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A Holocene marine pollen record from the northern Yenisei Estuary (southeastern Kara Sea, Siberia)

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Abstract

A 780 cm long sediment core from the northern Yenisei Estuary (southeastern Kara Sea) was analysed for pollen to reconstruct the Holocene vegetation and climate history of the coastal area of the Kara Sea region. The core shows a high and continuous deposition of sediments from 8900 yrs BP (9400 cal. BP) to ca. 600 yrs BP. A pronounced change of the lithology and the occurrence of marine to brackish water dinoflagellate cysts and molluscs indicate that the core location was reached by sea water at 8600 yrs BP (9200 cal. BP) when the global sea-level was approximately 30m below the present level. The depositional environment changed gradually from fluvial to estuarine conditions.

Favourable climatic conditions with higher mean temperature than at present and a widespread occurrence of spruce in boreal forests in the hinterland prevailed between 8900 and 7400 yrs BP (9400 to 8300 cal. BP). Between 7400 and 5000 yrs BP (8300 to 5700 cal. BP), relatively stable warm climatic conditions were established. Sedges dominated fens and peat bogs were widespread in the coastal lowlands indicating high water saturation and moist climate conditions. Since 5000 yrs BP (5700 cal. BP), and more pronounced since 3800 yrs BP (4200 cal. BP), long-distance transported pollen (mainly pollen of *Pinus sylvestris*) increased gradually and *Picea* pollen decreased reflecting the onset of climate cooling and the movement of the arctic tundra vegetation zone southward. A short-term warming event occurred between 4200 and 3800 yrs BP (4750 to 4200 cal. BP). The most pronounced change occurred at ca. 2200 yrs BP, when *Picea* pollen decreased notably indicating the retreat of the spruce tree line. Additionally, the simultaneous increase of pollen taxa such as *Salix*, *Artemisia*, Ranunculaceae, and *Thalictrum* suggests a colder climate.

1. Introduction

The paleoenvironmental evolution of the Kara Sea region has attracted much attention in the past years because of its crucial location at the eastern margin of the late Weichselian Barents-Kara Ice Sheet. Particularly, the eastern extent of the ice sheet during the Last Glacial Maximum (LGM) is a matter of controversy (e.g. Grosswald and Hughes, 2002; Mangerud et al., 2002). The generally accepted reconstruction, based on extensive fieldwork on well-dated land sections, implies that the southeastern Kara Sea was not glaciated, possibly with the exception of the northern part of the Taimyr Peninsula (e.g. Astakhov et al., 1999; Manley et al., 2001; Mangerud et al., 2001, 2002; Alexanderson et al., 2002; Forman et al., 2002). Therefore, the southern Kara Sea and the adjacent hinterland are well-suited for detailed studies of late Weichselian and Holocene paleoenvironments.

Palynological and macrofossil analyses performed on a number of sections from peat bogs and lakes in the hinterland of the Kara Sea revealed distinct movements of vegetation zones and associated changes in the position of the Arctic tree line since the LGM (e.g. Khotinskiy, 1984; Koshkarova, 1995; Velichko et al., 1997; Peteet et al., 1998; Andreev et al., 1998, 2001, 2002; Andreev and Klimanov, 2000; Kremenetski et al., 1998a; Hahne and Melles, 1999; MacDonald et al., 2000). Moreover, reconstructions of Siberian paleoclimate using numerical methods and models have yielded quantitative information on temperature and precipitation (Peterson, 1993; TEMPO, 1996; Ganopolski et al., 1998; Monserud et al., 1998; Tarasov et al., 1999; Andreev and Klimanov, 2000; CAPE, 2001; Velichko et al., 2002). However, paleoclimate data from the coastal regions of the southern Kara Sea are sparse due to the lack of continuous late Weichselian and Holocene sequences (e.g. Andreev et al., 1998, 2001; Serebryanny et al., 1998; Serebryanny and Malyasova, 1998). Thus, the northernmost land sections covering most of the Holocene are located more than 400 km south and southeast of the shore line (Clayden et al., 1997; Jasinski et al., 1998; Andreev et al., 1998; Hahne and Melles, 1999; Andreev and Klimanov, 2000). Therefore, terrestrial paleoclimate gradients cannot be adequately resolved in the coastal region and compared with the marine paleoclimate evolution of the southeastern Kara Sea.

Marine pollen sequences from the inner Kara Sea may fill this gap because estuaries such as those of the Yenisei and Ob rivers are areas of high and continuous deposition of sediments since they were flooded due to the postglacial sea-level rise (e.g. Stein et al., this vol.). Previous studies on Arctic and subarctic shelf sediments also illustrate the potential of pollen to reconstruct paleoclimate change in the adjacent coastal region and to link the terrestrial and marine paleoclimate records (e.g. Kulikov and Khitrova, 1982; Mudie, 1982; Mudie and Short, 1985; Hill et al., 1985; Mudie and McCarthy, 1994; Naidina and Bauch, 2001; Levac et al., 2001). Furthermore, offshore pollen spectra may provide supplementary information on large-scale patterns and processes occurring in the adjacent coastal area, whereas pollen records from terrestrial sites reflect rather the local and regional landscape development (Faegri and Iversen, 1989; Moore et al., 1991).

In this study, we present the first high-resolution, well-dated Holocene pollen record from the southern Kara Sea. We correlate this local pollen stratigraphy with published data from continental pollen sites and provide new information on the large-scale mid-Holocene warming and Late Holocene cooling trends, which were interrupted by short climatic events (e.g. Andreev and Klimanov, 2000), accompanied by vegetation zone shifts and tree-line movements in the hinterland.

2. Study area

2.1 Oceanography and Hydrography

The Kara Sea is one of the large Eurasian continental shelf seas covering an area of approximately 883,000 km^2 (Pavlov and Pfirman, 1995) (Fig. 1A). The bottom topography is much more variable than that of the other circum-arctic shelf seas. The western and northern parts are dissected by the deep (>400 m) Novaya Zemlya, St. Anna and Voronin troughs. The southeastern shelf is less than 50 m deep, with numerous shoals and islands north of the Ob and Yenisei estuaries and west of

Severnaya Zemlya. Submarine channels extend from the estuaries to the Novaya Zemlya Trough (Johnson and Milligan, 1967).

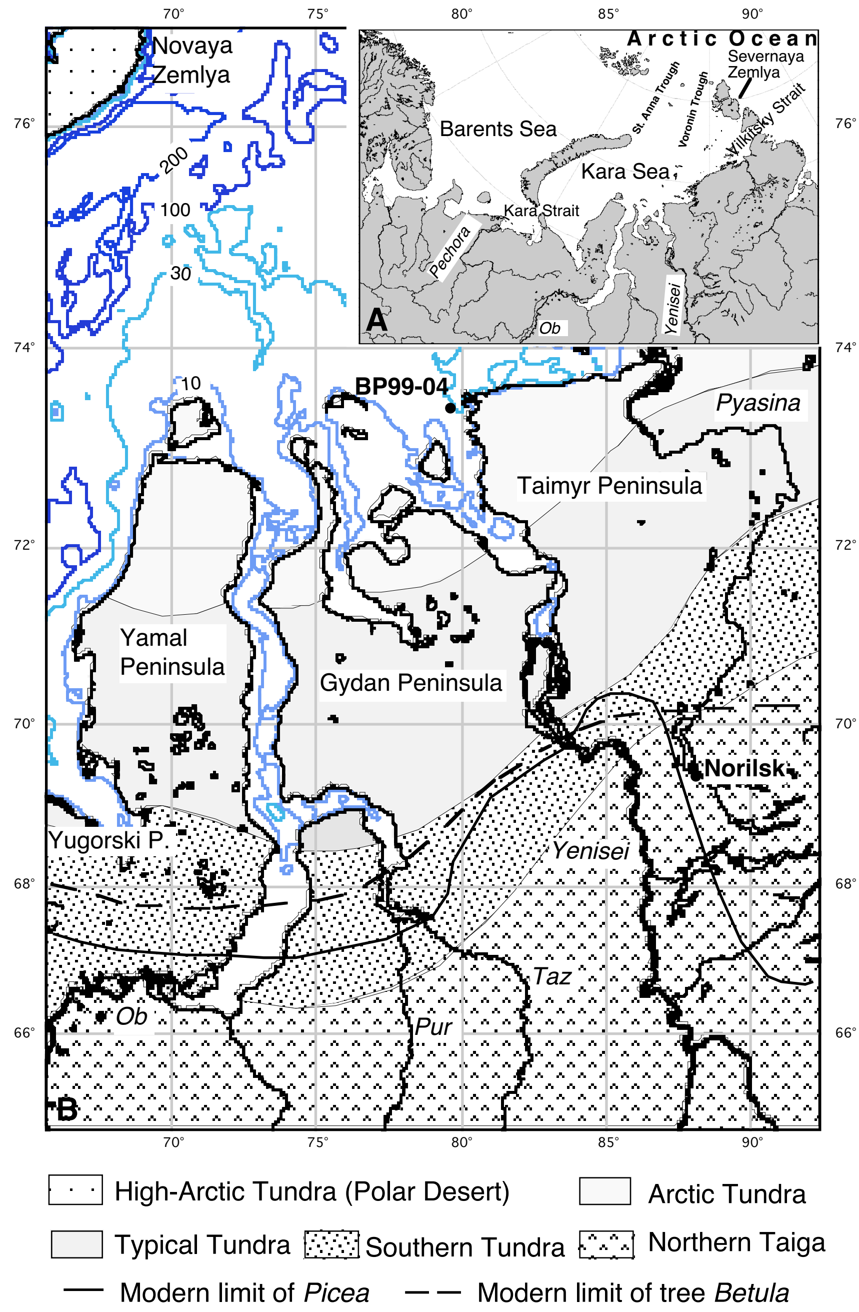

Fig. 1: (A) Overview map of northern Eurasia and the adjacent Siberian shelf seas with topographical data named in the text. (B) Detailed map of the southeastern Kara Sea with the core location of BP99-04. The vegetation zones and modern limits of *Picea obovata* and tree *Betula* in the coastal region and hinterland are shown (Atlas Arktiki, 1985; MacDonald et al., 2000; Kremenetski et al., 1998a).

The inner Kara shelf is semi-enclosed by Novaya Zemlya, the Severnaya Zemlya Archipelago, and the Siberian hinterland (Fig. 1A). The southern Kara Sea is connected with the Barents and Laptev seas through the Kara Strait and the Vilkitsky Strait, respectively. The St. Anna and Voronin troughs link the southern Kara Sea with the central Arctic Ocean. Freshwater discharge by the rivers Ob and Yenisei which drain about 2,580,000 km^2 strongly influence the hydrographical and depositional conditions in the southern Kara Sea (Pfirman et al., 1995; Gordeev et al., 1996; Polyak et al., 2002; Dittmers et al., this vol.). The riverine suspended matter was mainly deposited in the outer estuaries during the Holocene (Lisitzin, 1995; Dittmers et al., this vol.). Although various processes such as resuspension by storm activity, sea-ice formation and sea-ice gouging may lead to export of sediments from the depositional center (Pavlov and Pfirman, 1995), radiocarbon dating revealed that continuous Holocene sections may be retrieved at some locations (Stein et al., this vol.).

2.2 Climate

The modern climate conditions in the Kara Sea region near the shore are influenced on a broad scale in the cold season by Atlantic air masses (Icelandic low pressure system) and in the warm season by the Siberian anticyclonic high pressure system (Atlas Arktiki, 1985; Pavlov and Pfirman, 1995). Across the boundary of the West Siberian lowland and the middle Siberian plateau, parallel to the course of the Yenisei river, the climate changes by gradually increasing Siberian anticyclone activity that expands seasonally westwards. The prevailing wind direction in the warm season is from northeast to northwest and in the cold season from south to southeast (Atlas Arktiki, 1985; Pavlov and Pfirman, 1995). The storm activity is relatively high (Pavlov and Pfirman, 1995).

The average air temperature shows a large range during the cold season (January) between –20 ˚C in the western part to –30 ˚C in the eastern part, and in the warm season (July) between ca. +6 ˚C in the coastal area and +10 ˚C to +12 ˚C in the hinterland (Atlas Arktiki, 1985). The annual precipitation on average ranges between 300 to 600 (800) mm depending on the topographical location. Permanent permafrost soils cause characteristic periglacial pedogenetical and geomorphogical conditions (e.g. IPA, 1998; Schultz, 1995).

2.3 Modern vegetation

The modern vegetation in the coastal area and the adjacent hinterland is characterized by a latitudinal succession from south to north (Fig. 1B). Boreal forests and forest tundra are replaced by subarctic and arctic tundra and finally by polar desert covering most islands (Aleksandrova, 1980, 1988; Atlas Arktiki, 1985; Walter and Breckle, 1994). Longitudinal changes are most pronounced across the eastern boundary of the West Siberian lowland and the middle Siberian plateau (Taimyr Peninsula, Putorana Plateau), characterized by an increase of plant species numbers towards the east. While the western part of the study area is influenced by European species, the eastern part is covered by typical Siberian species (Alexandrova, 1988; Kienast et al., 2001).

The land area adjacent to the Yenisei Estuary belongs in a geobotanical sense to the tundra region, which is subdivided into the ”Yamal-Gydan-West Taimyr subprovince” of the subarctic tundra and the ”Yamal-Gydan-Taimyr-Anabar subprovince” of the arctic tundra (Aleksandrova, 1980, 1988). Lichen and moss-lichen variants of shrub and herb-dwarf shrub tundras occur in the first subprovince. Various stages of polygonal mires and numerous lakes are characteristic landscape elements. Shrubs such as *Betula nana*, *Salix lanata*, *S. pulchra* and *Alnus fruticosa* are widespread. Typical low shrubs covering this area are *Vaccinium vitis-idaea*, *V. uliginosum* ssp. *microphyllum*, *Ledum decumbens*, *Rubus chamaemorus* and *Empetrum hermaphroditum*. Herbs and sedges such as *Dryas punctata*, *Cassiope tetragona*, *Eriophorum angustifolium*, *Carex ensifolia* ssp. *arctisibirica*, *C. stans* and *C. rariflora* are characteristic elements. Peat mosses (*Sphagnum* sp.) are abundant among the mosses, particularly in the polygonal mires. Brown mosses like *Drepanocladus revolvens*, *Hylocomnium splendens*, *Aulacomnium* sp., *Dicranum* sp., *Calliergon* sp. and *Polytrichum* sp. are the most characteristic species. *Cladonia* and *Cetraria* species are the most widespread lichens.

In the second subprovince, the vegetation cover is closed or almost closed. Polygonal mires are less frequent. The most characteristic floristic elements are arctic willows such as *Salix polaris* and *S. nummularia*. Furthermore, *Dryas punctata*, *D. octopetala*, *Luzula confusa*, *Carex ensifolia* ssp. *arctisibirica* and *C. stans* have a widespread distribution. Characteristic mosses are peat mosses (*Sphagnum* sp.), brown mosses of the genera *Aulacomnium*, *Hylocomnium*, *Ptilidium*, *Dicranum*, *Drepanocladus* and *Polytrichum*. Characteristic lichens are the genera *Cladonia*, *Cetraria* and *Dactylina*.

The polar desert occurs in the Kara Sea region mainly on the small islands and in the northern part of Novaya Zemlya and is characterized by a decreasing vegetation cover and the predominance of cryptogamous over angiosperms and lichens over mosses (Alexandrova, 1980, 1988).

3. Material and Methods

The gravity core BP99-04/07 was collected during the Kara Sea expedition of RV ”Akademik Boris Petrov” in 1999 (Stein and Stepanets, 2000). It is located in the northern Yenisei Estuary (73°24,9´N, 79°40,5´E, 32 m water depth), approximately 30 km from the shoreline (Fig. 1A,B), where high sedimentation rates prevailed during the Holocene (Dittmers et al., this vol.). The core recovery was 795 cm, but the uppermost part was lost due to over-penetration during coring.

3.1 Lithology

The lithology of the core consists of relatively homogeneous bioturbated dark olive grey silty clays to clayey silts in the upper part, and bedded to bioturbated silty sands at the base (Fig. 2 and 3). Based on visual description, magnetic susceptibility data and acoustic profiles, Stein (2001) and Dittmers et al. (this vol.) distinguish two lithological units (Fig. 2). This description is refined by examination of x-radiographs, granulometric data and total organic carbon contents (TOC) (see also Stein et al., this vol.).

Unit Ia (0 to 740 cm) consists of homogeneous bioturbated silty clays to clayey silts. Bivalves (e.g. *Portlandia* sp.) occur down to the base of the unit, but decrease in abundance from 440 cm core depth to the top of the core. Dinoflagellate cysts occur also in the Unit Ia. At 510 cm core depth, a piece of wood was found. The TOC content slightly decreases from 740 to 370 cm core depth and is almost constant (~1%) from 370 to 120 cm core depth (Fig. 3). In the uppermost part TOC contents increase notably. Unit Ia was deposited in an estuarine environment.

The contact of Unit Ia and Ib is characterized by a transition from bioturbated to bedded sediments. Unit Ib (740 to 780cm) consists of silty sands and shows a maximum of magnetic susceptibility (Dittmers et al., this vol.; Stein et al., this vol.). Bivalves and dinoflagellate cysts are absent in Unit Ib. Bioturbation is highly variable. Parallel bedding (partly laminae with <1mm thickness) to cross bedding and channel infill structures are common. Laminae are usually disrupted by bioturbation. Contacts between bioturbated and bedded layers are irregular showing erosional features. The basal part of the sediment core was probably deposited in a fluvial sedimentary environment.

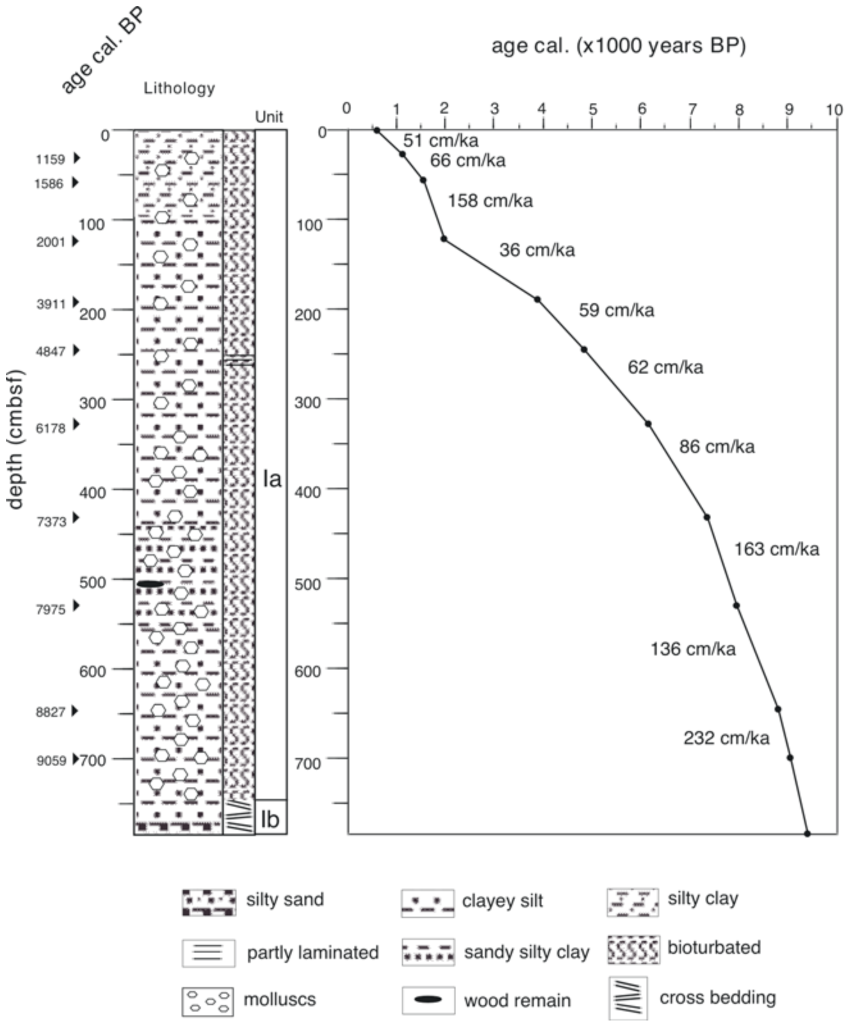

Fig. 2: Lithology, texture and linear sedimentation rates of sediment core BP99-04 (modified after Stein et al., this vol.).

3.2 Radiocarbon chronology

The age model is based on twelve AMS ^{14}C radiocarbon dates, which were performed on *Portlandia* sp. shells (Table 1; see also Stein et al., this vol.). The ^{14}C ages were corrected for a reservoir effect of 440 yr (Mangerud and Gulliksen, 1975) and were calibrated into calendar years BP with the program CALIB 4.3 (Stuiver et al., 1998). There is one age reversal at 646 cm core depth which is located in a massive layer indicating rapid sedimentation. Therefore, it is not used to obtain the final age model.

Ages for the core top and core base were extrapolated using the linear sedimentation rates of the next units.

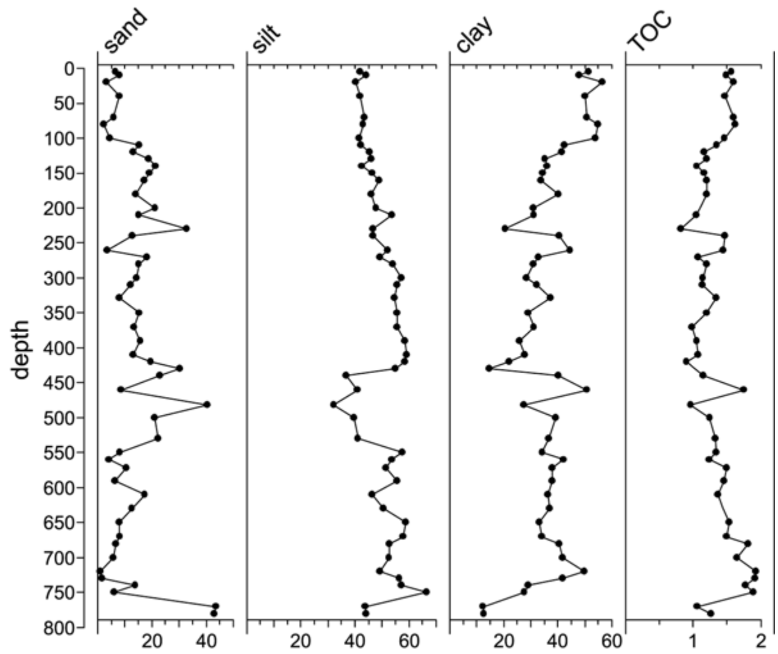

Fig. 3: Granulometric composition (%) and TOC content (%) of sediment core BP99-04.

Relatively high average sedimentation rates prevailed during the past ca. 9000 cal. yrs BP ranging from 36 cm/ka to 232 cm/ka (Fig. 2). The contact between Units Ia and Ib is dated at approximately 9200 cal. BP (8600 yrs BP).

Table 1: AMS ^{14}C datings of sediment core BP99-04 performed on shells of *Portlandia* sp. (Stein et al., this vol.). Reservoir correction after Mangerud and Gulliksen (1975). The interpolated age (*) was calculated for a depth midway between the dated levels at 350.0 and 700.0 cm core depth.

Core depth (cm)	^{14}C Age (BP)	Reservoir corrected age (-440 yr BP)	Calendar age (cal yrs BP)	Laboratory numbers
29.0	1630±20	1190±20	1159	KIA-12781
57.0	2070±25	1630±25	1586	KIA-12782
122.5	2450±30	1990±30	2001	KIA-10239
191.0	3980±30	3540±30	3911	KIA-10238
246.0	4695±30	4255±30	4847	KIA-10237
329.0	5800±40	5360±40	6178	KIA-10236
420.0	6855±35	6415±35	7234	KIA-10235
432.0	6890±45	6450±45	7373	KIA-10234
530.0	7585±35	7145±35	7975	KIA-10233
632.0	8345±50			KIA-10232
646.0		7887*	8827*	
658.5	8310±40			KIA-10231
700.0	8725±40	8285±40	9059	KIA-10230

3.3 Palynological analysis

In total, 52 samples were taken for palynological analysis at intervals of about 15 cm. The average temporal resolution ranges from 45 to 200 years, depending on the sampling interval and sedimentation rates.

The laboratory processing follows standard palynological procedures without using acetolysis (e.g. Rochon et al., 1999). After freeze-drying, samples were treated with cold hydrochloric (10%) and hydrofluoric acids (38-40%) to dissolve carbonates and silicates. Most of the fine organic matter was removed by wet sieving to enrich the particulate organic matter (POM) larger than 6 µm. *Lycopodium* spore tablets were added to calculate pollen concentrations (Stockmarr, 1971; Berglund and Jalska-Jasiewiczowa, 1986; Faegri and Iversen, 1989). Besides terrestrial palynomorphs, aquatic palynomorphs (cysts of dinoflagellates, chlorococcalean algae, acritarchs) were encountered. The results of the aquatic palynomorph studies will be published elsewhere. Reworked pre-Quaternary pollen were counted, but not assigned to taxa.

Pollen were identified and counted under a light-microscope (Fa. ZEISS) using x400 and x1000 magnification. The nomenclature and taxonomy of pollen and spores basically follows Moore et al. (1991). The TILIA and TILIAGRAPH software was used to plot the pollen data (Grimm, 1991). In total, 53 pollen types were identified.

Because of the specific fluvial and aeolian transport and deposition processes in neritic environments (Brush and DeFries, 1981; Heusser, 1983; Brush and Brush, 1994; Traverse, 1994; Mudie and McCarthy, 1994), the standard pollen sum is on average much lower than in lacustrine records or peat sections (Faegri and Iversen, 1989; Berglund and Jalska-Jasiewiczowa, 1986). The pollen sum includes all arboreal (AP) and non-arboreal pollen (NAP) excluding the spores (Fig. 4). For discussion of the regional vegetation changes, typical long-distance transported pollen is excluded from the pollen sum and is separately shown in Figure 5.

The complete data set can be retrieved from the PANGAEA information system at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven (http://www.pangaea.de).

4. Results

All analysed samples contain pollen in sufficient amounts (100-700 grains) to calculate percentage abundances (Fig. 4). Pollen concentrations show a maximum at the base of the core and are relatively constant from ca. 670 cm core depth to the top of the core although sediment grain sizes are relatively variable.

4.1 Pollen stratigraphy

Six local pollen assemblage zones (LPAZ) were defined and named after the location of the core in the Yenisei Estuary (Ye). The standard pollen diagram was plotted versus depth (cf. Berglund and Ralska-Jasiewiczowa, 1986; Moore et al., 1991).

The LPAZ Ye-I (780 – 674 cm) is characterized by maximum abundance of *Picea* pollen (>40%) in core BP 99-04, relatively high values (>40%) of *Pinus* Diploxylon pollen type, a notable decrease of *Betula* pollen, low values of Cyperaceae pollen (<20%), and the maximum of Polypodiales spores. Reworked pollen is rare. Total pollen concentrations increase from the base of the core to a maximum of >24,000 grains/g dry sediment.

At the base of LPAZ Ye-II (674 – 574 cm), the pollen spectra show a notable change. The arboreal pollen spectra are marked by a change in dominance from *Picea* pollen to *Pinus* pollen. The *Pinus* Haploxylon type increase in abundance and is continuously present in zone Ye-II. *Salix* pollen is more abundant at the base and the top of the zone. *Betula* and *Alnus* pollen decrease from a maximum at the base to the top of this zone. The non-arboreal pollen spectra are characterized by a sharp increase of Cypera ceae pollen and a peak of Poaceae, *Artemisia* and Ericaceae pollen in the upper part. Furthermore, *Thalictrum* pollen is present. An increase of reworked pollen is notable.

LPAZ Ye-III (574 – 298 cm) is characterized by relatively low percentages of *Betula* pollen and *Pinus* Diploxylon pollen type. *Salix* pollen is only sporadically present in some samples. *Abies* pollen shows a closed curve reaching approximately 5%. Cyperaceae pollen is abundant (around 40%). The appearance of *Typha latifolia*, *T. angustifolia* and *Polemonium* pollen is notable. Reworked pollen shows a sharp increase.

LPAZ Ye-IV (298 – 123 cm) is characterized by a distinct increase of the *Pinus* Diploxylon pollen type and *Betula* pollen. The *Picea* pollen curve shows fluctuations, but decrease notably in the upper part of this zone. The non-arboreal pollen spectra are marked by a slight decrease of Cyperaceae pollen, and an increase of *Artemisia* and *Thalictrum* pollen. Furthermore, pollen of *Anthemis* type and Gentianaceae pollen is present. Reworked pollen decreases in zone LPAZ Ye-V.

LPAZ Ye-V (123 – 0 cm) is defined by a minimum of *Picea* pollen (< 5%), and by a sharp increase of the *Pinus* Diploxylon pollen type up to ca. 80% in the lower part of this zone. Furthermore, *Betula* pollen increases slightly. The increase is more distinct, when *Pinus* Diploxylon pollen type is exluded from the pollen sum (see Fig. 5). *Pinus* Haploxylon pollen type decreases. *Salix*, *Artemisia*, Ranunculaceae and *Thalictrum* pollen are continuously present with low amounts. Reworked pollen decreases to a minimum in core BP99-04. Pollen concentrations increase slightly.

5. Discussion

5.1 Depositional processes

In marine systems, various factors influence pollen transport and deposition (e.g. Brush and DeFries, 1981; Heusser, 1983; Mudie and McCarthy, 1994; Traverse, 1994; Naidina and Bauch, 1999). The distance of the core location from the source of pollen, the atmospheric and the ocean circulation patterns are the major processes affecting the composition of marine pollen spectra. Thus, these spectra may reflect both transport processes and changes of the vegetation cover in the hinterland.

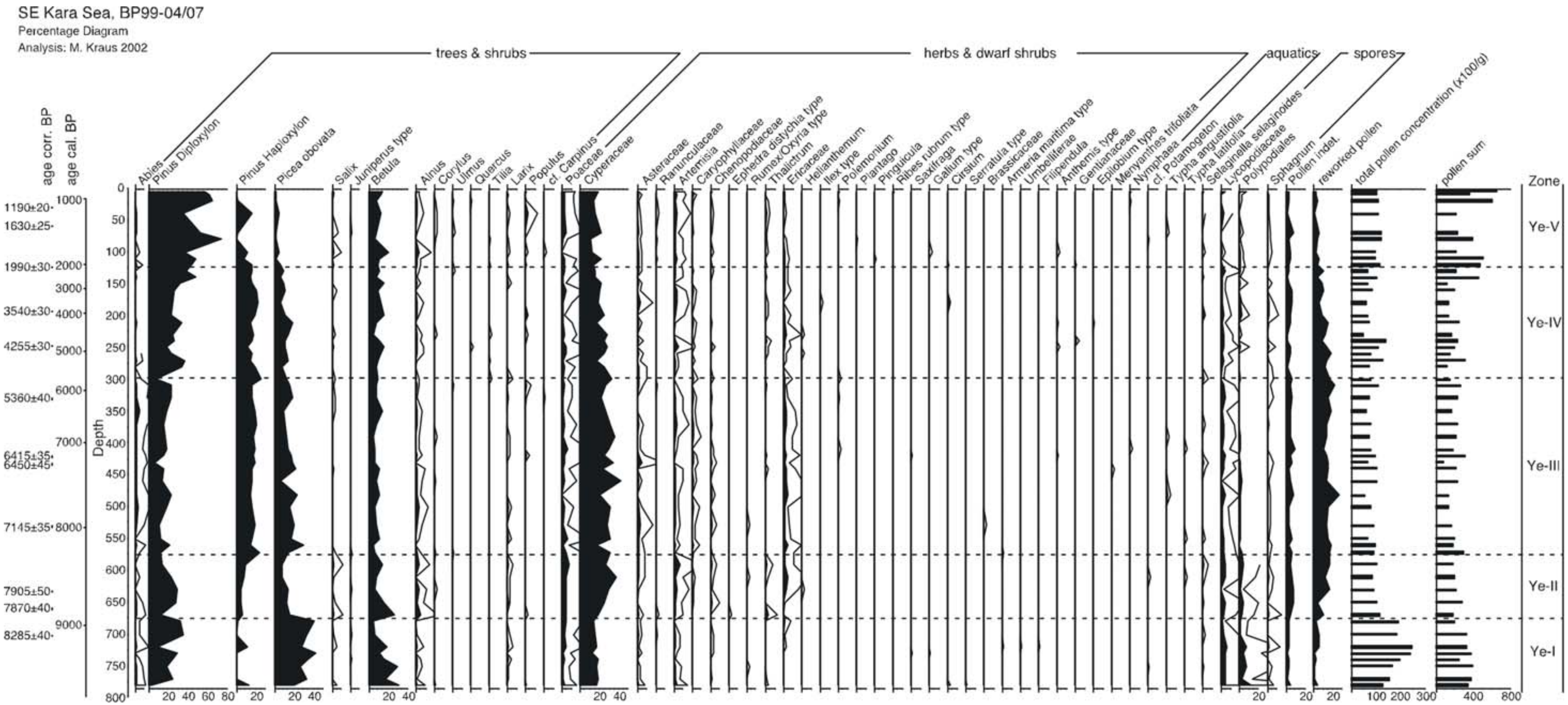

Fig. 4: Standard pollen percentage diagram of the marine sediment core BP99-04. The pollen sum includes AP and NAP (excl. spores). Low values are shown in 5x exaggeration.

Certain pollen taxa may be selectively enriched in marine assemblages with increasing distance from the source. Particularly, arboreal bisaccate pollen (e.g. *Abies*, *Pinus, Picea*) are an important component of the long-distance transported pollen (exotic pollen), whereas non-arboreal pollen such as herbs decrease their abundances rapidly further offshore (e.g. van der Knapp, 1987; Mudie and McCarthy, 1994). Thus, the AP:NAP ratio may change significantly until no realistic signal of the vegetation cover is preserved in the spectra.

Principally, it is assumed, that near-shore pollen records may reflect accurately the vegetation pattern in the coastal zone (e.g. Mudie and McCarthy, 1994). However, long-distance atmospheric transport may considerably influence pollen spectra in the Arctic region because of an extremely sparse vegetation cover or low pollen production (Gajewski et al., 1995; Andreev et al., 1997; Birks and Birks, 2000). Transport distances of up to 3000 km for pine and spruce were recorded for the Canadian Arctic under specific weather conditions (Campbell et al., 1999). Similarly, airborne sampling revealed significant amounts of exotic pollen over the Zevernaya Zemlya Archipelago (Kalugina et al., 1981) and Svalbard (Johansen and Hafsten, 1988). Exotic pollen in snow and firn samples from Franz-Josef Land and Severnaya Zemlya are sometimes dominated by *Pinus* pollen (Andreev et al., 1997; Bourgeois, 2000). In an ice core from Vavilov Ice Cap (79°27´N) on the Severnaya Zemlya Archipelago which is located in the polar desert, *Pinus* and *Picea* are the common components in the Holocene spectra (Andreev et al., 1997).

Modern and Holocene pollen spectra from Severnaya Zemlya and other remote areas such as the Svalbard Archipelago and Jan Mayen also contained exotic pollen (Kalugina et al., 1981; van der Knaap, 1987,1988). Conifer pollen which are not present in the vegetation of the adjacent coastal area reach more than 90% in recent sediments from the Laptev Sea (Naidina and Bauch, 1999). Holocene sediments from the Kara and Laptev seas may comprise up to 40% of *Pinus* pollen (Kulikov and Khitrova, 1982; Naidina and Bauch, 2001).

Although core BP99-04 is located 400 to 500 km north of the modern limits of spruce, larch and tree birches, and 700-800 km north of the tree line of pine (Kremenetski et al., 1998a; Peteet et al., 1998; MacDonald et al., 2000), both the core top sample and modern pollen spectra from the adjacent tundra contained exotic tree pollen (cf. Fig. 4 and 5; Clayden et al., 1996; Tarasov et al., 1998). This illustrates that, even in the tundra, deposition of exotic pollen overprints the spectra, and that tree pollen may occur far beyond their modern limit (e.g. Gervais and MacDonald, 2001). Therefore, the marine pollen record of core BP99-04 comprises both a signal of long-distance transport and regional coastal vegetation cover.

The depositional environment is further influenced by sedimentary processes, which can obscure the real vegetation patterns (e.g. Brush and DeFries, 1981; Naidina and Bauch, 1999). Sediments and pollen may be supplied from the hinterland and the coast by erosion and river run-off. Resuspension of bottom sediments in the Yenisei Estuary by currents and by storms may lead then to deposition outside the respective vegetation zones. Pollen of core BP99/04 was deposited in a fluvial to estuarine environment. Distinct changes in the composition of pollen spectra, however, do not correlate with any change in grain-size composition (Fig. 3), suggesting that the pollen spectra primarily reflect real changes in the vegetation zones and subordinate the effects of the sedimentary processes.

5.2 Pollen stratigraphical correlation of long-distance transported pollen and implications for tree line history

The long-distance transported pollen *Pinus, Picea*, and *Abies* (and broad-leaved forest trees such as *Ulmus*, *Quercus* and *Tilia*) were excluded from the pollen sum in order to discuss the Holocene vegetation history of the adjacent coastal area (Fig. 5). Macrofossil analyses suggest that these trees did not expand further north than 71°N during the Holocene (Kremenetski et al., 1998a; MacDonald et al., 2000) and therefore never reached the coast immediately adjacent to the core location. Radiocarbon ages are used to correlate the marine pollen record with previous studies on land sections, which were all discussed with respect to radiocarbon ages.

The signal of long-distance transported pollen may be an excellent tool for correlation of terrestrial and marine sequences. Their temporal distribution may provide age control of sediments in cases where radiocarbon dates are unavailable (e.g. Levac and de Vernal, 1997). Furthermore, application of radiocarbon ages of organic remains may pose some problems because different material, such as macrofossils, may reveal considerable offsets in ages (Wohlfarth et al., 1998; Kilian et al., 2002; Andreev et al., subm.). Arboreal pollen spectra and in particular long-distance transported pollen could fill this gap. However, a regional pollen stratigraphy which is a prerequisite for stratigraphic correlation is still missing in northern Siberia.

The terrestrial sites closest to core BP99-04 are located on the Taimyr Peninsula around Norilsk, in the Pur-Taz region, on the Yugorski Peninsula (Clayden et al., 1997; Hahne and Melles, 1997, 1999; Peteet et al., 1998; Andreev et al., 1998, 2001, subm.) and in the Pechora basin (Kaakinen and Eronen, 2000). The exotic pollen *Pinus* and *Picea obovata* may be excellent stratigraphic markers for correlation of marine and terrestrial Holocene pollen records along a north-south transect supporting the notion that wind-transport may cause the almost coeval changes at various sites.

Pollen of *Picea obovata* increased initially in the Pur-Taz region around 9150 yrs BP (Peteet et al., 1998) and in Lama Lake around 9200 yrs BP (Andreev et al., subm.). Both the Derevanoi Lake site (Clayden et al., 1997) and the Yenisei core BP99-04 did not recover sediments older than 9000 yrs BP but show consistent presence of *P. obovata* from the core base. The expansion of *Picea* to sites north of the modern tree line occurred between 9000 and 8000 yrs BP (MacDonald et al., 2000), which is well reflected in the high *Picea* percentages in the zone Ye-I between 8900 and 8100 yrs BP. Possibly, the high percentages of *Picea* in the marine pollen record at this time indicate the highest density of spruce in the hinterland. In the coastal zone of the Laptev Sea, *Picea* pollen occurred slightly later around 8500 yrs BP (Pisaric et al., 2001). In contrast, a pollen record from the Pechora basin showed a distinct increase of *Picea* around 9000 yrs BP (Kaakinen and Eronen, 2000). The continuous retreat of *Picea obovata* during the middle and late Holocene is observed in many pollen records but marked changes in abundance were apparently time-transgressive. Thus, the sharp decline in late Holocene occurred at 3800 yrs BP and more pronounced at 2000 yrs BP in core BP 99-04 (Figs. 4 and 5), at 3500 yrs BP in the coastal Laptev Sea (Pisaric et al., 2001), at 4000 yrs BP in Lama Lake (Andreev et al., subm.), at 2500 yrs BP in the

Yenisei section (Andreev and Klimanov, 2000), at ca. 3800 yrs BP (4200 cal. BP) in the peat section of the Salym-Yugan mire in the boreal West Siberia (Pitkänen et al., 2002) and at 5500 yrs BP in the Pechora basin (Kaakinen and Eronen, 2000). Generally, MacDonald et al. (2000) state, that the retreat of *Picea* occurred between 4000 and 3000 yrs BP.

Windblown pollen of *Pinus* Diploxylon type (i.e. *Pinus sylvestris*) shows an early Holocene double peak between 8900 to 8100 yrs BP corresponding with the *Pinus* pollen curve from the Entarny record situated further south and southwest in the taiga zone (peak at ca. 8200 yrs BP) (Velichko et al., 2002). Generally, the distribution of *Pinus sylvestris* in the early Holocene is not known in detail. Scots pine grew in the early Holocene beyond its present limit along the Yenisei river at 8000 yrs BP and retreated gradually to its present northern limit in late Holocene (Kremenetski et al., 1998b; Clayden et al., 1997). A substantial increase of *Pinus Diploxylon* pollen occurs during the last 5500 yrs and particularly since 2000 yrs BP (Fig. 4 and 5) correlating with an initial increase of *Pinus* at ca. 4500 yrs BP which became more pronounced at 2500 yrs BP in the Lama Lake diagram (Hahne and Melles, 1997, 1999; Andreev et al., subm.). Pitkänen et al. (2002) assess that *Pinus sylvestris* became the most abundant tree species after ca. 3900 yrs BP in the Salym-Yugan Mire area in boreal West Siberia. Finally, the Entarny diagram shows a noticeable increase with a double peak after ca. 2000 yrs BP (Velichko et al., 2002).

Pollen of *Pinus* Haploxylon type (*P. sibirica* and *P. pumila*) is abundant from ca. 8000 to ca. 2000 yrs BP with the most pronounced increase after 7500 yrs BP. Because of the biogeographical distribution (Kremenetski et al., 1998b) of both species, we assume, that the pollen in our record mainly belong to *P. sibirica*. The distinct increase at ca. 7500 yrs BP indicates that *P. sibirica* spread out later than other coniferous trees in the hinterland. The main period of spread and population growth occurred between 8000 and 4000 yrs BP (Kremenetski et al., 1998b). Peteet et al. (1998) found no macrofossils of *P. sibirica* in the Pur-Taz region, but registered a slight increase in windblown pollen between 8000 to 4500 yrs BP. In contrast to the notable late Holocene increase of windblown pollen of *Pinus sylvestris,* pollen of *P. sibirica* shows a sharp decrease after 2000 yrs BP apart from a solitary peak around 1400 yrs BP.

Pollen of *Abies* occurs sporadically in the whole sediment core, but is more abundant between 7150 to 5000 yrs BP with a small maximum at 5600 yrs BP. Blyakharchuk and Sulerzhitsky (1999) also observed maximum abundances in a pollen record from the Bugristoye bog (situated in the southeastern part of the West Siberian Plain in the Tomsk province) between 6500 to 5500 yrs BP when *Picea* and *Pinus sylvestris* pollen decreased. After 2000 yrs BP, *Abies* pollen disappeared almost completely. Thus, the distribution of *Abies* pollen in core BP99-04 reflects the northward advance of the fir tree line during the middle Holocene in the southern hinterland and its retreat after 2000 yrs BP (Peteet et al., 1998). However, the tree line history of fir in Siberia and their advance is little known to allow a more accurate correlation.

Macrofossil samples from *Larix* across northern Siberia revealed that it was probably the dominant tree genus in the northern taiga zone between 8000 and 4000 yrs BP (Koshkarova, 1995; Peteet et al., 1998; MacDonald et al., 2000). In the Yenisei pollen record, pollen of *Larix* is rare because of a general under-representation in marine pollen records (Janssen, 1984; Peteet et al., 1998; Pisaric et al., 2001).

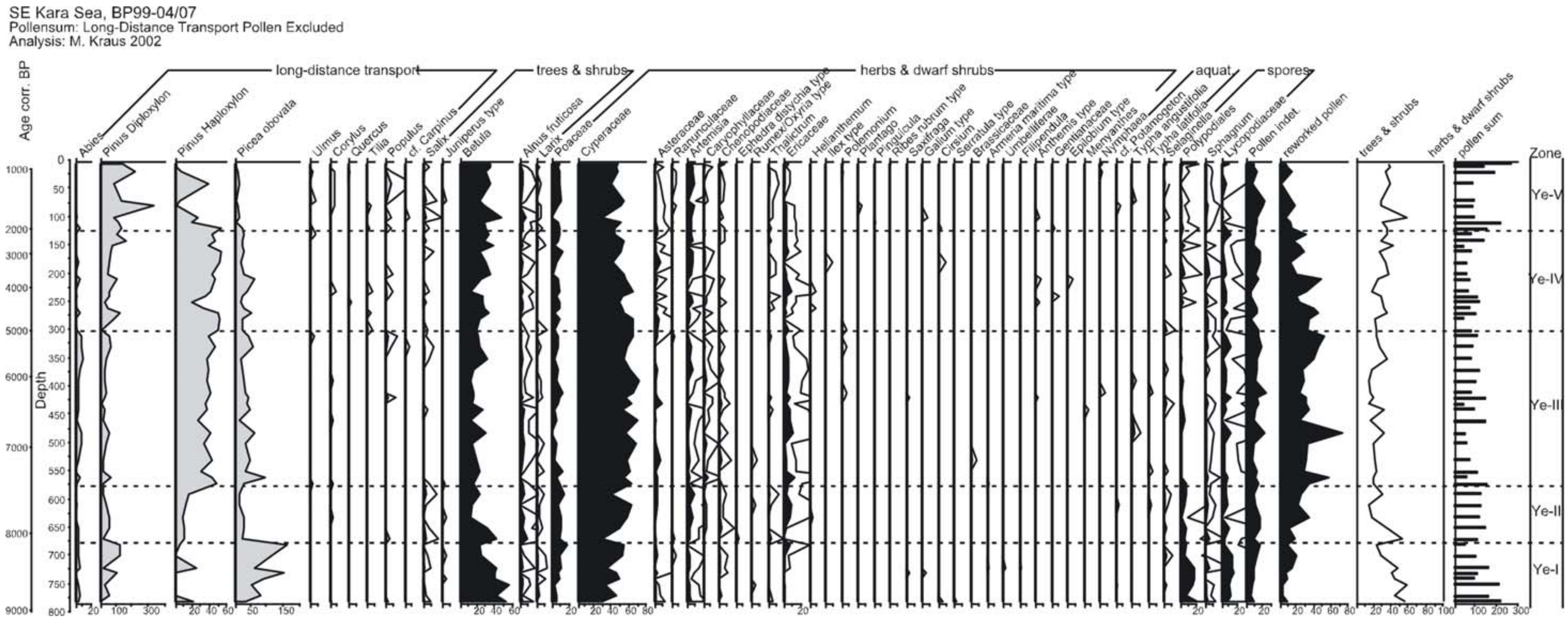

Fig. 5: Pollen percentage diagram of BP99-04. Long-distance transported pollen are excluded from the pollen sum.

5.3 Paleoenvironmental reconstruction

The extrapolated age of the core base (ca. 8900 yrs BP/9400 cal. BP) indicates that the vegetation development and tree line history cannot be reconstructed for the earliest part of the Holocene. The sedimentary texture of the silty sands in the lower part of zone Ye-I from 780 to 745 cm core depth (Fig. 2), and the absence of marine dinoflagellate cysts show that the core was located in a fluvial depositional environment. The bioturbated muds, the presence of brackish water molluscs and the continuous increase of marine dinoflagellate cysts from 740 cm core depth show that the location was reached by rising sea-level since ca. 8600 yrs BP (9200 cal. BP). It was gradually flooded until 8100 yrs BP (8900 cal. BP), that is indicated by the distinct increase of the concentration of marine palynomorphs from 670 cm core depth. This is in good agreement with the global sea-level (Fairbanks, 1989), which was approximately 30 m below the present level at that time. Without considering compaction, the contact of Units Ia and Ib at ca. 36 m below seafloor was at ca. 6 m water depth at that time.

Pollen Zone Ye-I (ca. 8900 to 8100 yrs BP)
The high content of *Betula* pollen (probably mainly tree birch) and Polypodiales spores in the lower part of this zone and the absence or low abundance of typical cold indicators such as *Salix*, *Thalictrum*, Ranunculaceae and *Dryas* pollen indicate favourable climatic conditions at least from ca. 8900 yrs BP (9400 cal. BP). Obviously, tree birch dominated forests in the hinterland preceeded spruce dominated forest communities, whereas tree birch probably never occurred in the adjacent coastal area. Dated macrofossils from northern Eurasia conform with this interpretation and indicate that the northern limit of tree *Betula* was approximately at 72°N in the Gydan and western Taimyr Peninsulas (MacDonald et al., 2000; Forman et al., 2002). The discontinuous increase of long-distance transported pollen (mainly *Picea*, *Pinus* Diploxylon type) up to the top of zone Ye-I indicates a northern extent of the boreal forest, which was dominated by larch (Peteet et al., 1998; MacDonald et al., 2000; Pisaric et al., 2001) but also characterized by the occurrence of spruce. The highest values of *Picea* pollen between ca. 8900 to 8100 yrs BP demonstrate the widespread occurrence of this tree corresponding well with the northward expansion of spruce in the early Holocene as documented by stomate analyses (Clayden et al., 1997; Kremenetski et al., 1998a; MacDonald et al., 2000; Pisaric et al., 2001). Since the region was not covered by the Barents-Kara ice sheet during the LGM (Mangerud et al., 2002), *Picea* could relatively rapidly expand northward from their glacial refuge.

Furthermore, the highest pollen concentration and high sedimentation rate of more than 230 cm/ka (Fig. 2) may indicate high pollen productivity and high river-input from the Yenisei river, giving evidence for favourable large-scale climatic conditions such as higher mean summer temperature than today in the area. This is supported by a coeval maximum of pollen concentrations at about 9000 yrs BP in the Lama Lake pollen record from Taimyr Peninsula (Andreev et al., subm.). This period corresponds well with a so-called Boreal thermal optimum, that was described from many sites in Northern Eurasia (Velichko et al., 1997; Andreev and Klimanov, 2000; Andreev et al., 2002).

The discontinuous decrease of *Betula* pollen and the synchronous increase of Poaceae in LPAZ Ye-I (Fig. 5) as well as the occurrence of Ranunculaceae pollen probably indicate a short-term cooling between 720 to 680 cm core depth from ca. 8400 to 8100 yrs BP

(9100 to 9000 cal. BP). This event is almost synchronous with a cooling event at ca. 8300 to 8000 yrs. BP, which was recorded from the whole northeastern European Russian Arctic (Khotinskiy, 1984; Velichko et al., 1997) and the Pur-Taz area and the Yugorski Peninsula in the hinterland of Yenisei Estuary (Peetet et al., 1998; Andreev et al., 2000, 2001). However, the sample interval is too low to unequivocally resolve this event in core BP99-04. Possibly, there is a relationship between this cooling event and the sharp decrease of *Picea* at the base of zone Ye-II because of a temporary degradation of spruce forests at their northern limits (cf. Khotinskiy, 1984).

Pollen zone Ye-II (ca. 8100 to 7400 yrs BP)

After this temporary deterioration, the arboreal pollen spectra reflect a stronger differentiation of the boreal forest than before. Alder and willow shrubs were more common. The presence of *Pinus* Haploxylon pollen type (*Pinus sibirica* and *P. pumila*) indicates long-distance transport from further south and east, respectively (*P. pumila*) and probably a northward migration of *P. sibirica* (Kremenetski et al., 1997, 1998b). However, the northern limit of *P. sibirica* during the mid-Holocene is not well known. Peteet et al. (1998) found a slight increase of *P. sibirica* from about 8000 to 4500 yrs BP, but did not find any macrofossils which might indicate local occurrence. The occurrence of *Corylus* pollen reflects the movement of southern broad-leaved forests northward. Large-scale favourable climate conditions were established (e.g. Khotinskiy, 1984; Velichko et al., 1997, Andreev et al., 2001). Generally, the advance of the tree line in early Holocene is related to the increase of continentality due to the lower sea-level (cf. CAPE, 2001), which was approximately 30 to 25 m below the present level (Fairbanks, 1989). The coastline was a few tens of kilometers north of its current position and extensive regions of the Kara Sea shelf area were still exposed. Additionally, increased summer insolation at high northern latitudes in early Holocene could enhanced the effect of increased summer temperatures (e.g. Ritchie et al., 1983).

The increase of Cyperaceae pollen particularly in this zone (see also Fig. 5) indicates moister conditions than before and reflects the development of wetlands such as fens and peat bogs. Usually, Cyperaceae pollen is under-represented in marine sediments (Mudie, 1982), whereas *Sphagnum* spores are over-represented (Heusser, 1983). This relationship is reflected e.g. in Holocene pollen spectra from the Laptev Sea (Naidina and Bauch, 2001). In contrast, *Sphagnum* spores are continuously rare in the Yenisei pollen record (Fig. 4). Furthermore, Mudie (1982) observed a seaward increase of *Sphagnum* spores in recent sediments from the Labrador Sea and explained this pattern with offshore aeolian rather than fluvial transport. Thus, the combination of high abundances of Cyperaceae pollen and low abundances of *Sphagnum* spores can be interpreted either as product of specific pollen transport processes and selective deposition in estuarine environments, or may also indicate the predominant genesis of type of mires. The second interpretation is more likely: Due to the gradual sea-level rise, the river was piled up and bursted its banks. As a further consequence the drainage was reduced and the water table rose. Fixed nutrients were released and were now available for plants. Relatively eutrophic open-water mineral wetlands emerged, enabling the establisment of grasses-sedges phytocoenoses. Sedges, particularly species of *Carex* are important peat producers, and minerogenous mires such as water rise mires and flood mires could develop (e.g. Joosten and Clarke, 2001).

In contrast, *Sphagnum* mosses are usually characteristic floristic elements of (oligotrophic-mesotrophic) ombrogenous mires such as ”aapa” mires (Velichko et al., 1998). With respect to this geobotanical background, widespread sedge-fens and sedge-peat bogs probably occurred in lowlands and river valleys in the coastal area in the early to mid Holocene. In any case, peat accumulation was widespread and played an important role in this area. Probably, polygonal mires, characteristic of continuous permafrost, were absent and appeared subsequently in the late Holocene (Vardy et al., 1997; Jasinski et al., 1998; Peteet et al., 1998; Oksanen et al., 2001). In the hinterland, typical mires of boreal forests such as "aapa" mires could have occurred in the boreal forest zone. However, the prevailing mire type in the low-lying coastal areas might have been water rise and flood mires, which are formed mainly by sedges.

The distinct increase of reworked pollen (pre-Quaternary pollen) in zone Ye-II and its continuous higher abundances mainly in zones Ye-III and Ye-IV is attributed to increased coastal erosion due to the sea-level rise. The constant high values of reworked pollen during the transgression shows that coastal erosion plays an important role in the Kara Sea for the sediment budget (cf. Rachold et al., 2000; Dittmers et al., this vol.).

Pollen zone Ye-III (7400 yrs BP to 5000 yrs BP)

The pollen spectra of zone Ye-III reflect increased differentiation of the vegetation communities and the further advance of the forest zone northward (Khotinskiy, 1984), which is indicated by the closed curve of *Abies* pollen, continuous high percentages of *Pinus* Haploxylon pollen type and *Picea* pollen, and the rare occurrence of *Salix* pollen. In conjunction with the highest abundance of Cyperaceae pollen, these pollen spectra indicate high water saturation in the coastal region and adjacent areas accompanied by an adequate precipitation rate and warm conditions. The appearance of *Typha latifolia* and *T. angustifolia* might support this interpretation (Andreev et al., 2001). The high abundance of Ericaceae pollen is attributed to dwarf shrubs of boreal forest as well as heath of wetlands. However, both ecological groups indicate wet conditions in the landscape. The mid-Holocene interval spans the so-called "Holocene climatic optimum" which was the warmest period in the Siberian Arctic during the Holocene (e.g. Velichko et al., 1997; Andreev and Klimanov, 2000; Andreev et al., 2002).

Pollen zone Ye-IV (ca. 5000 yrs BP to 2200 yrs BP)

The notable increase of windblown pollen of *Pinus sylvestris*, the decrease of *Abies* and *Picea* pollen and Cyperaceae pollen, the occurrence of *Thalictrum* pollen and the increase of *Artemisia* pollen indicate the onset of a substantial change in the marine pollen record and a trend to cooler climatic conditions.

This general trend is interrupted from ca. 4200 yrs BP to 3800 yrs BP shown by a *Picea* pollen peak, a *Betula* minimum, gaps in the *Artemisia* and *Thalictrum* pollen curves and a notable Ericaceae and Cyperaceae pollen peak. This warming event in the marine record is tentatively correlated with the lower part of the Lama Lake pollen zone VII at ca. 4200 yrs BP (Andreev et al., subm.). Khotinskiy (1984) described a "middle subboreal warming" from 4100 to 3200 yrs BP and emphasized that broad-leaved forest advanced in the southern and middle taiga in this warm interval. This is reflected in the simultaneous presence of *Quercus* and *Tilia* pollen in the marine record.

Picea pollen shows in the Yenisei pollen record a pronounced decrease after ca. 3800 yrs BP indicating a retreat of the spruce tree line (MacDonald et al., 2000; Pisaric et al., 2001; Pitkänen et al., 2002; Andreev et al., subm.) At the same time, *Artemisia* pollen is constantly abundant indicating the advance of the tundra zone southward. The lowest sedimentation rate with less than 40 cm/ka between 3500 and 2000 yrs BP (Fig. 2; Stein et al., this vol.) and the concomitant decrease of reworked pollen suggest that erosion in the hinterland and at the coast was strongly reduced. This was probably due to permafrost aggradation that commenced e.g. in the Labaz Lake area on the Taimyr Peninsula most pronounced after ca. 2900 yrs BP (Kienel et al., 1999) and at the Pechora Sea coast after 3100 yrs BP. (Oksanen et al., 2001) and the termination of the postglacial sea-level rise around 5000 yrs BP (Fairbanks, 1989).

Pollen zone Ye-V (ca. 2200 yrs BP to ca. 600 yrs BP)
The most pronounced environmental change occurred at the transition of zone Ye-IV to V. A strong cooling trend is indicated by a decrease of *Picea* pollen and *Pinus* Haploxylon pollen type, the occurrence of *Salix* pollen, the higher abundance of Poaceae and *Artemisia* pollen, the presence of Ranunculaceae and *Thalictrum* pollen and the decrease of Ericaceae pollen. The increase of windblown *Pinus* Diploxylon pollen type results from general impoverishment of vegetation cover.

The relatively high abundance of Cyperaceae pollen can be interpreted as widespread occurrence of sedges in vegetation communities, indicating continuing peat accumulation. Probably, peat accumulation was reduced but did not stop (see also Vardy et al., 1997). Due to the cooling trend, other genetic types of mires, particularly polygonal mires developed. Moreover, Cyperaceae pollen may reflect *Carex* species growing on wet mineral subsoils (e.g. *Carex ensifolia* ssp. *arctisibirica*) in the tundra vegetation zones (Aleksandrova, 1980, 1988).

Indirectly, the retreat of boreal forests in the hinterland indicates the expansion of continuous permafrost soils. A fundamental change in environmental conditions occurred which influenced both the marine and continental environments caused by complex interaction of the vegetation, atmosphere and ocean (e.g. TEMPO, 1996; Ganopolski et al., 1998; Peteet et al., 1998; MacDonald et al., 2000; CAPE, 2001).

6. Conclusions

The basal age of the marine sediment core is ca. 8900 yrs BP (9400 cal. BP), derived from the age model and supported by correlation of marine pollen stratigraphy with continental pollen zonation. At this time, the core was located in a fluvial environment on the exposed Kara Sea shelf. At 8600 yrs BP (9200 cal. BP), the seawater reached the core location due to the postglacial sea-level rise and a typical neritic-estuarine environment developed. High river discharge caused highest sedimentation rates in the Yenisei Estuary. The marine pollen spectra show a northward advance of boreal forest in the hinterland indicating warm and relatively moist environmental conditions. *Betula* dominated forests preceded *Picea* dominated forest communities. The role of larch is under-represented in this record caused by specific marine depositional environment. High values of *Picea* pollen indicate the northern occurrence of spruce woods at this time and their relatively high abundance in boreal forest. The highest pollen concentrations suggest high bioproductivity.

At ca. 8400 to 8100 yrs BP (9100 to 9000 cal. BP), a short-term climate deterioration overprinted the early Holocene favourable climate. Possibly, this cooling event involved a temporary degradation of spruce wood.

After ca. 8100 yrs BP to ca. 6400 yrs BP (9000 to 7300 cal. BP), the marine pollen spectra indicate the establishment of long-term favourable climate conditions in the coastal Kara Sea region and adjacent areas. The arboreal pollen spectra reflect a stronger differentiation of the boreal forest. In the lowlands of Yenisei and Ob rivers and their catchment area, sedge fen and peat bogs dominated water rise and flood mires asreconstructed mainly from the high abundance of Cyperaceae pollen. The distinct increase of reworked pollen is related to stronger coastal erosion due to the sea-level rise.

After ca. 6400 yrs BP (ca. 7300 cal. BP) favourable climatic conditions still prevailed but the changes in marine pollen spectra, in particular those of the arboreal pollen, suggest the onset of a long-term climate cooling. After a warming event from ca. 4300 to 3800 yrs BP (4900 to 4200 cal. BP), a pronounced retreat of boreal forest and the southward spread of tundra vegetation zone occurred. After ca. 2200 yrs BP unfavourable climatic conditions and the modern vegetation zones were established in the coastal area and in the hinterland of the Kara Sea region.

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