Clay Mineral Distribution in Surface Sediments of the Laptev Sea: Indicator for Sediment Provinces, Dynamics and Sources

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Abstract - Forty-eight surface sediment samples from the Laptev Sea taken during the Russian - German expedition Transdrift I in summer 1993 were analysed for their clay mineral composition (illite, smectite, chlorite, and kaolinite). Different clay mineral provinces, the role of fluvial sediment-supply, transport mechanisms, and possible source areas are discussed.

The distribution patterns of the clay minerals allow to distinguish between three different provinces: 1. In the western Laptev Sea sediments are particularly rich in smectite and are characterized by a slight enrichment in kaolinite. 2. Sediments in the eastern Laptev Sea are very poor in kaolinite. 3. The southeastern Laptev Sea is dominated by illite and chlorite.

The distribution of clay minerals in the Laptev Sea is controlled both by river run-off and summer surface currents. The Lena and Yana rivers mainly deliver illite and chlorite, smectite is supplied almost exclusively by the Anabar and Khatanga rivers, kaolinite by the Anabar, Khatanga, and Olenek rivers. From the river mouths, surface currents transport smectite and kaolinite hundreds of km eastward.

Illite and chlorite are most probably erosional products of Paleozoic slates cropping out in the drainage areas of the Lena and Yana rivers. Smectite originates from Mesozoic and Cenozoic weathering residues of the Permo- Triassic Putoran-Plateau flood basalts. Kaolinite is probably derived from the erosion of kaolinite-rich Mesozoic sediments of the Siberian Platform.

Introduction

Recent studies have shown that huge amounts of the sediment-laden sea ice in the Transpolar Drift (Figure 1) are formed over the shallow Siberian shelf areas (Colony and Thorndike, 1984; Pfirman et al., 1990). In particular, the smectite concentrations of sea ice sediment samples taken between 81° N and 83° N are in good correspondence with those in hitherto existing surface sediment samples of the Laptev Sea suggesting the Laptev Sea as one of the main sources for sea ice sediments transported by the Transpolar Drift (Silverberg, 1972; Wollenburg, 1993; Nürnberg et al., 1994).

This study presents detailed clay mineral distribution patterns of the Laptev Sea. It discusses different clay mineral provinces, the role of bathymetry, fluvial sediment supply, and transport mechanisms of the clay minerals. In addition, possible clay mineral source areas in the Siberian hinterland are shown.

Sedimentary environment and bathymetry of the Laptev Sea

Strongly different winter and summer ice conditions influence the sedimentary environment of the very broad and shallow Laptev Sea shelf, which has maximum water depths of 50 - 60 m at its edge. From October to mid-July the Laptev Sea is covered with ice. About 1.5 - 2 m thick fast ice builds up between shallow coastal areas and the 20 - 30 m isobath (Dethleff et al., 1993). An approximately 1800 km long and up to 100 km wide zone of open water (polynya) separates the fast ice from the northward drift ice zone (Zakharov, 1966; Barnett, 1991;

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Dethleff et al., 1993). As a result of the steep increase in river run-off with beginning river ice breakup in May followed by the gradual melting of the Laptev Sea ice cover, a large brackish surface plume extending up to 350 km northward covers large parts of the Laptev Sea during the short summer period (Létolle et al., 1993).

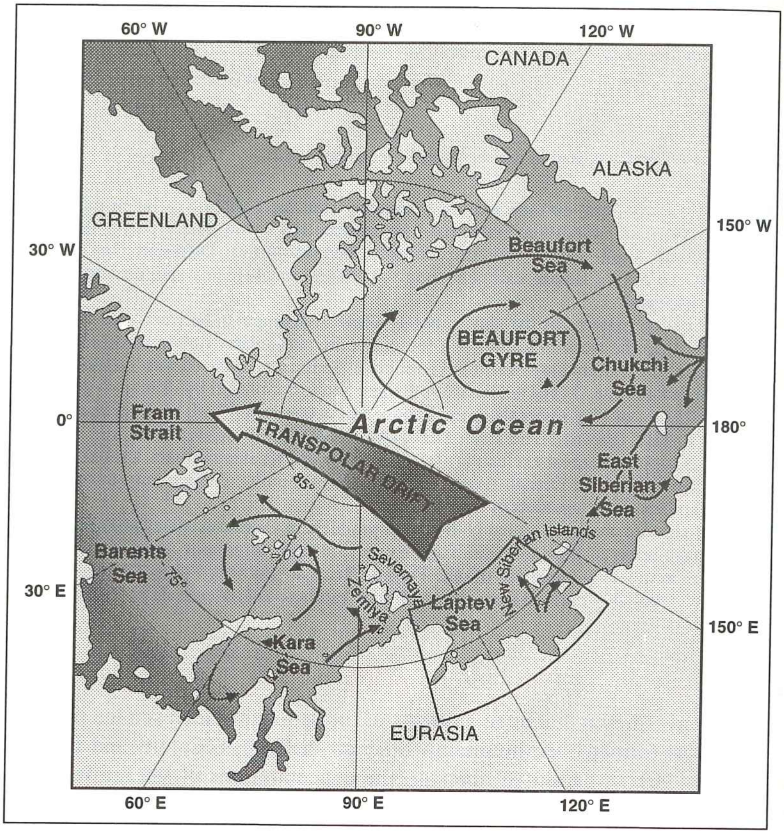

Figure 1: Generalized ice circulation in the Arctic Ocean (modified from Reimnitz et al., 1992).

As emphasised by Silverberg (1972), Holmes and Creager (1974), Kassens and Karpiy (1994), and Lindemann (1994), the Laptev Sea depositional environment is mainly controlled by terrigenous sediment supply due to large Siberian river systems. The Lena river for example has an average water discharge of 525 km^3/year and is discharging yearly about 17.6 x 10^6 t of suspended matter into the Laptev Sea (Gordeev and Sidorov, 1993). During the Pleistocene glacial periods five large northward extending valleys named after their eroding rivers incised into the shelf (Holmes and Creager, 1974) and characterize today's bathymetry of the Laptev Sea (Figure 2).

Main geological features of the Siberian hinterland

The eastern part of the Siberian hinterland is drained by the Yana, Lena, Olenek, and Anabar rivers and is predominated by Paleozoic to Mesozoic sedimentary rocks. Paleozoic rocks are cropping out on Taimyr Peninsula (Figure 2), on the Siberian platform, and in the Werchojansk-Fold-Zone, a giant Mesozoic anticline limiting the Siberian platform to the east.

Mesozoic, mostly clastic sediments are widespread in the western foreland basin of the Werchojansk-Fold-Zone and north of the Siberian Platform in the Jenissej-Khatanga-Basin. On the Siberian platform basement crops out in the Aldan-shield drained by the Lena river and in the Anabar-shield drained by the Anabar river (Dolginow and Kropatschjow, 1994; Nalivkin et al., 1965).

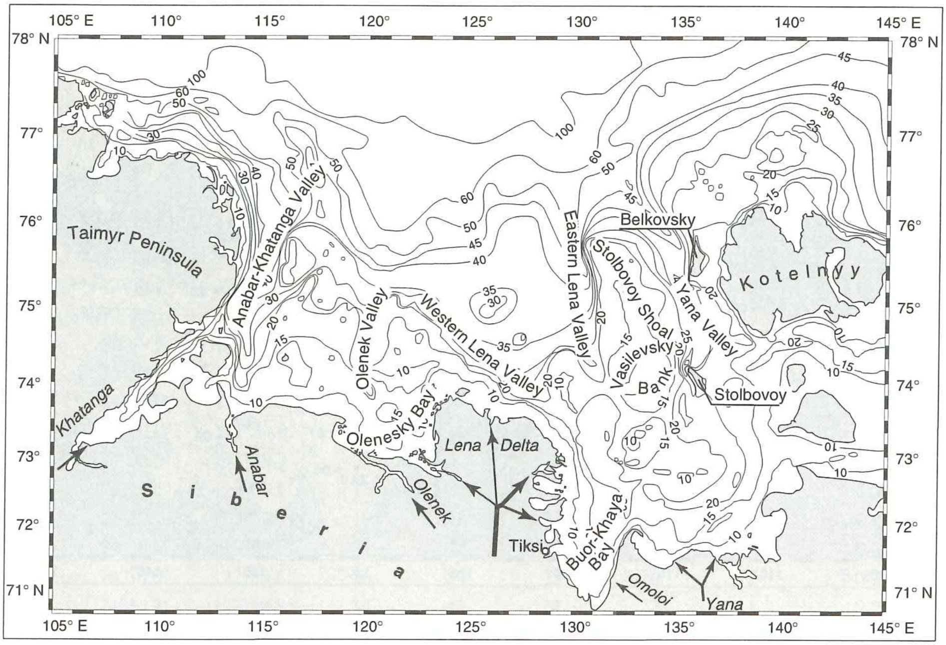

Figure 2: Bathymetric chart of the Laptev Sea Shelf (water depth in metres).

Volcanic rocks predominate the western part of the Siberian hinterland. Here, erosional remnants of formerly giant Permo-Triassic continental flood basalt sheets are forming the Putoran-Plateau drained by the Anabar and Khatanga rivers and by the Jenissej river which draines into the Kara sea (e. g., Nalivkin et al., 1965 and Coffin, 1992).

Materials and methods

During the Transdrift I-Expedition with the Russian RV Ivan Kireyev in summer 1993 (Kassens and Karpiy, 1994) 48 sediment samples were taken at 47 different locations (Figure 3 and Table 1) with a spade box corer, a gravity kasten corer or with a grab sampler. At each site the uppermost centimeter of the sediment was taken for sample and freeze-dried (Lindemann, 1994).

Each sample was shaked in a 10 % hydrogenic peroxide solution for 24 hours to disaggregate the sample and to remove organic carbon. After removing the sand-fraction (> 63 µm) by wet sieving, silt (2 - 63 µm) and clay (< 2 µm) were separated by the settling method based on Stoke's Law, using a 0.25 % NH_3 solution to avoid coagulation of the clay particles. The clay fraction was charged with $MgCl_2$ (Lange, 1982) and to remove free ions the clay fractions then were dispersed with deionized water in an ultrasonic cleaner and centrifuged for 20 minutes at

4000 r.p.m., decanting the clear water. This washing-procedure was repeated until no more clear water could be decanted after centrifugation. The cloudy water then was evaporated and the coagulating clay minerals were returned to the centrifuged sample. Because of the very small carbonate and opal concentrations, removal of these substances was not necessary.

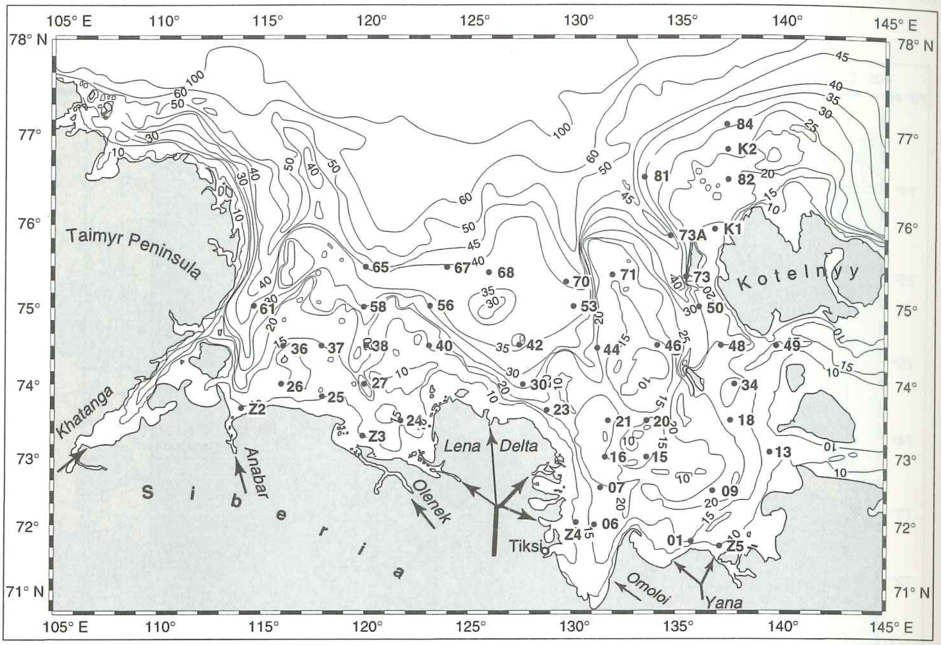

Figure 3: Stations of the expedition Transdrift I in 1993: surface sediment samples.

The dried clay fractions were carefully ground in an agate mortar and 200 mg of each sample were dispersed with 15 ml of deionized water. In order to prepare highly texturated slides without particle-size fractioning, 3 ml of the suspension (40 mg of clay) were sucked by vacuum filtration onto a membrane filter (cellulose nitrate, pore size 0.15 µm). The dried clay cakes were mounted on aluminium platelets using double-sided adhesive tape and carefully removing the filters. The thickness of the clay films was about 10 mg/cm^2.

All samples were analysed with a Philips PW 1830 X-ray difractometer (XRD) using copper radiation (Cu Kα, 45 KV, 40 mA), a theta-circle-integrated automatic divergence slit, a graphite monochromator, and an automatic sample changer. The samples were measured air dried and after solvating them with ethylene-glycol vapor at 60 °C for at least 12 hours. Scans were performed between 2° and 40° 2Θ with a step size of 0.01° 2Θ/s and between 24° and 26° 2Θ with a step size of 0.005° 2Θ/2s. For easier comparison with other studies (Wollenburg, 1993; Nürnberg et al., 1994; Nürnberg et al, 1995; Wahsner and Shelekhova, 1994) the scans were not converted into scans measured with fixed divergence slit as used by Biscaye (1964, 1965).

Table 1: Clay mineral concentrations and illite 'crystallinity' in Laptev Sea surface sediment samples. Latitude and longitude of sampling sites are indicated.

Sample	Latitude N	Longitude E	Water depth (m)	Illite (%)	Smectite (%)	Chlorite (%)	Kaolinite (%)	Illite 'crystallinity' (°Δ2Θ)
01	71°45.2′	135°39.6′	16	50	13	28	9	0.31
06	72°00.1′	131°00.0′	18	57	10	24	9	0.25
07	72°33.1′	131°17.6′	21	51	7	29	13	0.24
09	72°30.0′	136°40.0′	24	60	5	26	9	0.29
13	73°04.0′	139°22.2′	16	56	3	31	10	0.22
15	73°00.0′	133°29.9′	18	54	9	26	11	0.26
16	73°00.1′	131°30.0′	28	53	10	25	12	0.24
18	73°30.0′	137°30.0′	24	59	6	26	9	0.26
20	73°30.0′	133°30.0′	18	54	9	26	11	0.21
21	73°30.0′	131°40.4′	25	51	12	25	12	0.24
23	73°38.0′	128°39.8′	17	51	8	28	13	0.26
24	73°30.1′	121°40.1′	13	44	16	23	17	0.26
25	73°49.9′	117°52.3′	13	32	31	22	15	0.22
26	73°59.8′	115°54.0′	16	35	31	21	13	0.21
27	74°00.0′	119°51.7′	30	37	20	24	19	0.26
30	74°00.0′	127°30.0′	27	46	17	23	14	0.25
34	74°00.0′	137°39.8′	22	52	11	27	10	0.23
36	74°29.5′	115°59.6′	16	35	28	22	15	0.21
37	73°30.1′	117°50.9′	19	38	25	22	15	0.22
38	74°30.1′	119°58.5′	34	42	20	21	17	0.27
40	74°30.0′	122°59.6′	16	39	23	26	12	0.23
42	74°30.3′	127°19.8′	34	43	24	22	11	0.23
44	74°28.0′	131°05.9′	30	48	11	28	13	0.24
46	74°29.9′	134°00.7′	14	46	18	26	10	0.24
48-5	74°30.0′	137°01.0′	23	54	13	24	9	0.30
48-6	74°30.0′	137°01.0′	23	54	11	25	10	0.26
49	74°30.0′	139°40.0′	24	47	20	24	9	0.24
50	75°00.0′	136°00.0′	31	45	22	23	10	0.26
53	75°00.0′	129°57.3′	40	43	21	24	12	0.26
56	75°00.0′	123°00.0′	32	43	18	24	15	0.25
58	75°00.0′	119°50,0′	33	40	23	22	15	0.27
61	75°00.6′	114°32.2′	42	36	26	20	18	0.25
65	75°29.0′	119°54.0′	40	40	23	22	15	0.23
67	75°29.0′	123°50.5′	44	42	22	22	14	0.25
68	75°25.0′	125°51.0′	41	41	22	23	14	0.27
70	75°18.0′	129°34.0′	44	43	24	22	11	0.24
71	75°23.0′	131°48.2′	20	44	21	22	13	0.31
73	75°21.0′	135°22.0′	43	51	18	21	10	0.26
73A	75°51.1′	134°32.1′	47	48	18	23	11	0.26
81	76°31.6′	133°18.6′	37	48	19	22	11	0.25
82	76°29.9′	137°19.7′	25	51	12	26	11	0.25
84	77°06.7′	137°13.5′	33	54	11	24	11	0.26
K1	75°56.0′	136°42.0′	20	52	14	24	10	0.26
K2	76°50.1′	137°17.7′	30	54	9	27	10	0.25

Table 1 (continued):

Sample	Latitude N	Longitude E	Water depth (m)	Illite (%)	Smectite (%)	Chlorite (%)	Kaolinite (%)	Illit 'crystallinity' (°Δ2Θ)
Z2	73°39.9´	113°59.6´	9	31	30	20	19	0.27
Z3	73°17.5´	119°49.9´	12	42	15	24	19	0.29
Z4	72°02.0´	130°07.6´	14	51	14	26	9	0.27
Z5	71°41.4´	137°00.3´	11	56	1	35	8	0.24

For semi-quantitative calculations of the relative contents of smectite, illite, kaolinite, and chlorite the integrated peak areas of their basal reflections were multiplied by empirically estimated weighting factors (Biscaye, 1965). For smectite (here, scans of the glycolated samples were used) the 17 Å (001) peak area - after removing the 14 Å (001)-chlorite peak area - multiplied by one, for illite the 10 Å (001) peak area multiplied by four, and for kaolinite and chlorite the 7 Å (001/002) peak area multiplied by two were used for calculations. To determine the relative contents of kaolinite and chlorite the intensities of the 3.57 - 3.58 Å (001)-kaolinite peak and the 3.53 - 3.54 Å (002)-chlorite peak were considered (detailed scans), following Biscaye (1964, 1965).

For determination of the illite 'crystallinity' the Kübler index was applied. This index is defined as the half-height width of the (001)-illite basal reflection (Kübler, 1967, 1968, and 1984). Values for the low-grade and high-grade limit of the anchizone are 0.42° and 0.25° Δ2Θ/Cu Kα (Kübler, 1984). Considering that sample preparation methods affect the measured peak width, parameters applied in this study (grain size, thickness of the slides, Mg-saturation, use of air dried samples for measurements, and the goniometer scanning rate) lead to an increase in peak width (Kisch, 1987; Kisch and Frey, 1987; Krumm and Buggisch, 1991, and Krumm, 1992). Only the use of ultrasonic disaggregation causes decrease in peak width, simulating higher illite 'crystallinity' (Kisch and Frey, 1987).

In the following paragraphs percentages (%) always represent relative percentages (rel.-%) of the clay minerals.

Results

Illite is the main clay mineral in the investigated sediment samples with concentrations of 30 - 60 % (Figure 4 and Table 1). Highest concentrations of up to 60 % occur in the southeastern part of the Laptev Sea and northwest of Kotelnyy Island. Illite concentrations ranging from 40 to < 50 % dominate in the central and eastern Laptev Sea. Only in the western Laptev Sea illite concentrations are < 40 % (Figure 4 and Table 1).

Smectite was detected in concentrations between 1 % and 31 % (Table 1). In contrast to the illite distribution, smectite is enriched in the western Laptev Sea, especially near the mouths of the Anabar and Khatanga rivers where highest concentrations were measured (Figure 5 and Table 1). Concentrations gradually decrease to 15 - < 25 % in the eastern and to < 15 and < 5 % in the southeastern Laptev Sea (Figure 5). In the Olenek- and the Western-Lena-Valleys smectite concentrations are reduced to values between 15 and 20 % (Table 1).

In almost all samples chlorite concentrations range between 20 and < 30 % (Figure 6 and Table 1). Concentrations > 25 % can be found mainly in the southeastern Laptev Sea and northwest of Kotelnyy Island with up to 31 % and 35 % near the eastern mouth of the Yana river (Figure 6 and Table 1).

In most regions kaolinite concentrations are < 15 % (Figure 7 and Table 1). Only in the western Laptev Sea concentrations are ≥ 15 %. Highest values of up to 19 % were measured in the Olenek- and the Anabar-Khatanga-Valleys (Table 1).

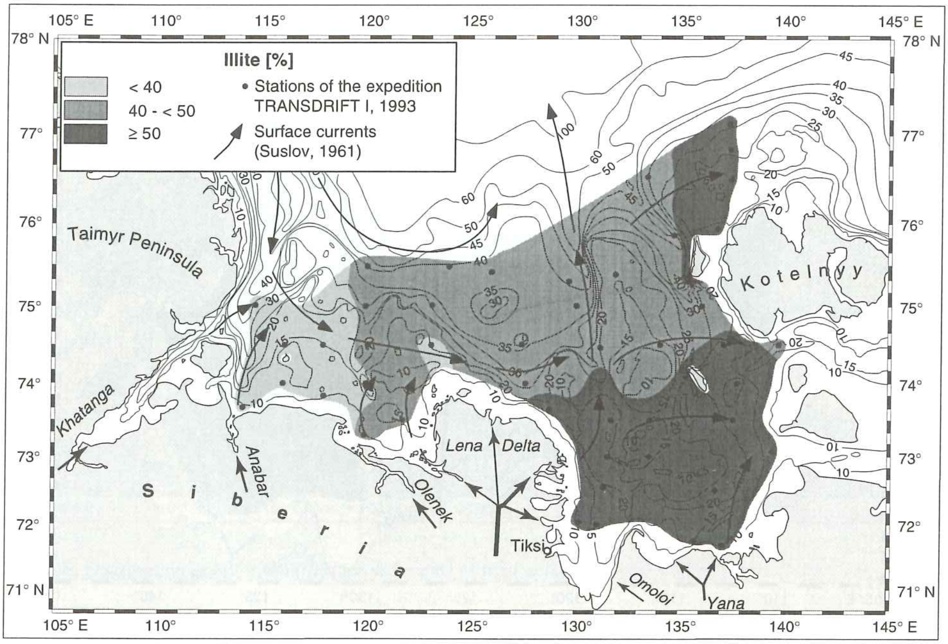

Figure 4: Distribution of illite in surface sediments of the Laptev Sea.

Discussion

Clay mineral provinces and sediment dynamics of the Laptev Sea Shelf

The clay mineral distribution of the Laptev Sea surface sediments (Figures 4 - 7) defines three provinces: 1. In the western Laptev Sea sediments are particularly rich in smectite and are characterized by a slight enrichment in kaolinite. 2. Sediments in the eastern Laptev Sea are very poor in kaolinite. 3. The southeastern Laptev Sea is dominated by illite and chlorite.

These clay mineral provinces correspond almost exactly with the benthic zonation of the Laptev Sea into a western and eastern marine region and a southern Estuarine-Arctic Region (Sirenko and Piepenburg, 1994). Furthermore, the distribution patterns of the surface sediment grain sizes (Lindemann, 1994) and of different sediment-echotypes (Benthien, 1994) allow to define two provinces: 1. The western Laptev Sea is dominated by sandy sediments which are characterized by a medium to low penetration of acoustic waves. 2. The eastern and southeastern Laptev Sea sediments are dominated by silt and clay, showing very high penetration of acoustic waves.

These zonations closely mirror the recent sediment dynamics of the Laptev Sea shelf which is strongly influenced by fluvial sediment supply (Silverberg, 1972; Holmes and Creager, 1974; Kassens and Karpiy, 1994; and Lindemann, 1994). The clay mineral distribution patterns (Figuress 4 - 7) indicate that all rivers, particularly Lena and Yana, deliver illite and chlorite - the most abundant clay minerals in cold regions. Smectite which today predominantly occurs in soils of warm-temperate and humid climate (e.g., Chamley, 1987) is mainly delivered by the

Anabar and Khatanga rivers. Kaolinite which cannot form under a polar climate is most probably supplied by the Anabar, Khatanga, and Olenek rivers.

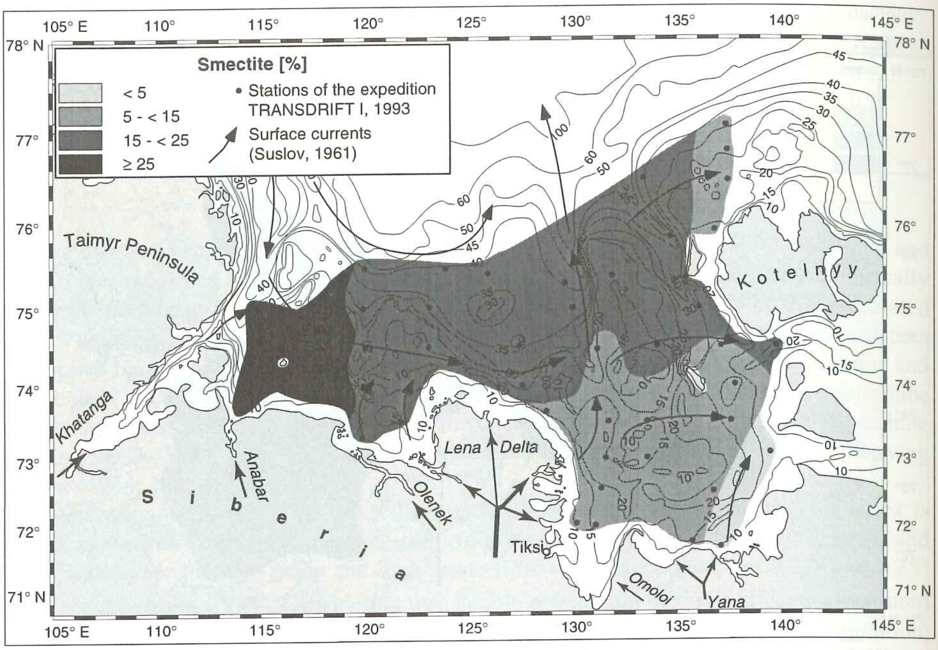

Figure 5: Distribution of smectite in surface sediments of the Laptev Sea.

Obviously, surface currents (Suslov, 1961) play an important role for the spatial distribution of the flaky clay minerals: eastward surface currents prevent westward transport of illite and chlorite, whereas kaolinite and in particular the small sized smectite cystals are transported in suspension hundreds of km to the east (Figure 8).

To explain the enrichment of illite and chlorite in the southeastern part of the Laptev Sea, bathymetry has to be considered: the southeastern part of the Laptev Sea is limited northward by the Vasilevsky Bank (Figure 2). The northern end of the brackish surface plume covering the southeastern Laptev Sea every summer is also located above this shoal (Létolle et al., 1993). Probably, the dominant clay minerals of the southeastern Laptev Sea, illite and chlorite, are settled out of a nepheloid layer described by Létolle et al. (1993) and Burenkov (1993) who observed this layer in close connection with the brackish surface plume in this area. The good correspondence of the clay mineral provinces and the benthic faunal zonation (Sirenko and Piepenburg, 1994) emphasises the combined supply of oxygen, nutrients, and sediment by the Yana and Lena rivers into the southeastern Laptev Sea.

Ice transport and aeolian input of clay minerals within the Laptev Sea shelf is not obvious from the clay mineral distribution patterns but cannot be excluded. After Pfirman et al. (1989, 1990) and Wollenburg (1993) aeolian transport of sediments into Arctic sea ice is generally negligible because of little fallout rates.

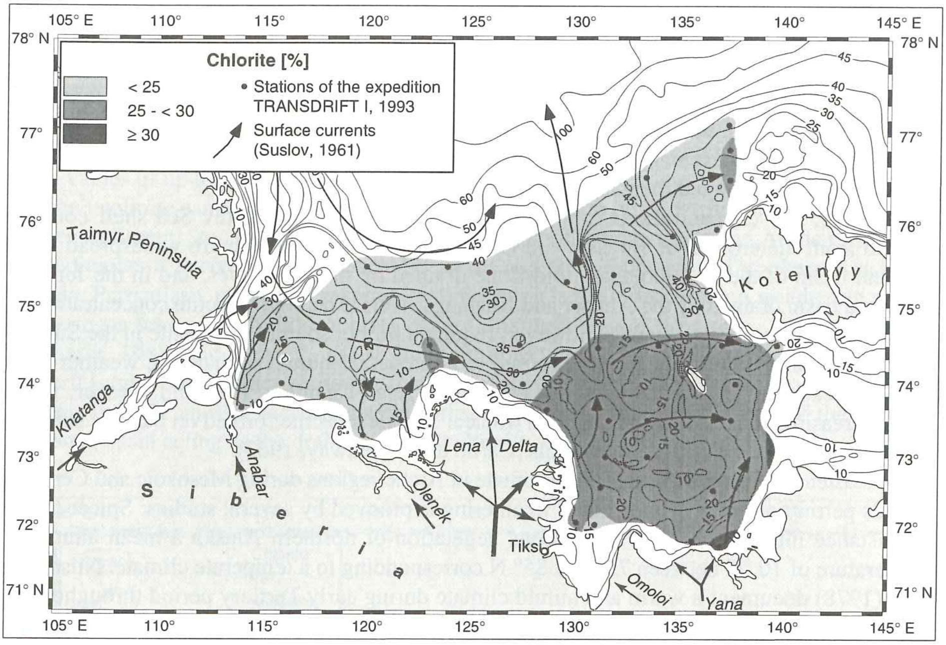

Figure 6: Distribution of chlorite in surface sediments of the Laptev Sea.

Potential clay mineral source areas in the Siberian hinterland

In arctic regions physical weathering is predominant. The formation of clay minerals by chemical weathering processes, for instance hydrolysis, is negligibly low so that the clay fraction in arctic soils only consists of - sometimes altered - fragments of the minerals of the parent rocks or soils (e. g., Chamley, 1987). Therefore, particularly in cold regions clay minerals are very good indicators for sediment origin.

Illite and chlorite

Due to alteration like mica foliation, feldspar sericitisation, and silica chloritization of widespread magmatic or metamorphic substrates illite and chlorite are the most abundant clay minerals in high latitudes (Chamley, 1987). This fact is clearly reflected by the high illite and chlorite concentrations in the Laptev Sea surface sediments (Figures 4 and 6, and Table 1). However, it is obvious that especially the Lena and Yana rivers deliver illite and chlorite (Figures 4, 6, and 8), two clay minerals which are main components of Paleozoic slates (e.g., Heim, 1990). Paleozoic slates occur on the Siberian platform and in the Werchojansk-Fold-Zone (Dolginow and Kropatschjow, 1994). Erosion of these rocks may therefore produce high amounts of illite and chlorite which are transported to the Laptev Sea by the Lena and Yana rivers. The illite 'crystallinity' measurements support this hypothesis: the 'crystallinity' of the Laptev Sea illites averages 0.25° $\Delta 2\Theta$ indicating that the illites originate from at least anchimetamorphic source rocks. Furthermore, the surface sediments near the Lena and Yana river mouths contain up to 5 wt.-% slate fragments in the coarse fraction (Rossak, 1995), confirming the assumed source area of chlorite and illite.

Smectite and kaolinite

Smectite and kaolinite can basically form by alteration of volcanic glass, feldspars, micas, and various FeMg (alumo-) silicates (Weaver, 1989). For the formation of smectite a warm-temperate and humid climate is necessary with lower drainage and rainfall and with lower temperatures than are necessary for kaolinite formation (Chamley, 1987 and Weaver, 1989). Today smectite is present in all soils of warm-temperate regions and is also abundant in Mesozoic and Tertiary sedimentary rocks, (Weaver, 1989).

Therefore, low concentrations of smectite in sediments of the Laptev Sea shelf could be derived from the erosion of Jurassic and Cretaceous sediments which are widespread in the foreland basin of the Werchojansk-Fold-Zone drained by the Lena river, and in the Jenissej-Khatanga basin drained by the Anabar and Khatanga rivers. The high smectite concentrations of the western Laptev Sea sediments, however, require a further source of smectite in the Siberian hinterland, namely volcanic rocks. Exposed to a temperate-humid climate the weathering of basaltic rocks may lead to the formation of smectite (e.g., Chamley, 1987 and Weaver, 1989). With increasing soil development under a tropical climate smectite formed on basaltic substrate transforms gradually into kaolin minerals (Caroll and Hathaway, 1963).

The existence of a warmer, non-polar climate in Arctic regions during Mesozoic and Cenozoic periods permitting intensive chemical weathering is prooved by several studies: Spicer (1987) for instance infered from late Cretaceous vegetation of northern Alaska a mean annual air temperature of 10 °C between 75° and 85° N corresponding to a temperate climate. Nilsen and Kerr (1978) document a warm and humid climate during early Tertiary period throughout the North Atlantic region and into the Arctic Ocean region: on a plateau basalt of the Iceland-Faeroe Ridge a laterite soil containing smectite at the bottom and kaolinite at the top of its profile (see Caroll and Hathaway, 1963) developed during early Tertiary period.

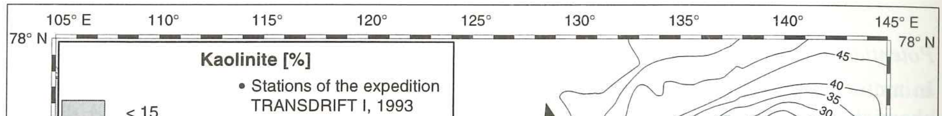

Figure 7: Distribution of kaolinite in surface sediments of the Laptev Sea.

For the Putoran Plateau flood basalts drained by the Anabar and Khatanga rivers the development of soils including the formation of smectite and possibly even of kaolinite therefore is probable during Mesozoic and Cenozoic periods. Erosion of these smectite-bearing remnants of paleosols explain the high concentrations of smectite in western Laptev Sea sediments. Since the Putoran Plateau is also drained by the Jenissej river, smectite concentrations of the Kara sea should also be high. In fact, concentrations of smectite even reach values of up to 70 % off the Jenissej river mouth (Wahsner and Shelekhova, 1994).

Since kaolinite cannot form under a polar climate, it has to be of detrital origin in Laptev Sea surface sediments, too. According to Darby (1975), kaolinite in Amerasian Arctic Ocean deep sea sediments is derived from reworked deposits and from relict soils of northern Alaska and Canada. Particularly in Mesozoic series kaolinitization is the most common weathering process indicating a warm and humid climate during this period (e.g., Chamley, 1987; Sigleo and Reinhardt, 1988, and Weaver, 1989). In addition to volcanic origin, kaolinite enrichment in western Laptev Sea surface sediments can therefore be explained by the erosion of kaolinite-bearing Jurassic and Cretaceous clastic series of the Siberian Platform and of the Jenissej-Khatanga basin acting as the drainage area of Olenek, Anabar, and Khatanga rivers.

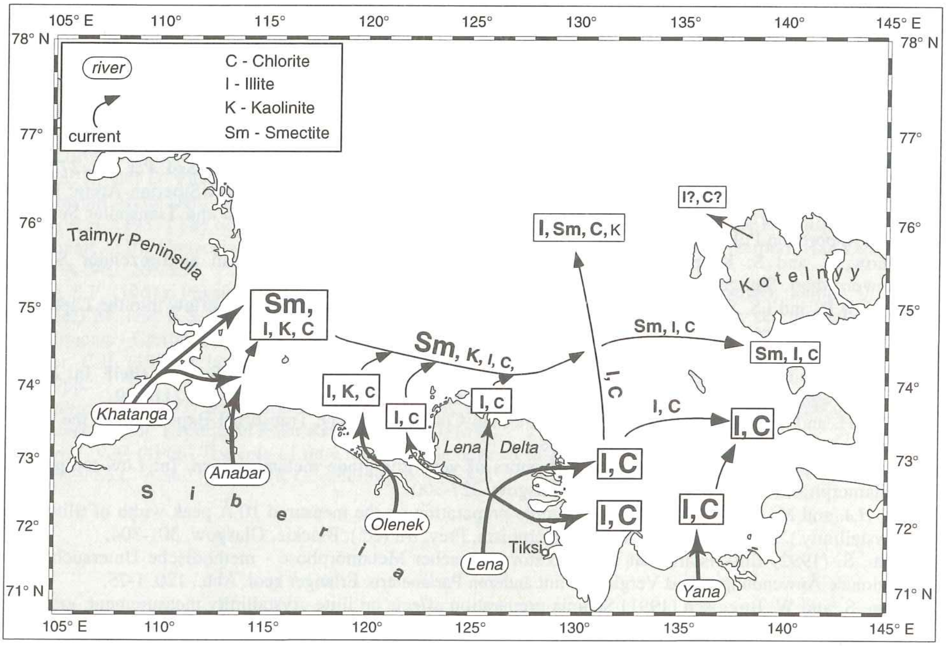

Figure 8: Relationship between fluvial input and surface currents (Suslov, 1961) in the distribution of clay minerals on the Laptev Sea shelf. The sizes of the symbols correspond to the regional significance of the clay minerals, not to their absolute concentrations.

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References

Barnett, D. (1991) Sea ice distribution in the Soviet Arctic. In: The Soviet Maritime Arctic, Brigham, L.W. (ed.), Belhaven Press, London, 47-62.

Benthien, A. (1994) Echographiekartierung und physikalische Eigenschaften der oberflächennahen Sedimente in der Laptevsee. Unpubl. Diplomarbeit, Teil II, Geologisch-Paläontologisches Institut, Univ. Kiel, 80pp.

Biscaye, P.E. (1964) Distinction between kaolinite and chlorite in recent sediments by X-ray diffraction. Amer. Mineralogist, 49, 1281-1289.

Biscaye, P.E. (1965) Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. Geol. Soc. America Bull., 76, 803-832.

Burenkov, V.I. (1993) Distribution of suspended matter in the Laptev Sea waters (from optical data). Third International Symposium: The Arctic Estuaries and Adjacent Seas: Biogeochemical Processes and Interaction with Global Change, Abstracts, 9-10.

Caroll, D. and J.C. Hathaway (1963) Mineralogy of Selected Soils from Guam, with a section on description soil profiles by C.H. Stensland. Geol. Survey Prof. Paper, 403-F, 1-53.

Chamley, H. (1989) Clay Sedimentology. Springer, Berlin, 623pp.

Coffin, M.F. (1992) Large igneous provinces studied. EOS, 73, 66-67.

Colony, R. and A.S. Thorndike, (1984) An estimate of the mean field of Arctic sea ice motion. J. Geophys. Res., 89, 10623-10629.

Darby, D.A. (1975) Kaolinite and other clay minerals in Arctic Ocean sediments. Journ. Sed. Pet., 45, 272-279.

Dethleff, D., D. Nürnberg, E. Reimnitz, M. Saarso and Y.P.Savchenko (1993) East Siberian Arctic Region Expedition '92: The Laptev Sea - Its Significance for Arctic Sea-Ice Formation and Transpolar Sediment Flux. Reports on Polar Research, 120, 1-44.

Dolginow, J. and S. Kropatschjow (1994) Abriß der Geologie Rußlands und angrenzender Staaten. Schweizerbart, Stuttgart, 174pp.

Gordeev, B.B. and I.S. Sidorov (1993) Concentrations of major elements and their outflow into the Laptev Sea by the Lena River. Mar. Chem., 43, 33-45.

Heim, D. (1990) Tone und Tonminerale. Enke, Stuttgart, 157pp.

Holmes, M.L. and J.S. Creager (1974) Holocene history of the Laptev Sea continental shelf. In: Marine Geology and Oceanography of the Arctic Sea, Herman, Y. (ed.), Springer, New York, 211-229.

Kassens, H. and V.Y. Karpiy (1994) Russian-German Cooperation: The TransdriftI Expedition to the Laptev Sea. Reports on Polar Research, 151, 1-168.

Kisch, H.J. (1987) Correlation between indicators of very low-grade metamorphism. In: Low temperature metamorphism, Frey, M. (ed.), Blackie, Glasgow, 227-300.

Kisch, H.J. and M. Frey (1987) Effect of sample preparation on the measured 10 Å peak width of illite (illite 'crystallinity'). In: Low temperature metamorphism, Frey, M. (ed.), Blackie, Glasgow, 301-304.

Krumm, S. (1992) Illitkristallinität als Indikator schwacher Metamorphose - methodische Untersuchungen, regionale Anwendungen und Vergleiche mit anderen Parametern. Erlanger geol. Abh., 120, 1-75.

Krumm, S. and W. Buggisch (1991) Sample preparation effects on illite crystallinity measurement, grain size gradation and particle orientation. J. metamorphic Geol., 9, 671-677.

Kübler, B. (1967) La cristallinité de l'illite et les zones tout à fait supérieures du métamorphisme. In: Étages tectonipues, Colloque de Neuchâtel, 18-21 avril 1966, Institut de Géologie de l'Université de Neuchâtel (ed.), À la Baconnière, Neuchâtel, Suisse, 106-122.

Kübler, B. (1968) Evaluation quantitative du métamorphisme par la cristallinité de l'illite. Bull Centre Rech. Pau-SNPA, 2, 385-397.

Kübler, B. (1984) Les indicateurs des transformations physiques et chimiques dans la diagenèse, température et calorimétrie. In: Thérmométrie et barométrie géologiques, Lagache, M. (ed.), Soc. Franç. Minér. Crist., Paris, 489-596.

Lange, H. (1982) Distribution of chlorite and kaolinite in eastern Atlantic sediments off North Africa. Sedimentology, 29, 427-431.

Létolle, R., J.M. Martin, A.J. Thomas, V.V. Gordeev, S. Gusarova and I.S. Sidorov (1993) ^{18}O abundance and dissolved silicate in the Lena delta and Laptev Sea (Russia). Mar. Chem., 43, 47-64.

Lindemann, F. (1994) Sonographische und sedimentologische Untersuchungen in der Laptevsee, sibirische Arktis. Unpubl. Diplomarbeit, Teil II, Geologisch-Paläontologisches Institut, Univ. Kiel, 75pp.

Nalivkin, D.V., A.P. Markovskiy, S.A. Muzylev, E.T. Shatalov and L.P. Kolosova (eds.)(1965): Geological Map of the Union Of Soviet Socialist Republics, Scale 1 : 2 500 000. The Ministry of Geology of the USSR, Moscow.

Nilsen, T.H. and D.R. Kerr (1978) Paleoclimate and paleogeographic implications of a lower Tertiary laterite (latosol) on the Eceland-Faeroe Ridge, North Atlantic region. Geol. Magazine, 115, 153-184.

Nürnberg, D., M.A. Levitan, J.A. Pavlidis and E.S. Shelekhova (1995) Distribution of clay minerals in surface sediments from the eastern Barents and south-western Kara seas. Geol. Rundsch., 84, 665-682.

Nürnberg, D., I. Wollenburg, D. Dethleff, H. Eicken, H. Kassens, T. Letzig, E. Reimnitz, and J. Thiede (1994) Sediments in the Arctic sea ice: Implications for entrainment, transport and release. Mar. Geol., 119, 185-214.

Pfirman, S.L., M.A. Lange, I. Wollenburg and P. Schlosser (1990) Sea ice characteristics and the role of sediment inclusions in deep-sea deposition: Arctic - Antarctic comparisons. In: Geological History of the Polar Oceans: Arctic versus Antarctic, Bleil, U. and J. Thiede (eds.), Kluwer, Dordrecht (NATO ASI Series C), 187-211.

Pfirman, S.L., I. Wollenburg, J. Thiede and M.A. Lange (1989) Lithogenic sediment on Arctic pack ice: Potential aeolian flux and contribution to deep sea sediments. In: Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport, Leinen, M. and M. Sarnthein (eds.), Kluwer, Dordrecht (NATO ASI Series C), 463-493.

Reimnitz, E., L.J. Marincovich, M. McCormick and W.M. Briggs (1992) Suspension freezing of bottom sediment and biota in the Northwest Passage and implications for Arctic Ocean sedimentation. Can. J. Earth Sci., 29, 693-703.

Rossak, B. (1995) Zur Tonmineralverteilung und Sedimentzusammensetzung in Oberflächensedimenten der Laptevsee, sibirische Arktis. Unpubl. Diplomarbeit (Laborteil), Institut für Geologie/GEOMAR Forschungszentrum für marine Geowissenschaften, Univ. Würzburg/Univ. Kiel, 101pp.

Sigleo, W. and J. Reinhardt (1988) Paleosols from some Cretaceous environments in the southeastern United States. In: Paleosols and weathering through geologic time: principles and applications, Reinhardt, J. and W.R. Sigleo (eds.), Geol. Soc. Am., Boulder, Colorado (special paper 216), 123-142.

Silverberg, N. (1972) Sedimentology of the Surface Sediments of the East Siberian and Laptev Seas. Unpubl. PhD-thesis, Department of Oceanography, Washington D.C., 185pp.

Sirenko, B. and D. Piepenburg, (1994) Current knowledge on biodiversity and benthic zonation patterns of Eurasian Arctic shelf seas, with special reference to the Laptev Sea. Reports on Polar Research, 144, 69-77.

Spicer, R.A. (1987) The Significance of the Cretaceous Flora of Northern Alaska for the Reconstruction of the Climate of the Cretaceous. In: Das Klima der Kreide-Zeit, Kemper, E. (ed.), Schweizerbart, Hannover (Geol. Jb. A, 96), 265-291.

Suslov, S.P. (1961): Physical Geography of Asiatic Russia. Freeman & Co., San Francisco, 594pp.

Wahsner, M. and E.S. Shelekhova (1994) Clay-mineral distribution in Arctic deep sea and shelf surface sediments.- Greifswalder Geologische Beiträge, A (2), 234 (Abstract).

Weaver, C.E. (1989) Clays, Muds, and Shales. Elsevier, Amsterdam (Developments in Sedimentology 44), 819pp.

Wollenburg, I. (1993) Sedimenttransport durch das arktische Meereis: Die rezente lithogene und biogene Materialfracht. Reports on Polar Research, 127, 1-159.

Zakharov, V.F. (1966) The role of flaw leads off the edge of fast ice in the hydrological and ice regime of the Laptev Sea.- Acad. Sci. USSR Oceanology, 6, 815-821.