The Holocene 13,5 (2003) pp. 715–731

Four new pollen sections tracing the Holocene vegetational development of the southern part of the West Siberian Lowland

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Received 27 November 2001; revised manuscript accepted 10 September 2002

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Abstract: In the southeast of Western Siberia within the zone of birch and pine forests in the Ob'–Tom' interfluve area, four new pollen diagrams from sites in different landforms (interfluve, terraces, floodplain, and ancient drainageways) with sandy and clay soils were correlated with two published pollen diagrams. Two main types of pollen stratigraphy are characteristic for areas with clay and sandy soils, reflecting different vegetational developments during the Holocene that were controlled by changes in climate and soil properties. Open birch forest-steppe with *Artemisia* and Chenopodiaceae was widespread in the Ob'–Tom' interfluve during the early Holocene, whereas the young floodplains had flooded meadows and willow scrub. The principal vegetation change from open steppe and forest-steppe to dense forest took place about 7000 yr BP, after which forest vegetation has prevailed. On sandy soils the dominant tree species was *Pinus sylvestris* throughout, but on clay *Pinus sibirica* and *Abies sibirica* together with *Betula pendula* had more important roles, alternating periodically with *Pinus sylvestris*. Expansion of *Pinus sibirica* and *Abies sibirica* in this area started about 4500–4000 yr BP, but in some places they declined markedly during recent centuries due to human influence. Based on the vegetational development, the climate in the southeast of Western Siberia changed from cold-dry to warm-dry (9500 yr BP) then to warm-wet (7000 yr BP), and finally to cool-wet (4000 yr BP).

Key words: Palaeogeography, pollen diagrams, *Pinus, Abies, Betula*, climate, vegetation history, Holocene, Siberia.

Introduction

The vast area of the West Siberian Lowland, which stretches 2800 km from north to south (73–49° N) and 1800 km from west to east (60–90° E), shows a clear latitudinal zonation of vegetation from tundra in the north to steppe in the south, with transitional vegetation at ecotones (Figure 1a) (Krylov, 1955; Shumilova, 1962). Holocene climatic changes caused zonal boundaries to shift, especially in the northern part of the forest zone (Kaz and Kaz, 1946; Kaz, 1969; P'yavchenko, 1971). Questions about the time and extent of movement of the southern boundary of the forest zone are not resolved. Indirect evidence indicates shifts of the southern boundary of the steppe zone, the zone of birch forests, and even the southern taiga zone. For example, soils of the southern taiga and the birch forests in Western Siberia are enriched in carbonates (Bronzov, 1936). Gerasimov (1936) and Ufimtseva (1974) postulate that these carbonates accumulated during dry and cold conditions of glacial times. Volkov (1965), however, considers that the carbonates accumulated in a dry and warm period at the end of the last glacial time. Ufimtseva (1974) considers the formation of a second humus horizon in soddy-podzolic, bog-podzolic and soddy-grey solodized soils in the present-day southern taiga zone to be a relic of dark-coloured calcareous soils formed during the Holocene climatic optimum, which suggests a northward shift of the steppe zone into the present-day zones of birch forests and southern taiga. According to this author, the present-day southern taiga zone in Western Siberia was occupied by forest-steppe during the middle Holocene, followed by coniferous taiga as a result of climatic cooling after the Holocene climatic optimum, which caused a change in pedogenic processes leading to the second humus horizon.

The existing scarce and often not well-dated pollen data do not give a clear picture of palaeogeographic changes in the south of Western Siberia, which has lead to conflicting interpretations. Neishtadt (1957) and Khotinskiy (1970; 1977) postulated a rather stable position of the southern boundary of the forest zone in

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Western Siberia compared to the northern boundary, whereas P'yavchenko (1983) gives evidence for northward shifts of the northern boundary of the forest-steppe zone in the first half of the Holocene. Volkova and Levina (1985) and Arkhipov and Volkova (1994) postulate that during the Lateglacial and the early Holocene the steppe zone did not exist at all in the territory of Western Siberia, but that it was situated far to the south, in Kazakhstan, and that only during the Boreal did a real steppe zone form in the south of Western Siberia. Levina and Orlova (1993) reconstruct, on the basis of lake-level changes in the steppe zone and a few pollen diagrams, several periods during the Holocene when the zonal boundaries of steppe and forest-steppe shifted 200–300 km either south or north. Velichko *et al.* (1997) give a generalized picture of vegetational change in Western Siberia as follows: 'During the Allerød periglacial vegetation was dominant in Western Siberia, with prevailing wormwood [*Artemisia*] steppe and rare birch patches'. In the Younger Dryas 'tundra and steppe elements dominated the periglacial complex'. (Recently, Velichko *et al.*, 2001, stressed the importance of 'patches of open larch forest with spruce, birch and pine' in Western Siberia during the Lateglacial.) In the Preboreal, 'birch-spruce open woodland replaced Lateglacial periglacial landscapes in the south of Western Siberia, large areas being taken up by steppe. Steppe and tundra associations grew in importance during the second half of this period'. In the Boreal 'open spruce-birch forests and pine-birch forests with spruce were dominant in Western Siberia, large areas being taken up by meadow-steppe formations'. Dense forests predominated in the Atlantic, Subboreal, and Subatlantic. However, most palaeogeographic reconstructions are based on few pollen diagrams only, many of which are not well dated and not satisfactorily correlated among each other.

The complex structure of the southern ecotone of the forest zone in the southeast of Western Siberia is influenced both by features of the climate and by the diversity of soils and geomorphology, and the most detailed pollen diagrams covering the entire Holocene should be correlated for better palaeogeographic reconstructions. The Ob'–Tom' interfluve area and floodplain, situated in the zone of birch and pine forests, is an appropriate place for such a detailed investigation, as it lies in the southern ecotone of the forest zone, and the soils and geomorphology of the area are well known. Only two representative pollen diagrams exist from this area (P'yavchenko, 1983; Arkhipov and Votakh, 1980) for the main vegetation reconstructions. They are different, and no comparison has been made. (Recently, Velichko *et al.*, 2001, made a new, more detailed pollen diagram of Zhukovskoe Mire, which reflects the same main features but gives an older radiocarbon date for the basal sediments.) In the present study these two diagrams and four new pollen diagrams are used from different landforms (interfluve area, terraces, floodplain and ancient drainageways) to reconstruct the entire Holocene vegetational history. The landform concept as used here includes a large area with a uniform type of bedrock and a consistent type of vegetation and drainage pattern. Areas with sandy soils are represented by Kirek Lake (Figure 1b, site 1) and Chaginskoe Mire (site 2) on the second terrace of the Ob' and Tom' Rivers and by Zhukovskoe Mire (site 3) (first published by P'yavchenko, 1983) situated in an interfluve area with sandy soils developed along an ancient drainageway. Floodplains with predominant clay soils are rep-

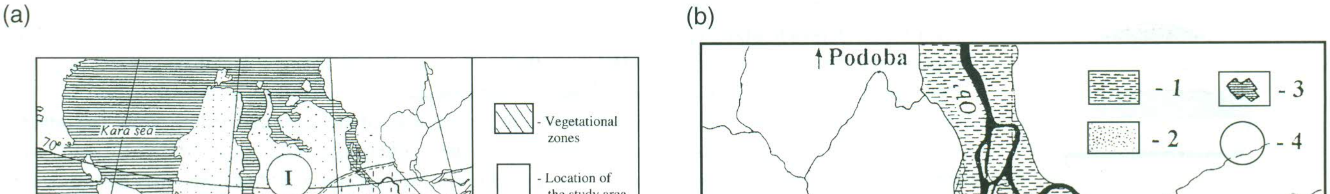

Figure 1 (a) Map of vegetational zones of Western Siberia according to Krylov (1955). (I) Tundra; (II) forest-tundra; (III) thinned spruce (*Picea obovata*)-larch (*Larix sibirica*) forests; (IV) larch-Siberian pine (*Pinus sibirica*) and Scots pine (*Pinus sylvestris*) river-belt forests (northern taiga); (V) Siberian pine and Scots pine paludified forests (middle taiga); (VI) birch (*Betula*) – dark-coniferous forests (southern taiga); (VII) birch and Scots pine forests; (VIII) forest-steppe; (IX) steppe; (X) mountain dark-coniferous taiga and larch forests. (b) Ob'–Tom' Rivers region with location of the study sites. (1) Floodplain; (2) area of terraces above floodplain and drainageways; (3) towns and villages; (4) location of study sites. Site 1: Kirek Lake. Site 2: Chaginskoe Mire. Site 3: Zhukovskoe Mire. Site 4: Novo-Uspenka. Site 5: Kulymany. Site 6: Tom' River Mouth peat section.

resented by Novo-Uspenka (site 4) and Kulymany (site 5), two fens along the Ob' River, and the site called here Tom' River Mouth peat section (site 6) first published by Arkhipov and Votakh (1980). To strengthen the interpretation, macrofossil analysis of the peat sections was carried out and stratigraphic profiles were constructed along the investigated mires.

Study area

The area of investigation is situated in the southeast of Western Siberia and includes the Ob'–Tom' interfluve area and the floodplain of the Ob' and Tom' Rivers (56°06′–56°50′N, 84°13′–84°53′E; Figure 1). The main natural feature of this area is the intersection of two geomorphic features: the West Siberian Lowland and the Kusnetsky Alatau mountain system. It lies in the zone of West Siberian birch forests and is influenced by two neighbouring vegetational zones: taiga and forest-steppe (Figure 1a). The area of investigation thus has features of taiga, forest-steppe, and mountain vegetation (Khromykh, 1997).

The basement of the Ob'–Tom' interfluve is formed by Palaeozoic schists, which are exposed on the right bank of the Tom' River near Tomsk and occur to a depth of 200 m in the western part of the interfluve (Surkov and Zhero, 1981). Over the basement there are gently dipping layers of Mesozoic and Cenozoic sediments (Geologiya SSSR, 1967). The uppermost part of the section is formed by sediments of Quaternary age, the base of which are situated at the river level.

The Ob'–Tom' interfluve is a flat alluvial plain interrupted by tectonic breaks (Khromykh, 1997), expressed as straight hollows elongated northeast–southwest and filled with alluvial sediments of middle- and late-Pleistocene proglacial lakes. These were drainageways of proglacial lakes (Sinel'nikov, 1983) (Figure 1b). They have an average width of about 4–6 km and a depth of 40–60 m.

Above the floodplain of the Ob' River a system of terraces was formed during the middle and late Quaternary (Zemtsov, 1976; Arkhipov and Panychev, 1980). In the area of investigation there are two clear terraces above the floodplain on the western slope of the interfluve (Khakhalkin, 1984). The Tom' River has also two terraces that are not so well expressed. According to Volkov (1969) strong discharge took place in five periods during the Pleistocene, when the discharge of the Siberian rivers was many times greater than today, and the widest valleys were formed. In the area of investigation the second terrace (Urtamskaya), with a height of 18–25 m, consists of sediments of a proglacial lake of Sartan age (late Weichselian), dated to 23 000–12 300 ^{14}C yr BP according to Arkhipov and Votakh (1980). The first terrace above the floodplain, with a height of 8–12 m in the area of the middle Ob' River, has an age of 12 300–9800 ^{14}C yr BP. The formation of the first terrace was completed in the beginning of the Holocene (Arkhipov and Panychev, 1980; Arkhipov *et al.*, 1980; Volkov, 1986). After that the contemporary floodplain of the river started to form, and peat mires developed in the floodplain, in the interfluve areas, and on the terraces.

According to Volkov and Volkova (1965; 1981) dry periods with intensive aeolian activity occurred after each period of strong discharge of the Siberian rivers in the second half of each glaciation, and sand dunes were formed in areas with sandy soils. The last dry period occurred about 18 000–15 000 ^{14}C yr BP (Volkov *et al.*, 1978; Volkov, 1980). In the area of investigation sand dunes occur on the terraces and in some parts of the interfluve area (Khromykh, 1997).

The climate of the middle part of Western Siberia is boreal and continental, transitional from the temperate climate of the European part of Russia to the markedly continental climate of Central Siberia (Shumilova, 1962). It is dominated by air masses of Arctic and Polar cyclones together with Polar, Asiatic and Azoric anticyclones. In summer Arctic cyclones originating near Iceland move to Western Siberia and bring rainy weather. According to Orlova (1962) the most important climatic factor in the Tomsk district is the predominance of westerly winds; warm and moist temperate air masses are brought by western and northwestern cyclones. In summer, tropical air masses come from Central Asia and cold winds come from the north. In winter, the Asiatic anticyclone (with its centre in Tuva and Mongolia) influences Western Siberia and brings frosty and sunny weather. The transformation of Arctic and oceanic temperate air masses during their long passage over land results in the temperate continental climate that dominates in Tomsk both in winter and in summer (Trifonova, 1982).

According to Khromykh (1997) the climate of the Ob'–Tom' interfluve is continental-cyclonic temperate-warm, and wet with prevailing westerly air masses from the Atlantic. The area has a positive hydrologic balance, with an effective moisture (precipitation minus evapotranspiration) of 100 mm. Annual precipitation is 517 mm. The Ob'–Tom' interfluve belongs to a zone of temperate moist climate, in July with 14.5–16.0 mb absolute humidity and 56–61% relative humidity (Kozhenkova and Rutkovskaya, 1966) and an average annual temperature of 0.6°C.

About 15 % of the area is paludified. Most of the mires are concentrated on the floodplain of the Ob' River, on the terraces, and on the bottom of the ancient drainageways. Most of these mires are sedge-Hypnaceae fens, with birch and pine on the strings. Birch mires and pine-*Sphagnum* mires can also be found in the area.

The vegetation of the interfluve area today consists of herb and dwarf-shrub pine-birch forests, mostly in areas of logged or burned pine forests (Khromykh, 1997). Pure pine forests with Scots pine (*Pinus sylvestris* L.) dominate on the sandy soils of the first and second terraces and in the interfluve area on the sandy slopes of the ancient drainageways. Pine-lichen forests occupy the driest localities on tops of sand dunes and low hills. On clay soils of the terraces and on the bottom of ancient drainageways forests of fir (*Abies sibirica* Ledeb.), Siberian pine (*Pinus sibirica* Du Tour), spruce (*Picea obovata* Ledeb.), and aspen (*Populus tremula* L.) occur, along with mires and secondary birch (*Betula pendula* Roth.) and aspen forests. Along the small rivers Um and Bolshaya Chernaya, there are strips of dark-coniferous spruce-fir forests. Most of the ancient drainageways are occupied by mires, and only a few dry areas contain patches of aspen-birch forest. Large areas of the interfluve with heavy soils are covered by secondary birch and aspen forests in places where the original pine and dark-coniferous forests were logged in the 1930s. Pure pine forests are more frequent in the eastern part of the interfluve. Pine-birch forests predominate in the southwestern part, but forests are sparse in the east of the interfluve and are interrupted by agricultural areas. Eutrophic forested and open fens, willow thickets, and meadows occur on the wide floodplains of the Ob' and Tom' Rivers (Lapshina, 1987). Poplar (*Populus nigra* L. and *Populus alba* L.) and pine groves can also be found on floodplains.

Sites in upland areas with sandy soils

The two new pollen diagrams from sites on sandy soils are derived from river terraces with sand dunes covered by pure pine forests, including Kirek Lake situated on the second terrace of the Ob' River (Figure 1b, site 1) and Chaginskoe Mire on the second terrace of the Tom' River (Figure 1b, site 2). Zhukovskoe Mire (first published by P'yavchenko, 1983) lies in an ancient drainageway on sandy soils and is surrounded by pine forests (Figure 1b, site 3).

Kirek Lake

Kirek Lake (Figure 1b, site 1) is situated in the southwest of the investigated area on the surface of the second terrace (Khakhalkin, 1984) of the Ob' River (84°13′E, 56°06′N, 90 m a.s.l.). It extends 1400 m from southwest to northeast with a width of about 400 m. Pure pine forest grows on the eastern and northern sides of the lake. To the west there is a vast mire, forested by pine and birch. The lake is a residual pool (Khromykh, 1997). The depth of the lake ranges from 1.5 m to 7 m in the central part. A thick layer of calcareous gyttja (5–9 m) with pH 7.3–7.9 covers the bottom of the lake (Dzhabarova and Nemirovich-Danchenko, 1982). The Kirek River flows from the southern part of the lake. A core of gyttja 495 cm long was taken from the middle of Kirek Lake near the western bank below a water depth of 220 cm. The upper 19 cm of liquid gyttja were not analysed for pollen.

Chaginskoe Mire

The raised bog Chaginskoe Mire is situated 80 km northeast of Kirek Lake (84°53′E, 56°27′N, 80 m a.s.l.) on the second terrace of the Tom' River in a round hollow of about 700 m diameter (Figure 1b, site 2). The sand on the surface of this terrace is underlain by clay, which forms an impermeable bed favourable for paludification (Khromykh, 1997). Pure pine forests extend on sand dunes around the bog (Figure 3).

Zhukovskoe Mire

This pollen section was published by P'yavchenko (1983). The core was taken from a sedge mire situated on the floodplain of the Zhukovka River in the area of an ancient drainageway of a proglacial lake (84°20′E, 56°25′N, 120 m a.s.l.) (Figure 1b, site 3). Pine forests on sand occur around the mire.

Sites on the floodplain with heavy soils

Eutrophic fens are widespread on the Ob' River floodplain. They were investigated in detail by Lapshina (1987). The continuous eutrophic fen 'Obskoe boloto' stretches for about 150 km along the left bank of the Ob' River from the village Kozhevnikovo to the village Podoba (Figure 1b). Birch and pine forests grow along the high terrace of the Ob' River. The bottom of the terrace is occupied by eutrophic fens with forested and open mire expanses. The natural vegetation of the floodplain fens is zoned in belts parallel to the river. These belts are controlled by differences in water chemistry, called by Lapshina (1987) zones of water-mineral nourishment (Figure 7). In wider parts of the fen the open areas lie closer to the terrace and have sedge-Hypnaceae fen vegetation with long strings covered by dwarf-birch-fern vegetation with *Betula nana* L. and *Thelypteris palustris* Schott. Forested fen with spruce, pine, and birch (*Betula pubescens* Ehrh.) occurs in the central parts. Closer to the river willow-sedge (*Salix-Carex*) vegetation occurs. The position of the boundaries between the vegetation belts is very sensitive to long-term and short-term climatic change (L'vov, 1979; Lapshina, 1987; Blyakharchuk and Klimanov, 1989). The islands in the Ob' River and dry parts of the floodplain are covered by meadows. The entire floodplain system of the Ob' River is geomorphologically dynamic due to the flat relief, which favours meandering.

Novo-Uspenka

The investigated pollen section Novo-Uspenka (Figure 1b, site 4) was taken from the fen 'Obskoe boloto' on the left bank of the Ob' River south of the village Trubachevo (84°13′E, 56°39′N, 60 m a.s.l.) 70 km northwest of Chaginskoe Mire. The floodplain fen here is not wide and a belt of open vegetation is absent. The core was taken adjacent to the terrace part of the fen at the boundary of two belts of mire vegetation controlled by different water chemistries (Figure 7).

Kulymany

The pollen section Kulymany (Figure 1b, site 5; Figure 6) was taken from the forested floodplain fen on the right bank of the Ob' River opposite the Novo-Uspenka section. Twenty years ago this mire was drained, and the modern vegetation consists of mixed pine-birch herb-sedge secondary forest.

Tom' River Mouth peat section

This pollen diagram was published by Arkhipov and Votakh (1980). The section was taken from a natural peat exposure along the bank of the Tom' River 1.5 km before the river mouth (84°30′E, 56°51′N) (Figure 1b, site 6). It consists of buried peat deposits 2 m thick, covered by 1 m of mineral sediments (soil, sandy clay, clay) and underlain by sandy loam.

Methods

Six pollen diagrams are presented here. Four of them are new and two are modified from published diagrams (Zhukovskoe Mire, P'yavchenko, 1983; Tom‘ River Mouth peat section, Arkhipov and Votakh, 1980). The modification consists of recalculating the pollen percentages (measured by hand from the printed diagrams) and establishing a numerically based zonation, as explained below. Pollen and macrofossil analyses, radiocarbon dating, and peat-stratigraphical analyses were used for palaeogeographic reconstruction.

The pollen diagrams are presented in two groups: the first group includes those from sites in areas with (light) sandy soils (the second terrace and the interfluve areas); the second group includes those from sites in areas with (heavy) clay soils (floodplain). The interpretation of the pollen diagrams takes into account the features of predominant vegetation on these two types of soil.

Sediment cores from Kirek Lake were taken with a 5 cm diameter piston corer (Wright, 1991). The description of the lithology and core sampling were carried out in the Institute of Plant Sciences, Bern (Switzerland). Pollen samples were taken at intervals of 8 cm, except in gaps between core segments, where the gaps were larger (25, 32, 40 cm).

The pollen cores from the peatlands (Chaginskoe Mire, Novo-Uspenka, Kulymany) were taken with a Hiller corer of 4 cm diameter. Pollen and macrofossil samples were taken in the field at 10 cm intervals. Wet samples were collected in plastic bags and labelled. Additional peat cores were taken from peatlands for the construction of stratigraphic transects. Chemical processing of pollen samples from Kirek Lake was carried out in the Laboratory of Palaeobotany and Palynology, Utrecht (The Netherlands), from Chaginskoe Mire in the Institute of Plant Sciences, Bern (Switzerland), and from Novo-Uspenka and Kulymany in the Research Institute of Biology and Biophysics, Tomsk (Russia). Macrofossil analysis of peat samples was carried out in the Research Institute of Biology and Biophysics, Tomsk. Botanical components of peat were determined to species, genus, or group with the use of a microscope at ×50 magnification and the atlases of Dombrovskaya *et al.* (1959) and Kaz *et al.* (1977). Different macrofossils in peat were expressed as proportion of the total volume. Such detailed macrofossil analysis reveals a clear picture of the vegetation succession on the mire (L'vov, 1979), which is important for the interpretation of the results of the pollen analysis.

Peat samples for pollen analysis were processed according to the method of Grichuk and Zaklinskaya (1948) without use of HF. Samples of gyttja were prepared with the use of HF. Pollen and macrofossil analyses of all samples were carried out in the Institute of Biology and Biophysics (Tomsk) using microscopes with ×400 and ×50 magnification. Identification of pollen types was carried out with reference to Kupriyanova (1965, which includes a subdivision of *Betula* pollen), Kupriyanova and Aleshina (1972; 1978), Bobrov *et al.* (1983, which includes a subdivision of *Pinus* pollen), and Moore *et al.* (1997) in combination with reference collections. Nomenclature of pollen and spore types follows the conventions of the EPD (European Pollen Database, Arles, France). In each sample 250–500 grains of tree taxa were counted, plus other types of pollen and spores. The pollen types are grouped on an ecological basis as trees, shrubs, dry-soil plants, ruderals, mesophilous herbs, wetland plants (herbs and *Betula nana*), and aquatic plants. These pollen groups reflect the vegetation in a gradient from a regional to a local scale. Percentages of all pollen types are based on a pollen sum of regional pollen, including trees, shrubs, ruderals, dry-soil plants, and mesophilous herbs. Pollen of wetland and aquatic plants are not included in the pollen sum.

Chronostratigraphic zones in the sense of Mangerud *et al.* (1974) were not applied. The method of zonation follows the recommendations of Bennett (1996). Numerical zonation was carried out using the method of optimal sum-of-squares partition, and the number of statistically significant splits was determined with reference to the broken-stick model (MacArthur, 1957). The method is applied to regional pollen only; excluded are pollen and spores from marsh plants and aquatic plants, and those resulting from long-distance transport. In Chaginskoe Mire, the zonation was carried out on a data set in which the pollen sample at 470 cm is omitted. This pollen sample forms an outlier with its high values of *Betula pendula* and low values of *Pinus sylvestris* and *Pinus sibirica*, which are unexplained. In a test in which the sample was included, it constituted a statistically significant pollen zone on its own. A small number of additional pollen zones was distinguished subjectively on the basis of pollen stratigraphy. Correlations and palaeogeographic reconstructions were made on the basis of these zones, taking into account peculiarities of the local environment.

The radiocarbon dates are listed in Table 1. Radiocarbon ages of three samples from Kirek Lake were determined by accelerator mass spectrometry (AMS) at the de Vries Laboratory in Utrecht.

Table 1 Radiocarbon dates

Depth from the water surface (cm)	^{14}C age (uncalibrated)	Material dated	Laboratory number
Kirek Lake			
529	3687 ± 34 BP	Charcoal	UtC-8350
617	6508 ± 42 BP	Charcoal	UtC-8351
677	9320 ± 50 BP	Charcoal	UtC-8352
Chaginskoe Mire			
370–380	1690 ± 110 BP	Peat	GIN-10095
540–550	6400 ± 100 BP	Peat	GIN-10096
Novo-Uspenka			
140–150	1290 ± 40 BP	Woody peat	KI-4052
210–220	2910 ± 40 BP	Woody peat	GIN-5509
240–250	3650 ± 140 BP	Woody peat	GIN-5508
280–290	3540 ± 130 BP	*Menyanthes* peat	KI-4053
410–420	5260 ± 160 BP	*Menyanthes* peat	KI-4054
Zhukovskoe Mire			
275–300	3550 ± 60 BP	Peat	
675–700	8040 ± 80 BP	Peat	
850–875	9625 ± 110 BP	Gyttja	
Tom' River Mouth peat section			
100–110	200 ± 69 BP	Peat	COAN-341
120–130	780 ± 50 BP	Wood	COAN-336
180–190	2700 ± 20 BP	Peat	COAN-340
240–250	4560 ± 50 BP	Peat	COAN-339
310–120	6320 ± 70 BP	Peat	COAN-338
340–350	8450 ± 60 BP	Peat	COAN-337

The chronology of the pollen sections from mire deposits is based on ^{14}C dates made at the Laboratory of Isotope Geochemistry and Geochronology of the Geological Institute of RAS in Moscow by means of liquid-scintillation counting from benzene converted from alkaline extraction. Three samples were analysed by the same method in the Radiocarbon Centre of Radiogeochemistry of Environment in Kiev. The timescale was calculated by linear interpolation between radiocarbon dates when possible. The pollen diagram Novo-Uspenka covers only the last *c.* 5260 years. The diagram of Kulymany has no radiocarbon dates, but the pollen stratigraphy is so similar to that of Tom' River Mouth peat section that synchronicity for similar features is assumed.

Bryales/Algae, an informal name, comprises a broad morphological group of spores, including Type 303 (van Geel *et al.*, 1981), Type 234c (van Geel *et al.*, 1989) and Bryophyta according to Kaz *et al.* (1977) and Moore *et al.* (1997). In Western Siberia, the highest abundances of Bryales/Algae are usually encountered in basal peat deposits which also contain macrofossils of wet-eutrophic mire-plant communities and in gyttja (Blyakharchuk, 1989). In this paper a high abundance of Bryales/Algae is therefore interpreted, with caution, as indicating wet conditions.

Pollen diagrams from sites in upland areas with sandy soils

Kirek Lake pollen section (Figure 1b, site 1; Figure 2)

The radiocarbon dating shows that the Kirek Lake section covers the entire Holocene. The lake sediments to a depth of 618 cm below the water surface consist of alternating layers of dark-brown and light-brown calcareous gyttja. The presence of calcium carbonates in lakes is characteristic of the southern taiga and birch-forest zones of Western Siberia, where carbonates have been leached from soils into lakes during humid periods (Kargopolov, 1956).

At 618–715 cm below the water surface, there is a sand layer with varying proportions of humus. The upper pollen sample of this sand layer and the overlying gyttja reveals a very rich forest-pollen assemblage. The directly underlying samples from grey-coloured sand do not contain pollen, but the four basal samples from a black layer and dark sand at the bottom of the core contain a small amount of pollen indicative of open, weakly forested landscapes. A piece of charcoal from the black layer belongs to a conifer tree (identification by Lucia Wick, Bern, Switzerland). The pollen diagram (Figure 2) is divided into four local pollen assemblage zones (LPAZ), as follows.

LPAZ KIR-1: Botrychium

This pollen zone consists of the basal pollen sample only, and differs markedly from the overlying zone by the absence or low values of trees, *Artemisia*, and Gramineae and a maximum of *Botrychium*. It suggests open-tundra vegetation. In the absence of radiocarbon dating of this level, it can be either Glacial or Lateglacial in age.

LPAZ KIR-2 (9300–10 000 ^{14}C yr BP):
Artemisia*–Gramineae*

This pollen zone includes the black layer and dark sands at the base of the core with dominant non-arboreal pollen: *Artemisia*, Gramineae, Chenopodiaceae, and some other herbs. Pine pollen (*Pinus sylvestris* and *Pinus sibirica*) plays a subordinate role. Birch pollen is represented by three species: *Betula pendula, Betula pubescens*, and *Betula nana* (identified according to Kupriyanova, 1965). Characteristic is the regular presence of *Larix sibirica* Ledeb. pollen and a slightly increased amount of

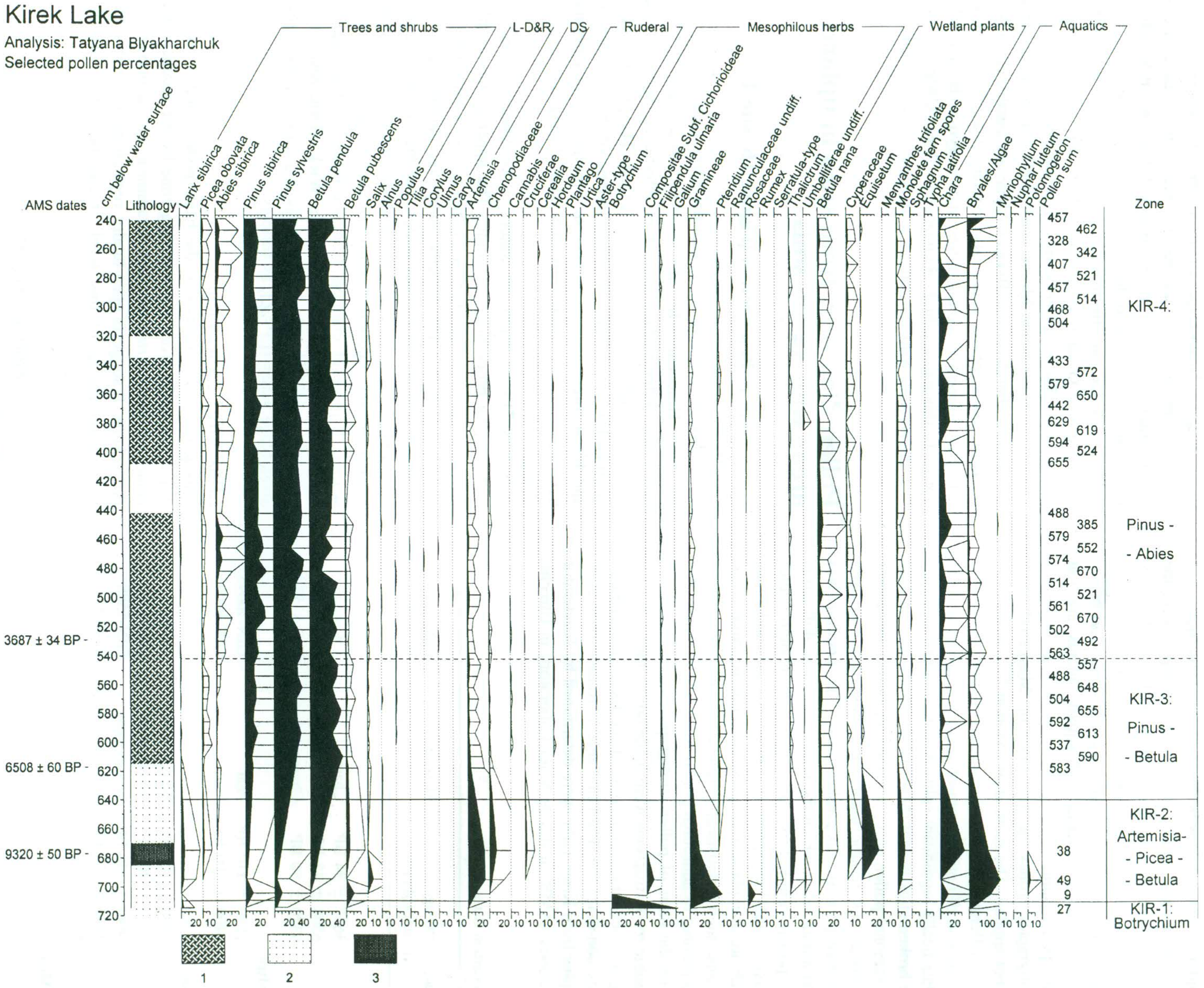

Figure 2 Pollen percentage diagram of Kirek Lake. Pollen percentages are drawn in black, with five-times exaggerated scale with depth bars. Statistically significant zone boundaries are drawn as solid lines (for explanation, see text); others are dashed. Pollen groups are: trees and shrubs; long-distance transported and reworked pollen (L-D&R); dry-soil plants (DS); ruderal plants; mesophilous herbs; wetland plants; and aquatic plants. Some pollen types are omitted to save space. Lithology: (1) calcareous gyttja; (2) sand; (3) black layer.

Picea pollen. Microfossils of aquatic and wetland-herb taxa (Cyperaceae, *Equisetum, Potamogeton*, Bryales/Algae) are very abundant. The Monolete fern spores (without perine) possibly belong to *Thelypteris palustris*, which forms dense vegetation on minerotrophic mires in the south of Western Siberia today. The occurrence of macroscopic wood evidences the former existence of forested fen (minerotrophic mire).

This zone probably reflects unforested or weakly forested upland areas with small expanses of woodland vegetation in wet hollows with minerotrophic mires. *Chara* oospores, *Potamogeton* pollen, and abundant Bryales/Algae indicate that shallow warm pools or fen existed at the site of Kirek Lake.

The grey sand at 620–670 cm depth does not contain any pollen. This gap in the pollen diagram covers the interval from about 9000 to 6500 yr BP. Thus, in the early Holocene the accumulation of pollen at the site was interrupted for some reason. This indicates that the modern Kirek Lake was formed only after 6500 years BP, when gyttja sedimentation started.

LPAZ KIR-3 (6500–4000 ^{14}C yr BP): Betula–Pinus

This pollen zone starts with calcareous gyttja overlying the grey sands. The pollen assemblage reflects the development of forest. *Betula* and *Pinus* pollen become abundant and *Pteridium* spores increase. Pollen of dry-soil plants (*Artemisia,* Chenopodiaceae, Gramineae) decreased sharply along with aquatic and wetland herbs. This indicates that after 6500 yr BP unforested surfaces in the Tom'–Ob' interfluve areas had declined and were replaced by dense birch and pine forests with ferns, which is a more southern type of forest (Shumilova, 1962).

LPAZ KIR-4 (4000 ^{14}C BP to present): Pinus–Abies

Although the lower boundary of this pollen zone is not statistically significant, it marks the ecologically important rational limit of *Abies*. Such a late increase of *Abies* is typical for pollen diagrams from the southern taiga and birch-forest zones (Blyakharchuk, 1989). *Pinus* and *Betula* pollen remain predominant. The increase of Cyperaceae and the occurrence of *Sphagnum* probably reflect paludification of the area, and also the spread of sedges in the groundcover of forests, replacing *Pteridium*, which is a more northern type of forest (Shumilova, 1962). The sharp increase in Bryales/Algae in the uppermost samples may be caused by either warming of the climate or eutrophication of the lake as a result of human influence.

Chaginskoe Mire pollen diagram (Figure 1b, site 2; Figure 3; Figure 4)

The upper radiocarbon date (Table 1) seems too young, because the accumulation of 375 cm of peat probably needs much more time than 1690 years. The too-young age may have been caused by young roots penetrating from the surface of the mire and included in the bulk sample dated.

Pollen analysis reveals a forest pollen assemblage with a dominance of birch and pine for most of the core, but open less forested areas near the bottom of the core (Figure 4).

LPAZ CHAG-1 (before 7000 ^{14}C yr BP):
Artemisia–Picea–Betula

This pollen zone covers part of the sands underlying the peat. It has abundant *Betula* pollen, a good deal of *Picea*, dry-soil plants Chenopodiaceae, *Artemisia*, and Gramineae, the wetland plant Cyperaceae, and the aquatic Bryales/Algae. The vegetation of the area consisted of forest-steppe, with birch and pine groves scattered in extensive steppe areas. Spruce most likely grew along depressions and rivers.

LPAZ CHAG-2 (7000–4000 ^{14}C yr BP):
Pinus–Betula–Bryales/Algae

Pollen and spores of local wetland and aquatic vegetation retain high values (*Betula nana*, Cyperaceae, Bryales/Algae, and Monolete fern spores). This, together with the lithology, indicates that wet eutrophic Hypnaceae mire may have formed about 7000 years BP at the location of Chaginskoe Mire. At the end of this pollen zone the aquatic Bryales/Algae decreased and *Scheuchzeria, Equisetum*, Monolete fern spores (*Thelypteris palustris*), and *Betula nana* became more abundant, indicating that the local mire vegetation changed from a eutrophic Hypnaceae mire to a mesotrophic *Scheuchzeria* mire. At that time the forest vegetation on dry land did not change, suggesting stable climatic conditions.

The development of forests is shown by a marked increase of both *Pinus sylvestris* and *Pinus sibirica* pollen, permanent but low presence of *Abies* pollen, an increase of *Pteridium* spores, and marked decreases of pollen of dry-soil plants. Scots pine forest spread on sandy soils and *Pinus sibirica* and *Betula* on heavy soils. Open steppe and meadows almost disappeared from the uplands.

LPAZ CHAG-3 (4000–1800 ^{14}C yr BP):
Pinus sylvestris–Betula–Abies

The lower boundary of this pollen zone is not statistically significant but it marks the rational limit of *Abies*. The ecology of *Abies sibirica*, which today does not grow outside the taiga zone with its rather moist climate, suggests that this indicates further moistening of the climate and the spread of dark-coniferous forests. The increase of *Sphagnum* spores and the decreases of other wetland plants indicate *Sphagnum* paludification in the area.

LPAZ CHAG-4 (1800–600 ^{14}C yr BP):
Pinus sibirica–Abies

Maxima of *Pinus sibirica* and *Abies sibirica* pollen and high values of *Sphagnum* spores indicate a further expansion of dark-coniferous forests on dry soils and *Sphagnum* on mires. The increase of *Betula pubescens* pollen later in this pollen zone may reflect the expansion of this tree in the complex of mire plant communities together with *Scheuchzeria* and Hypnaceae mosses.

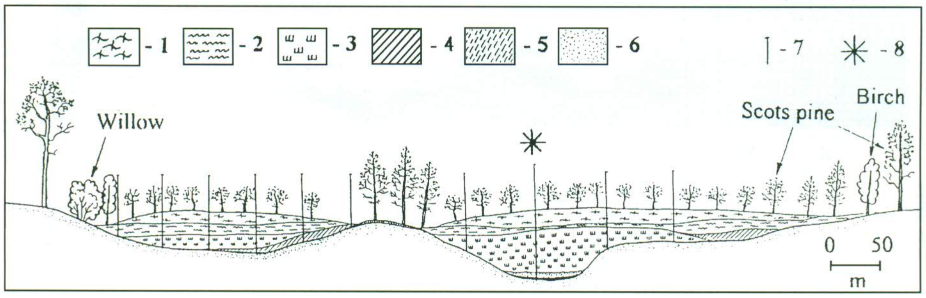

Figure 3 Cross-section of peat deposits of Chaginskoe Mire in E–W direction. (1) Ologotrophic *Sphagnum* peat; (2) oligotrophic *Sphagnum magellanicum* peat; (3) mesotrophic *Scheuchzeria* peat; (4) sedge peat; (5) brown-moss (Hypnaceae) peat; (6) sand; (7) location of the additional peat sections; (8) location of the palynologically investigated site at Chaginskoe Mire.

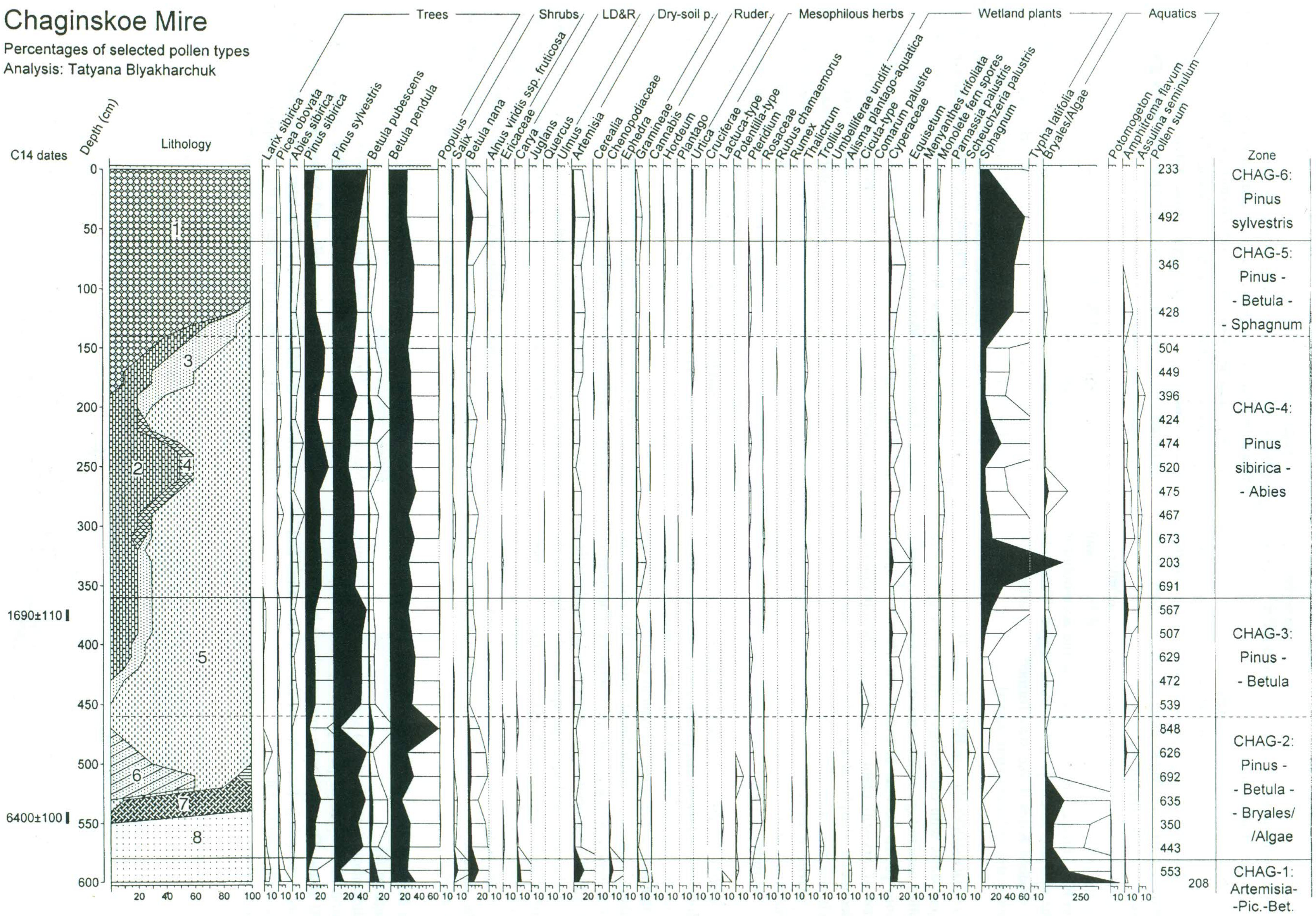

Figure 4 Pollen percentage diagram of Chaginskoe Mire. Pollen percentages are drawn in black, with five-times exaggerated scale with depth bars. Statistically significant zone boundaries are drawn as solid lines (for explanation, see text); others are dashed. Pollen groups are: trees; shrubs; long-distance transported and reworked pollen (LD&R); dry-soil plants (Dry-soil p.); ruderal plants (Ruder.); mesophilous herbs; wetland plants; and aquatic plants. Some pollen types are omitted to save space. Lithology: (1) *Sphagnum fuscum*; (2) *Sphagnum magellanicum*; (3) *Sphagnum cuspidatum*; (4) *Carex*; (5) *Scheuchzeria*; (6) *Drepanocladus aduncus*; (7) sand with some *Scheuchzeria*; (8) sand.

LPAZ CHAG-5 (600–200 ^{14}C yr BP.): Pinus–Betula–Sphagnum

Although not statistically significant, the lower boundary of this pollen zone delimits a major decrease of *Pinus sibirica* and a marked increase of *Sphagnum*, whereas *Pinus sylvestris* and *Betula pendula* pollen slightly increased. These features indicate a decreased role of Siberian pine in the forest and suggest that the mire reached the oligotrophic *Sphagnum* stage of development, which is confirmed by the peat stratigraphy.

LPAZ CHAG-6 (200 ^{14}C BP to present): Pinus sylvestris

This pollen zone shows increasing *Pinus sylvestris*, herbs of dry soils, and *Betula nana* and decreasing *Abies, Pinus sibirica*, and *Betula pendula*. This change could have been caused either by drying of the climate or by logging of coniferous trees during recent centuries.

Zhukovskoe Mire pollen diagram (Figure 1b, site 3; Figure 5)

This pollen diagram was first published by P'yavchenko (1983). The interpretation given in this paper is in general agreement with his interpretation. In addition to it all boundaries between pollen zones have been numerically determined, but only one out of the five boundaries used here is statistically significant (ZHU-3/4). The time covered by pollen zones ZHU-2 and ZHU-3 is not represented in the pollen diagram of Kirek Lake due to the sterile sand layer at that site.

LPAZ ZHU-1 (9700–9000 ^{14}C yr BP): Artemisia–Larix

This pollen zone has a predominance of *Artemisia* and *Betula* pollen and the presence of *Larix*. Large areas were covered by steppe vegetation with groves of birch and larch in wet hollows. According to P'yavchenko (1983) the occurrence of aquatics (*Myriophyllum*) indicates that the climate was not so cold. We can suppose that the climate was rather continental with short hot summers and long cold winters. Permafrost most likely occurred, for larch dominates today in more continental areas of Siberia with widespread permafrost (Shumilova, 1962). In a recent publication, Velichko *et al.* (2001) placed the corresponding pollen zone in the Allerød.

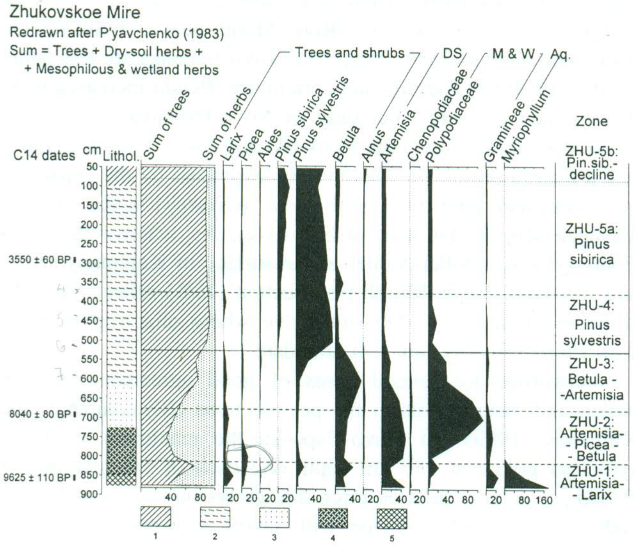

Figure 5 Pollen percentage diagram of Zhukovskoe Mire, recalculated and redrawn from P'yavchenko (1983). Pollen percentages are drawn in black. The single statistically significant zone boundary is drawn as a solid line (for explanation, see text); others are dashed. Pollen groups are: trees and shrubs; dry-soil plants (DS); mesophilous and wetland plants (M & W); and aquatic plants (Aq.). Lithology: (1) sedge peat; (2) sedge/brown-moss (Hypnaceae) peat; (3) herb peat with remnants of ferns and *Menyanthes*; (4) sapropel; (5) lake and river sediments.

LPAZ ZHU-2 (9000–8000 ^{14}C yr BP): *Artemisia–Picea–Betula*

The increase of *Picea* in this pollen zone is interpreted as increased precipitation, favourable for the expansion of spruce into the steppe. P'yavchenko (1983) also mentions rising groundwater levels as a result of higher water levels in the river, which allowed spruce to spread on sandy soils on which this tree can grow only with sufficient moisture supply. The increase of soil moisture may in part have been caused by the melting of permafrost. As is the case today, the permafrost probably melted first in river valleys and other low-lying areas, allowing spruce to spread there. A modern parallel of such a landscape is found in the southeastern Altai Mountains (Kurai Valley), with extensive *Artemisia* and Chenopodiaceae steppe areas and belts of spruce and larch along rivers and springs. Birch pollen may mostly be derived from *Betula nana*, suggesting that the landscape may have been very open until 8000 yr BP. The transition from gyttja to peat indicates that the climate was rather dry and the lake dried up. Permafrost may have disappeared completely in the second half of this pollen zone, so that the soils became dry and spruce declined. Velichko *et al.* (2001) correlate this pollen zone with the Younger Dryas.

LPAZ ZHU-3 (8000–~~7000~~ 6000 ^{14}C yr BP): Betula–Artemisia

The continued abundance of *Artemisia* pollen and increase of *Betula* indicates the expansion of birch forest-steppe; *Betula* pollen is here inferred to be derived from tree-birch. The *Artemisia* decrease at the end of this pollen zone suggests a gradual expansion of dense birch forests. The abundance of 'Polypodiaceae' spores indicates the predominance of *Thelypteris palustris* in the local mire vegetation, which is supported by a layer of fern peat deposited during this time.

LPAZ ZHU-4 (7000–4000 ^{14}C yr BP): Pinus sylvestris

The lower zone boundary is the only one in the pollen diagram that is statistically significant, and forms the main transition in biostratigraphy, dated about ~~7000~~ 6000 yr BP. It divides the entire pollen diagram into two distinct parts. The marked increase of *Pinus sylvestris* and decrease of *Artemisia* indicate that dry steppe and birch forest-steppe disappeared from the area and dense pine forests expanded, probably on sandy soils. This indicates that the climate became wetter. From this time onwards the climate was rather stable.

LPAZ ZHU-5A (4000–500 ^{14}C yr BP): Pinus sibirica

The increase of *Pinus sibirica* pollen suggests the expansion of Siberian pine possibly on clay soils.

LPAZ ZHU-5B (500 ^{14}C yr BP to present): *decline of* Pinus sibirica

This pollen zone is weakly expressed in Zhukovskoe Mire. The decline of *Pinus sibirica* pollen in the uppermost level is probably connected with anthropogenic influence, especially logging in the last century.

Pollen diagrams from sites on the floodplains with clay soils

The three floodplain pollen diagrams differ from those of sandy areas mainly in the late Holocene, in the rapid alternations of *Pinus sylvestris* and *Betula* maxima in the former and very uniform pollen curves in the latter. These rapid alternations are less suited for chrono-correlation among the three floodplain pollen diagrams, because the two tree taxa grew locally on the studied mires and their behaviour may differ among the mires. Chrono-correlation is therefore based on the less abundant but diagnostic pollen curves of trees growing outside the mires, mainly *Pinus sibirica* and *Abies sibirica*. The high degree of similarity (based on diagnostic tree species) among the three floodplain pollen diagrams allowed the establishment of a common zonation of synchronous pollen zones, named FLO-0 to FLO-4.

Two different zonation schemes are applied to the pollen diagram of Novo-Uspenka (Figure 1b, site 4; Figure 6). Pollen zones FLO-2/4 represent synchronous zones among the floodplain pollen diagrams, whereas pollen zones N-1/6 are site-specific and mark the alternating phases of *Pinus sylvestris* maxima (N-2, N-4, and N-6) and *Betula pendula* maxima (N-1, N-3, and N-5). Relatively abundant *Artemisia* pollen in zones N-2 and N-5 suggest drier periods, whereas maxima of *Chara* oospores in zones N-1 and N-3 may reflect wetter climatic conditions. The peat at Novo-Uspenka (Figure 7) consists of a regular alternation of woody peat and *Menyanthes* peat with an admixture of *Thelypteris palustris, Equisetum*, and Hypnaceae. The radiocarbon dates of Novo-Uspenka show a small inversion in the middle of the core (Table 1). A possible cause is that the material dated at 285 cm contained tree roots penetrating from above.

The Kulymany section shows an alternation of woody and herbaceous peat (Figure 1b, site 5; Figure 8). The pollen diagrams of Kulymany and the Tom' River Mouth peat section (Figure 1b, site 6; Figure 9) have many features in common, such as increased *Betula* in pollen zones FLO-1 and FLO-4, a predominance of *Pinus sylvestris* in pollen zones FLO-2 and FLO-3, and a maximum of *Abies sibirica* in pollen zone FLO-3.

Description of the pollen zones valid for all three floodplain pollen diagrams is as follows.

Pollen zone FLO-0 (before 8400 yr BP): Betula–*Varia*

This pollen zone was found only in the Tom' River Mouth peat section in the sandy loam below the peat. It has a predominance of *Betula* pollen and much unidentified herb pollen called Varia. Because *Artemisia* pollen has a high degree of variability, one may suppose that Varia include *Artemisia* in addition to different herbs. Other tree pollen (*Pinus* both species, *Alnus*) is relatively scarce. The past vegetation was probably an open birch forest-steppe.

Pollen zone FLO-1 (8500–6000 ^{14}C yr BP):
Betula–Larix–Salix

This pollen zone is present in Kulymany and the Tom' River Mouth peat section. The main features are the abundance of *Betula* and the presence of *Larix, Salix*, and *Artemisia*. Wetland and aquatic plants have their highest abundance. The abundant *Ephedra* pollen in Tom' River Mouth peat section may have been transported by the river from drier areas in the south. This zone probably reflects a young floodplain with flooded meadows and willow thickets, in which the floodplain pools are in their initial stage of terrestrialization, whereas the uplands were covered by birch forest-steppe.

Pollen zone FLO-2 (6000–5000 ^{14}C yr BP):
Pinus sylvestris

This pollen zone and the following one are present in all three floodplain pollen diagrams. *Pinus sylvestris* pollen became dominant, whereas *Betula* pollen strongly decreased. It is likely that, from this time onwards, *Pinus sylvestris* forests were widespread in the upland of the Tom'–Ob' interfluve. *Pinus sibirica, Abies sibirica*, and *Picea obovata* started to form continuous curves in Novo-Uspenka and Kulymany. In the Tom' River Mouth peat section the expansion of *Abies* and *Picea* started earlier. *Salix* is still abundant though decreasing in Novo-Uspenka and Kulymany, but absent in the Tom' River Mouth peat section. The abundance of wetland plants indicates a widespread paludification of the floodplain. This is confirmed by the observation by Lapshina (1987) that most of the Ob' floodplain mires started to form in this period. The mire vegetation included *Betula pubescens, Betula nana, Pinus sylvestris, Salix, Thelypteris palustris* (Monolete fern spores), and various species of *Carex* and Bryales.

Pollen zone FLO-3 (5000–1000 ^{14}C yr BP):
Pinus sibirica

The increase of *Pinus sibirica* pollen indicates the regional expansion of Siberian pine, suggesting a more humid and cooler climate. Such a shift in climate is also suggested in the Tom' River Mouth peat section by the expansion of *Sphagnum* and the replacement of ferns (Filicales) and grasses (Gramineae) maxima by a maximum of Ericales. *Abies* pollen became more abundant in this pollen zone probably because of immigration from the north. At the end of this pollen zone there was a short dry period during which a layer of woody peat (in Novo-Uspenka with pieces of charcoal dated *c*. 1290 yr BP) was formed in all the floodplain mires studied.

Novo-Uspenka shows decreasing *Pteridium* spores. *Pteridium* grows today mostly together with different herbs and grasses in a southern type herb-rich pine forest (Shumilova, 1962). After *c*. 5000 yr BP the southern type of forest rich in ferns was possibly replaced by a more northern type of dwarf shrub-rich pine forests with *Vaccinium vitis-idaea* L. and *Vaccinium myrtillus* L. (increase of Ericales in Tom' River Mouth peat section).

Pollen zone FLO-4 (1000 ^{14}C yr BP to present):
Betula–Pinus sylvestris

Pinus sibirica started to decrease in all three floodplain pollen diagrams already immediately after the dry period at the end of the last pollen zone and this became especially pronounced during recent centuries. Extensive logging and increased agriculture in more densely populated areas like the Ob'–Tom' interfluve caused *Pinus sibirica* and *Abies sibirica* to decline and Gramineae and herbs to increase (herbs listed as Tricolporate indet. in Kulymany and part of Varia in the Tom' River Mouth peat section). In contrast, areas with large peatlands like Novo-Uspenka are less populated and had less logging and agriculture. *Betula* increased in all three pollen diagrams, but only in Novo-Uspenka it decreased again towards the top (zone FLO-4B) and *Pinus sylvestris* pollen had a maximum (60%). This may be explained by the expansion of oligotrophic pine bogs (with *Pinus sylvestris*) in the vast Big Vasugan Mire 30 km west of Novo-Uspenka, whereas the lower *Pinus sylvestris* pollen values at the surface of Kulymany (25%) and the Tom' River Mouth peat section (15%) reflect more the situation in the Tom'–Ob' interfluve where oligotrophic mires with *Pinus sylvestris* are less abundant.

Noteworthy are several cases of good agreement between pollen and macrofossils in the peat sections (Blyakharchuk and Klimanov, 1989). At Novo-Uspenka the maximum of *Pinus sylvestris* pollen at 150 cm depth and each of two maxima of *Betula pubescens* (the tree birch that grows on mires) at 250 cm and 325 cm depth coincide with layers of woody peat. This undoubtedly reflects phases of local development of forested mires. The conclusion is that pollen diagrams from the floodplain reflect both a common climatic signal and local changes of vegetation caused by the development of the floodplain and its mires. It is therefore useful to carry out pollen analysis and detailed macrofossil analysis of the peat on one and the same core, in order to distinguish short-time fluctuations of climate from local development of peat-forming vegetation.

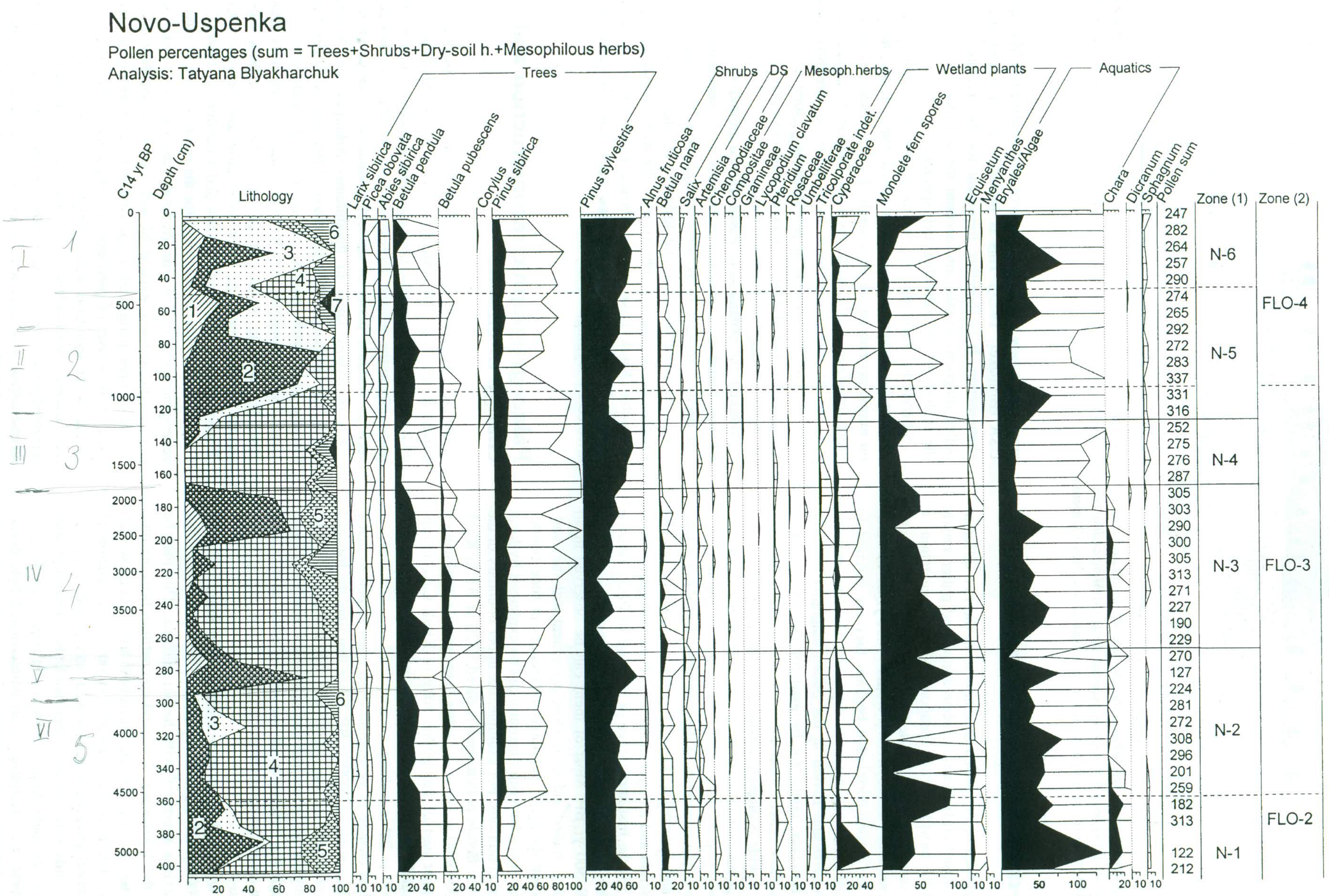

Figure 6 Pollen percentage diagram of Novo-Uspenka. Pollen percentages are drawn in black, with five-times exaggerated scale with depth bars. Statistically significant zone boundaries are drawn as solid lines (for explanation, see text); others are dashed. Pollen zones (1) N are site-specific. Pollen zones (2) FLO are inferred to be synchronous with those in Kulymany and Tom' River Mouth peat section. Pollen groups are: trees; shrubs; dry-soil plants (DS); mesophilous herbs; wetland plants; and aquatic plants. Lithology: (1) sedges (*Carex*); (2) *Menyanthes*; (3) brown-mosses (Hypnaceae); (4) wood; (5) *Thelypteris palustris*; (6) *Equisetum*; (7) charcoal.

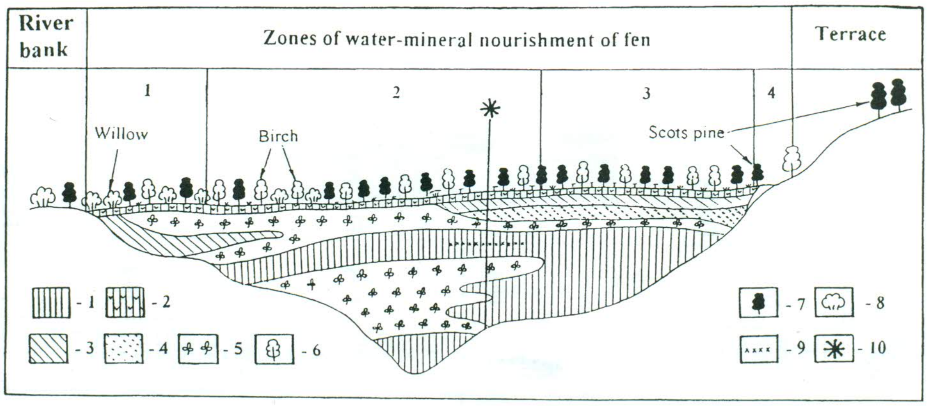

Figure 7 Cross-section of the fen 'Obskoe boloto' according to Lapshina (1987) with the study site of Novo-Uspenka. (1) woody peat; (2) wood-herbaceous peat; (3) sedge peat; (4) brown-moss (Hypnaceae) peat; (5) *Menyanthes* peat; (6) birch (*Betula*); (7) Scots pine (*Pinus sylvestris*); (8) Willow (*Salix*); (9) charcoal; (10) location of the palynologically investigated site Novo-Uspenka.

Chrono-correlation and discussion

Chrono-correlation of the pollen diagrams from the two different landforms is based on both radiocarbon dating and pollen trends which reflect the most important components of the vegetation on dry soils, as shown in Table 2. The first maximum of *Betula* and the major increase of *Pinus sylvestris* from *c.* 7000 yr BP onwards are suitable for chrono-correlation because they are inferred to reflect regional forest expansion on dry soils. The later maxima of *Pinus sylvestris* and *Betula* in the pollen diagrams from the floodplains, however, could not be used for chrono-correlation because they may reflect local effects of competition between species with a wide ecological amplitude in floodplain fens.

The criteria for chrono-correlation characterize the main vegetational development of the area. They are, in chronological order: (1) the initial maximum of dry-soil plants *Artemisia*, Chenopodiaceae, and *Ephedra* 8500–9625 yr BP; (2) the first marked increase of *Betula* and a major increase of *Pinus sylvestris* 7000–6000 yr BP; (3) the first appearance or increase of *Pinus sibirica* and *Abies sibirica* 5000–4500 yr BP; and (4) the decline of *Pinus sibirica* 1000–500 yr BP. Most of them can be observed in all pollen diagrams studied and are in close agreement with the available radiocarbon dating. Exceptional differences in time boundaries of pollen zones between diagrams can be explained by local environmental conditions. For example, the upper boundary of the *Artemisia-Picea-Betula* pollen zone is dated 9320 yr BP in Kirek Lake but 7000–6500 yr BP in the other diagrams. An explanation is that the upper part of this pollen zone in Kirek Lake is represented by sand devoid of pollen, so that information on the period 9320–7000 yr BP is lacking.

The principal change in vegetation from open steppe to dense forest took place at about 7000 yr BP. Since that time the forested stage of development of vegetation was not interrupted (apart from anthropogenic deforestation during recent centuries at some sites), although the behaviour of the tree species could differ among pollen diagrams for different reasons. A few examples are discussed here.

The areas with sandy soils were dominated by *Pinus sylvestris* from 6500–7000 yr BP onwards, whereas in floodplains with clay soils pine maxima alternated with *Betula* maxima. This may be explained by the dependence of natural competition between pine and birch on the soil type. On clay soils both trees can grow with equal success, but local fires initially favour the expansion of birch as the faster-growing tree, followed later in the succession by pine. On sandy soils, on the other hand, the succession after fire in pine forests starts directly with young pine trees, as birch can not compete here, resulting in an uninterrupted pine dominance. Similar differences in vegetation succession between small areas with sandy and clay soils were also observed in Michigan, USA (Brubaker, 1975). This is probably a widespread natural phenomenon. It is therefore important for the interpretation of pollen diagrams to take into account the soil characteristics and the ecology of the individual tree species.

Siberian fir, *Abies sibirica*, has the narrowest ecological amplitude among all Siberian trees (Shumilova, 1962). It does not grow on mires, permafrost, or poor sands. Pollen of *Abies* is therefore more abundant in areas with clay soils. Only in the southern taiga zone do fir and spruce form pure stands on interfluve areas, whereas north of this zone fir penetrates only along river valleys. The pollen curve of *Abies* is therefore the most precise indicator of climatic change in Western Siberia.

Although the expansion of *Pinus sibirica* around 4500–5000 yr BP was found to be almost synchronous in all sites studied, the last decline appears to be time-transgressive. The last decline started in floodplain sites and followed in sites on sandy soils, whereas no decline was observed in the most remote and least accessible Kirek Lake. *Abies sibirica* pollen shows a similar pattern. The declines of these two trees mark the areas most affected by logging.

Palaeogeographic reconstruction and change of climate

In the early Holocene before 7000 yr BP the environmental conditions in the Tom'–Ob' interfluve area were not favourable for widespread peat accumulation and lake formation, which took place only in the deepest depressions with abundant groundwater, such as residual pools in ancient drainageways (P'yavçhenko, 1983) or oxbow lakes in floodplains (Arkhipov and Votakh, 1980). The landscape of the interfluve of that time was open birch forest-steppe, with groves of spruce and larch along wet depressions. Permafrost may have persisted into the early Holocene. The melting of the permafrost resulted in shallow lakes, around which spruce and birch could grow also on sandy soils (P'yavchenko, 1957; Blyakharchuk and Sulerzhitsky, 1999).

A number of data sources exist for the reconstruction of palaeogeographic events of that time. At Kirek Lake the layer of sand and black detritus dated to 9320 yr BP with a pollen assemblage indicative of an open periglacial steppe covers the early Holocene. After 9320 yr BP a layer of pure sand was deposited in this lake on the surface of the sediments with a periglacial pollen assemblage. This layer covers *c.* 9320–6508 yr BP. The reason why this sand was deposited is not clear. Possibly it indicates that the area of the modern second terrace was inundated. This would be in agreement with the opinion of Arkhipov *et al.* (1980) that the modern floodplain of the

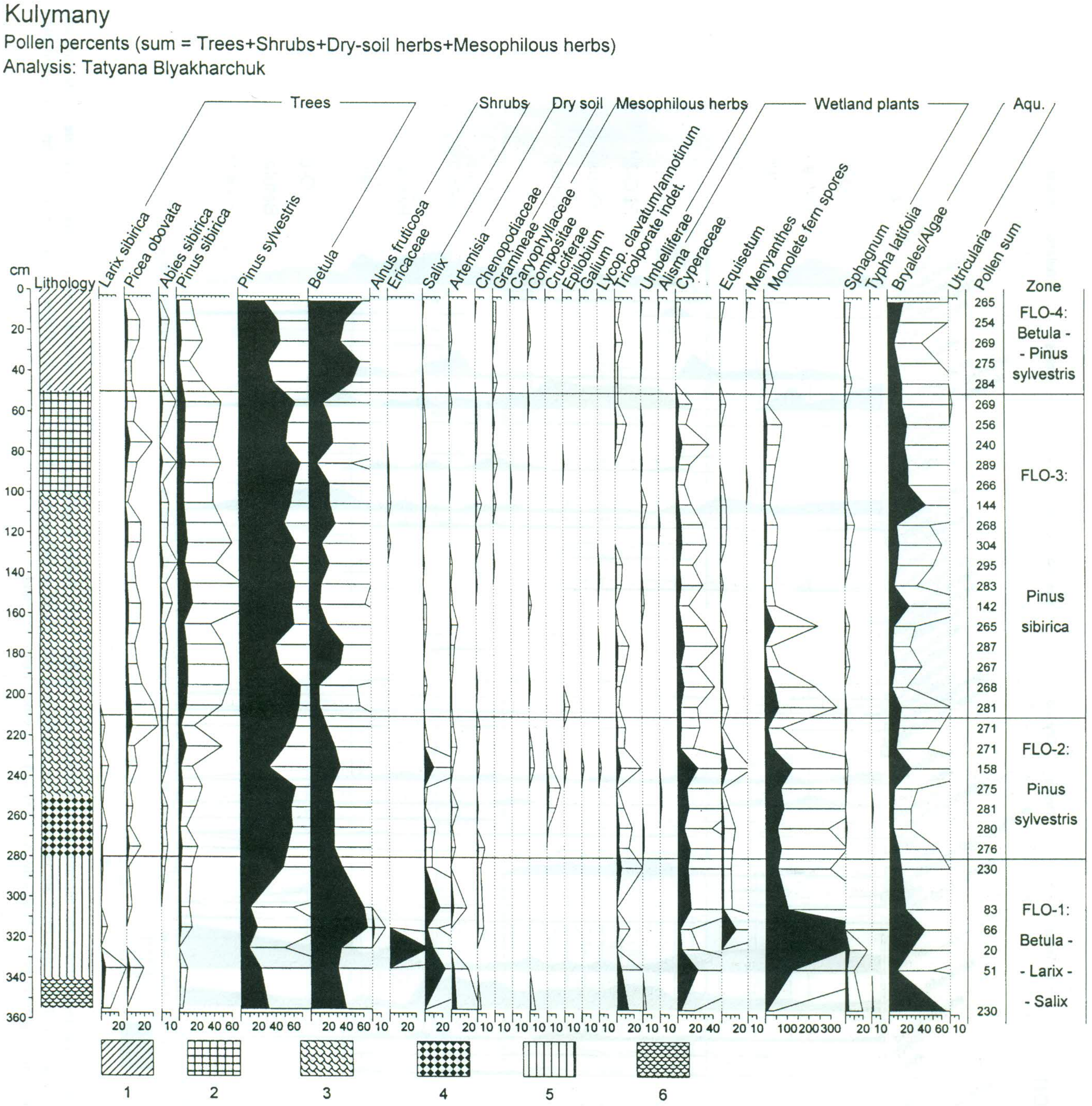

Figure 8 Pollen percentage diagram of Kulymany. Pollen percentages are drawn in black, with five-times exaggerated scale with depth bars. Zone boundaries are statistically significant (for explanation, see text). Pollen zones FLO are inferred to be synchronous with those in Novo-Uspenka and Tom' River Mouth peat section. Pollen groups are: trees; shrubs; dry-soil plants; mesophilous herbs; wetland plants; and aquatic plants (Aqu.). Lithology: (1) sedge peat; (2) wood–sedge peat; (3) *Thelypteris*–sedge peat; (4) wood–*Thelypteris* peat; (5) woody peat; (6) *Thelypteris* peat.

Ob' River started to form only in the middle Holocene. Before that time the riverbed was higher than the modern floodplain. The first terrace of the Ob' River near Kolpashevo (300 km to the north) was also formed in the period from 9900 to 6700 yr BP. P'yavchenko (1983) infers a rather high groundwater level at Zhukovskoe Mire during that time. Pollen data from this period indicate rather dry climatic conditions, favourable for the expansion of birch forest-steppe on dry soils. Vast areas were covered with steppe with *Artemisia* and Chenopodiaceae, alternating with groves of birch on moist soils. The pollen zone of dry forest-steppe is expressed especially clearly in Zhukovskoe Mire (P'yavchenko, 1983) and also in the pollen diagram from the floodplain mire 'Boloto Gladkoe' near Novosibirsk 300 km to the south (Firsov *et al.*, 1982) (Figure 1a). It is further reflected in our pollen diagram of Kulymany and is fragmentary at Kirek Lake (below the layer of pure sand). It seems likely that the relic steppe soils were formed during this time. These observations support the assumption that the layer of pure sand at Kirek Lake was deposited by wind deflation of sand dunes under dry climatic conditions.

After 7000 yr BP the climate became wet and dense forest spread on the Ob'–Tom' interfluve. The climate was favourable for lake and mire formation and most floodplain mires are therefore younger than 7000 yr BP. Most pollen diagrams presented here also cover the middle and late Holocene; peat accumulation in Chaginskoe Mire and gyttja sedimentation in Kirek Lake started almost simultaneously about 6500 yr BP.

Precipitation is the main factor limiting the expansion of forest in the southern ecotone of the forest zone of Western Siberia today (Shumilova, 1962). After 7000 yr BP dense birch and then pine forest developed in the interfluve and steppe vegetation

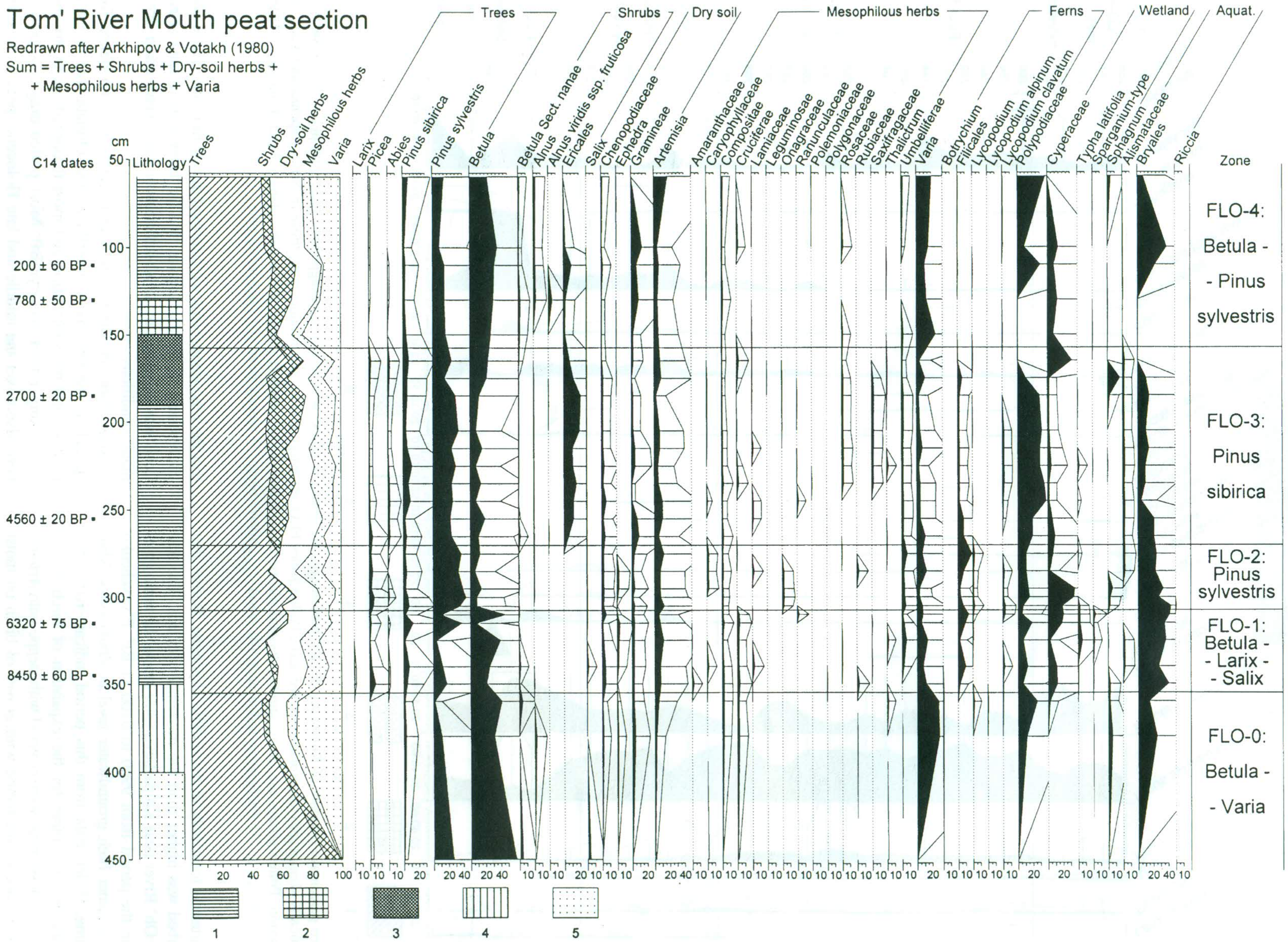

Figure 9 Pollen percentage diagram from the Tom' River Mouth peat section, recalculated and redrawn from Arkhipov and Votakh (1980). Pollen percentages are drawn in black, with five-times exaggerated scale with depth bars. Zone boundaries are statistically significant (for explanation, see text). Pollen zones FLO are inferred to be synchronous with those in Kulymany and Novo-Uspenka. Pollen groups are: trees; shrubs; dry-soil plants; mesophilous herbs; ferns; wetland plants; and aquatic plants (Aquat.). Lithology: (1) peat; (2) woody peat; (3) soil; (4) sandy loam; (5) sand.

Table 2 Correlation of the pollen diagrams from the Ob'–Tom' Rivers area

Sites on sandy soils			Sites on clay soils			Time limits (yr BP)	Reconstruction of past vegetation
Kirek Lake	Chaginskoe Mire	Zhukovskoe Mire	Novo-Uspenka	Kulymany	Tom' River Mouth peat section		
Pollen zones; approximate ages BP							
	CHAG-6 + CHAG-5 0–600	ZHU-5B 0–500	FLO-4 0–1000	FLO-4 0–1000	FLO-4 0–1000	0–800	Decline of *Pinus sibirica*
KIR-4 0–4000	CHAG-4 + CHAG-3 600–4000	ZHU-5A 500–4000	FLO-3 1000–4500	FLO-3 1000–5000	FLO-3 1000–5000	800–4500	Maximum expansion of dark-coniferous forest trees: *Pinus sibirica* and *Abies sibirica*
KIR-3 4000–6500	CHAG-2 4000–7000	ZHU-4 4000–7000	FLO-2 4500–5260	FLO-2 4500–6000	FLO-2 4500–6000	4500–7000	Expansion of dense *Pinus sylvestris* and *Betula* forests
KIR-2 9320	CHAG-1 7000–	ZHU-1 + ZHU-2 + ZHU-3 7000–9700		FLO-1 6000–8500	FLO-1 + FLO-0 6000–>8500	7000–9625	Open forest-steppe with *Artemisia,* Chenopodiaceae, and groves of *Larix sibirica, Betula*, and *Picea obovata*
KIR-1 10000							
Site no. on map (Figure 1b)							
Site 1	Site 2	Site 3	Site 4	Site 5	Site 6		
Figure no. of pollen diagram							
Figure 2	Figure 4	Figure 5	Figure 6	Figure 8	Figure 9		

retreated to the south, suggesting that the climate became wetter. *Pinus sylvestris* expanded on sandy soils, forming pure pine forests, and tree birch and *Pinus sibirica* expanded on the heavier clay soils. With the development of dense forest, podzolization started on primary steppe soils, forming the second humus horizon characteristic for this area. With further moistening of the climate, fir and spruce forest expanded in the interfluve and on the terraces, and widespread paludification of low-lying parts of the terraces, floodplains, and other lowlands started.

According to the assumption of Khotinskiy (1989) the moistening of climate in the south of Western Siberia was usually connected with cooling. The behaviour of *Abies* pollen supports this. For example, according to pollen data farther north (Blyakharchuk and Sulerzhitsky, 1999) (Figure 1a), fir forests declined after 5000 yr BP in the area of the middle taiga because of climatic cooling and retreated to the south. In contrast, in the south in the zone of pine-birch forests, fir increased its participation in the forests after 4000 yr BP. According to its ecology this tree could migrate to the south only with moistening and hence cooling of the climate. Thus the south boundary of dark-coniferous forests moved south due to the cooling of the climate in the late Holocene.

Betula nana is widespread in eutrophic fens in the Ob' floodplain (Lapshina, 1987). In the author's point of view it is not an indicator of climatic cooling during the Holocene for the study area, at least during the forest stage of development. The expansion of dwarf-shrub strings with *Betula nana* and *Thelypteris palustris* on eutrophic floodplain fens reflect short-time oscillations of climatic moisture. It is known from special studies that the width of dwarf-shrub strings increases with decreasing moisture (Glebov *et al.*, 1980; Blyakharchuk and Klimanov, 1989; Lapshina, 1995).

Acknowledgements

I am grateful to colleagues from the Scientific Research Institute of Biology and Biophysics at Tomsk State University, in particular to E.Ya. Muldiyarov and E.D. Lapshina for providing help in fieldwork and in macrofossil analysis of Novo-Uspenka and Kulymany. The investigation of Kirek Lake was carried out with support of grants to H.E. Wright from the National Geographic Society and the US National Science Foundation (NSF grant 99–75264). The investigation of Chaginskoe Mire was supported by a grant to the author from the MacArthur Foundation N 98–52191 (USA). Part of the pollen samples was prepared in the laboratory by Florencia Oberli (Bern, Switzerland) and Jan van Tongeren (Utrecht, The Netherlands). Radiocarbon samples coded with 'UtC-' were prepared, processed, and AMS dated in the R.J. Van de Graaff Laboratorium, University of Utrecht, The Netherlands. I thank Brigitta Ammann (Institute of Plant Sciences, University of Bern) and Herb E.Wright (USA) for their help in field investigation of Kirek Lake and providing ^{14}C dates, for providing the opportunity to prepare this manuscript in the Institute of Plant Sciences, Bern, and for the careful correction of the English text. I am thankful to the reviewers Anson Mackay and John Birks for their attentive analyses of my manuscript and advice which allowed me to improve both the content and the form of the text. I thank Pim van der Knaap for his enormous help in providing the numerical zonations, printing of pollen diagrams and careful revision of the text.

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