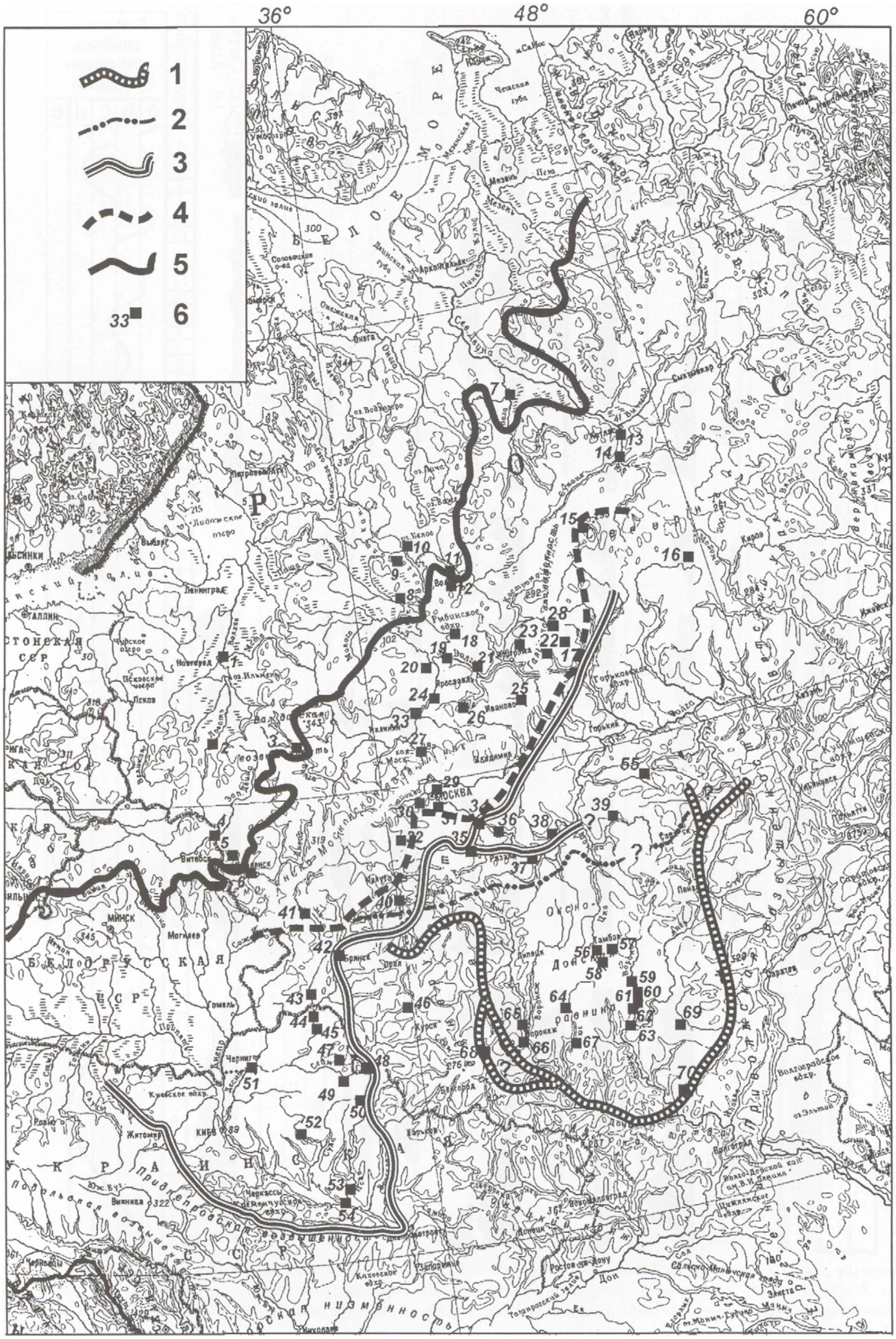
36°
48°
60°
64°
56°
48°
1
2
3
4
5
6
33
МОСКВА

Fig. 4. Glacial limits and key sections in the East European Plain.(opposite page)

The boundaries of the ice sheets:
1 - Don,
2 - Oka,
3 - Dnieper,
4 - Moscow (Warta),
5 - Valdai.

Key sections:
1 - Savino (dn., ms, vd),
2 - Lyakhovo (dn, ms, vd),
3 - Bulatovo, Tyaglitsy, (ok, lh, ms),
4 - Drichaluki, Shapurovo (ms, vd),
5 - Mikulino (mk, vd),
6 - Smolensk, Kuchino (dn, ms, mk),
7 - Shenkursk (vd),
8 - Cherepovets (dn, ms, mk),
9 - Moeksa (dns, dn, vd),
10 - Ferapontovo (dns, dn, vd),
11 - Puchka (dn, ms, vd),
12 - Molochnoe (dn, ms),
13 - Kotlas (dns, dn, ms),
14 - Veliky Ustyug, Dymkovo (dns, dn, ms),
15 - Anyuk (dn, mc),
16 - Vavilyata (pre-dns, dns),
17 - Pepelovo (dns, mč),
18 - Yakovlevskoe, (ok, lh, dn, ms),
19 - Rybinsk, Chermenino (pre-dns, dns, lh, dn, ms),
20 - Shestikhino (ms, vd?),
21 - Tutaev, Dolgopolka (ms, mk,),
22 - Chelsma (dns, mč, dn-ms),
23 - Zakharyino(dns, mč , dn, ms),
24 - Verkhniye Ploski, Altynovo (dns, dn, ms),
25 - Bibirevo(dns, mč, ms),
26 - Cheremoshnik (ms, mk),
27 - Dmitrov (ms, mk),
28 - Gorki (dns, mč, ms),
29 - Balashikha (dns, mč ms),
30 - Akulovo (pre-dns, dns, mč, ms),
31 - Okatovo (pre-dns, dns, ok, ms),
32 - Borovsk, Satino (pre-dn, dn, ms),
33 - Alkhimkovo (pre-dns, dns, ok, lh, dn - ms),
34 - Golutvin, Gololobovo (dn, ms),
35 - Zaraisk, Solomovo (dns, dn, mk),
36 - Alpatyevo (dns, pre-dn, mk),
37 - Troitsa, Fatyanovka (dns, ok, pre-dn, dn),
38 - Elatma, Kasimov (pre-dn, dn),
39 - Narovatovo (dns, ok, lh),
40 - Chekalin, Bryankovo (dns, ok, lh, dn),
41 - Roslavl, Konakhovka, Malakhovka, Sergeevka (pre-dns, dns, mč, ok, lh, ms),
42 - Bryansk (dn, mk),
43 - Pogar (dn, mk),
44 - Pushkari (dn, mk),
45 - Arapovichi, Mezin (dn, mk).
46 - Zheleznogorsk (pre-dn, mk),
47 - Banichi (dn, mk),
48 - Markovo (dn, mk),
49 - Igorevka (lh, dn, mk),
50 - Gadyach (dn, mk),
51 - Novoselki (dn, mk),
52 - Priluki (pre-dn, dn, mk),
53 - Ostapye, Gunki (lh, dn, mk),
54 - Gradizhsk (dn, mk),
55 - Lukoyanov (pre-dns. dns), .
56 - Tambov (dns, mč - dn),
57 - Rasskazovo (dns, mč, lh - dn),
58 - Kotovsk (dns, pre-dn),
59 - Inzhavino (dns, mč, lh, pre-dn),
60 - Muchkapsky, Korostelevo (dns, mč, lh, pre-dn, mk),
61 - Bolshaya Rzhaksa, Perevoz, Posevkino (pre-dns, dns, lh, pre-dn),
62 - Borisoglebsk (dns, mč, pre-dn, mk),
63 - Novokhopersk (pre-dns, dns),
64 - Polnoye Lapino (dns, mč),
65 - Bogdanovka, Verkhnyaya Emancha (dns, mč, lh, pre-dn),
66 - Uryv (pre-dns, dns),
67 - Klepki (pre-dns, dns),
68 - Stolinsky (pre-dns, dns),
69 - Nizhne - Dolgovsky (dns, mč),
70 - Mikhailovka (pre-dns. dns, pre-dn, mk).

faunal assemblage was recovered from ancient fluvial sediments near the Karai-Dubina (Dnieper drainage basin) by Markova (1982) who attributed it to the final stage of the Matuyama Epoch.

Akulovo Interglacial

The following interglacial, the Akulovo, was identified in the Akulovo section mentioned above and at another site at Krasikovo (south-eastern Tver region, near Kimry). It is characterized by the oldest seed flora (Maudina *et al.*, 1985), including over 30% of local and regional exotic taxa and more than 11% of extinct species.

The antiquity of the Akulovo flora which bears similarities to undoubtedly Pliocene assemblages is suggested by the diversity of the coniferous pollen present with high percentages of *Pinus sec. Cembra* (up to 30-50%), *P. sec. Strobus* (up to 5-8%), as well as *P. sec. Mirabilis, P. sec. Omorica, Tsuga* and *Taxus*. Of the broad-leaved taxa (which comprise 35-50% at the climatic optimum) *Quercus, Ulmus, Carpinus, Zeltis, Zelkova, Fagus, Pterocarya, Juglans, Castanea, Ilex, Morus, Eucommia, Vitis, Ligustrum, Corylus, Ostrya* and *Myrica* are all represented (Fig. 3).

The subsequent cooling restored a tundra-like landscape to the Moscow region.

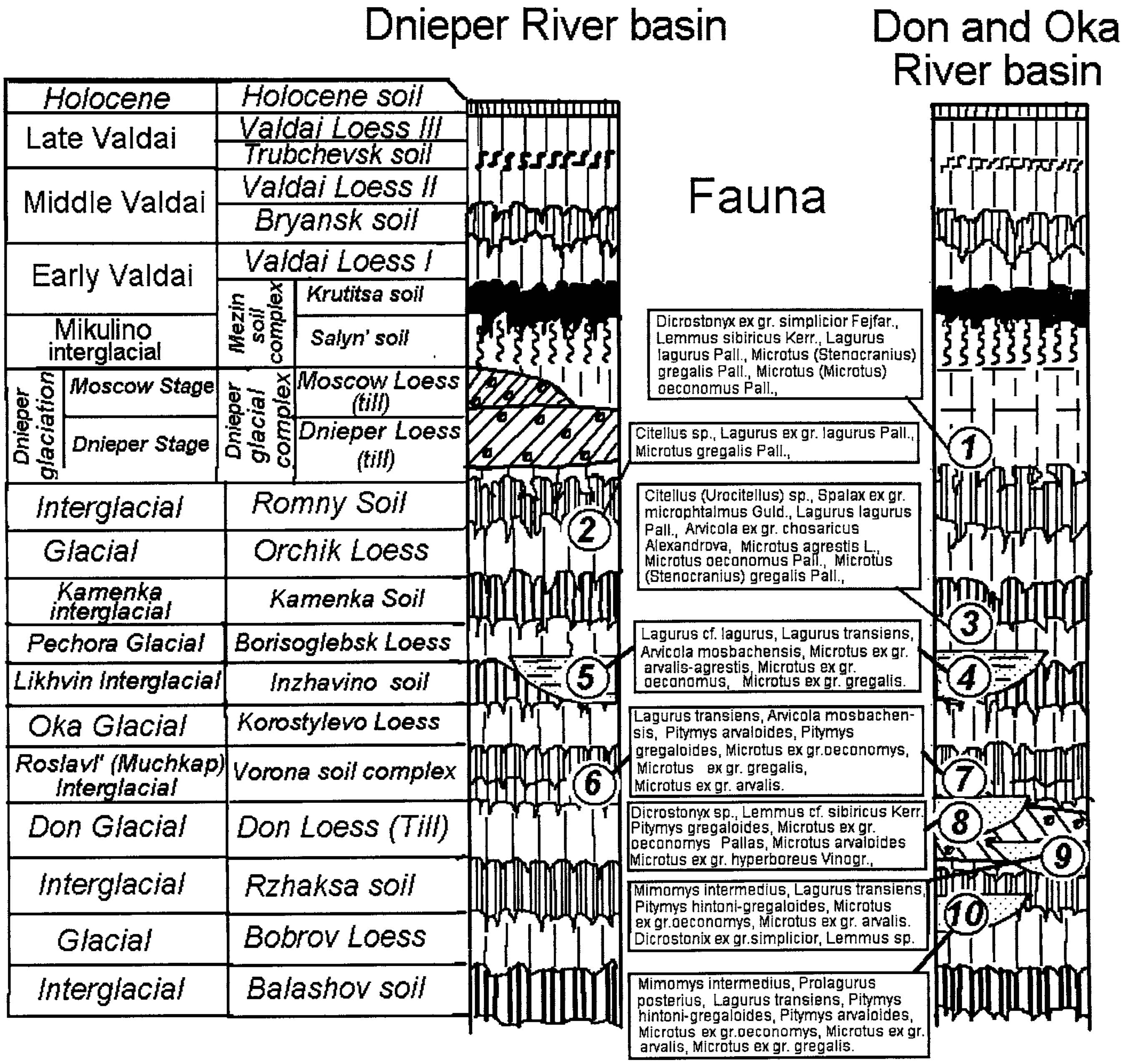

Fig. 5. Correlation between the glacial and interglacial units and stratigraphical position of tills in the Dnieper and Don river basins. Key sections: 1-Alpatjevo, Troitsa, 2-Priluki, 3-Rasskasovo, 4-Verkhnyaya Emancha, 5-Gunki, 6-Roslavl, 7-Posevkino, Perevoz, Muchkap, 8-Troitsa, 9-Bogdanovka, 10-Klepki (by Velichko et al., 1977).

Setun' Glaciation

The so-called Setun' ice sheet (named after the Setun' River in the Moscow region) expanded as far south as the northern margin of the Tula region. The Setun' Till (described by the Geological Survey team) is represented by massive brownish and greenish dark-grey loams and sandy loams. Magmatic rocks of Scandinavian provenance comprise about 40 to 60% of the clasts. The till is characterised by an amphibole-epidote-garnet-disthene mineral association.

The interglacial that followed the Setun' Glaciation has been studied in detail, however, much of its sediments were destroyed by the subsequent (and by far the largest) ice sheet. Fragmentary data on flora and fauna have so far only been obtained for the middle Volga drainage basin, in the vicinity of Nizhny Novgorod (Pisareva, 1992).

Okatovo Interglacial

The subsequent interglacial is known as the 'Okatovo' warm Stage. Its deposits were drilled west of Moscow, 4 km east of Vnukovo station, near Okatovo (Fursikova *et al.*, 1992) and near Skhodnya station, at Dubrovka. This younger flora is poorer than the Akulovo in every respect. Unlike the previously described interglacial, its climatic optimum featured polydominant broad-leaved forests (with several - 5 to 10 on the average - dominant tree species), primarily composed of oak, elm, and lime trees, and later with hornbeam and other species characteristic of a mild temperate climate (Fig. 3).

That the Akulovo and Okatovo warm stages are really separate interglacials is attested by the fact that each of them was preceded by an essential cooling when open birch forests with some cryoxerophyllic plant communities expanded into the region.

Don Glaciation

The subsequent expansion of the ice sheet known as the Don Glaciation corresponds to the maximum ice extent on the East European Plain. Its age is determined primarily from its relation to palaeontological evidence from over- and underlying sediments. Until the late 1970s it was generally assumed that the maximum glaciation on the East European Plain was the late Middle Pleistocene Dnieper (Saalian) Glaciation, and the oldest known ice sheet, the Oka ice sheet was correlated to the Elsterian Stage in western, central Europe.

New multidisciplinary studies and analysis of the relations between tills belonging to the two largest ice lobes of Russia (the Dnieper and the Don lobes) on the one hand, and loess-palaeosol periglacial sequences on the other, revealed that the tills of the two lobes differed substantially in age (Gerasimov & Velichko, 1980). Studies of loess and soil horizons exposed in many sections and analysis of palaeontological evidence allowed the identification of several glacial stages in which active loess accumulation occurred (Fig. 5). In contrast to the glacial sequence of the Dnieper lobe that was formed by the largest Middle Pleistocene ice sheet, the Don Till was deposited by the largest of all the Pleistocene ice sheets dated to the Tiraspolian. The limits of the Don ice sheet are only clearly defined east of the Central Russian Uplands, while to the west their position is indistinct. The maximum glaciation of the East European Plain, the Don Glaciation, expanded far south, into the drainage basin of the middle and lower Don (fig. 4). Unfortunately, thermoluminescence (TL) dates obtained for the till exposed in sections west of Moscow and in the Kostroma region show a wide scatter - from 365±90 to 595±150 ka BP (Fursikova *et al.*, 1992).

The correlation of the Don Glaciation to the 'Cromerian Complex' Stage has been substantiated by investigations of glacial and loess-palaeosol sequences in the Don and Dnieper drainage basins. Palaeontological evidence has confirmed beyond any doubt the late Tiraspolian age of fossil rodent remains recovered from numerous sections both above and below the Don Till (Gerasimov & Velichko, 1980; Krasnenkov *et al.*, 1997). At most sites (Vol'naya Vershina, Korotoyak-4, Korostelevo-2, Kuznetsovka and others in the Don basin, as well as in the vicinity of Roslavl', at Konakhovka, Podrudnyansky and Sergeevka in the Dnieper basin) the late Tiraspolian small mammal remains recovered from the beds immediately underlying the till are somewhat older than those found in the overlying sediments. Thus, a fauna dominated by *Lemmus* in combination with *Mimomys, Pitimys* and *Microtus oeconomus* has been identified in the overlying sediments. These assemblages compare closely to the Tiraspolian faunas in Moldavia, Czechoslovakia, Hungary, and France (Aleksandrova, 1982; Agadjanian, 1992). The investigations have provided corroborative evidence for the different age of the ice lobes extending southward into the Dnieper and Don basins, as well as for the different age of their tills. Consequently, the Cromerian palaeogeography of the East European Plain has had to be revised (Fig. 5). The Don Formation glacial sequence as a rule is between 3-5 and 15-20 m thick and consists of several till units which can be traced all over the Don lobe area. Individual strata differ slightly in both composition and clast orientation (Grishchenko, 1976; Shick, 1984; Sudakova & Faustova, 1995). The most characteristic feature of the Don Till is its abundance of small gravel, while large pebbles and boulders are only occasionally found. Most large particles are derived from local sedimentary rocks varying in composition throughout the area, whilst far-travelled clasts are chiefly granites, metamorphic rocks, and quartzite-like sandstone (Fig. 6). The maximum content of the 2 to 5 cm debris (up to 15-20%) has been found in the western portion of the lobe; in the central and eastern parts debris concentration decreases to 4-7% (Gribchenko, 1980; Maudina *et al.*, 1985).

With regard to crystalline indicator rocks, the Don Glaciation tills differ markedly from all the other tills in the central, northern and northwestern Russian Plain (Fig. 6). The fact that the Don Till lacks the main index rocks which Chirvinsky (1914), Yakovlev (1939), Viiding *et al.* (1971) have identified in the Middle and Late Pleistocene tills, suggests a more northeasterly position of the Don Glaciation centre. This is supported by a southwestern orientation of clasts in many sections (e.g. Gerasimov & Velichko, 1980). The mineralogy of the Don Till matrix varies considerably regionally. In contrast to the younger tills, minerals of local and medium distance provenance dominate, whilst the actual percentages of exotic minerals, such as hornblende, amphibole, pyroxene and biotite, do not exceed 6-10%. Amphiboles are more frequent in the western sector, whilst epidote, tourmaline, ilmenite and rutile are most typical of the central and eastern sectors. The most conspicuous result of relief-forming activities of the Don ice sheet are numerous linear depressions eroded

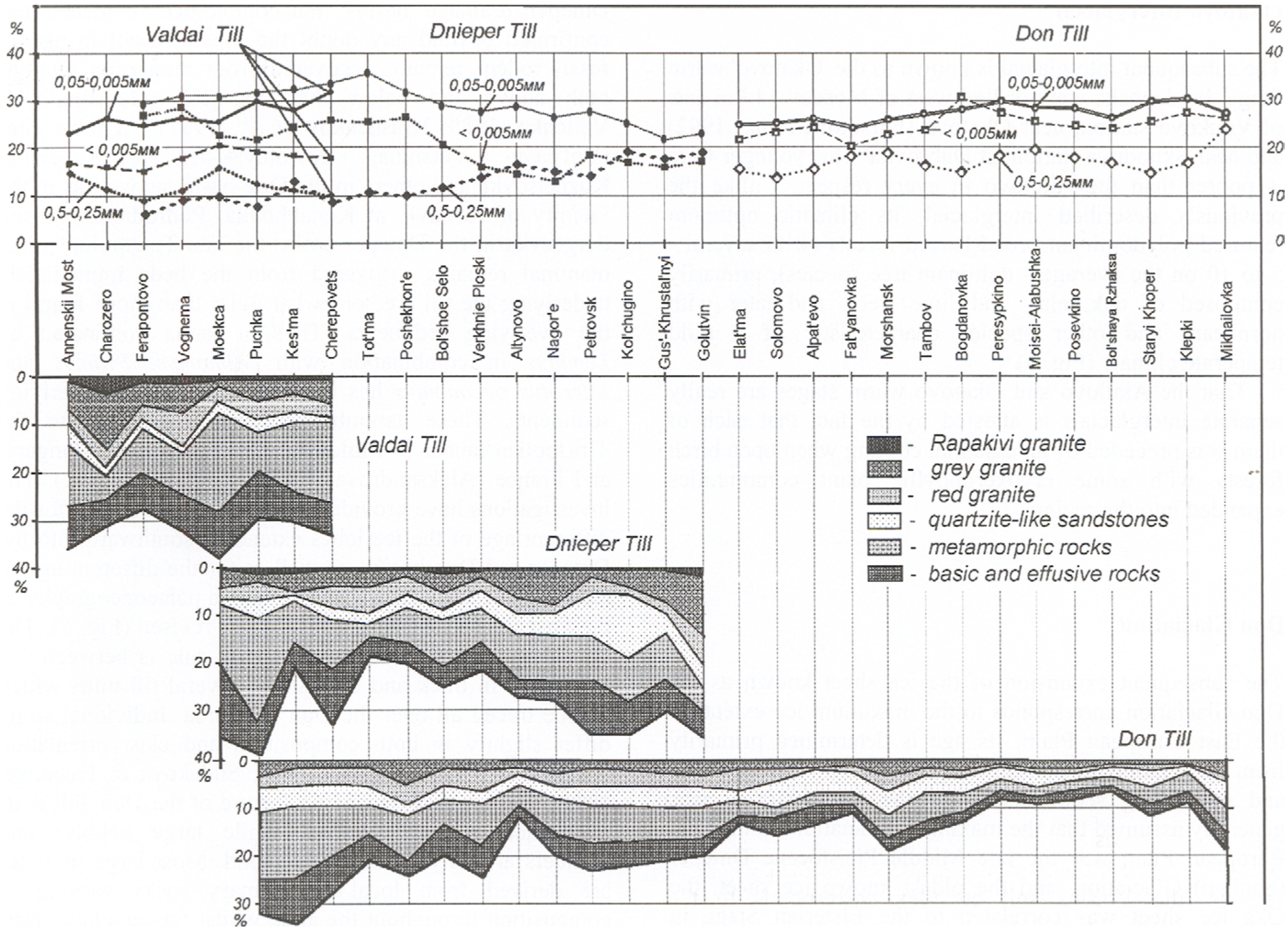

Fig. 6. Composition of tills of different ages.

by the moving ice. Later, during the Muchkap Interglacial Complex they were filled with sediments characterised by a late Tiraspolian rodent fauna (Agadjanian, 1992).

Muchkap Interglacial

The Muchkap Interglacial is characterised by two or perhaps even three climatic optima that alternate with cooler climate phases. The two earliest optima (Glazov and Konakhovka) were recognised in sections within the Roslavl' region near Konakhovka, in the upper Dnieper drainage basin (Fig. 7, 8) (Biryukov *et al.*, 1992) and in the Moscow region, at Akulovo (Maudina *et al.*, 1985). The third optimum is represented in the Akulovo section and also at Balashikha, east of Moscow, and at Galich city in the upper Volga basin (materials obtained by Pisareva). During the first (Glazov) optimum polydominant broad-leaved forests were established in the area between 59°N and 51°N. Mild temperate species, such as *Juglans, Pterocarya* and *Carya*, grew in the upper Dnieper basin. *Pterocarya* even grew at the latitude of Moscow. In the second (Konakhovka) optimum, *Quercus* and *Carpinus* forests grew in the upper Dnieper basin, and forests of *Pinus* and *Picea* and an admixture of *Carpinus* were common near Moscow. During the possible third (Galich) optimum, they were replaced by coniferous-broad-leaved forests with *Abies* and *Carpinus*. Cooler intervals between the optima were characterised by a boreal vegetation, with dominant spruce or spruce-pine forests in which bogs developed locally.

The most distinct palaeofaunal and palaeofloral characteristics of the Muchkap interglacial deposits were determined from sections in the Oka-Don Lowland, the upper Dnieper basin, near Roslavl' and in the vicinity of Moscow. Late Tiraspolian fauna recovered from organic sediments, which were attributed to the late Middle Pleistocene until recently (up to the 1980s), allow the latter to be correlated to the same interglacial. Spore and pollen spectra and plant macrofossil remains from the Muchkap = Roslavl' sediments at Konakhovka (near Roslavl') and Sergeevka (also in the upper Dnieper basin) include taxa indicative of their antiquity including *Ligustrina amurensis* RUPR., *Pterocarya* sp., *Juglans* sp., *Carya* sp., *Tilia* cf. *amurensis* RUPR. and *Woodsia* cf. *manchuriensis* HOOK. On the whole, the Muchkap = Roslavl' sediments correlate well

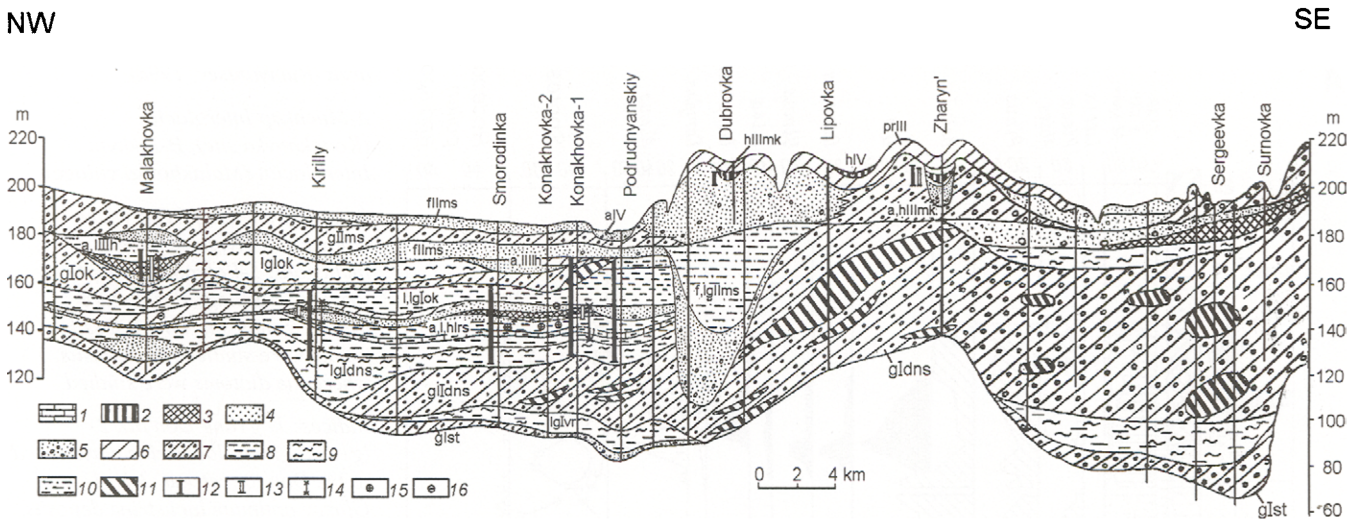

Fig. 7. Longitudinal geological section of the Roslavl area (Konakhovka and Sergeevka sites). Compiled by Pisareva, after Zarrina (1991) and Rumyantsev (1998)
1-marl, 2-peat, 3-gyttja, 4-sand, 5-sand with pebbles, 6-loam, 7-boulder clay (till), 8-glacio-lacustrine clay, 9-glacio-lacustrine loam, 10-sandy loam, 11-detached blocks.
12-position of palynological samples, 13-position of carpological samples, 14-position of samples for diatom analysis, 15- thermophyllic small mammals, 16-cryophyllic small mammals.

with those described from the Ferdynandow section in Poland (Janczyk-Kopicowa, 1975). Thus, the relationship of the Roslavl' to Likhvin (Holsteinian) floras can be clarified: the Roslavl' sediments occur between the Don and Oka tills, whereas the Likhvin interglacial deposits overlie both tills. In the loess-palaeosol sequences of the periglacial regions, the Vorona soil complex corresponds to the Muchkap Interglacial. It has been extensively investigated in a number of key sections within the Don and Dnieper basins using palaeopedological and palaeofaunal methods (Markova, 1982; Agadjanian, 1992).

Oka Glaciation

The Oka Glaciation can be correlated with the Elsterian Stage of central Europe. From about 500 to 460 ka BP, the Oka ice sheet reached as far south as the Oka River basin. However, the recognition of its exact boundaries is still unsettled.

Unfortunately, the central regions of the East European Plain generally lack sections where the till of Oka age can be unambiguously demonstrated by its relation to overlying and underlying glacial and interglacial strata associated with loess and fossil soils. In a few sections, where the till is present, its age is inferred from its lithology which is closely similar to that of the other older tills. It is grey, greenish grey or greyish brown and contains gravel of local provenance, together with rare clasts of exotic rocks. The till can be identified by its relatively low hornblende content (Sudakova, 1990).

Judging from clast orientation, the ice moved into the East European Plain from north to south. Exotic rock fragments are more abundant in the Oka Till than in the Don Till. Sedimentary rocks are dominant, together with an admixture of erratic boulders of granite, gneiss and igneous rocks. The most typical heavy mineral association is garnet - hornblende. The Oka Till has been most reliably identified in the Upper Dnieper and Upper Volga basins; in the sections of Malakhovka (Smolensk region), Maryino and Pan'kovo (north of Moscow) the till grades into glaciolacustrine and glaciofluvial sediments and then into lacustrine and paludal deposits. The severe climate of the Oka Cold Stage is suggested by bones of cold-tolerant animals (such as *Dicrostonyx simplicior okaensis* ALEXANDROVA) found in the Chekalin section on the Oka River (Aleksandrova, 1982) and in the Mikhailov quarry in the Kursk region (Agadjanian, 1992) as well as teeth of *Microtus ex gr. hyperboreus* VINOG. at Bogdanovka in the Upper Don basin (Markova, 1982). At present this vole inhabits tundra and forest-tundra.

Likhvin Interglacial

The Likhvin Interglacial, which followed the Oka Glaciation, correlates closely with the Holsteinian Stage of central Europe. The interglacial deposits are exposed in the Chekalin stratotype and in other type sections at Yakovlevskoye and Rybinsk in the Yaroslavl' region, at Malakhovka in the Smolensk region (Fig. 7), and at Maryino and Pan'kovo near Moscow (Fig. 3). Comprehensive faunal and floral evidence from these deposits have been published (Markov, 1977; Grichuk, 1989; Pisareva, 1997). The Likhvin fauna includes archaic *Arvicola mosbachensis* SCHMIDTGEN which replaced *Mimomys intermedius* NEWTON. The wealth of evidence not only permits the reconstruction of the interglacial climate and vegetation, but also the understanding

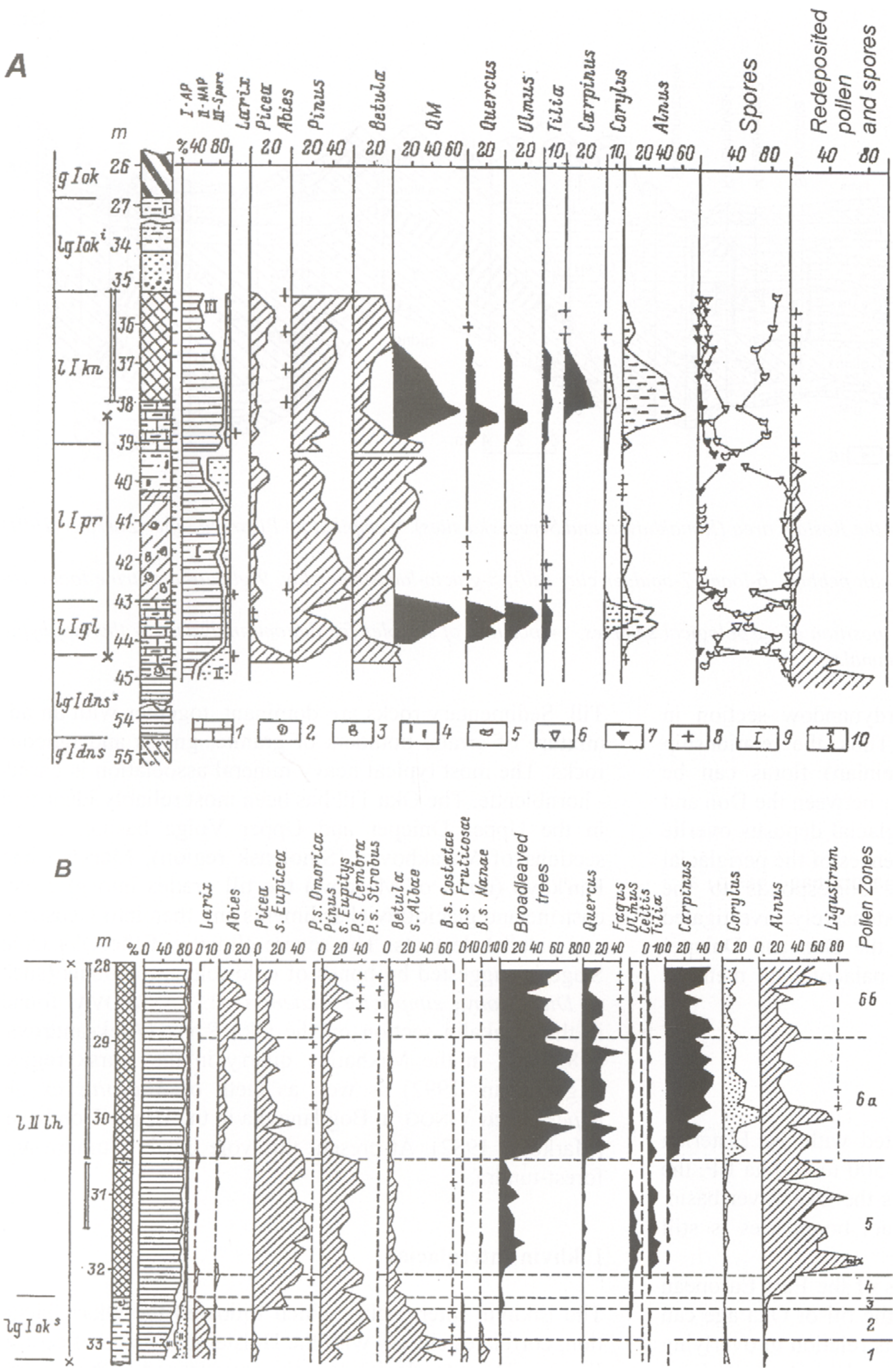

Fig. 8. Pollen diagrams of the deposits in the Roslavl stratotype area (Rumyantsev, 1998)

A-Muchkap Interglacial (Konakhovka site), B-Likhvin Interglacial (Malakhovka village)

1-marl, 2-shells of fresh-water molluscs, 3-vivianite, 4-peat inclusions, 5-Polypodiaceae, 6-Bryales, 7-Sphagnales, 8-rare grains, 9-deposits, where fossil plants were studied, 10-deposits, where the diatoms were studied.

Indices: 1- gldns-Don till, 2-lgldns^s-glacio-lacustrine clays dated to the Don ice retreat, 3-llgl-Glazov optimum lacustrine deposits, 4-llpr- Podrudnyanski cooling lacustrine deposits, 5-llkn-Konakhovka optimum lacustrine deposits, 6-lglok^i glaciofluvial deposits associated with the advance of the Oka ice sheet, 7-glok-detached block of the Oka Till, 8-lglok^s-glaciolacustrine deposits of the time of Oka ice retreat, 9-llllh-Likhvin Interglacial lacustrine deposits.

of the landscape zone dynamics (Grichuk, 1989; Pisareva, 1998). The whole area under consideration, including the southernmost regions, was positioned within the forest zone, although the forest differed in composition. South of the latitude of Moscow, a mixed polydominant coniferous-broad-leaved forest grew, in which first oak and hornbeam and later hornbeam and fir assemblages prevailed. Increased rainfall enabled the forests to expand into the Don basin. The temperate, slightly oceanic climate favoured the continued presence of relict plants, such as *Taxus, Ilex, Castanea, Buxus, Pterocarya* and *Fagus*; their pollen have been recovered from the Likhvin stratotype section at Chekalin (Grichuk, 1989). Many of the taxa only occurred occasionally at the latitude of Moscow and were completely absent farther north. There composite spruce forests with *Quercus, Carpinus* and *Abies* occurred.

A sequence of alternating warm and cold phases between the Likhvin Interglacial and Dnieper Glaciation

The results of recent investigations have shed new light on the sequence of Middle Pleistocene cold and warm stages. Additional large-scale climatic fluctuations have been recognised within the interval between the Likhvin Interglacial and the Dnieper (Saalian) Glaciation. Detailed investigations into the relationship between glacial and loess-palaeosol series in the periglacial areas have revealed that the Likhvin Interglacial is represented in these areas by the Inzhavino soil (Velichko *et al.*, 1997a). Until the late 1960s the Dnieper Glaciation was assumed to have occurred immediately after the Likhvin Interglacial. However, Moskvitin (1967) pointed out that there were palaeosols between the Likhvin and Dnieper layers. Recently, studies of loess-palaeosol sequences have confirmed the existence of an additional interglacial between the Likhvin Warm Stage and the Dnieper Glaciation which corresponds to another palaeosol, the Kamenka soil (Velichko, *et al.*, 1992, 1997a). As follows from palaeobotanic data, no less than two interstadials occurred subsequent to the Likhvin Interglacial (Fig. 3) The Kosha Interstadial is exposed in sections at the Bolshaya Kosha river near Bulatovo and Tyaglitsy in the Tver' region Grichuk, 1989; Rumyantsev, 1998). The Maryino Interstadial is known from a section in Maryino village north of Moscow (Pisareva, 1998). In addition to the interstadials, at least one warming of interglacial rank has also been recognised in these sections and in those at Lipna (in the Klyazma drainage basin) and Bibirevo (in the Yaroslavl' region) (Zarrina, 1991; Rumyantsev, 1998). At its optimum the central regions of the Russian Plain were covered with mixed coniferous broadleaved forests of somewhat limited floral diversity.

This interglacial was preceded by a deep cooling known from the central East European Plain under the name of Kaluga (Markov, 1977). It is not inconceivable to associate it with the lower Middle Pleistocene till which will be discussed below (the till is not shown in the maps nor in Fig. 4 as its spatial limits have not been ascertained as yet).

The Middle Pleistocene sequence of the northern East European Plain suggests at least two large glacial phases; two or even three till units can be distinguished in the composite geological transects across the East European Plain from north-west to south-east. The units differ considerably in their characteristics.

A distinctive feature of the lowest Middle Pleistocene till, (named Pechora after the drainage basin of the Pechora river) in both the central and the north-eastern regions, is a rather high content of local rocks and minerals. In the north-eastern regions there are sedimentary and metamorphic rocks derived from the Urals and Timan found in the till, including agate-bearing basalts. Among the minerals there are glauconite, sulphides, siderite and other minerals of local and transit provenance.

An ilmenite-garnet heavy mineral association predominates and is characterised by a remarkable presence of epidote and a relatively low content of hornblende (less then 20%). The clast orientation in the till suggests that the ice moved southwards (in the western regions) and south-eastwards (in the central and south-eastern regions An extensive ice sheet which formed three large ice streams (Belomorsky, Cheshsko-Mezensky and Pomorsky) moved into the East European Plain from the Scandinavian and the Ural - Novaya Zemlya glacial centres. Judging from the indicator-clast composition, the ice streams were related to different source areas. The Pomorsky stream flowed from the Pai-Khoi and Novaya Zemlya provinces (indicators: Silurian bituminous limestones and dolomites with coral fauna, as well as Permian and Triassic polymict sandstones). The source area of the Cheshsko-Mezensky stream was primarily in Novaya Zemlya, as indicated by boulders of rose marble-like crinoid-bryozoan Ordovician limestones. As for chronological correlation of the Pechora till, there is still disagreement among specialists. Some researchers (e.g., Andreicheva *et al.*, 1997) correlate it with the Dnieper (Saale) one, while others object against such a far-fetched correlations.

It is not inconceivable that the Pechora Till may be older than the Dnieper Till of the central regions, considering the possibility of heterochroneity in the development of the Scandinavian and Kara-Novaya Zemlya glacial centres. Therefore, the spatial correlations of the lower tills in the central and Pechora regions must be considered as tentative. The Middle Pleistocene age of the latter was demonstrated by the find of remains of *Dicrostonyx* genera both in underlying and overlying sediments.

In the northeast of the East European Plain the Pechora till is overlain with the Rodionov Interglacial deposits; stratigraphically the latter lie above the Likhvin layers. Pollen spectra present suggest that during the Rodionov Interglacial, the Pechora basin was covered by Pinus and Betula forests with Picea, Abies and some broad-leaved species, such as Ulmus and Tilia (e.g. Guslitser, 1981; Duryagina & Konovalenko, 1993). As for the central regions of the East European Plain, the Rodionov Interglacial presumably corresponds to a warming (Fig. 3) when the Kamenka soil developed in the Dnieper basin and the Chekalin one in the Oka basin (Likhvin stratotype).

Dnieper Stage

In the west (in the Middle Dnieper drainage basin, the Ukraine and Belarus) there is one Middle Pleistocene glacial complex. In the Dnieper basin, where it consists of several strata, its stratigraphical position is everywhere fixed by the overlying Mezin soil complex, the earlier part of which is related to the Mikulino Interglacial. This Dnieper Till is closest to the surface and can be traced northeastwards into the Upper Dnieper and Upper Oka drainage basins. In the Likhvin stratotype section the till rests directly on lacustrine silts dating from the early Dnieper Substage which contain a lemming fauna (Markov, 1977). Farther north, the Dnieper Till is the second till from the top. The Middle Pleistocene glacial complex here often includes thick intermorainic sediments, allowing the differentiation of two glacial units. At Rybinsk (in the Yaroslavl' region) the Dnieper Till also overlies lacustrine silts with an identical lemming fauna of the same evolutionary level as that found from the Likhvin section.

In some central and northern portions of the plain, the uppermost till unit differs considerably from that beneath in both lithological and mineralogical characteristics. Velichko and Gribchenko (Velichko & Shik, 1992) consider that this till belongs to the Moscow Substage (Warta) of the single Dnieper Glaciation. Contrary to this, Sudakova & Faustova (1995) hold to the idea that differences in lithology and glaciodynamics of the upper and lower tills are too great; the data strongly suggests that the post-Likhvin - Dnieper advance could be an individual stage separated from the subsequent Moscow stage by a prolonged warm interval (major interstadial or interglacial). Differences are strongly pronounced in the whole granulometric spectrum of the till, from pebbles and boulders down to the clay fraction. The uppermost till was deposited by an ice sheet moving southeastwards. At that time (190 to 150 ka BP), the ice began to draw on other source areas, which resulted in changes in till composition. The Scandinavian glacial centre became the most important as reflected in the increasing proportion of exotic Scandinavian components at the expense of local materials. The ice sheet advanced in five major ice streams: the Baltic, Lagozhsky, Onezhsky, Belomorsky and Pomorsky. The outermost limit of the ice sheet can be traced from the Dnieper basin into the drainage basins of the Upper Volga, Kama and Vyatka rivers. In the lower reaches of Pechora and the upper Vychegda the till corresponding to the Moscow one is known as the Vychegda till (Fig. 4).

The marginal landforms of the principal (Dnieper) ice advance were essentially destroyed in the central region of the Russian Plain by the subsequent Moscow advance. The latter left behind a well-defined assemblage of landforms, including ice-marginal and radial ridges, such as Smolensko-Roslavl'skaya, Klinsko-Dmitrovskaya, Tverskiye, Galichsko-Chukhlomskaya and others. Frontal ice-marginal features forming at least ten end moraine belts mark stages of the ice retreat. They often include push moraines, with detached blocks and glaciotectonic dislocations. The radial landforms are highly diverse in structure and morphology and include interstream, inter-lobate and intertongue hilly massifs and ridges, as well as systems of ridges formed within the ice-divide and ice-contact zones. Many investigators have pointed out that the ice sheet was active even during deglaciation. In fact, landforms of active ice are more abundant than in the last glaciation area (Goretskiy *et al.*, 1982). During the Moscow ice retreat numerous temporary meltwater drainage valleys and large proglacial lakes were formed; most of which no longer exist.

Because the Dnieper and Moscow ice advances differed in dynamics and direction of ice flow, they might have been separated by a considerable time-interval. However, studies of organic deposits interstratified between the till units in the central glaciated area indicate that the interval between the two advances was only of interstadial rank (Fig. 3). This conclusion has been confirmed by investigations in the periglacial regions, where only an interstadial soil horizon has been found in equivalent deposits

Mikulino Interglacial

During the Mikulino Interglacial the 'Boreal Transgression' flooded northern part of the East European Plain. Numerous boreholes penetrated its sediments containing a Lusitanian mollusc fauna on the Kola Peninsula, on the Finnish Gulf coasts, in Karelia, in the lower Severnaya Dvina, Mezen and Pechora river basins.

The Mikulino Interglacial (= Eemian Stage of central Europe) vegetation has been thoroughly studied. Palaeobotanical remains recovered from about 150 sections allow the identification of 7 vegetational phases in the central part of the East European Plain, from pine forests at the beginning to broad-leaved forests at the optimum and further to mixed pine-birch forests at the end of the interglacial. The majority of evidence indicates that only one climatic optimum occurred in this stage. A second, sometimes seen in pollen diagrams, can be usually assigned to redeposition, and birch forest appearance at the mid-optimum (as recorded in a few sections) may be attributed not to endothermal cooling (as suggested by Bolikhovskaya, 1995), but to forest fires. Global warming in the Mikulino Interglacial resulted in open birch and pine woodlands expanding into the Pai-Khoi, Bolshezelemelskaya and Malozemelskaya tundras, and birch forests with pine and spruce developed on the Kola Peninsula. The Onega, Severnaya Dvina and Mezen drainage basins were covered with spruce and birch forests with oak and elm. Similar forests with an admixture of hornbeam occupied northern Karelia and part of the Vetluga drainage basin, whilst the northern limit of broad-leaved forests was north of Vologda towards the upper Unzha (left-bank tributary of the Volga). East of the Volga the Saratov region supported a forest-steppe where only grassland steppe exists at present.

Valdai Glaciation

The last, the Valdai (= Weichselian) Glaciation has been much more extensively studied than the previous events; in particular the end of the interval, both within glaciated and periglacial regions, is well understood. The Early Valdai Substage saw a succession of warmings and coolings (Fig. 9). The first distinct post-Mikulino cooling (about 100 ka BP) is recorded in cryogenic deformations of the periglacial zone deposits. It was followed by a phase of warmer climate. This warmest period of the whole Early Valdai is

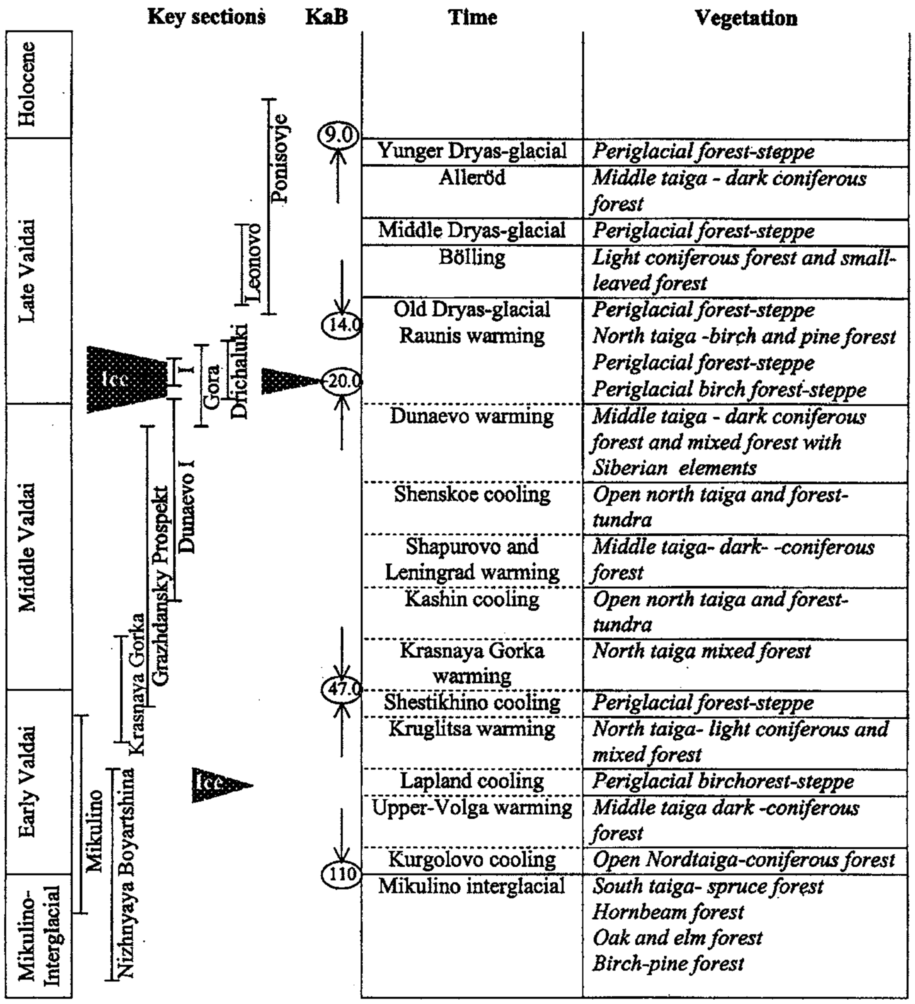

Fig. 9. Chronostratigraphy and landscapes of the Valdai Stage.

known as the Verkhnevolzhsky Interstadial, that has been tentatively correlated with the Brørup, including the Amersfoort. The subsequent cold interval was marked by the coldest conditions (periglacial steppe with species characteristic of tundra) which suggest an ice sheet in the northern part of Eastern Europe (Borisova & Faustova, 1994). This ice sheet in all probability did not expand beyond the Baltic Shield area. The last two climatic events of the Early Valdai - warming and cooling - are not so well pronounced. Final cooling was marked by a gradual increase of climate severity and, simultaneously, of aridity which in all probability prevented a glaciation. This is supported by stratigraphical investigations of numerous sections within the Valdai glacial zone, where only one till unit overlies the Mikulino sediments and those dated to the Early and Middle Valdai periods. Radiocarbon dates suggest that the till was deposited between 24 and 17 ka BP (Gerasimov & Velichko, 1982; Zarrina & Shik, 2000)

As follows from investigations in the periglacial zone, two cold phases of the Early Valdai (marked by cryogenic deformations) are separated by a single warming known as the Krutitsa phase of the Mesin (Mikulino) pedocomplex. Evidence from fossil soils (Gerasimov & Velichko, 1982) also demonstrate that no sizable ice sheet existed in the East European Plain at that time. Indeed they agree well with the concept of temporal and spatial asymmetry of the glacial systems in the Late Pleistocene (Velichko *et al.*, 1997b) (Fig. 10). This suggestion of a small-sized Early Valdai ice sheet has been recently corroborated by geological surveying in the Upper Volga drainage basin (Zarrina & Shik, 2000) . There are, however, a few sections beyond the last Valdai glaciation limits where the Mikulino sediments are overlain by a thin layer of what is considered by some investigators to be early Valdai till (Zarrina, 1991; Sudakova, 1990). Such sequences are described from sections at Raibola, Podporozhye (north of St. Petersburg), Chermenino, Yakovka and others in the Upper Volga basin (Rybinsk and Yaroslavl regions). Some sections in the Kola Peninsula expose two units of Late Pleistocene tills (Yevzerov & Koshechkin, 1980).

The Late Pleistocene tills described from the nothern East European Plain often differ in clast composition (Faustova & Gribchenko, 1995). The lower till is distinguished by its dominance of rocks from the Belomorsk Formation (garnet-bearing granite-gneiss and amphibolites). Rare pebbles of Kola nepheline syenites are

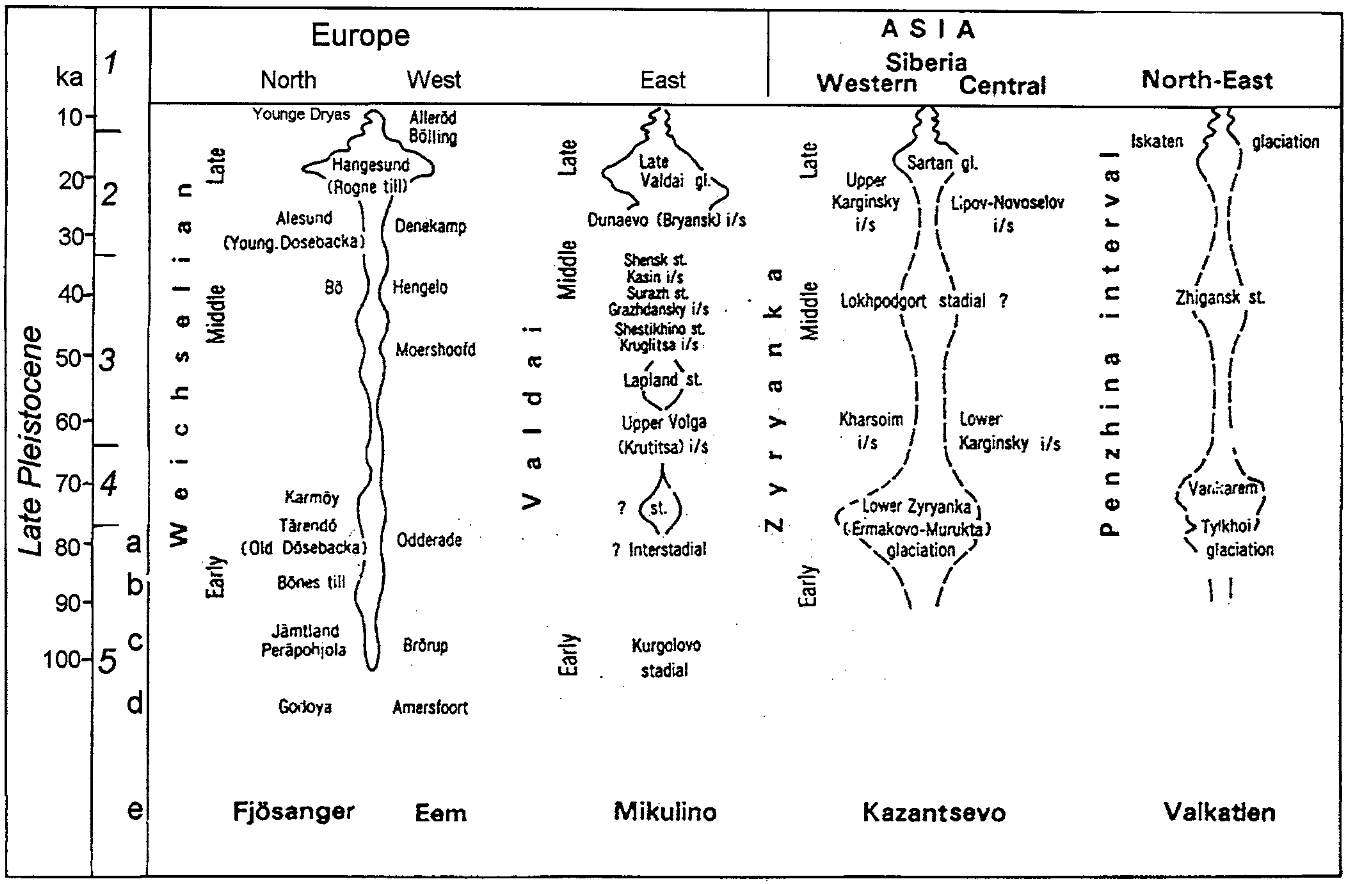

Fig. 10. Temporal and spatial asymmetry of glacial systems in the Late Pleistocene.

also present. A change in the environment about 50 ka BP marked the beginning of a new - Middle Valdai - substage charac-terized by alternating warmer and cooler phases against a background of a moderately cold and comparatively wet climate. Both warming and cooling were less prolonged, and coolings were less severe than in the Early Valdai (Gerasimov & Velichko, 1982; Arslanov *et al.*, 1981; Borisova & Faustova, 1994). In the north-west and central regions of the East European Plain climate was more severe than today. During warmer intervals a taiga-like vegetation dominated by dark coniferous species occurred, while the cold intervals were marked by an open northern taiga in combination with shrub tundra. The last warming of interstadial rank during the Middle Valdai, the so-called Dunaevo Interstadial (31 to 25 ka BP) can be broadly correlated with that recorded in the periglacial zone (the Bryansk fossil soil) (Gerasimov & Velichko, 1982; Borisova & Faustova, 1994). The subsequent pre-glacial cooling (24 to 17 ka BP) was marked by the expansion of the Late Valdai ice sheet into an open tundra-steppe land-scape (Velichko *et al.*, 1987; Nazarov, 1984; and others).

Typically the Late Valdai till includes regular changes in erratic clast composition over the area related to the flow pattern of the Scandinavian ice sheet. In comparison to older tills, these deposits include boulders and pebbles derived from more westerly source areas (the Baltic and Ladoga-Onega provinces). In addition, the Late Valdai till lithology depends to a large extent on the composition of underlying older tills, especially within the ice-marginal formation zones (Faustova & Gribchenko, 1995).

The reconstruction of the Late Valdai glacial system in northern Eurasia is based on the results of integrated international and national research programmes; important evidence has been obtained by drilling on the sea floor and on land, comprehensive studies of sections, seismo-acoustic profiling, micropalaeontological studies, and analysis of the glacial isostasy isobases. All these data suggest rather limited glaciation on the shelf and islands of the Russian Arctic (Velichko & Faustova, 1989; Velichko *et al.* 2000). During the Valdai Glaciation, the ice moved into the East European Plain from two glacial centres: Scandinavia in the NW and Pai-Khoi - Polar Urals - Novaya Zemlya in the NE (Fig. 11). In the late Valdai, the activities of the latter were restricted to the islands proper. Estimates based on geological, geomorphological and palaeobotanical infor-mation suggest that the ice sheet was less than the present land area in the archipelago (Krasnozhen *et al.*, 1987; Malyasova & Serebryanny, 1993). No fresh morainic ridges have been found south of the islands, and there is no evidence of contact between the Scandinavian and Novaya Zemlya ice sheets (moraines or glacial dislocations) (Pav-lidis, 1992).

The question of the age of glacial landforms in the northeastern part of the East European Plain is closely

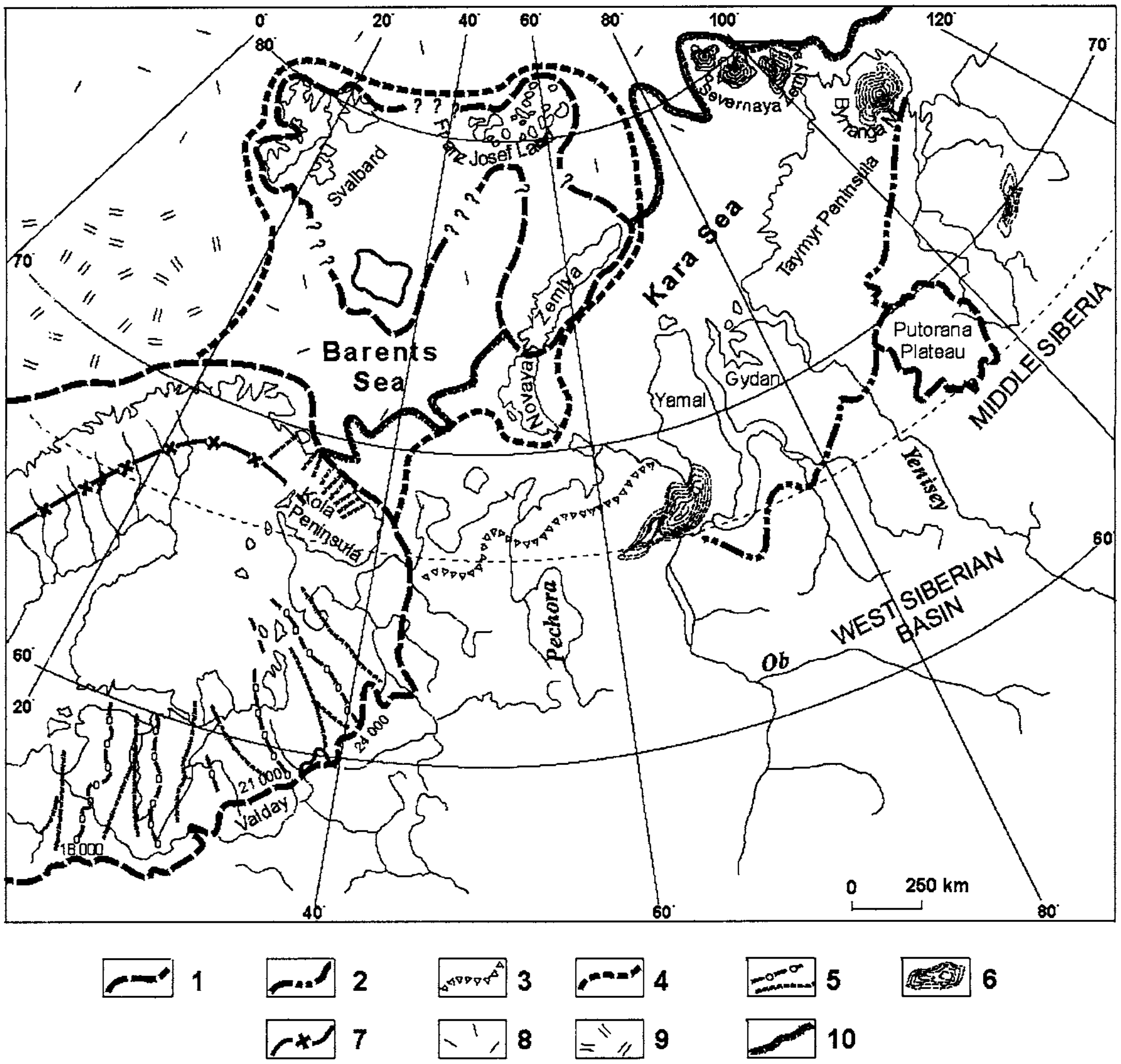

Fig. 11. Glaciation of northern Eurasia during the last glacial maximum. (by A. Velichko, M.Faustova and Yu. Kononov)
1 - glaciated areas during the last glacial maximum
2 - boundary of the Kara ice sheet after Astakhov (1979),
3 - boundary of the Novaya Zemlya ice sheet after Astakhov et al.(1998),
4 - glacial limit during the last glacial maximum according to Svendsen et al.(1999),
5- ice divides between the large ice streams and ice lobes,
6- areas of reticulated and mountain-valley glaciation during the last glacial maximum and ice cover on the shelf,
7- main ice divide of the Scandinavian ice sheet,
8 - perennial sea ice,
9 - seasonal sea ice,
10 - coastline at the last glacial maximum.

related to estimates of the Ural-Novaya Zemlya ice sheet size. Radiocarbon dates obtained for deposits underlying till near the presumed limit of the Valdai Glaciation in the north-eastern region (the Pechora drainage basin) are much older than those obtained for identical deposits near the Scandinavian ice sheet boundary (Velichko & Faustova, 1989). The dates suggest an age of 33 to 45 ka BP or older. This was originally interpreted as evidence of a heterochronous expansion of the ice sheets from the Scandinavian and northeastern glacial centres, so that the NE of the East European Plain was glaciated well before the so-called 'LGM' (Last Glacial Maximum - 20 to 18 ka BP). This interpretation disagreed with another concept, according to which the Pechora basin had been invaded by ice both during the LGM and the early Holocene - Preboreal periods (Lavrov & Potapenko, 1989). This was based on preliminary investigations of the Markhida section (Pechora River basin). However, the results of recent geological-geomorphological studies of the section, together with newly-obtained radiocarbon dates (Mangerud *et al.*, 1996) have revealed that the submorainic sediments predated by far the LGM, thus confirming the concept of an older (in all probability - Early Valdai) age of the ice sheet in the Pechora basin. In more recent publications the cited authors (Svendsen *et al.*, 1999) consider the glacial relief age in NE European Russia to be older than Late Valdaian. The youngest till in the extreme northeast of the East European Plain contains material of Ural - Pai-Khoi - Novaya Zemlya provenance (Andreicheva, 1992). Farther west, in the northwest of the Pechora lowland, Fennoscandian material predominates, with Palaeozoic dark grey and black limestones and boulders of rosé crinoid-bryozoan limestones indicative of the northeastern glacial centre.

The most extensive glacial advance during the Valdai was from the Scandinavian centre. At its maximum, this ice sheet approached the upper reaches of Nieman, Dnieper and Zapadnaya Dvina rivers, invaded the Mologa-Sheksna lowland and extended into the Onega basin.

The Scandinavian ice sheet advanced onto the East European Plain forming several large ice streams - Baltic, Chudsky, Ladoga, and Onega - Karelian ones; the relief-forming activities of the streams were discussed in detail in a number of monographs and papers (e.g. Chebotareva, 1977; Gerasimov & Velichko, 1982). Three major phases of deglaciation have been distinguished; they differ in degree of ice-marginal mobility. The initial phase (before 16 ka BP) is noted for its gradual and synchronous retreat of the ice margin (a regressive deglaciation), the integrity of the ice sheet being preserved, together with the outlines of the ice lobes. Well-pronounced marginal deposition left linear or festoon-like (large festoons) landform assemblages. The ice margin retreated spasmodically, phases of rapid ice melt apparently alternated with short, cool intervals of stagnation. The receding ice-marginal zones can be easily correlated, thus enabling the reconstruction of the ice-margin configuration. In the outermost about 30 km wide zone, the ice thickness presumably did not exceed 100-150 m. The dominant landforms are flat-topped pre-Valdai elevations covered by a thin mantle of clayey Valdai Till in association with the diverse landforms related to dead-ice found on slopes of higher areas and in meltwater valleys. The area north of the peripheral zone was modelled by thicker ice which became detached from the thin, stagnant peripheral ice in the process of retreat. The retreating ice tongues, still highly active, formed 2 to 4 belts of hills and ridges, often composed of sand and gravel. At the contacts of adjacent ice lobes broad zones of radial deposition developed, typified by isolated uplands and hilly massifs, while zones of ice divergence are marked by angular massifs, often associated with deep linear depressions. The proglacial zone included vast ice-dammed basins and smaller glaciofluvial plains.

The type of deglaciation changed after a short but pronounced glacial readvance along the whole ice front; this Vepsovo (= Pomeranian) advance occurred at about 15.5 ka BP. It was preceded by a cold interval. During the advance, the ice margin became twice as dissected as before and oscillated incessantly. The well-defined end moraines of this phase form a continuous belt from the Baltic ridge, in the west, to the Onega drainage basin in the east. Numerous minor radial landforms were formed, such as 'inter-tongue' angular massifs. Twice during the retreat the ice margin underwent reactivation, as shown by the Luga and Neva ice-marginal formations. As ice thickness decreased, all major oscillations ceased. This accounts for the narrower ice-marginal zones and thinner glacial deposits. The ice itself molded to the underlying topography, and transgressive-regressive lobate deglaciation gave way to individual decaying glacier tongues. This second stage of deglaciation was characterised by a rapid transition from active to passive ice. The most important of these glacial 'litho-morpho-complexes' are various in-version landforms related to dead-ice (zvontsy, for example) which are closely associated genetically to active-ice landforms, such as terminal moraines and hummocky topography. At the second stage of deglaciation substantial proglacial lakes appeared which rapidly changed their margins as the ice retreated; some smaller lakes came into being as a result of thawing of isolated ice blocks, together with ice-dammed lakes in the marginal zones. The proglacial zone featured various levels of valley trains and multiple-cone deltas. At the end of that stage, in the Bølling, the East European Plain became completely ice-free (Faustova, 1994).

The last stage of deglaciation (predominantly areal decay) began about 11 ka BP. Its marginal formations are found in the adjacent Baltic region. In Russia, the last advance of the ice front in the Younger Dryas only affected Karelia and the Kola Peninsula (Velichko, 1993).

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