Modern river discharge and pathways of supplied material in the Eurasian Arctic Ocean: Evidence from mineral assemblagesand major and minor element distribution

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ORIGINAL PAPER

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Modern river discharge and pathways of supplied material in the Eurasian Arctic Ocean: evidence from mineral assemblages and major and minor element distribution

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Abstract Clay-mineral, heavy-mineral, and elemental distributions in sediments from the Arctic Ocean and the adjacent Laptev and Kara seas can be attributed to the geology of the hinterland and the transport of terrigenous material by rivers onto the shelves. Kara Sea sediments are characterized by increased contents of smectite and elevated Ni/Al-, Ti/Al-, and Cr/Al ratios. In the western Laptev Sea sediments are enriched in smectite and clinopyroxene and increased in Ti/Al-, Cr/Al-, and Ca/Al ratios. The composition of the sediments reflects suspended matter input from the large trap basalt of the Putoran Mountains. The eastern Laptev Sea sediments display increased illite and amphibole contents as well as a chemical composition similar to average shale. This composition is due to the discharge from the Lena and Yana rivers, which drain a large catchment area consisting of sedimentary Mesozoic and Paleozoic rocks. Material from the eastern Laptev Sea is transported by ocean currents and sediment-laden sea ice along the Transpolar Drift into the central Arctic Ocean. This is indicated by similar values of Ti/Al-, Cr/Al-, Rb/Al-, and K/Al ratios as well as increased concentrations of amphibole and illite, determined in sediments from the Lomonosov Ridge. A minor input from the Beaufort Sea into the central Arctic Ocean is suggested from increased Ca/Al ratios and increased contents of opaque minerals.

Keywords Arctic Ocean · Laptev Sea · Kara Sea · Heavy minerals · Clay minerals · Chemical elements · Sources of sediment · Transport pathways of sediment

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Introduction

In this paper a combination of mineralogical and geochemical data sets of Arctic Ocean sediments are presented. These studies identify source areas and transport pathways of terrigenous, mainly siliciclastic, matter in the Arctic Ocean. In this context the fluvial input and its distribution and accumulation on the shelves were studied to determine the source areas of the sediments (Behrends et al. 1999; Eisenhauer et al. 1999; Lukashin et al. 1999; Müller and Stein 1999; Peregovich 1999; Rachold 1999; Schoster and Stein 1999; Wahsner et al. 1999). These studies concentrated mainly on the Kara and Laptev seas because of the large volume of water and particulate matter that is supplied by the large Siberian rivers Lena, Ob, and Yenisei (Aagaard and Carmack 1989; Martin et al. 1993; Gordeev et al. 1996; Rachold et al. 1996). The Lena, Ob, and Yenisei rivers discharge 520, 530, and 603 km^3/a fresh water, respectively, and 17.6×10^6, 16.5×10^6, and 5.9×10^6 t/a total suspended matter, respectively, into the Arctic Ocean (Aagaard and Carmack 1989; Gordeev et al. 1996). Due to this large fresh-water supply into the Laptev and Kara seas, salinity is lowered in the surface water masses, which allows for extensive production of sea ice. In September 1997 salinity of the surface water in the Ob and Yenisei estuaries had values between 4 and 20 psu, and bottom water salinity reached values up to 32 psu (Churun and Ivanov 1998). Particulate matter as well as sediments from shallower areas in the estuaries have been observed to be incorporated into the sea ice (Aagaard and Carmack 1989; Eicken et al. 1997). The further transport of terrigenous material toward the open ocean by currents and sediment-laden sea-ice is of major importance for the disposal and distribution of terrigenous material in the Arctic Ocean (Stein and Korolev 1994).

The main surface-water current systems in the Arctic Ocean are the Beaufort Gyre and the Transpolar

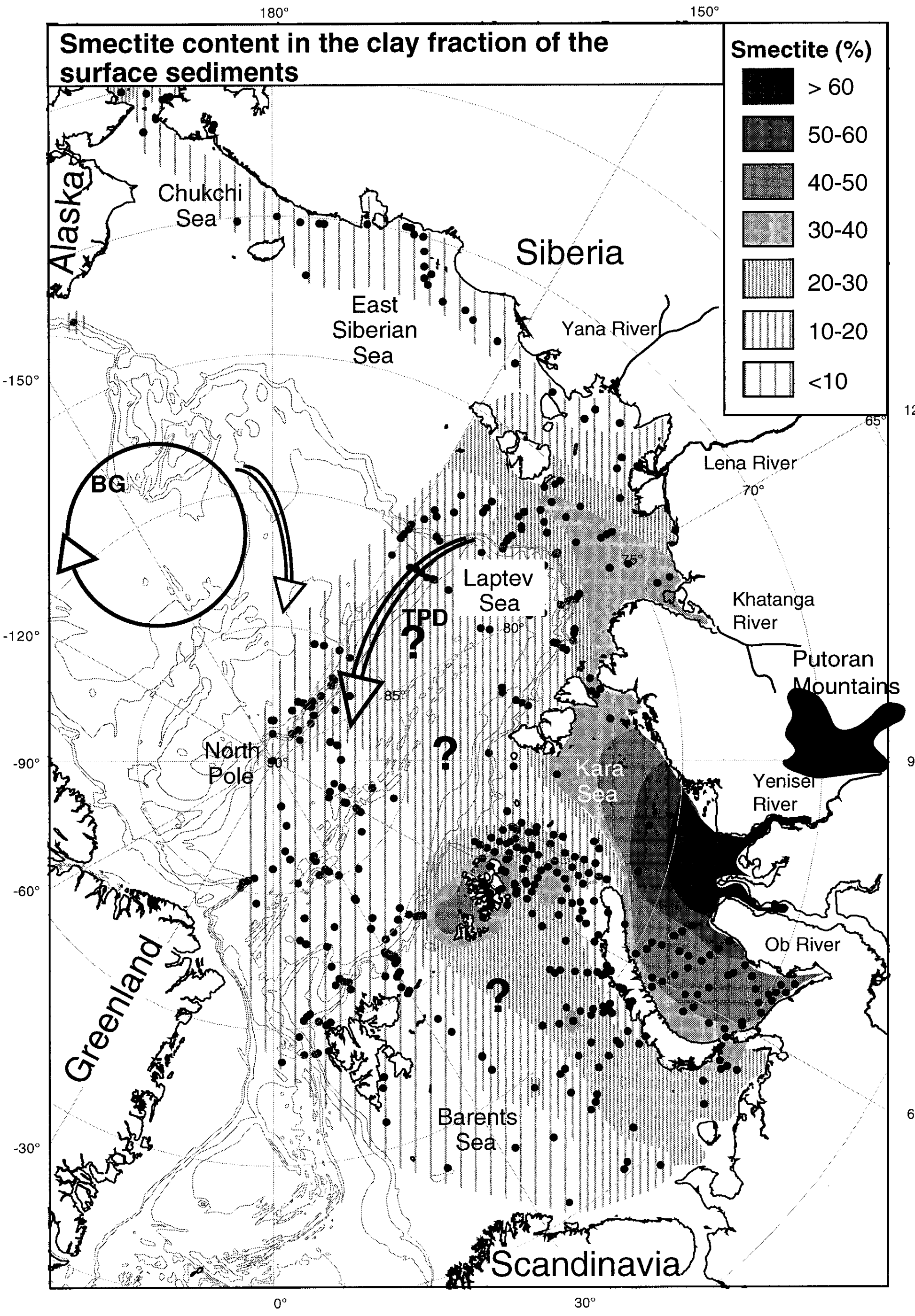


Fig. 1 Smectite distribution of the <2-μm grain-size fraction in Arctic Ocean surface sediments (from Wahsner et al. 1999); *BG* Beaufort Gyre; *TPD* Transpolar Drift

Drift, which transport sediment-laden sea ice through the Arctic Ocean via the Fram Strait and into the Atlantic Ocean (Pfirman et al. 1997). As the sea ice melts, sediments are released into the water column. The coarse-grained and/or high-density minerals settle more rapidly than the fine-grained material and are less affected by currents. Fine-grained materials, such as clay minerals, are distributed over a wide area by currents or winnowing processes (Wahsner et al. 1999). In intermediate water depths, Atlantic-derived water masses may transport fine-grained materials along the Eurasian margin and into the Laptev Sea (Müller and Stein 2000). Transport processes can therefore be distinguished by clay-mineral vs heavy-mineral data sets.

Previous investigations of transport processes (e.g., Behrends et al. 1999; Wahsner et al. 1999; Schoster and Stein 1999) have been based on either clay-mineral and heavy-mineral abundances or elemental composition. In this study a combination of all three parameters was investigated – bulk sediments were analyzed for elemental composition, the <2-μm grain-size fraction for clay minerals, and the 63- to 125-μm grain-size fraction for heavy minerals.

Methods

Surface sediment samples were obtained using a giant box corer, a multicorer, or an ocean grab sampler during several German and Russian expeditions in the Arctic Ocean between 1991 and 1997 (see Behrends et al. 1999, Schoster and Stein 1999, and Wahsner et al. 1999 for references). Sample stations are shown in Figs. 1, 2, and 3. Three hundred twenty samples were analyzed for clay minerals, 210 samples for heavy minerals, and 246 samples for elemental composition.

Clay mineralogy

Samples were treated with hydrogen peroxide (H_2O_2) to remove any organic matter and then separated into sand, silt, and clay fractions to calculate the grain-size distribution. The <2-μm fraction was prepared for X-ray diffraction (XRD), which was measured using CoKα radiation in a goniometer (Philips, PW1820) equipped with an automatic divergence slit. The clay-mineral groups smectite (peak at 17 Å in glycolated state), illite (10 Å), kaolinite (7 Å, 3.58 Å), and chlorite (7 Å, 3.54 Å) were identified. Clay-mineral con-

Fig. 2 Amphibole distribution of the 63- to 125-μm grain-size fraction in Arctic Ocean surface sediments (from Behrends et al. 1999)

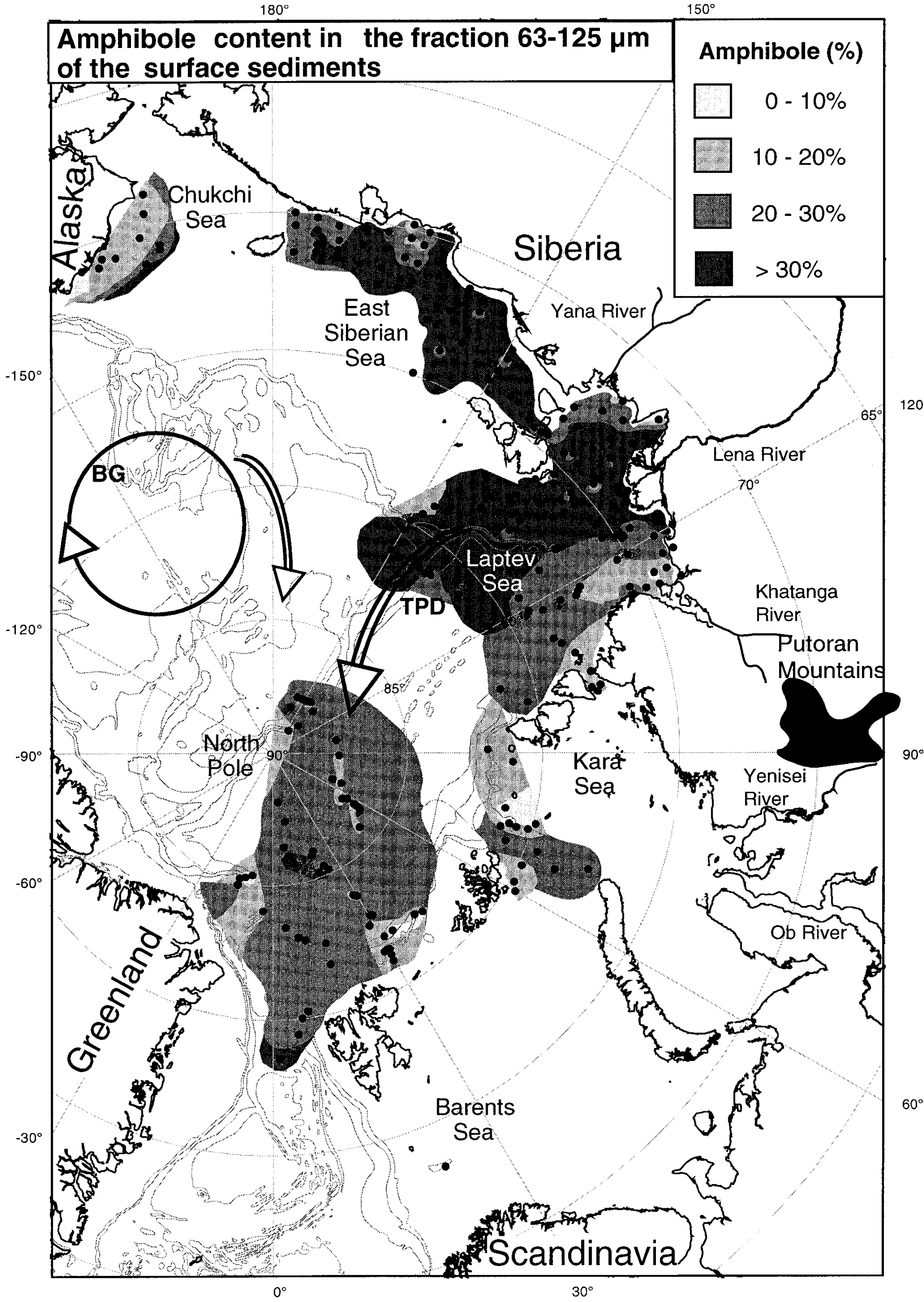
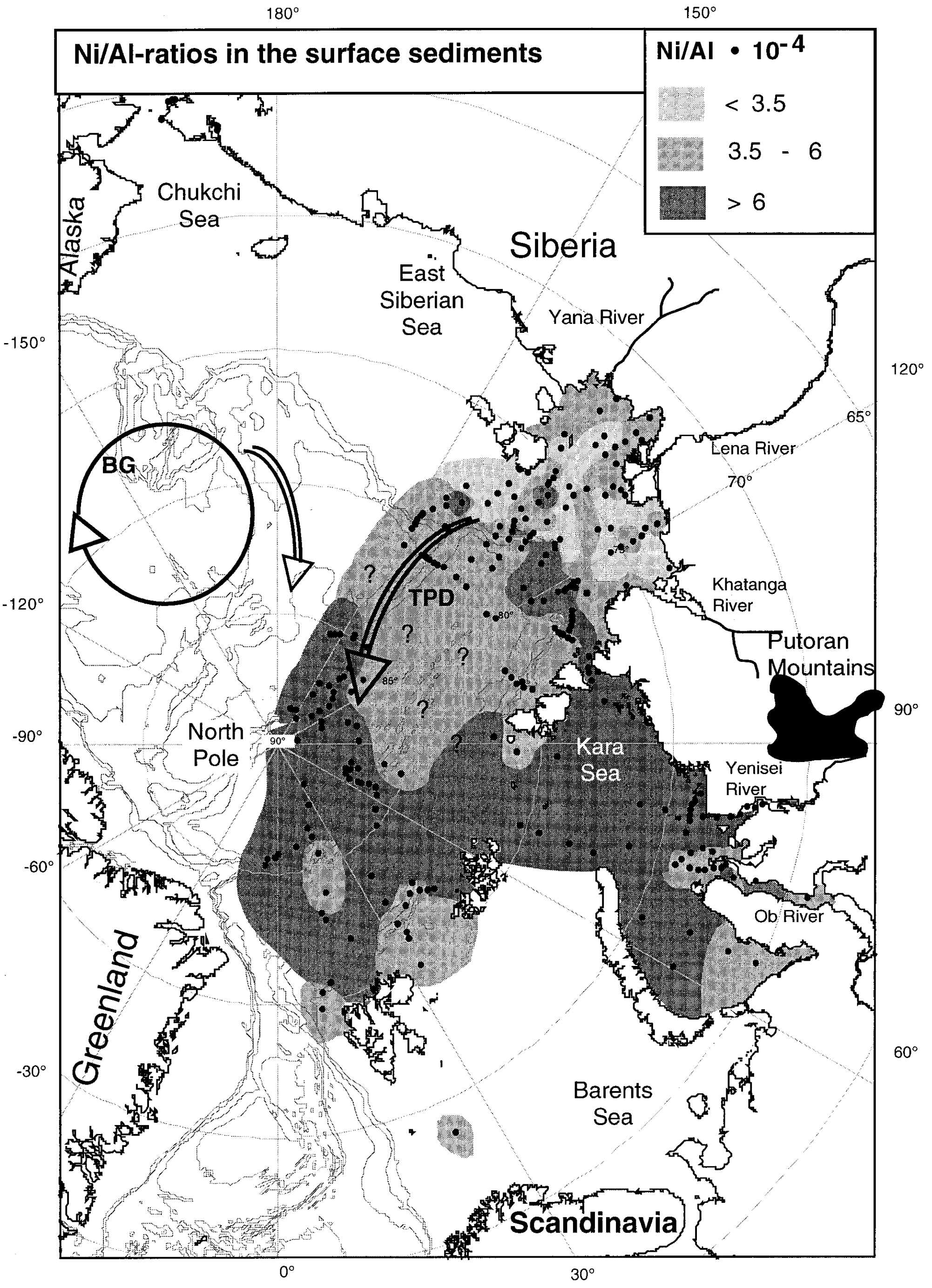


Fig. 3 Distribution of Ni/Al ratios in Arctic Ocean surface sediments;



tents were calculated by using empirical factors after Biscaye (1965) and calculated to a sum of 100%. For further details, see Wahsner et al. (1999) and Müller and Stein (2000).

Heavy minerals

Heavy-mineral analysis was applied to the 63- to 125-µm sub-fraction. The heavy minerals were separated from this sub-fraction using sodiummetatungstate [$Na_6(H_2W_{12}O_{40})$] with a density of 2.83 g/cm^3. The heavy minerals, mounted on glass slides with Meltmount (n=1.68; Mange and Maurer 1991), were optically identified and counted using a polarization microscope. Approximately 220 grains per slide were counted. For further details see Behrends et al. (1999).

Geochemical analysis

Bulk-sediment samples were dried, ground, and then analyzed using an X-ray fluorescence spectrometer

Table 1 Standard deviations of the selected chemical elements

Element	Standard deviation (%)
Al	0.8
Ti	0.9
K	0.7
Ca	1.4
Cr	2.5
Ni	1.7

equipped with a Rh tube (PW 2400 and PW 1400, Philips, Eindhoven, The Netherlands) for major and minor element concentrations (for details see Schoster and Stein 1999). The results were compared with international reference standard samples: GSR 5 (shale; Govindaraju 1994); "Alkaline Agpaite Granite" (granite); and house standard sample TW TUC (shale) of ICBM Oldenburg University, Germany. Standard deviations of the selected elements, which were analyzed, are given in Table 1.

Results

The surface sediments were recovered from very different water depths ranging from only a few meters on the shelves to >4000 m in the deep basins of the central Arctic Ocean; thus, the grain-size distribution displays distinct spatial differences. The sediments are generally much coarser on the shelves than in the deeper Arctic Ocean basins (Müller 1999). On the Laptev Sea shelf the clay fraction (<2 μm grain size) ranges between 25 and 50% in the area east of 120°E, whereas in the western part of the Laptev Sea, the clay fraction only reaches values up to 25% (Silverberg 1972; Wahsner 1995; Müller 1999). In the deep basins north of the Laptev Sea, the clay fraction shows values between 50 and 70% (Wahsner 1995; Müller 1999). In the Nansen Basin the clay fraction dominates with values between 60 and 90%, whereas on the Gakkel Ridge the sediments are more coarse-grained with contents of clay fraction between 50 and 60% (Letzig 1995). A higher quartz content at several locations on the Lomonosov Ridge is, in general, related to the higher occurrence of coarse-grained sediments on the ridges, compared with the basins (Vogt 1996). This higher occurrence is attributed to the transport by sediment-laden sea ice from the shelves into the deep Arctic Ocean (Nürnberg et al. 1994; Spielhagen et al. 1997).

Concerning the clay-mineral and heavy-mineral data, we concentrate on the spatial variations of smectite and amphibole abundances, respectively, because they seem to be the most indicative minerals (cf., Behrends et al. 1999; Wahsner et al. 1999). In the Kara Sea close to the estuaries of Ob and Yenisei rivers (Fig. 1), the clay-mineral distribution shows a distinct maximum of smectite (>60%). Enhanced smectite content (up to 40%) in surface sediments also occurs in the Laptev Sea, near the mouth of the Khatanga River, and in the area surrounding Franz-Josef-Land. Around Franz-Josef-Land the kaolinite content of surface sediments is also increased (ca. 30%; Wahsner et al. 1999). Illite content is elevated in the central Arctic Ocean as well as in the eastern Laptev Sea and in the shelf areas of the East Siberian Sea and Chukchi Sea (Table 2; Naugler et al. 1974; Wahsner et al. 1999).

The sediments from eastern Laptev Sea and the East Siberian Sea show amphibole contents of >30 grain% in the heavy-mineral fraction (63–125 μm) (Fig. 2). Maximum clinopyroxene concentrations of >30 grain% occur in the area surrounding Franz-Josef-Land and in the western Laptev Sea near the mouth of the Khatanga River. In contrast, sediments of the Beaufort Sea and the outer Kara Sea show maximum opaque mineral contents of >30 grain% (Behrends et al. 1999). The sediments of the central Arctic Ocean are characterized by approximately 10–30 grain% opaque minerals, 10–30 grain% clinopyroxene and

Table 2 Mean values of heavy-mineral and clay-mineral contents as well as selected element/Al ratios of eastern and western Laptev Sea sediments and Kara Sea sediments. For comparison, element/Al ratios of Siberian trap basalt, upper continental crust, and average shale are given (Lightfoot et al. 1990; Taylor and McLennan 1985)

	Eastern Laptev Sea	Western Laptev Sea	Kara Sea	Siberian trap basalt	East Siberian Sea	Chukchi Sea	Beaufort Sea	Central Arctic Ocean	Upper continental crust	Average shale
Amphibole	30	21	14	n.d.	25	18	12	22		
Clinopyroxene	13	29	27	n.d.	10	15	12	14		
Opaque minerals	13	13	25	n.d.	14	24	37	24		
Illite	48	40	33	n.d.	69	57	n.d.	56		
Smectite	18	23	33	n.d.	4	9	n.d.	7		
Chlorite	22	22	19	n.d.	19	25	n.d.	22		
Kaolinite	13	15	15	n.d.	8	9	n.d.	16		
Ti/Al	0.053	0.064	0.069	0.08	n.d.	n.d.	n.d.	0.057	0.037	0.06
K/Al	0.33	0.31	0.28	0.03	n.d.	n.d.	n.d.	0.29	0.35	0.31
Ca/Al	0.15	0.18	0.17	0.92	n.d.	n.d.	n.d.	0.45	0.37	0.09
Cr/Al*10	9.8	12.2	14.6	19.6	n.d.	n.d.	n.d.	11.1	4.4	11
Ni/Al*10	4.5	5.5	6.4	11.4	n.d.	n.d.	n.d.	7.7	2.5	5.5

20–30 grain% amphibole (Fig. 2; Table 2; Behrends et al. 1999).

The elemental concentrations are normalized to the Al content. Al is imported by terrigenous material such as clay minerals and Al silicates. Elemental concentrations can be affected by dilution with strong input of minerals such as quartz, a high total organic carbon supply, or enrichment due to diagenetic processes. By normalizing on Al these dilution effects are negotiated for those elements which are not affected by the dilution. Representative for the chemical composition five element (Ti, Ca, K, Ni, and Cr)/Al ratios were chosen to identify the source areas of the studied surface sediments, because these elements show great spatial variations in the marine sediments.

Ni/Al ratios reach maximum values up to Ni/Al $>8.5\times10^{-4}$ in the Kara Sea and western Laptev Sea sediments (along the continental margin) as well as in the central Arctic Ocean (Fig. 3). The mean Ni/Al value of sediments in the eastern Laptev Sea is lower (Ni/Al=4.5×10^{-4}; Table 2). Ti/Al-, Ca/Al-, and Cr/Al ratios are also increased in the western Laptev Sea and the Kara Sea sediments (Table 2). In the eastern Laptev Sea sediments are characterized by slightly elevated K/Al ratios (Table 2).

Discussion

Kara Sea

The surface sediments of the Kara Sea are characterized by high smectite contents as well as, compared with the upper continental crust composition (Taylor and McLennan 1985), increased Ni/Al-, Cr/Al-, and Ti/Al ratios (Table 2; Müller and Stein 1999; Schoster and Stein 1999; Wahsner et al. 1999). The available data indicate that the Putoran Mountains are one of the main source areas of the terrigenous material accumulating in the Kara Sea. The Putoran Mountains consist of Triassic flood basalts (Lightfoot et al. 1990). Paleoweathering of the basalts produced smectite-rich soils which are eroded and mainly transported by the Yenisei River into the Kara Sea. Elevated Ti/Al-, Cr/Al-, and Ni/Al ratios, as well as decreased K/Al ratios in the Kara Sea sediments, also indicate the Siberian trap basalts as being the most important source area. These trap basalts are characterized by very high Ti/Al-, Cr/Al-, and Ni/Al ratios, as well as very low K/Al ratios (compared with the upper continental crust composition; Table 3). The available data for river sediments (heavy minerals) and suspended matter (clay minerals, element/Al ratios) of the Yenisei River confirm the transport of material derived from the Siberian trap basalt (Table 3). Additionally, the sediments and suspended matter of the Ob River show a high smectite content and elevated Ni/Al- and Cr/Al ratios compared with the upper continental crust. The Ti/Al ratios and the clinopyroxene content in the Ob River sediments and suspended matter, however, are significantly lower than in the Yenisei River. Therefore, the source area of this smectite-rich and clinopyroxene-poor material in the drainage area of the Ob River, which does not drain the Putoran Mountains and their surrounding tuff deposits (Duzhikov and Strunin 1992), must be different. Such a source area has not been described in the literature thus far.

Table 3 Mean values of heavy-mineral contents of river sediments and mean values of clay-mineral contents as well as element/Al ratios of suspended matter in rivers (Levitan et al. 1996; Behrends et al. 1999; Lukashin et al. 1999; Müller and Stein 1999; Rachold 1999)

	Yenisei	Ob	Khatanga	Lena	Yana
Amphibole	10	10	9	22	5
Clinopyroxene	48	31	27	8	2
Opaque minerals	22	22	16	19	42
Illite	23	28	n.d.	n.d.	n.d.
Smectite	44	43	n.d.	n.d.	n.d.
Chlorite	18	15	n.d.	n.d.	n.d.
Kaolinite	15	14	n.d.	n.d.	n.d.
Ti/Al	0.07	0.03	0.08	0.05	0.06
K/Al	n.d.	n.d.	0.15	0.3	0.3
Ca/Al	0.13	0.05	0.45	0.21	0.08
Cr/Al*10^{-4}	23.5	12.9	n.d.	n.d.	n.d.
Ni/Al*10^{-4}	26	23	12	7.5	5.6

Western Laptev Sea

The broad Laptev Sea shelf can be distinguished into eastern and western parts. In the western Laptev Sea enhanced clinopyroxene (Table 2) and smectite contents of up to 30% (Fig. 1) indicate terrigenous sediment supply from the Putoran Mountains. Paleoweathered material from trap basalts is transported by the Khatanga River into the western Laptev Sea. The chemical composition of the suspended matter from the Khatanga River also points to the Siberian trap basalts in the Putoran Mountains as the main source area (Rachold 1999). On the western Laptev Sea shelf increased Cr/Al-, Ti/Al-, and Ca/Al ratios (Table 2) are also attributed to the Khatanga river supply. Ni/Al ratios are only slightly enhanced in the most western part, but they are markedly reduced towards the east. The Ni-containing minerals are mainly enriched in the <2-μm fraction which is similar to tidal flat sediments from the German part of the North Sea (Hild 1997). We assume that the fine-grained material of the western Laptev Sea is reworked and resuspended on the shelf and then transported further northeast, as suggested from the distribution pattern of smectite (Fig. 1). In this area along the continental margin, Ni/Al ratios are increased compared with the upper continental crust composition and the sediment composition of the shallower western Laptev Sea (Fig. 3). Furthermore, the sediments in the western Laptev Sea show a high sand content supporting the assumption

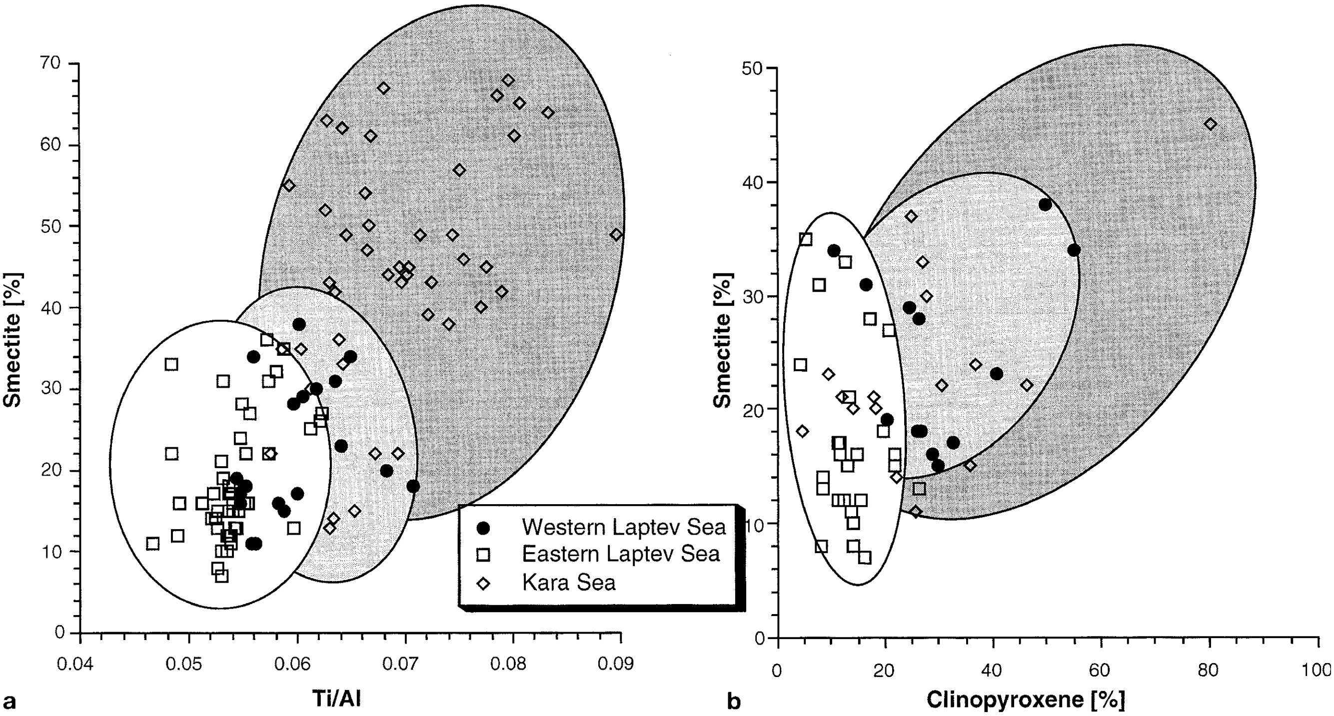


Fig. 4 Smectite contents vs **a** clinopyroxene contents and **b** Ti/Al ratios of sediments from the eastern and western Laptev Sea and the Kara Sea

of reworked sediments (Lindemann 1998; Müller 1999). The combination of high smectite and clinopyroxene contents, as well as elevated Ti/Al ratios in Kara Sea sediments, indicate a pronounced supply of material from the Siberian trap basalts (Fig. 4); thus, the western Laptev Sea sediments can be interpreted as a mixture of material originating from source areas of Kara Sea and eastern Laptev Sea sediments.

Eastern Laptev Sea

The sediments of the eastern Laptev Sea and the East Siberian Sea are characterized by increased contents of illite (Table 2; Wahsner et al. 1999) and amphibole (Fig. 2). The chemical composition is similar to average shale (Taylor and McLennan 1985). Thus, Ti/Al-, Cr/Al-, and Ca/Al ratios are lower than in Kara Sea or western Laptev Sea sediments, and K/Al ratios are slightly elevated (Table 2). Rachold (1999) determined a comparable chemical composition in the suspended matter of Yana and Lena rivers (Table 3). These rivers transport large amounts of material characterized by high concentrations of illite and amphibole into the eastern Laptev Sea (Gordeev et al. 1996; Rachold et al. 1996).

Central Arctic Ocean

The distribution of terrigenous material in the central Arctic Ocean is caused by surface-water currents, such as the Transpolar Drift, as well as by intermediate water masses such as the Atlantic-water inflow along the Eurasian continental margin (Wollenburg 1993; Nürnberg et al. 1994; Wahsner et al. 1999; Müller and Stein 2000). These currents mainly transport fine-grained material; thus, clay minerals are a valuable indicator for transport by oceanic currents. Additionally, much of the terrigenous material, especially the heavy minerals, are transported by sediment-laden sea ice (Behrends et al. 1999). Bulk element composition gives further information about the source area of the terrigenous material and, therefore, about the transport processes.

Increased amphibole contents in central Arctic Ocean sediments indicate that the eastern Laptev Sea is the main source area. The material is most likely transported by sediment-laden sea ice within the Transpolar Drift (Behrends 1999). The chemical composition of the sediments on the Lomonosov Ridge in the central Arctic Ocean shows a pattern similar to the eastern Laptev Sea sediments (Fig. 5). Most of the elements, such as P, Ti, K, Cr, Rb, Zn, and Ba, are not enriched or depleted on the Lomonosov Ridge compared with the eastern Laptev Sea. Si and Zr show lower element/Al ratios on the Lomonosov Ridge than in the eastern Laptev Sea due to more coarse-grained material (i.e., quartz or zircon) on the shelf. The elements Mn, Fe, Co, Pb, and Ni display higher ratios on the Lomonosov Ridge. These higher ratios are explained by a high input of Mn by the

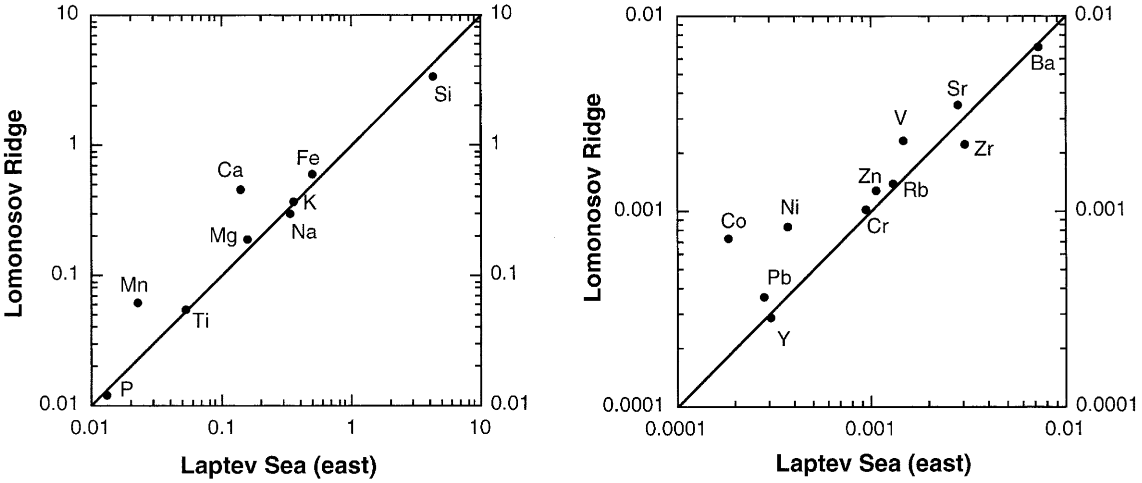


Fig. 5 Mean values of element/Al ratios of surface sediments from the Lomonosov Ridge vs mean values of element/Al ratios of eastern Laptev Sea surface sediments

Lena River into the Laptev Sea. Hölemann et al. (1999) calculated that the mean dissolved Mn concentration in Lena water is two times higher than in global river water (Martin and Whitfield 1983). After precipitation due to increasing salinity, Mn is then distributed with the other terrigenous material onto the shelf (Hölemann et al. 1999). Because of remineralization of TOC in the sediments, reduced Mn may be released into the water column, where it is slowly oxidized. The Mn-oxyhydroxides act as scavengers for other metals such as Co, Ni, Pb, or Fe. In the shallow regions of the Laptev Sea shelf, these Mn-oxyhydroxide particles are incorporated in newly formed sea ice (Hölemann et al. 1999). This sediment-laden sea ice is transported by the Transpolar Drift into the central Arctic Ocean, where the particulate material is released. During settling of these particles, additional scavenging may occur (Chester 1990).

The elements Ca, Mg, and Sr are also enriched in the sediments from the Lomonosov Ridge (Fig. 5) because of the occurrence of biogenic and/or terrigenous carbonate. On the Lomonosov Ridge biogenic carbonate consists mainly of foraminifer (Nørgard-Pedersen 1996; Spielhagen et al. 1997) and small, but significant, amounts of terrigenous (detrital) calcite and dolomite (Vogt 1996). The source area for detrital carbonate minerals is located in the Canadian Arctic region (Darby et al. 1989). From there, carbonate is transported by sea ice via the Beaufort Gyre into the central Arctic Ocean. The Canadian Arctic shelf sediments are further enriched in opaque minerals; thus, slightly increased amounts of opaque minerals observed in central Arctic Ocean sediments also support the idea of a Canadian Arctic source area and transport by sea ice (Behrends et al. 1999).

Conclusion

Based on clay-mineral and heavy-mineral data, as well as the chemical composition of surface sediments, different source areas and transport pathways of terrigenous material can be identified in the Eurasian continental margin area and the central Arctic Ocean. According to the geology of the hinterland, the Lena River transports illite- and amphibole-rich matter with a chemical composition similar to average shale found in the eastern Laptev Sea. Via the Transpolar Drift this material is supplied to the central Arctic Ocean by sediment-laden sea ice, as suggested from the similarity of the chemical composition of Lomonosov Ridge and eastern Laptev Sea sediments. The Khatanga and Yenisei rivers transport suspended matter originating from the paleoweathered soils of the Siberian trap basalts in the Putoran Mountains into the western Laptev Sea and the Kara Sea. This material is characterized by high contents of smectite and clinopyroxene as well as high Ni/Al-, Cr/Al-, and Ti/Al ratios. The Ob River also supplies particulate matter with a high smectite content and high Ni/Al- and Cr/Al ratios. This material is distributed along the Eurasian continental margin but does not reach the central Arctic Ocean in significant amounts.

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