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Long-term Arctic peatland dynamics, vegetation and climate history of the Pur-Taz region, western Siberia

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Stratigraphic analyses of peat composition, LOI, pollen, spores, macrofossils, charcoal, and AMS ages are used to reconstruct the peatland, vegetation and climatic dynamics in the Pur-Taz region of western Siberia over 5000 years (9300 - 4500 BP). Section stratigraphy shows many changes from shallow lake sediment to different combinations of forested or open sedge, moss, and *Equisetum* fen and peatland environments. Macrofossil and pollen data indicate that *Larix sibirica* and *Betula pubescens* trees were first to arrive, followed by *Picea obovata*. The dominance of *Picea* macrofossils 6000-5000 BP in the Pur-Taz peatland along with regional *Picea* pollen maxima indicate warmer conditions and movement of the spruce treeline northward at this time. The decline of pollen and macrofossils from all of these tree species in uppermost peats suggests a change in the environment less favorable for their growth, perhaps cooler temperatures and/or less moisture. Of major significance is the evidence for old ages of the uppermost peats in this area of Siberia, suggesting a real lack of peat accumulation in recent millennia or recent oxidation of uppermost peat.

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Arctic and boreal peatlands are important components of climate change because they play a key role in the terrestrial/atmospheric carbon balance (Billings 1987). Peatlands are large sources and sinks of greenhouse gases, most notably carbon dioxide and methane (Billings 1987; Matthews & Fung 1987; Schlesinger 1990). The Arctic is highly sensitive to climate change (Chapin *et al.* 1980; Hansen *et al.* 1993), and may respond to greenhouse warming either with positive feedbacks (more trace gas production) or negative feedbacks (more carbon storage) due to complex interactions involving permafrost limits, fire, nutrient mineralization rates, and water-table changes. Whether or not the Arctic tundra is presently acting as a carbon source or sink is controversial (Oechel *et al.* 1993; Keeling *et al.* 1996).

The northern peatlands of Russia comprise one of the largest carbon resources on earth (Gorham 1991). Botch *et al.* (1994) estimate the long-term (apparent) rate of carbon accumulation as 52 Tg C/yr. We investigate the local and regional vegetational history of the Pur-Taz region, western Siberia, in order to understand past, current and future peatland dynamics within a particular regional palaeoclimatic setting.

Of particular interest is the balance of carbon accumulation versus decay in northern continental peatlands today. Little is known of the long-term (millennial) history of permafrost peatland accumulation/decay rates in the acrotelm (predominantly oxic surface layer) and the catotelm (anoxic lower layer) due to the difficulty in dating acrotelm peat and the lack of high-resolution ^{14}C

dating of peat profiles. While dynamical peat models (Olsen 1963; Clymo 1984, 1991) postulate a decrease in rate of accumulation resulting in a limit to peat-bog growth, several recent studies fail to show a decrease in rate of accumulation over millennia (Charman *et al.* 1994; Belyea & Warner 1996; Kuhry & Vitt 1996). Thus it is important to establish the rates of peat accumulation over millennia, and to determine the age of upper surface peats.

The northern part of Pur-Taz interfluvial region (Fig. 1) was chosen for a study of the history of the vegetation because of its proximity to the northern limits of birch, larch and spruce trees (Arealy derev'ev i kustarnikov SSSR 1977). Examination of the peat, pollen, macrofossil, charcoal, and loss-on-ignition history of a peat section from the Molodoto Lakes region, between the Pur and Taz rivers, provides a long-term view of vegetation dynamics, peatland change, fire, and climate history at the Arctic treeline.

Setting

The site is located at 66°42' N, 79°44' E, to the east of the Ob River and to the west of Yenisey River (Fig. 1). It is an area of low elevation peatlands that span many kilometers between the Pur and Taz rivers. Depth to permafrost in the summer is about 30 cm today, suggesting that the frozen lower peat is not available for carbon exchange. Numerous thermokarst lakes occur in this region, and many are connected by small streams. Most of the lakes are shallow, probably because of the relatively brief seasonal span available for thermokarst melting and possible infilling by reworked peat. Banks of peat were exposed along the shore of a large lake, which is continuing to expand by thermokarst processes. Our studied section was taken from one of the frozen exposures along the lake.

The region is designated as a forest-tundra zone underlain by continuous permafrost. *Larix sibirica* is the dominant tree, with rare *Picea obovata* forming an open parkland forest in the southern part of the region. *Betula nana*, *Alnus fruticosa* and *Salix spp.* are the most abundant shrubs today.

On the modern peatland surface *Ledum palustre, Carex, Polytrichum* and *Cladonia* dominate along with*Vaccinium uliginosum* and *Rubus chamaemorus.* In drier areas, lichens predominate.

Climate

Average July temperature is 13-14°C, and January mean temperatures range from -26 to -28°C, resulting in an annual temperature of -8 to -9°C. The frost-free period is about 75 days, from mid-June until August 21-30 (Klimaticheskiy atlas SSSR 1960). However, annual precipitation is about 450-500 mm (100 mm during the winter), which makes it a relatively humid climate, resulting in a thick snow cover (about 70-80 cm) which prevents more severe permafrost (Shevelyova & Khomichevskaya 1967).

Geomorphology and Glacial History

Two competing hypotheses exist concerning the geomorphic development in this part of Siberia. One suggests that the northern part of the West Siberian plain has not been glaciated for the last 40-50 000 years (Danilov 1987; Faustova & Velichko 1992; Astakhov 1998). Based upon investigations of lithology and geomorphology, Danilov (1987) suggests that widely distributed stones were transported into this region by sea ice during the Karga transgression of the Kara Sea 50 000-30 000 BP. Their petrology indicates that to the east of the Taz river, the stones originated from the Putoran Mtns and the Taymyr Peninsula. West of the Ob, the stones originated from the Ural Mtns. During the LGM (last glacial maximum) the Kara sea shelf would have been free from ice and well-drained (Faustova & Velichko 1992). Supporting evidence for this view is given by Michel (1998) based on ^{18}O of ground ice in the region, and on scanning electron microscopy of Pleistocene sands (Mahaney 1998). In an alternative viewpoint, Grossvald (1980, 1998) and Arkhipov & Volkova (1994) and Arkhipov (1998) believe that this area was covered by an ice sheet during the last glacial which had its center in the Kara Sea area. This ice sheet would have resulted in blockage of the Ob and Yenisey Rivers, forming sand, silt, and clay lake sediments in this area.

Field and laboratory methods

The thickest peat exposures measured were up to 3.44 m, and one section was selected for detailed sampling. A monolith was collected by first cleaning with a shovel to expose frozen peat, then cutting 100 cc blocks of contiguous samples at 3 to 5-cm and transferring them to sample bags. The samples were later refrigerated. A total of 70 samples were collected for analysis of LOI, peat composition, pollen and spores, plant macrofossils and AMS radiocarbon dating. LOI was measured following procedures outlined in Dean (1974). Pollen and spores were concentrated from 1 cm^3 sediment subsamples. Processing included KOH deflocculation, HCl and heavy liquid separation (Berglund & Ralska-Jasiwiczowa 1986) followed by acetolysis and mounting in glycerin. A minimum of 300 pollen grains were counted; spores were tallied in addition. Determination of relative frequency of pollen was calculated based upon the total pollen sum, and percentage of spores was based upon a sum of pollen and spores. *Betula* pollen was identified according to criteria developed for Eurasian birches by N. Filina (1976, 1978). The pore cavity of *B.* sect. *Nanae* are very small and the ektexine is thin. In contrast, the pore cavity of *B.* sect. *Albae* is larger and the ektexine is thicker. The pollen grains of *B.* sect. *Fruticosa* are between the two types and are not easy to establish with certainty.

Macrofossils were separated from their organic matrix by soaking 50 cm^3 of peat overnight in 5% KOH, then washing with water through screens of 0.5 and 0.25 mm mesh. The constituent needles, leaves, seeds, other plant parts and charcoal were stored in water and refrigerated. Macrofossil composition is shown per 50 cm^3 of sample. Nomenclature for vascular plants follows Czerepanov (1995). Hand-picked, identified terrestrial macrofossils were selected for AMS ^{14}C dating (Table 1). All dates discussed are in the radiocarbon time scale.

Results

Peat composition, % LOI and peat accumulation

The section lithology (Fig. 2) indicates that underlying clay sediments are overlain by a sequence of sedge stem matrix and *Carex* seeds up to 320 cm with overlying moss (*cf. Calliergon*)-sedge mixtures up to about 215 cm depth. Sediments from 215 to 140 cm are predominantly sedge-*Equisetum*, wood-*Equisetum-Sphagnum*, *Sphagnum*, and wood-sedge-*Sphagnum* peat layers. A more decomposed, sandy wood-*Equisetum-Sphagnum* zone is present between 140 and 70 cm, also distinctive due the presence of black round fungal sclerotia. The upper 70 cm exhibits a return to woody *Sphagnum* peat, with *Sphagnum* present up to about 10 cm, above which the surface moss *Polytrichum cf. commune* dominates.

The LOI curve (Fig. 2) shows that the transition from clay to sedge peat at 340 cm is abrupt. The peat stratigraphy shows very high organic matter up to about 130 cm, where sand mixed with the peat lowers the % LOI. A return to high organic matter at 75 cm depth continues to the top of the section.

The sediment accumulation curve (Fig. 3) shows a rather gradual accumulation curve from 9200 BP to 4900 BP (0.8 - 0.4 mm/yr), and a higher rate from 4900 years to 4570 BP (1.7mm/yr). From 25 cm to the surface, it is clear that accumulation dropped sharply (0.05 mm/yr).

Plant macrofossils

PT-I (9200 to 8700 BP, 344 - 315 cm). The base of the section (Fig. 4) is AMS-dated to 9200±60 BP (Table 1) and the presence of clay, *Nuphar luteum* seeds, *Hippuris* seeds, *Potamogeton* seeds, and bryozoan statoblasts indicate a shallow lake environment. Diatoms from the bottom clay layer are a mixture of fresh-water and poorly preserved marine taxa, with the majority being fresh-water (L. Burckle, pers. comm.). It is not possible to determine whether the marine diatoms are of aeolian origin or *in situ*,; their presence is inconclusive in supporting the suggestion of a Kargian age (35 000-26 000 yr BP) Kara Sea transgression in the region (Danilov 1987). The basal charcoal may indicate a local pyric origin for the formation of the lake, as fire today plays a significant role in lake formation in permafrost regions (Zoltai 1993). *Larix sibirica* needles, seeds, and a cone scale, along with *Betula pubescens* seeds and bracts are present.

PT-IIa (8700 to 8000 BP, 315 - 250 cm). The peat stratigraphy is a mixture of moss (*cf. Calliergon*) and sedges and reveals a complete lack of aquatic macrofossils. *Oxycoccus microcarpus* leaves, fruits, and seeds, *Vaccinium uliginosum* and *Andromeda polifolia* seeds and *Betula nana* seeds and bracts are present. *Larix* needles and seeds are dominant, along with *Betula pubescens* seeds and bracts, strikingly well-preserved *Betula sp.* (*cf. B. fruticosa* - a possible hybrid between *Betula pubescens* and *Betula nana*) bracts.

PT-IIb (8000 to 7300 BP, 255 - 195 cm) reveals a wetter environment, with the dominance of *Sphagnum*, and seeds of *Carex, Comarum palustre, Calla palustris*, and *Menyanthes trifoliata*. Polypodiaceae pinnae are present. *Larix* needles and seeds, *Betula pubescens* seeds and bracts occur throughout this zone. *Picea obovata* needles and sterigmata first appear.

PT-III (7300 to 6900 BP; 195 - 175 cm). *Larix* needles are greatly diminished in this zone and *Betula pubescens* macrofossils are also fewer. In contrast, two distinctive types of *Carex* seeds (trigonous and lenticular) are present, along with seeds of *Comarum palustre, Lysimachia thyrsiflora, Menyanthes trifoliata, Hippuris, Potamogeton* and *Daphnia* epiphia.

PT-IV (6900 to 5200 BP, 175 - 100 cm). *Picea* needles dominate this zone, while *Betula* seeds and bracts are noticably scarce. *Larix* needles are present until about 160 cm depth, approximately 6600 BP, when they disappear in the macrofossil record. Both types of *Carex* seeds are present, along with *Rubus cf. arcticus* and *Rubus cf. saxatilis* seeds, a Caryophyllaceae seed, and several *Menyanthes* seeds. Noticeable in this zone are fungal sclerotia, charcoal, and well-decomposed wood fragments.

PT-V (5200 to 4700 BP, 100 - 50 cm). The absence of *Picea* needles and very few *Betula pubescens* seeds are notable in this zone, which is dominated by lenticular *Carex* seeds, some trigonous *Carex* seeds, *Comarum palustris* seeds, *Viola* seeds, and at the top of the zone, *Menyanthes* seeds. *Equisetum* peat dominates from 80 to 50 cm.

PT-VI (4700 to 4300 BP, 50 - 10 cm). This zone is characterized by a few *Carex* seeds of both types, a few wingless *Betula* seeds, the appearance of *Andromeda* seeds, and many *Chamaedaphne calyculata* seeds.

PT-VII (4300 to modern, 10 - 0 cm). The top zone is modern, and contains no recognizable macrofossils other than moss (*cf. Polytrichum*), a charred leaf, and moss capsules.

Pollen Zones

Pollen zone 1 *Larix-Betula* (9200 to 9150 BP, 344 - 337 cm). This zone (Fig. 5) is notable for its large amounts of *Larix* pollen (about 20%) and high percentages of both *Betula* sect. *Albae* and *Betula* sect. *Nanae*.

Pollen zone 2 *Larix-Betula-Picea-Sphagnum* (9150 to 8500 BP, 337 - 280 cm). This zone displays the first appearance of *Picea* pollen, large amounts of *Betula* pollen, and maximal amounts of *Sphagnum* spores. Minor occurrences of *Pinus* are attributed to longdistance transport. Peaks in Cyperaceae and Polypodiaceae also occur.

Pollen zone 3 *Picea-Betula-Larix* (8500 to 7500 BP, 280 - 210 cm). A sustained increase in *Picea* pollen coincides with a decline in *Larix* pollen, though Larix maintains its presence throughout the zone. A decline in *Betula* sect. *Albae* pollen is paralleled by increases in *Betula* sect. *Nanae* and Cyperaceae pollen, while *Sphagnum* spores are low throughout most of the mid-zone. The upper portion of the zone shows an increase in *Sphagnum* spores.

Pollen zone 4 *Picea-Betula* (7500 to 6100 BP, 210 - 135 cm). This zone is dominated again by *Betula* sect. *Albae* pollen, with lower amounts of *Larix* and *Betula* sect. *Nanae*, and fluctuating percentages of *Picea* and Cyperaceae pollen. Poaceae pollen increases, and *Equisetum*, Polypodiaceae and *Sphagnum* spores fluctuate.

Pollen zone 5 *Picea-Betula*-Ranunculaceae-*Equisetum* (6100 to 4700 BP, 135 - 50 cm). *Larix* and *Picea* pollen drop in this zone, but *Abies sibirica* pollen first appears. *Betula* sect. *Albae* is still dominant, and less *Betula* sect. *Nanae* is present. Distinctive to this zone is the presence of Ranunculaceae pollen, along with major increases in Polypodiaceae at the base of the zone, followed by a drop in Polypodiaceae and major dominance of *Equisetum* spores.

Pollen zone 6 *Betula-Picea*-Ericales-*Sphagnum* (4700 BP to modern, 50 - 0 cm). This zone records maximum values of *Abies* pollen, sustained values of *Picea* and *Betula* sect. *Albae* pollen, maximum values of Cyperaceae and Ericales pollen, a marked drop in *Equisetum* spores, and large increases in *Sphagnum* spores.

Discussion

Peatland and vegetational history

The discussion of peatland types through time follows a progression of hydrological changes, associated with changes in nutrient content, pH, aeration, and degree of canopy cover. When viewed in a regional context through comparison with other sites (with bulk ^{14}C dates), patterns of regional climatic change are also revealed within the local peatland stratigraphy.

Shallow lake (9250 to 9200 BP)

At 9250 years BP, the lake was largely surrounded by *Larix sibirica* and *Betula pubescens* trees, with some shrubby *Betula nana*. *Larix* may have been present in the region as early as 15 000 BP, according to one date from wood on the Gydan Peninsula (site 25) of 15 000±250 BP. Other larch dates from the Gydan are 10 000±70 BP, LU-1153; 9730±100 yr BP, MGU-763 (Ukraintseva 1982) and 10 500±500 BP, IM-671, (Belorusova *et al.*, 1987) from the Taymyr Peninsula.

Although *Larix* is an important species of the forests in this region today, its history is not well known because of its poor representation in pollen diagrams. Rare even in surface samples from larch forests throughout Siberia (Vas'kovsky 1957; Popova 1961; Giterman 1963; Savvinova 1975; Andreev & Klimanov 1989), *Larix* low pollen frequency does not reflect its true abundance in a forest. Thus, even scant larch pollen in pollen records are interpreted as reflecting widespread *Larix* distribution.

The initial presence of *Larix* and *Betula pubescens* in the region, and even as far north as the Gydan and Taymyr Peninsulas, indicates that summers in the late-glacial and early Holocene were warm enough to support trees. The presence of lower sea level resulting in exposure of Arctic shelves and the existence of a continuously frozen Arctic Ocean until the early Holocene contributed to a more continental climate. Warmer summers and colder winters due to Milankovitch forcing (Berger 1978) would have also favored *Larix* growth. Modern distribution of larch extends to Northeastern Yakutia with winter lows as cold as -60° C today (Karavaev & Skryabin 1971). The large numbers of Siberian rivers which empty into the Arctic Ocean would have facilitated migration northward, because the open, warmer, well-drained river sands and silts would have favored seed germination and establishment.

Several locations in the region demonstrate widespread early Holocene peat initiation at this time. For example, near Igarka (Fig. 1, site 10), the bottom of a peat section was dated at 9480±120 BP (Levkovskaya *et al.* 1970). The basal age of a peat section from the Nadym-Kazym Rivers watershed (site 11) was dated to 9000±50 yr BP, IGAN-387 (Khotinsky & Klimanov 1985). A number of peat cores were investigated using pollen, macrofossil and radiocarbon analyses on the Pyaku-Pur, Pur-Pe, and Tydyotta River valleys (the western tributaries of the Pur River) and Long-Yugan River valley, the western tributary of Nadym River (sites 12-15). The oldest radiocarbon date is 9320±120 BP, LU-934 (Malyasova *et al.* 1991). To the north, ^{14}C dates from the Yamal Peninsula (sites 20-23) of 10 700±140 BP, LU-1042; 9600±160 BP, LG-30; 9300±100 BP, GIN-2442; 9230±50 BP, GIN-2479, published by Vasil'chuk *et al.* (1983) and from Sverdrup Island, Kara Sea (site 24), of 11 640±40 BP, GIN-7625, 10 490±380 BP, GIN-7626, and 9770±280 yr BP, GIN-7627 (Andreev *et al.* 1997) suggest that peat accumulation was locally initiated as early as the late-glacial.

Forested, wet sedge fen (9200 to 8700 BP)

A wet sedge fen characterized the area, as evidenced by the change from floating aquatics (*Nuphar*) to emergents (*Hippuris*), the sedge matrix with *Carex* achenes, and the appearance of *Calla palustris* and *Menyanthes trifoliata*. *Larix* pollen percentages drop with increasing percentages of Cyperaceae, but abundant larch macrofossils indicate its dominance at the site until about 7300 BP. *Betula cf. fruticosa* makes its first appearance.

The initial increase of *Picea* pollen is indicative of the movement of *Picea* into the region. The increase in *Picea* pollen about 9150 BP suggests that *Picea* reached the region at this time, and other nearby studies support this view. In particular, studies from a peat section near Igarka (site 10) (Levkovskaya *et al.* 1970) contains abundant *Picea* pollen, which appears to correlate with undated peat sections sampled by Katz and Katz (1947, 1958) near Novyy Port, Salekhard, Norilsk, Dudinka, Igarka and in the Taz-Turukhan Rivers watershed areas (sites 1-6). These data appear to also correlate with undated sections investigated by P'yavchenko (1971) in the Taz-Yenisey watershed (site 7) and near Igarka (site 8) and with samples from Yamsavey River valley (site 9) (Levkovskaya 1966). The radiocarbon date from the Levkovskaya et al. (1970) section (site 10) suggests that spruce forest was well established by 9200±40 BP. The pollen record from the Nadym-Kazym Rivers watershed (site 11) shows a peak of *Picea* pollen below a peat layer, dated to 8660±50 BP, IGAN-389 (Khotinsky & Klimanov 1985).

Movement of *Picea obovata* into the region suggests increasing moisture and warmth, because today the limit of *Picea* is to the south of *Larix* and *Betula pubescens*. Regionally there is an increase of spruce pollen between 9000 and 4500 BP. The oldest radiocarbon-dated spruce macrofossils (wood and cones) from a large area of West Siberia are dated to 8800-8400 BP (MacDonald *et al.* submitted).

Forested, Sphagnum-Calliergon and Sphagnum-sedge peatland (8700 to 8000 BP)

Sphagnum and *cf. Calliergon* moss are abundant in the lower part and in the upper part *Sphagnum*-sedge is dominant. Ericaceous species such as *Andromeda polifolia*, *Oxycoccus microcarpus* and *Vaccinium uliginosum* suggest that the peatland became raised above the water table. The pH probably dropped. *Larix* and *Betula pubescens* continued to dominate the forest, and *Betula cf. fruticosa* became extremely abundant around 8100 BP.

The first appearance of *Picea* macrofossils about 8000 BP suggests a warmer and perhaps moister climate overall compared with previous millennia and with today. The mid-Holocene *Picea* dominance is also seen in pollen stratigraphy from peats along the tributaries of the Pur river and the Long-Yugan River (sites 12-15) (Malyasova *et al.* 1991). Around the mouth of the Malay Kheta River (site 17) *Picea* pollen and macrofossils are also abundant in peat layers dated to 8500±250 BP, GIN-26; 6800±250 BP, GIN-25; and 4610±250, LE-382 (Alekseeva *et al.* 1965; Kind 1974). Near Igarka (site 18), *Picea* macrofossils were dated to 8210±250 BP, KRYL-126 and 5180±250 BP, KRYL-125 (Koshkarova 1986).

We note a peak in *Betula* sect. *Nanae* pollen between about 8300 and 8000 BP, which may correlate with the large increase in *Betula cf. fruticosa* macrofossils, slight coolings at about the same time at site 17 (Kind 1974), site 11 (Khotinsky & Klimanov 1985) and other locations in Northern Eurasia (Andreev & Klimanov 1989; Andreev *et al.* 1993, 1995; Klimanov & Levina 1989, Velichko *et al.*, 1997). Alternatively, it may be a local occurrence. Whether or not these indications of cooling are precisely correlative needs future study.

Forested, wet Equisetum fen (8000 to 6900 BP)

A drop in peatland ericaceous species and an increase in *Comarum palustre*, *Calla palustris*, *Hippuris*, *Lysimachia thyrsiflora*, *Menyanthes trifoliata* and *Daphnia* headshields suggests shallow water and more flow of water and nutrients through the site, resulting in a fen. Large numbers of wingless *Betula* seeds reveal a higher level of oxidation which contributed to seed degradation, thus supporting this interpretation. The decline in larch pollen and macrofossils around 7300 BP is paralleled by the slight rise in *Picea* macrofossils.

Forested, dry Equisetum-sedge fen (6900 to 6100 BP)

Spruce becomes dominant at the site, and many spruce woody remains are present along with spruce needles. *Equisetum* is very abundant, as evident in both the spore and peat stratigraphy. Sedge, *Rubus cf. arcticus*, *Rubus cf. saxatilis* and *Menyanthes* are also present. The rising increase in fungal sclerotia and these *Rubus* species reflect the overall drier conditions, although the presence of *Menyanthes* suggests that small pools were also present. The appearance of a few charcoal pieces indicates that fire was a local environmental factor, in contrast to the lack of charcoal in earlier deposits.

Forested, Equisetum-sandy-sedge fen (6100 to 5200 BP)

The LOI curve shows a marked drop in organic matter, which is visible in the sediment as very sandy grains mixed with the *Equisetum*-sedge peat. The sand is well-mixed throughout the peat and we interpret this phase as indicative of strong winter winds contributing sand from riverbanks or terraces. Alternatively, spring floods may have resulted in local transport of sand to the peatland. The presence of Caryophyllaceae and *Viola* seeds suggest a drier environment locally.

Abies pollen appears for the first time, but it probably was south of our site. Its arrival correlates well with *Abies* pollen data from sites 12-15 to the southwest investigated by Malyasova *et al.* (1991). The appearance of *Abies sibirica* pollen along with increases in *Alnus fruticosa* pollen suggests enhanced mid-Holocene atmospheric moisture with warmth. *Abies* pollen maxima of 10% about 4500 yr BP may indicate that the northern limit of *Abies* was close to the site.

Quantitative reconstructions of temperature from regional pollen records (Khotinsky & Klimanov 1985) indicate that the warmest time in the area during the Holocene was 6000-5000 BP. This is approximately the same time as the dominance of *Picea* macrofossils at our site (Fig. 4) and sites 17, 18 (Fig. 1). *Picea* macrofossils are restricted to this interval at site 16, which indicates northward treeline movement. The decline in *Betula pubescens* macrofossils at our site at this time is probably local, because the pollen record indicates that *Betula* was still present regionally.

Pinus sylvestris as and *Pinus sibirica*, which both have their northern limit to the south (Fig. 1) today, moved into the southern part of this region much later than *Picea* in the latter half of the Holocene and did not extend as farth north as *Picea*. We do not find macrofossils of these trees in our section, but slight (windblown) pollen increases about 8000-4500 BP suggests that they also were migrating northward with the increasing warmth. To the south at Yamylimyaganto Lake (site 26) in the Pur River valley near Urengoi where pine grows today (Subetto *et al.*. 1995), the appearance of *Pinus sylvestris* about 2800 BP and its subsequent increase to 30% reveals slow migration northward throughout the Holocene.

Open, sedge-moss fen (5200 to 4300 BP)

A return to wet, more organic-rich fen conditions is evident from the high organic content in the top 70 cm of the core, the drop in woody fragments, the total disappearance of tree macrofossils, the abundance of *Chamaedaphne calyculata* seeds, the presence of *Menyanthes*, and an increase in *Sphagnum* spores.

Open, dry cf.Polytrichum-lichen community (4300 to modern)

Very dry conditions are evident from well-decomposed peat with no fragments other than *cf. Polytrichum* and charcoal. The striking lack of mosses and macrofossils and presence of charcoal suggests that recent drought may have contributed to oxidation of the uppermost peat.

The age of 4570±60 BP at 25-30 cm depth in our peat corresponds with the evidence of peat degradation or lack of accumulation regionally in recent millennia, possibly suggesting a drier climate or other conditions less favorable for peat accumulation. Peat from a section near Igarka (site 10) was dated to 6030±70 BP at 40 cm depth (Levkovskaya *et al.* 1970). A peat sample from Karaginsky Mys (site 16) shows an age of 2420±150 yr BP, SOAN-55, at 20 cm depth (Levina & Nikitin 1973; Firsov *et al.* 1974). A date of 3800±40 BP, IGAN-392, was also retrieved from peat at 20 cm depth at site 11. Near this site, a date of 4900±50 BP, GIN-2292, from another palsa at a depth of 20-30 cm demonstrates another mid-Holocene age for near-surface peat (Khotinsky & Klimanov 1985). On the Yugorsky Peninsula a date of 4140±70 BP, WAT-2995 was obtained from peat at 10-15 cm depth (Andreev *et al.* in press). A number of sites from the Gydan Peninsula also show old ages for surface peats: 6520±60 yr BP, GIN-3624 at 20 cm depth; 3230±60 BP, GIN-3620 at 20 cm depth; and 3760±100 BP, GIN-3599 at 30 cm depth (Vasil'chuk, 1992).

It is also significant that similar old ages for surface peats are seen in the Canadian Arctic and Subarctic (Zoltai & Tarnocai 1975; Vardy *et al.*, 1997), supporting the contention that arctic peatlands may be presently acting as more of a source of carbon to the atmosphere than a sink (Warner *et al.* 1993; Belyea & Warner 1996). The reason for the lack of accumulation in recent millennia in Canada has been attributed to climatic cooling (Terasmae 1972), and the mechanisms may involve feedbacks such as less growth due to decreased nutrient mineralization (Bridgham *et al.* 1995), elevated drier peats due to increased permafrost action (Zoltai & Tarnocai 1975), or increased oxidation due to increased winds. Evidence for neoglacial cooling in recent millennia is also found in subarctic coastal Alaskan peatlands (Heusser *et al.* 1985; Peteet 1986, 1991) and glacial records from the St. Elias Mts., Alaska (Denton & Karlen 1973) as well as Ellesmere Island, Canada (Koerner & Fisher 1990).

Significance of Peatland, Arboreal, and Palaeoclimate changes

1. This high-resolution, complex record of peatland changes demonstrates the high degree of variability in peatland growth over the span of over 5000 years in a permafrost environment. Because the area today is mapped as continuous permafrost in this part of western Siberia, we attribute many of the changes in peat type to be a result of local hydrological changes (thermokarst action, stream movement), or even beaver activity (Levina and Nikitin 1973) within a changing climate. However, the proximity of discontinuous permafrost to the south (Shpolyanskaya 1981) suggests that during the early Holocene discontinuous permafrost may have affected this region, resulting in palsas and collapse scars (Zoltai 1993). Further high resolution research on West Siberian peatlands should reveal if the peatland stratigraphic patterns we find from 9300 - 4500 BP are repeated, and therefore represent regional rather than local conditions.

2. The migration of trees into this region is expressed at our site by a macrofossil pattern of *Larix sibirica* and *Betula pubescens* arrival, followed by *Picea obovata*. The decline of pollen from all of

these trees in the uppermost peats, along with the modern absence of *Betula pubescens* and *Picea* growth locally, suggests a change in the environment less favorable for their growth; perhaps cooler temperatures and/or less moisture.

3. The role of fire appears to be a minor one in the history of this peatland, except possibly in the initiation of the early Holocene lake sediments. This minor pyric role contrasts with the fire history in Finnish peatlands, where more than half of the carbon loss in peatlands is attributed to fire (Tolonen *et al.* 1992). Charcoal is more abundant, though still scarce, in the wooded phase between 6500 and 5500 BP, which may reflect the greater local influence of fire in a better-drained forest environment in contrast to the previously moister environments. However, the top of the peat section also contains a charred leaf, suggesting recent fire with the drier, more decomposed peat and some *cf. Polytrichum* remains. This surface charcoal could reflect destruction of surface peats by fire and the pyric origin of modern lakes on the landscape.

4. Overall, the sedimentation rates from 9100 to 4500 BP are not extremely different between tiepoints, as Fig. 3 demonstrates, until the top 30 cm is reached. At this age of 4530 BP, we do not know if peat accumulation suddenly slowed dramatically, with accumulation almost balanced by degradation, or whether the peat which accumulated to the present has been only very recently oxidized.

5. Of major significance is evidence for surprisingly old ages of the uppermost peat in this part of Siberia. These results suggest a clear lack of peat accumulation in recent millennia, either due to

very low net productivity, or alternatively, recent oxidation of fossil peats. The reasons for these changes are complex, and future studies of additional peat sections involving bulk density, C/N ratios, and bryophyte species identification are needed to further examine the role of Siberian peatlands in the carbon cycle.

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TABLE 1. AMS Radiocarbon dates and macrofossils dated from the investigated site

Lab Number	Depth, cm	Sample Type	Age
CAMS-24132	25-30	*Betula nana* twig	4570±60
CAMS-24133	85-90	*Betula nana* twig	4920±60
CAMS-24134	168-173	*Betula twig*	6830±60
CAMS-2427	263-268	*Betula* sect. *Albae* bark & wood	8370±60
CAMS-2428	339-344	*Betula* and *Larix* twigs	9200±60

Figure Captions

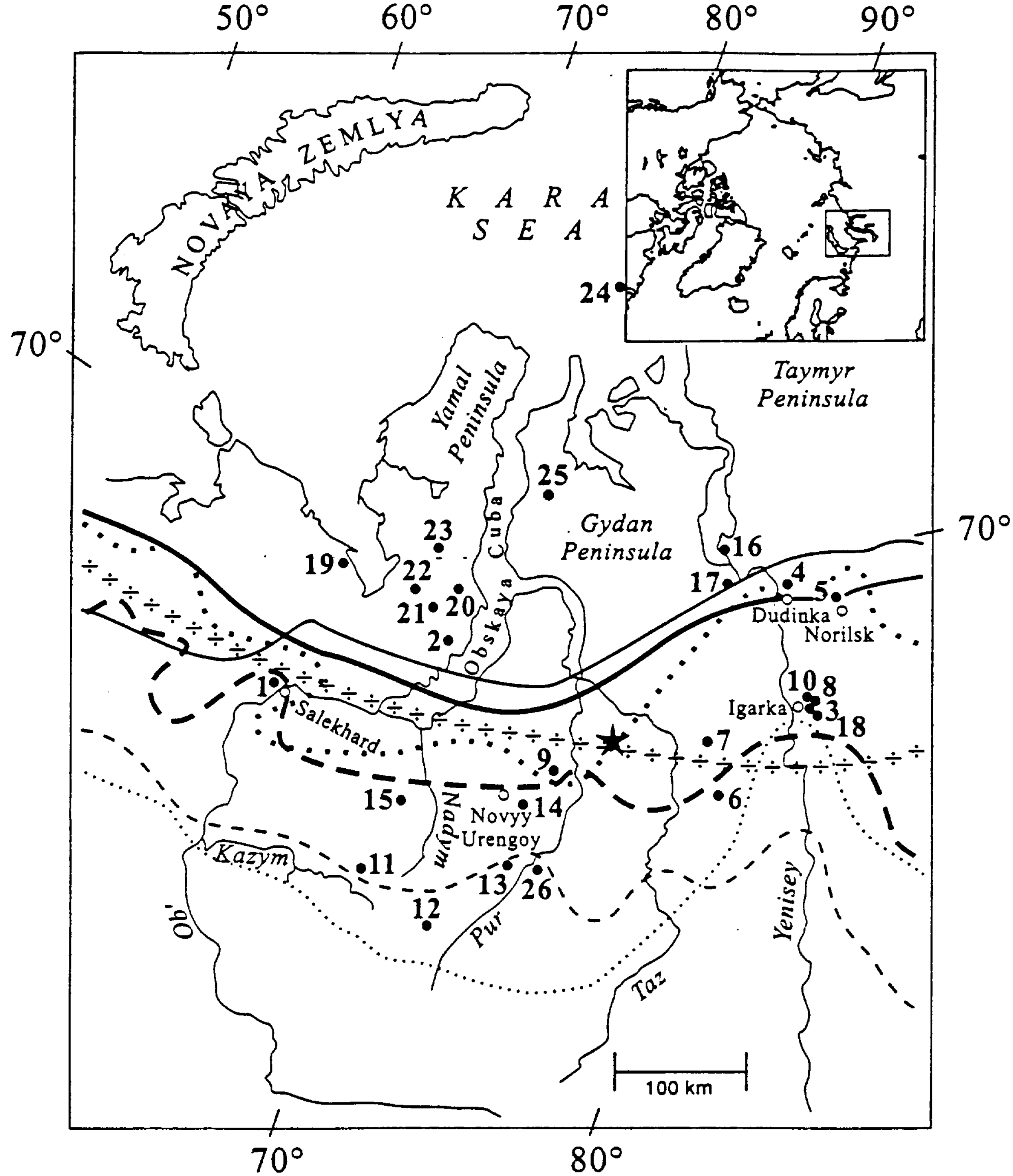
Fig. 1. Study region of western Siberia including the investigated site (this paper), previous palaeostudy sites, and modern treeline limits.

Fig. 2a. Peat composition and % loss-on-ignition (LOI) at 550^{o}C.

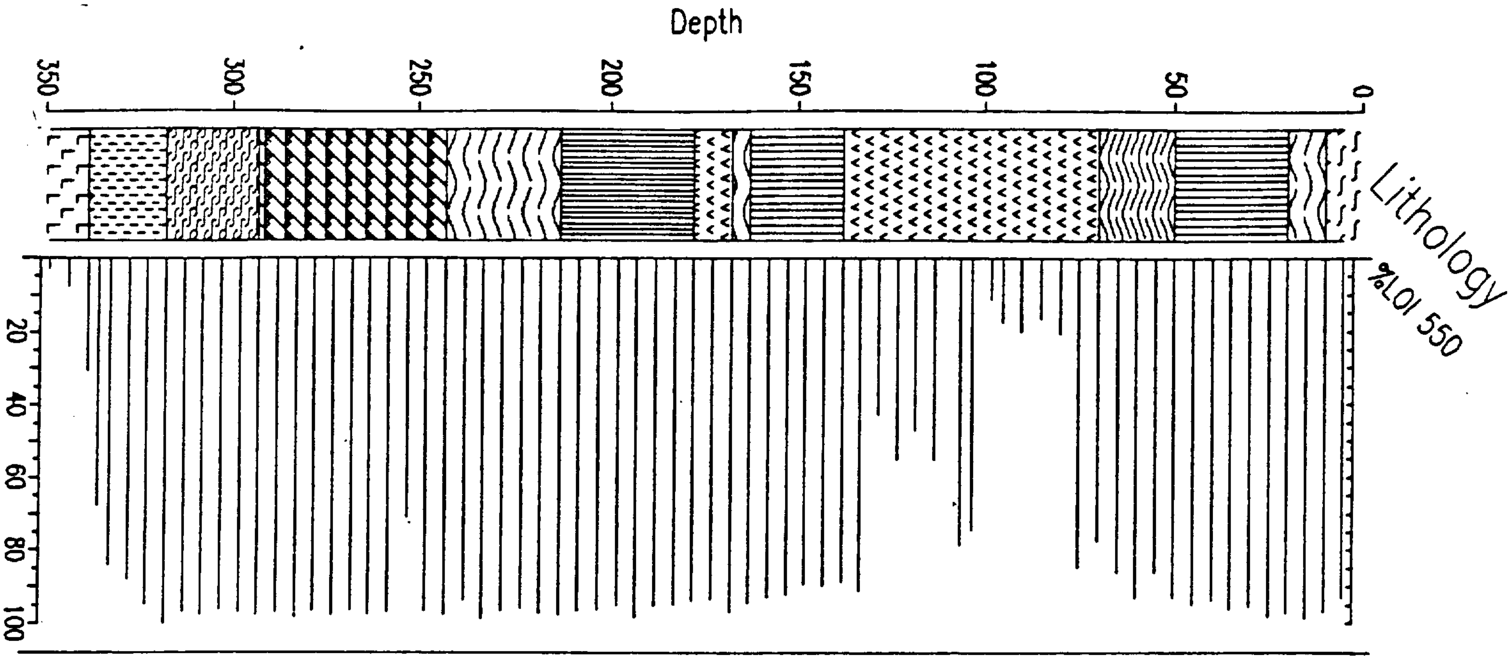
Fig. 3. Age-depth curve for the site using linear interpolation between AMS ^{14}C -dated levels. We give all dates in uncalibrated ^{14}C ages for ease in comparison with other studies.

Fig. 4. Macrofossil stratigraphy, Pur-Taz Section, western Siberia. Concentrations are numbers per 50 cm^3 per sample. Key for lithological units is shown in Fig. 2.

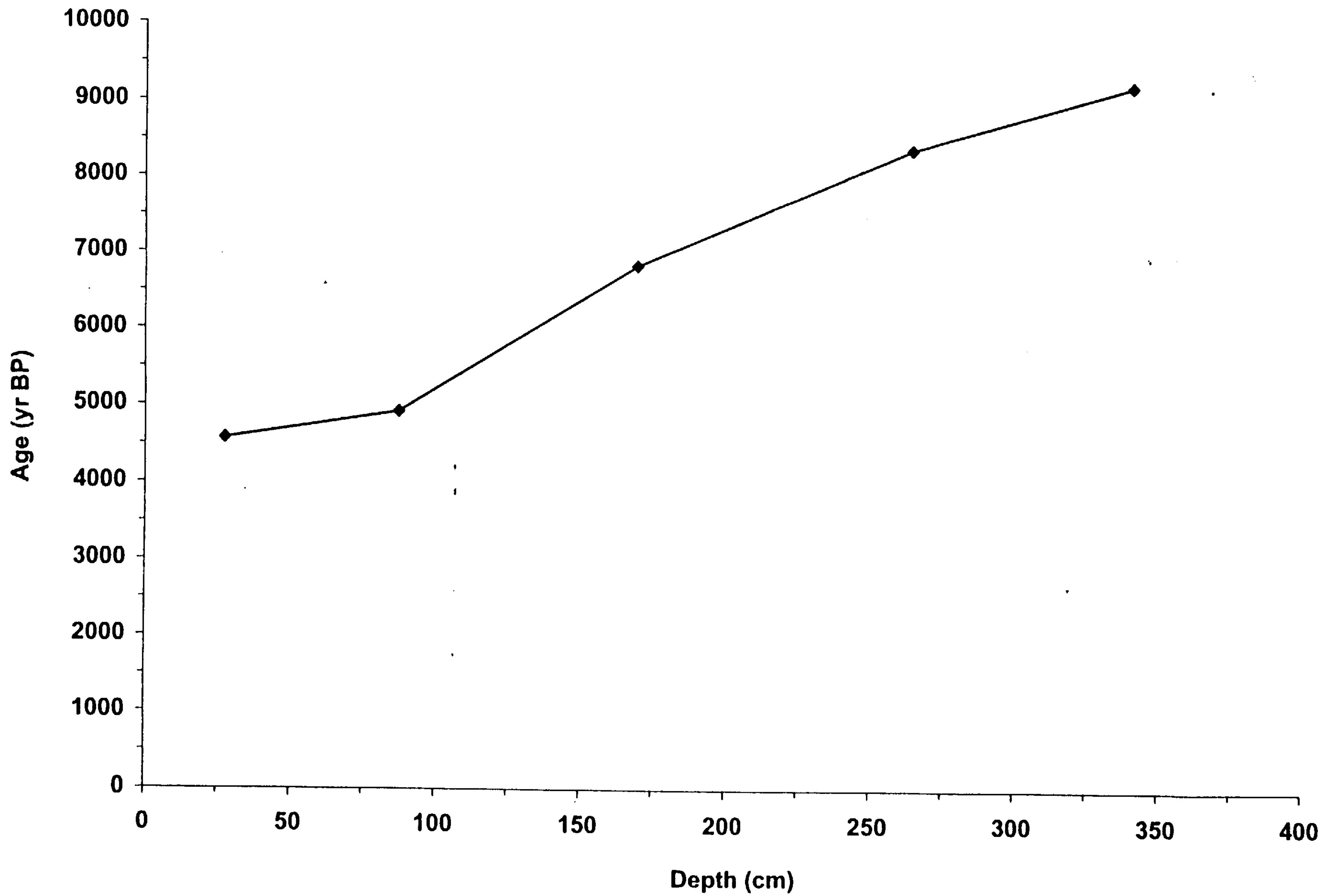
Fig. 5. Pollen and spore stratigraphy, Pur-Taz Section, western Siberia.

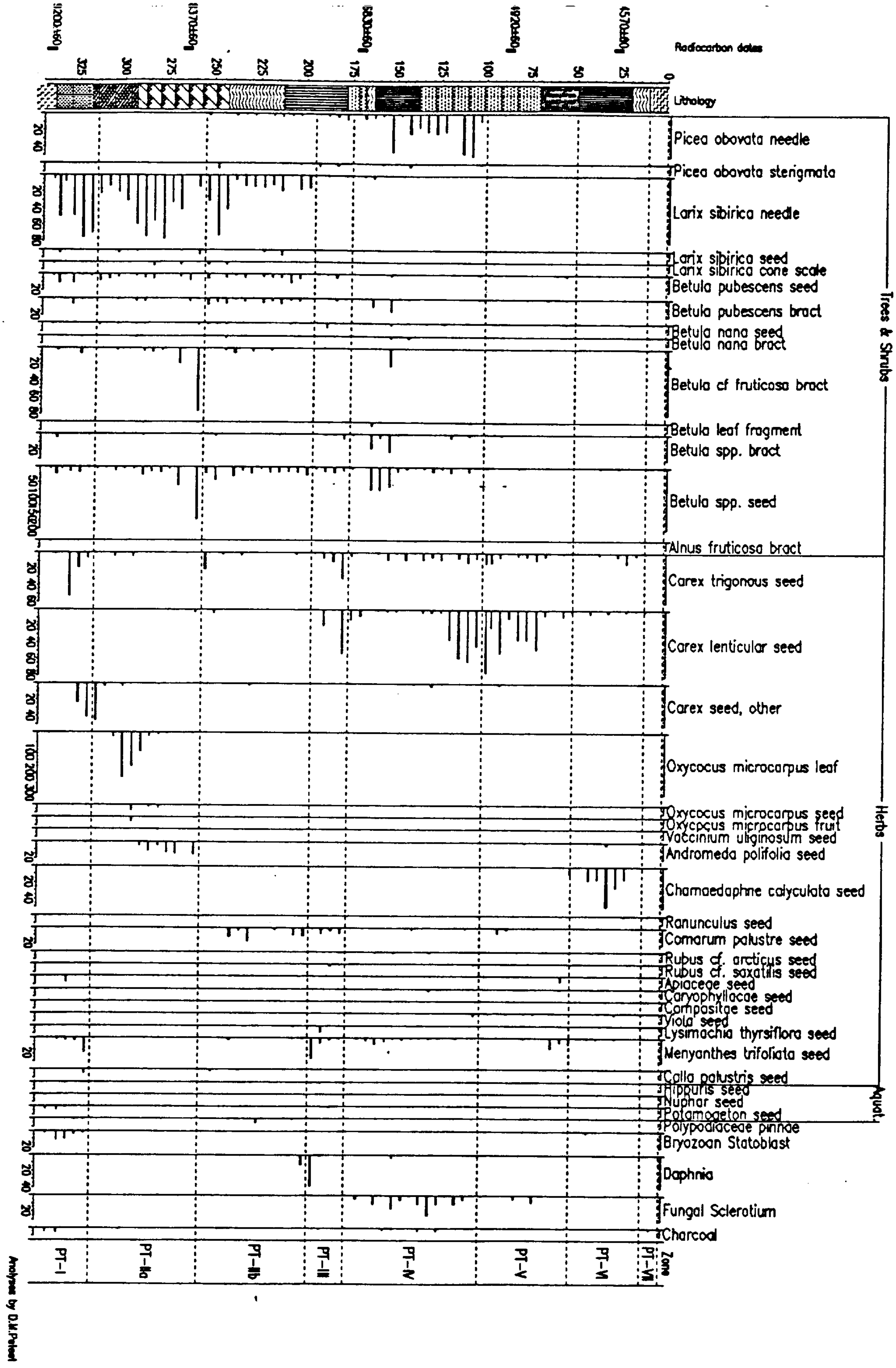


★ Investigated site	1) Salekhard	14) Tydyotta
÷ ÷ ÷ Arctic circle	2) Novyy Port	15) Long-Yugan
········ *Abies sibirica*	3) Igarka I	16) Karginsky Mys
• • • • *Picea obovata*	4) Dudinka	17) Malaya Kheta
- - - - *Pinus sylvestris*	5) Norilsk	18) Igarka IV
— — *Pinus sibirica*	6) Taz-Turukhan	19) Yugorsky Peninsula
—— *Larix sibirica*	7) Taz-Yenisey	20) Yamal-1
—— *Betula pubescens*	8) Igarka II	21) Yamal-2
	9) Yamsavey	22) Yamal-3
	10) Igarka III	23) Yamal-4
	11) Nadym-Kazym	24) Sverdrup Island
	12) Pyaku-Pur	25) Gydan
	13) Pur-Pe	26) Yamylimuyaganto Lake

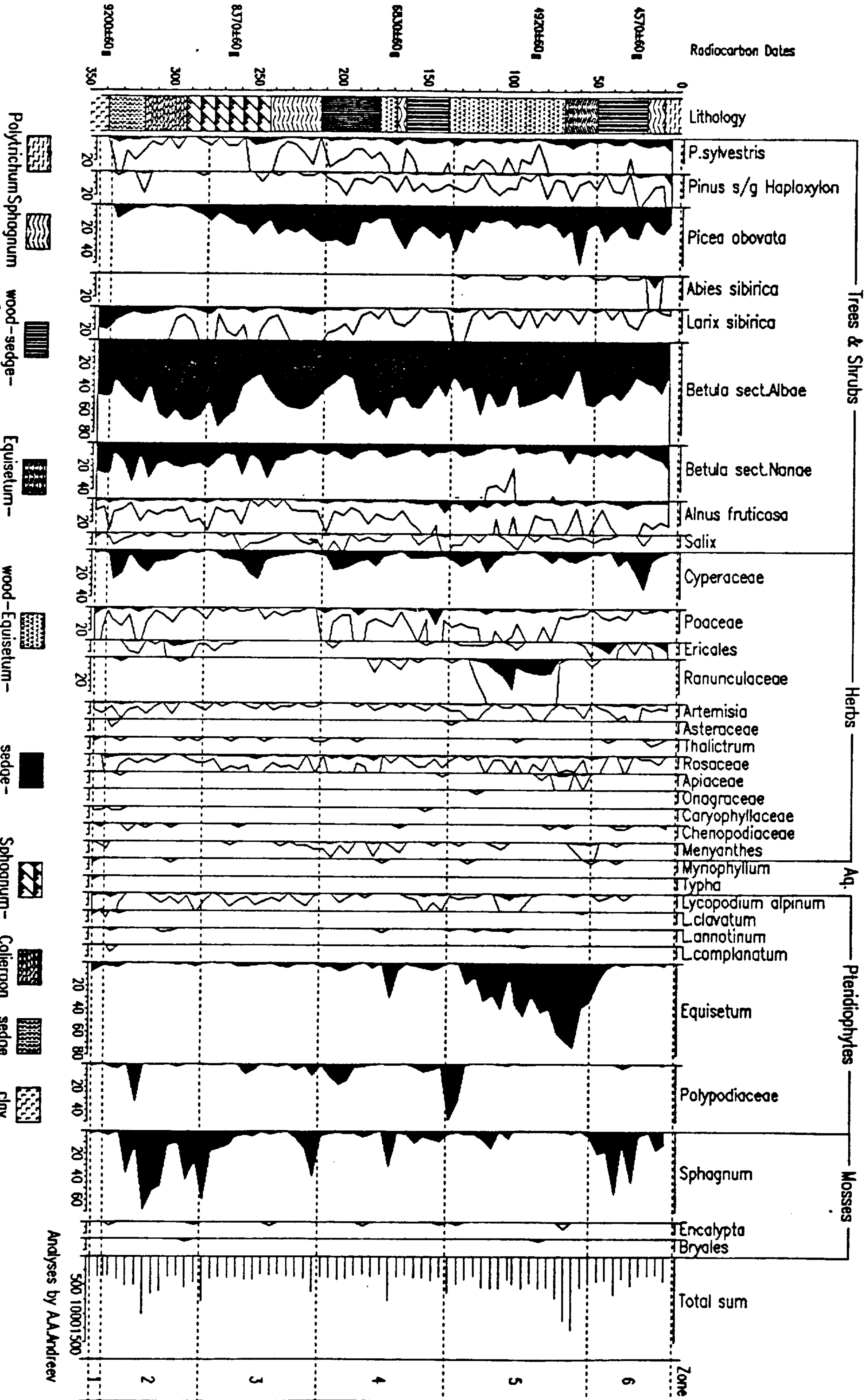


Depth
0
50
100
150
200
250
300
350
Lithology
%LOI 550
20
40
60
80
100


Age (yr BP)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
Depth (cm)



Radiocarbon dates
Lithology
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Picea obovata needle
Picea obovata sterigmata
Larix sibirica needle
Larix sibirica seed
Larix sibirica cone scale
Betula pubescens seed
Betula pubescens bract
Betula nana seed
Betula nana bract
Betula cf fruticosa bract
Betula leaf fragment
Betula spp. bract
Betula spp. seed
Alnus fruticosa bract
Carex trigonous seed
Carex lenticular seed
Carex seed, other
Oxycocus microcarpus leaf
Oxycocus microcarpus seed
Oxycocus microcarpus fruit
Vaccinium uliginosum seed
Andromeda polifolia seed
Chamaedaphne calyculata seed
Ranunculus seed
Comarum palustre seed
Rubus cf. arcticus seed
Rubus cf. saxatilis seed
Apiaceae seed
Caryophyllacae seed
Compositae seed
Viola seed
Lysimachia thyrsiflora seed
Menyanthes trifoliata seed
Calla palustris seed
Hippuris seed
Nuphar seed
Potamogeton seed
Polypodiaceae pinnae
Bryozoan Statoblast
Daphnia
Fungal Sclerotium
Charcoal
Trees & Shrubs
Herbs
Aquat.
PT-I
PT-IIa
PT-IIb
PT-III
PT-IV
PT-V
PT-VI
PT-VII
Zone
Analyses by D.M.Peteet



Radiocarbon Dates
9200±60
8370±60
6530±60
4920±60
4570±60
Lithology
P.sylvestris
Pinus s/g Haploxylon
Picea obovata
Abies sibirica
Larix sibirica
Betula sect.Albae
Betula sect.Nanae
Alnus fruticosa
Salix
Cyperaceae
Poaceae
Ericales
Ranunculaceae
Artemisia
Asteraceae
Thalictrum
Rosaceae
Apiaceae
Onagraceae
Caryophyllaceae
Chenopodiaceae
Menyanthes
Mynophyllum
Typha
Lycopodium alpinum
L.clavatum
L.annotinum
L.complanatum
Equisetum
Polypodiaceae
Sphagnum
Encalypta
Bryales
Total sum
Zone
1
2
3
4
5
6
Trees & Shrubs
Herbs
Aq.
Pteridiophytes
Mosses
Polytrichum-Sphagnum
wood-sedge-Sphagnum
Equisetum-Sphagnum
wood-Equisetum-Sphagnum
sedge-Equisetum
Sphagnum-sedge
Calliergon
sedge
clay
Analyses by A.A.Andreev