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Clay Minerals as Indicators of Late Quaternary Sedimentation Constraints in the Mendeleev Rise, Amerasian Basin, Arctic Ocean

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Abstract—The results of study of six cores taken from different morphostructural zones in the Mendeleev Ridge area are discussed. Average contents of minerals of the illite group, chlorite, kaolinite, and smectite are about 60, 21, 12, and 5%, respectively. It was found that fluctuations of minerals along the section correlate with variations in sedimentation constraints in the Late Quaternary. Peaks of kaolinite usually coincide with increased contents of the sand fraction, probably, due to its delivery by icebergs. In contrast, illite shows good correlation with the pelite fraction, testifying to its transport mainly by ices and currents. Minerals of the chlorite and smectite groups in the studied cores are less informative.

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Although the Arctic Ocean (AO) is the Earth's smallest ocean, it plays an essential role in the evolution of climatic system in the North Hemisphere. Owing to relatively small dimensions and closed shape, the AO represents a natural "sedimentation trap" for large volumes of sediment. Annually, 592–666 Mt of terrigenous material is transported to marginal shelf seas of the Arctic from various sources (Stein, 2008). A significant portion of this material is delivered to the oceanic basin. Sediments are steadily accumulated not only in basins, but also on underwater ridges and rises. This is confirmed by numerous seismic data (Backman et al., 2004; Bruvoll et al., 2010; 2012; Jokat, 2003) and results of the submarine drilling near the polar zone of the Lomonosov Ridge (Moran et al., 2006). It was found that thickness of sediments varies from 0.5 to 1.2 km in the central part of the Alpha Ridge (Bruvoll et al., 2010, 2012). On the Mendeleev Ridge, the thickness is about 0.6–0.8 km at rises and 1.8 km in grabens. Bedding in the upper 200-m-thick section is nondistorted (Bruvoll et al., 2010). Seismic data indicate that the Lomonosov, Alpha, and Mendeleev ridges, which separate the deep-water AO basins, commonly represented accumulative structures rather than major suppliers of terrigenous material to basins in the Neogene–Quaternary. Erosional processes undoubtedly took place at ridges, but their scale and role in sedimentation should not be overestimated. Terrigenous material is mainly delivered to basins and ridges from the ambient land.

It is important to study clay minerals, because the fine-dispersed material is the main component of bottom sediments in the AO. Cold climate and physical weathering prevailed in the AO in the Neogene–Quaternary. Therefore, the main mass of clay minerals in sediments represents the terrigenous material. Since currents and ice draft were the main transport agents, clay minerals can be used not only as tracers of provenances and variations therein, but also for the reconstruction of paleocirculations. In addition, clay minerals serve as important indicators of sedimentation constraints in the geological past (Krupskaya et al., 2011; and others).

MATERIALS AND METHODS

Bottom sediment samples were recovered with gravity corer during the Arktika-2000 cruise of the R/V *Akademik Fedorov* in 2000. The paper presents the results of study of clay minerals in six cores recovered from different morphostructural zones: Podvodnikov Basin (AF00-23, AF00-28), top of the Mendeleev Rise (AF00-08), shelf zones of the Mendeleev Rise (AF00-34, AF00-37), and Mendeleev Basin (AF00-02) (Fig. 1, Table 1).

The semiquantitative determination of clay minerals (less than 0.002 mm in size) and the selection of samples of this fraction for analysis were carried out at the Alfred Wegener Institute for Polar and Marine Research (AWI, Bremerhaven). Measurements were accomplished with a Philips PW 1820 diffractometer (CoKα radiation; operation conditions 40 kV, 40 mA). We analyzed oriented preparations in the air-dry and ethylene glycol-saturated states. Preparation of sam-

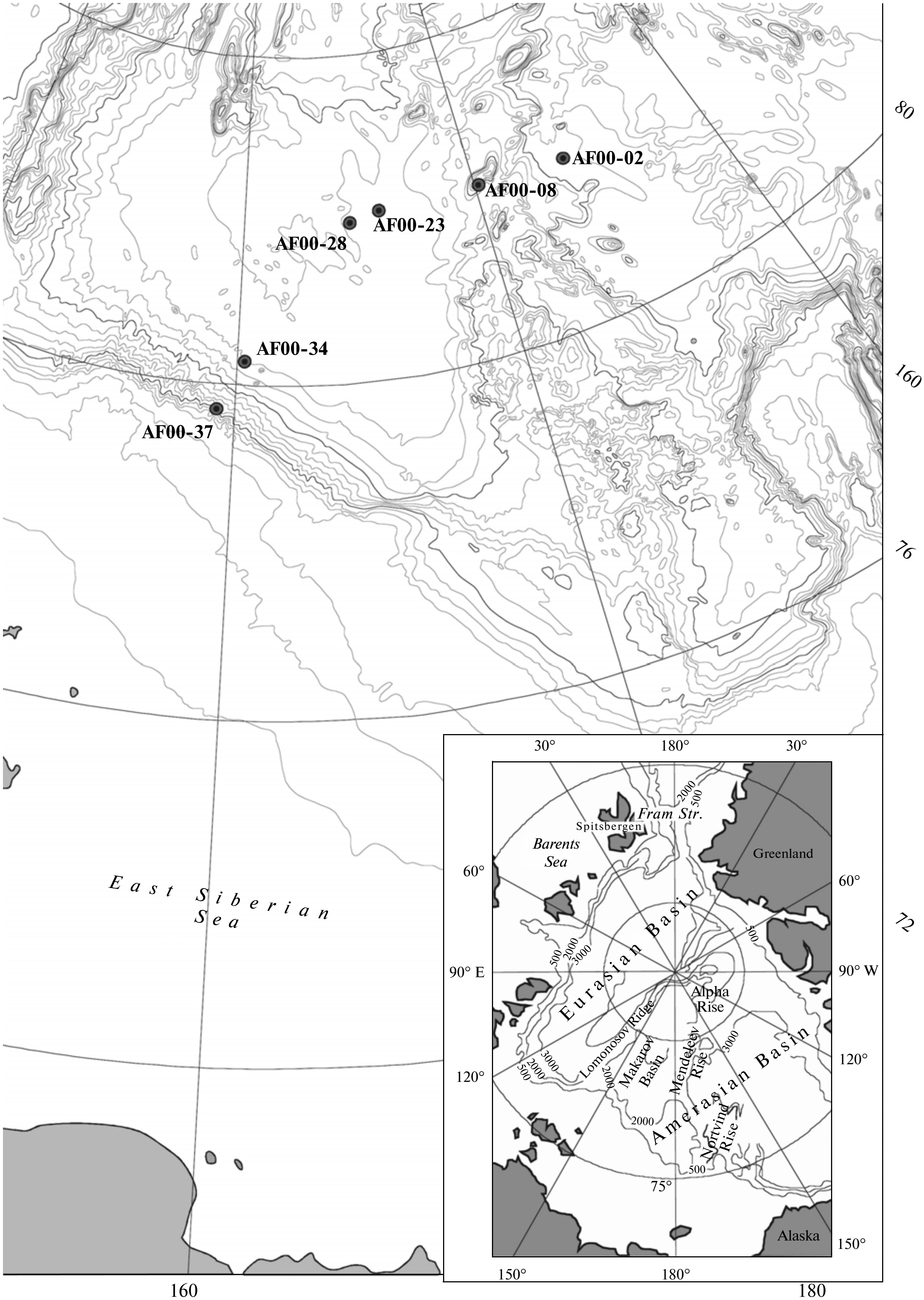
80
AF00-02
AF00-08
AF00-23
AF00-28
AF00-34
160
AF00-37
76
72
East Siberian Sea
160
180
30°
180°
30°
Fram Str.
Spitsbergen
Barents Sea
Greenland
60°
60°
Eurasian Basin
90° E
90° W
Alpha Rise
Lomonosov Ridge
Makarov Basin
Mendeleev Rise
Amerasian Basin
Nortvind Rise
120°
120°
75°
Alaska
150°
150°
180°

Table 1. Location of stations, ocean depth, and core length

Station	Latitude	Longitude	Depth, m	Core length, cm
AF00-02	81°56.86′ N	171°40.61′ W	3238	310
AF00-08	82°05.22′ N	179°52.0′ W	1530	265
AF00-23	82°00.95′ N	171°53.89′ W	2780	330
AF00-28	81°54.90′ N	167°52.32′ W	2828	334
AF00-34	80°51.80′ N	160°31.5′ W	1420	282
AF00-37	79°30.69′ N	159°05.62′ W	621	323

ples for the analysis and scanning conditions are scrutinized in (Wahsner et al., 1996; 1999). The measurement range was 2°–40°2Θ (step 0.02°2Θ and scanning time at one point was 2 s. The obtained diffractograms were processed with the MacDiff software (Petschik et al., 1996). The semiquantitative calculation was accomplished with the Biscaye method (Biscaye, 1965), which is widely used for marine and oceanic sediments. Despite obvious shortcomings of the Biscaye method, it is a simple tool that can be used for the correct comparison of the results of our measurements with numerous data on the distribution of clay minerals in the Arctic reported by researchers from the AWI (Bremerhaven, Germany) and Bremen University, as well as the results obtained during the joint Russian-German projects (Krylov et al., 2008; Levitan et al., 1995; Nürnberg et al., 1995; Shelekhova et al., 1995; Stein, 2008; Vogt and Knies, 2008; 2009; Wahsner et al., 1999; and others).

Share of minerals of the smectite and illite groups was estimated on the basis of the area of 17 and 10 Å peaks, respectively, with a coefficient of 4; while share of the kaolinite and chlorite groups was based on the area of 7 Å peak with a coefficient of 2 (Biscaye, 1965). Proportions of the latter two mineral groups were based on the splitting of reflexes 3.57–3.58 Å for kaolinite and 3.53–3.54 Å for chlorite.

The 13-fraction grain size analysis was carried out in the Lithomineralogical Laboratory of VNIIOkeangeologiya (St. Petersburg) with the water-sieve method of V.P. Petelin modified by N.N. Lapina (1977). We used the following classification of sediments widely used in lithology (in mm): gravel-gruss 1–10, sand 1–0.05, silt 0.05–0.005, pelite <0.005 (Logvinenko, 1984). We analyzed sediments from all cores except AF00-37.

Since samples for the grain size analysis and determination of clay mineral contents were taken from similar intervals, correlations were estimated for these parameters. Reliability and significance of the obtained correlation coefficients were examined with the Student's criterion and Fischer transform. The latter method was used for short samplings (series length less than 30) at correlation coefficient higher than 0.3.

SOURCES OF CLAY MINERALS IN THE ARCTIC OCEAN AND CONDITIONS OF THEIR TRANSPORT

Clay minerals are commonly used for determining the AO provenances (Darby, 1975; Krylov et al., 2008; Stein et al., 1994; Stein, 2008; Viscosi-Shirley et al., 2003; Vogt, 1997; Wahsner et al., 1999; and others). Smectite is mainly delivered from the Kara Sea (as suggested by distinct maximums of this mineral in the Ob and Yenisei estuaries) and the western Laptev Sea (Khatanga River mouth). Smectite is transported to this zone owing to the erosion of Permian and Triassic basalts of the Putorana Plateau (Gorbunova, 1997; Schoster et al., 2000; Shelekhova et al., 1995; Vogt and Knies, 2008; Wahsner et al., 1999). High contents of smectite were also detected in the Franz Josef Land area (Ivanov et al., 1999; Wahsner et al., 1996). Relatively high contents of this component (~20%) were recorded in the Chukchi Sea (Naidu et al., 1982; Viscosi-Shirley et al., 2003).

Illite is the major mineral in both the AO and ambient shelf seas. A slight decrease of the illite content in the Kara Sea is related to its dilution by smectite. Sediments in the eastern Laptev Sea and East Siberian Sea are enriched in illite, relative to the remaining regions (Wahsner et al., 1999).

Distribution of chlorite is sufficiently homogeneous in the AO surface sediments. Since chlorite dominates in sediments of the northern Pacific, this mineral can be considered a tracer of the passage of Pacific waters through the Bering Strait (Kalinenko, 2001; Naidu and Mowatt, 1983; Ortiz et al., 2009)

Potential sources of kaolinite are limited in the AO. Local exposures of Triassic and Jurassic rocks on the Barents Sea bank, as well as Mesozoic rocks of Franz Josef Land, are the main suppliers of kaolinite in the Eurasian Basin of the AO (Nürnberg et al., 1995; Stein, 2008). In the Laptev Sea, the Late Oligocene–Early Miocene weathering crust (kaolinite and kaolin-

Fig. 1. Location of stations in the Mendeleev Ridge area.

ite–hydromica clays) are known on Bol'shevik Island, Anabar–Olenek interfluve, Lena River delta, Van'kina Guba area, and Svyatoi Nos Cape (Kim and Slobodin, 1991). In addition, the kaolinite weathering crust was exposed by drilling in the Danian rocks in the Aion Island area of the East Siberian Sea (Slobodin et al., 1990). Some Mesozoic and Cenozoic beds in northern Alaska and the Canadian Arctic are also enriched in kaolinite (Darby, 1975; Naidu and Mowatt, 1983; Dalrymple and Maass, 1987). In particular, the Oligocene weathering crust with traces of erosion was outlined on Banks Island (Kim and Slobodin, 1991). High contents of kaolinite are also noted in the Ellef Ringnes Island area (Darby et al., 2011).

Clay minerals are transported from provenances by currents, ices, and icebergs. Transport by icebergs and pack ices is more typical of deglaciation periods, whereas transport by ices (pack and seasonal) and currents is characteristic of interglacial periods. During glaciations, the AO was covered with a thick sheet of pack ice, naturally leading to the retardation of sedimentation processes up to the point of hiatuses recorded on the Mendeleev Ridge at the 2nd marine isotope stage (MIS 2) (Polyak et al., 2004).

The ice-mediated transport of terrigenous material is accomplished at present by two major systems: Beaufort Gyre and Transpolar Drift. How stable were these systems in the past is a debatable issue. Microprobe data on iron oxides and analysis of their distribution over the AO area suggested a significant variation of glacial systems in the Quaternary (Bischof and Darby, 1997). However, study of terrigenous minerals and rock clasts revealed their sufficient stability along core sections during the last 80–160 ka (Norgaard-Pedersen et al., 1998; Phillips and Grantz, 2001; Spielhagen et al., 2004). Similarity of heavy mineral assemblages is retained until the Middle Miocene in boreholes drilled in the polar zone of the Lomonosov Ridge (Krylov et al., 2008). This fact is a serious argument in favor of stability of the ice circulation system over millions of years. Further detailed studies are needed to eliminate the existing contradictions. However, we can already assume now that the general stability of ice drift paleosystem was complicated by periodic (sometimes, quite appreciable) spatial fluctuations. For example, current variations in the atmospheric pressure gradient ("Arctic oscillation") affect significantly both the penetration range of transpolar ice drift system into the Amerasian Basin and the Beaufort Gyre dimension (Darby et al., 2006; and others).

STRATIGRAPHY OF BOTTOM SEDIMENTS

Stratigraphy of bottom sediments in the central Arctic remains a debatable issue for many years mainly because of the lack of a reliable biostratigraphic basis. This issue was scrutinized in (Backman et al., 2004; Gusev et al., 2012 Krylov et al., 2011; Polyak et al., 2004, 2009; and others). In virtually all publications of the 1960s–1990s, reconstruction of the age of sedimentary sections on the Alpha and Mendeleev ridges was based on magnitostratigraphy. The first consistent normal-to-negative polarity transition was compared with the Brunhes–Matuyama boundary (Clark et al., 1980; and others). In accordance with this concept, the average sedimentation rate on rises in the central Amerasian Basin was approximately 1 mm/ka for the Brunhes Epoch. According to the alternative ("young") model, the stable decrease of remnant magnetization matched the Biwa II geomagnetic field excursion within the Brunhes Epoch rather than the Brunhes–Matuyama transition (Jakobsson et al., 2000). Correspondingly, the sedimentation rate also increased significantly.

A detailed stratigraphic subdivision of several cores recovered during the Arktika-2000 cruise supplemented with a comprehensive description of the distribution of foraminifers and ostracods was also presented in the "old" age model (Andreeva et al., 2007). Since stratigraphy of cores on the northern Mendeleev Ridge (AF00-02, AF00-08, AF00-23, and AF00-28) compiled in accordance with the young model is also published (Krylov et al., 2011), we shall not dwell on this issue in the present paper.

On the whole, the AO bottom sediments are characterized by alternation of the brown (microfauna-rich) and gray or olive (microfauna-poor) beds. The brown beds are compared with the interstadial varieties; the gray beds, with the glaciation epochs (Belov and Lapina, 1961; Clark et al., 1980). Boundaries between the beds on submarine ridges are usually characterized by higher contents of the sand fraction. This is particularly well seen at MIS 1–7 interval. This situation is quite natural, because the onset of deglaciation triggers a large-scale thawing of pack ices and icebergs leading to discharge of the drafted terrigenous material (Phillips and Grantz, 2001; Polyak et al., 2004; Spielhagen et al., 2004; and others.). However, this period was also marked by intensification of currents due to increase in the AO water exchange with the Atlantic and Pacific oceans via the Fram and Bering straits. These processes could also promote the washout of fine particles and concentration of coarse

Fig. 2. Schematic stratigraphic subdivision of cores AF00-02, AF00-08, and AF00-23. (a) Sediment color: (1) Pink-beige interbed, (2) brown and gray-brown, (3) olive green-brown, pale brown, (4) brown-olive green, gray-olive green, (5) olive green; (b) distribution of sand and gravel fractions (wt %): (6) sand, (7) gravel; (c) orientation of remnant magnetization;(d) microfauna: (8) planktonic foraminifers (%), (9) benthic foraminifers at station AF00-02 (number of tests), (10) *Oridorsalis tener* (lower boundary, core AF00-02), (11) *Emiliania huxleyi* (core AF00-02). (SALS) Clark's standard Arctic lithological subdivision; (MIS) marine isotope stage.

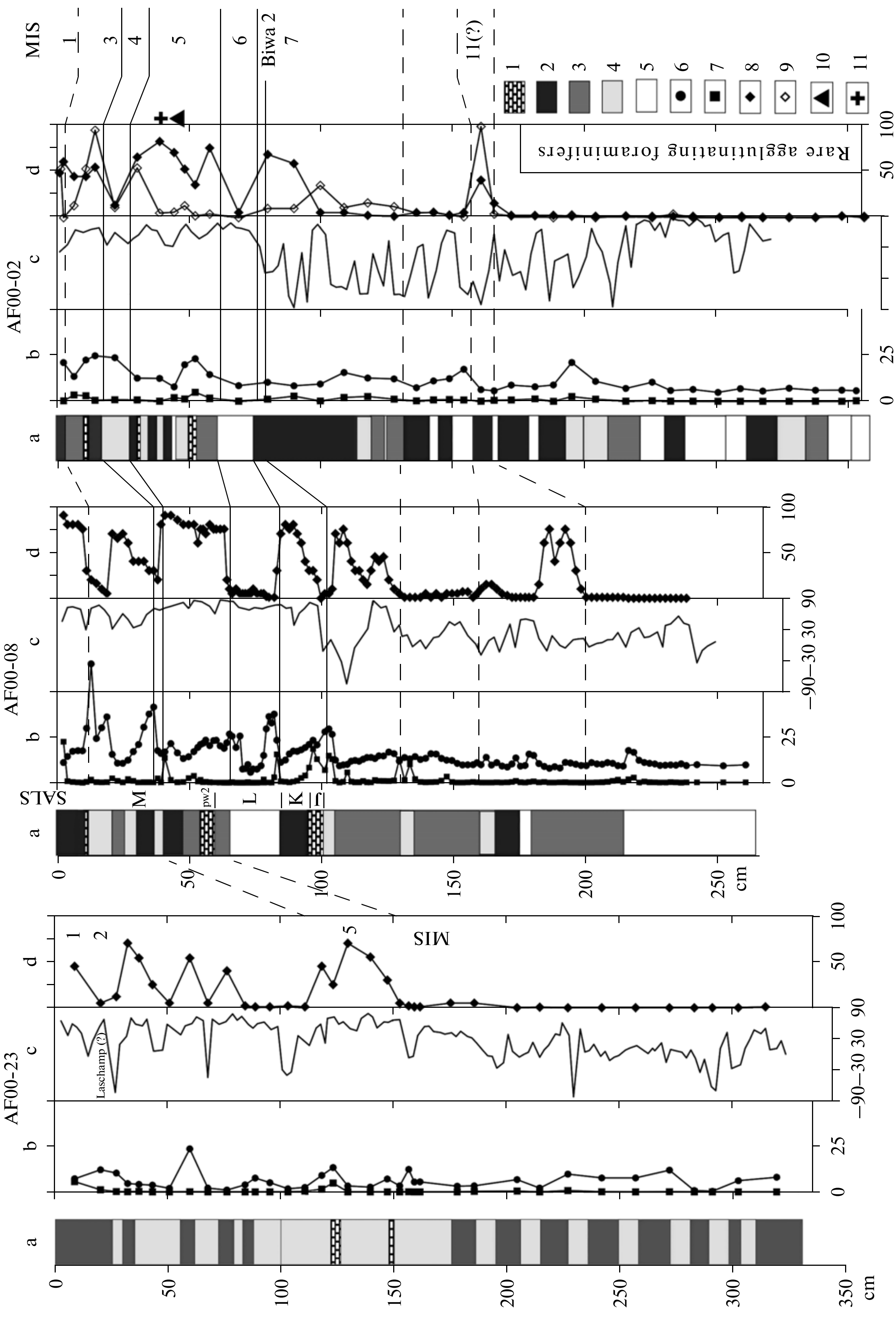
MIS
1
3
4
5
6
Biwa 2
7
11(?)
Rare agglutinating foraminifers
AF00-02
AF00-08
AF00-23
a
b
c
d
SALS
M
pw2
L
K
J
Laschamp (?)
0
50
100
150
200
250
300
350
cm
25
−90 −30 30 90
1
2
3
4
5
6
7
8
9
10
11

Table 2. Contents of clay minerals in the studied cores (%)

Smectite	Illite	Kaolinite	Chlorite	Station
4.7 2–11/1.64	60.7 52–65/3.12	13.3 10–20/2.22	21.3 18–24/1.36	AF00-02 $N = 39$
5.1 1–8/1.54	57.9 46–63/4.71	14.5 11–25/3.56	22.5 20–27/1.64	AF00-08 $N = 36$
4.4 2–10/1.83	61.6 49–68/4.07	11.8 7–21/2.31	22.2 20–26/1.26	AF00-23 $N = 36$
4.6 1–12/1.84	61.6 46–67/3.90	11.8 8–23/2.48	21.9 19–25 /1.24	AF00-28 $N = 50$
5.9 2–12/1.97	61.2 49–68/5.59	11.9 9–20/2.77	21.0 17–25/1.91	AF00-34 $N = 21$
4.2 2–12/2.99	62.1 53–66/3.27	10.9 8–14/1.27	22.9 20–25/1.43	AF00-37 $N = 23$

The numerator shows the average content; the denominator, variation range and standard deviation.

fractions in the sediments (Bjork et al., 2007). At the beginning of cold stages, activation of bottom currents could be related to intense ice formation and downslope discharge of the "heavy" saline waters (Lisitsyn, 2001). In the deep-water basins of the AO, such regularities in the vertical distribution of beds and sand fraction are distorted by gravity flows (turbidites). Therefore, sections in such basins are commonly unsuitable for paleogeographic/paleoclimatic reconstructions.

Stratigraphic subdivision of cores AF00-02, AF00-08, and AF00-23 shown in Fig. 2 is based on the results of paleomagnetic measurements, sediment color data (olive-green/brown beds), distribution of the sand and gravel fractions, and microfauna finds. We could more or less confidently date sediments from MIS 1–7 interval. In sediments of cores AF00-02 and AF00-08, MIS 11 was defined conditionally (Krylov et al., 2011). Reliable dating of beds in cores AF00-28, AF00-34, and AF00-37 is hampered by several reasons, among which the activity of turbidite flows is prominent. In addition, neither paleomagnetic nor microfaunal analyses were carried out for sediments in cores AF00-34 and AF00-37. Nevertheless, lithological features of sediments at the latter two stations suggest that sedimentation rate therein was considerably higher than that in the remaining northern cores.

DISTRIBUTION OF CLAY MINERALS IN SECTIONS OF BOTTOM SEDIMENTS

Table 2 presents average contents of the main groups of clay minerals in the studied cores. It is seen that these values are strikingly similar at all stations. The mineral groups demonstrate the following distribution pattern (in the decreasing order): illite (average content 60%), chlorite (21%), kaolinite (12%), and smectite (5%). In general, this distribution is consistent with the pattern reported in previous publications (Levitan et al., 1995). However, a slight decrease of kaolinite concentration is noted toward the Makarov Basin and shelf zone of the East Siberian Sea (Table 2, Fig. 1). Values of the standard deviation show that the distribution of minerals of the chlorite and illite groups demonstrates the minimal and maximal variability, respectively (Table 2).

Distribution of the sand and gravel fractions, as well as clay minerals, in core AF00-02 recovered from the Mendeleev Basin is shown in Fig. 3. It is seen that illite and kaolinite demonstrate negative correlation (Table 3). At the same time, the distribution of kaolinite and sand in the section is similar, as suggested by high coefficient of their correlation. Their contents decrease gradually downward the section. It is noteworthy that peak of the sand fraction at the interval of 196 cm coincides with a distinct smectite maximum (11%), and this level is also marked by an increase in kaolinite.

Distribution pattern of clay minerals in core AF00-08 located near the summit of the Mendeleev Ridge (Fig. 3) is similar to that at the previous station. One can see a significant correlation between sand, kaolinite, and illite. The sand–kaolinite pair shows a direct correlation; the sand–illite and kaolinite–illite pairs, a reverse correlation (Table 3). Moreover, in contrast to the remaining cores, the above core is marked by a significant correlation between the clay minerals and gravel fraction. Contents of both kaolinite and sand slightly decrease toward the section base. Chlorite and smectite demonstrate usually opposite distribution trends. At the top of the section, all clay minerals are marked by the presence of numerous minimums and maximums, resembling the sand fraction

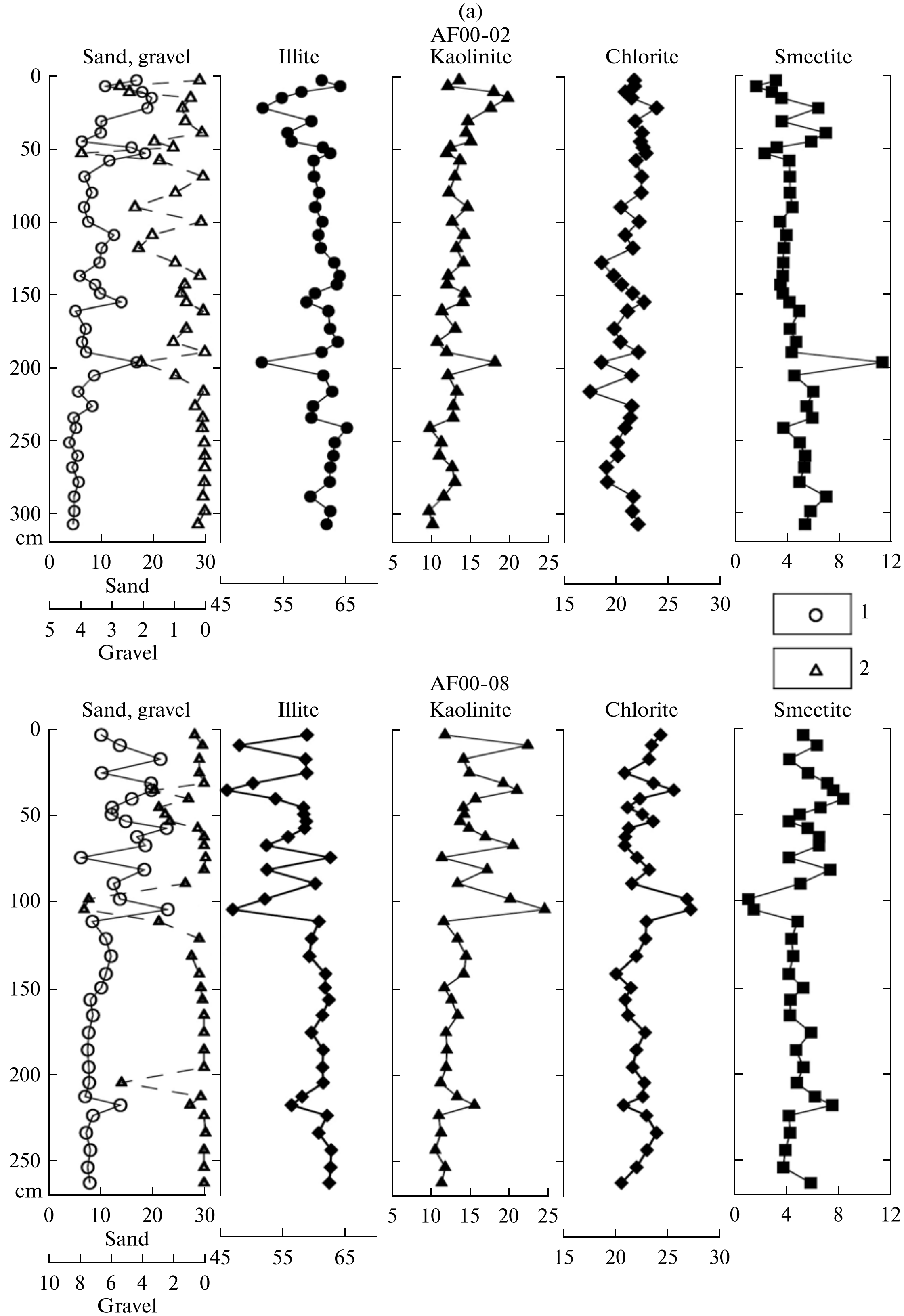

Fig. 3. Distribution of sand, gravel, and clay minerals (%) along the section at stations. (a) AF00-02, AF00-08; (b) AF00-23, AF00-27; (c) AF00-34, AF00-37. (1) Sand; (2) gravel.

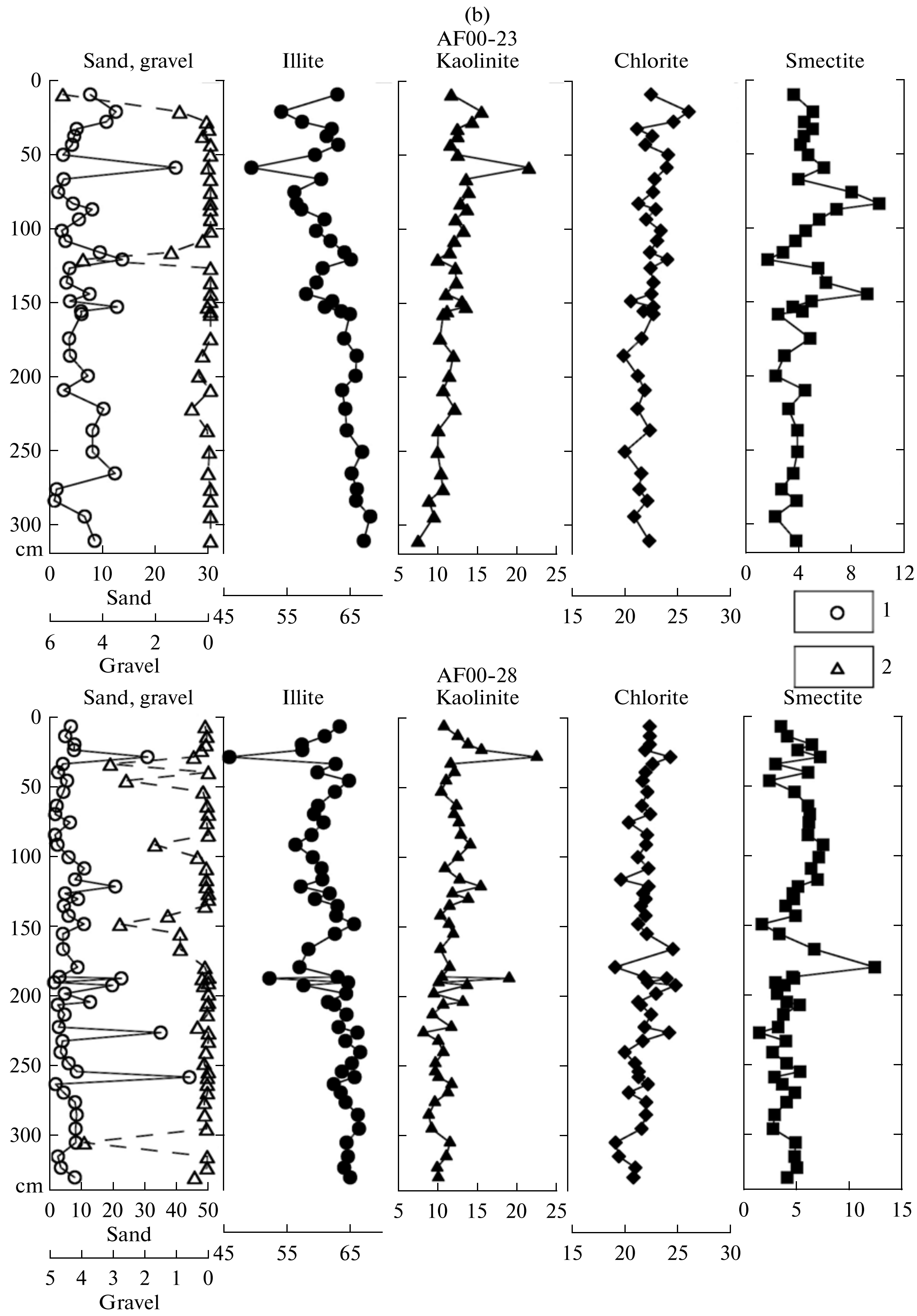
(b)
AF00-23
Sand, gravel
Illite
Kaolinite
Chlorite
Smectite
cm
Sand
Gravel
1
2
AF00-28
Sand, gravel
Illite
Kaolinite
Chlorite
Smectite
cm
Sand
Gravel

Fig. 3. Contd.

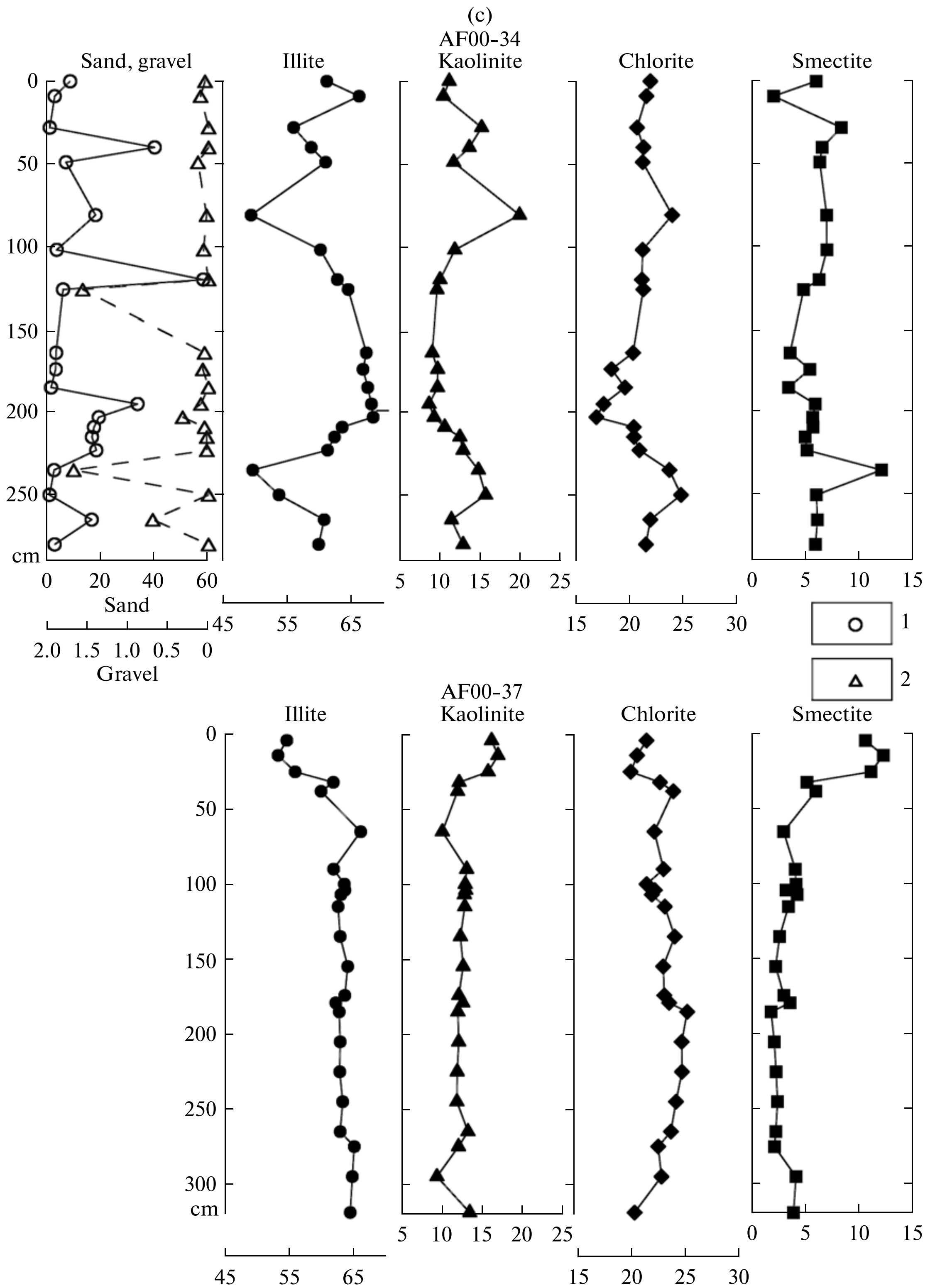

Fig. 3. Contd.

distribution. Distribution of both minerals and sand is more regular at the base.

Cores AF00-23 and AF00-28 are confined to the Makarov Basin. On the whole, distribution of sand, illite, and kaolinite retains the previous relationships, but they are statistically less distinct (Fig. 3, Table 3). Peaks with high contents of kaolinite coincide usually with those of the sand fraction, while illite demon-

Table 3. Coefficients of correlation (r, $t_{cr} = 0.05$) between clay minerals and different grain size fractions. Significant values are shown in bold

	1–10 mm	1–0.05 mm	0.05–0.005 mm	<0.005 mm	Illite	Kaolinite	Chlorite	Station
Smectite	–0.25	–0.15	0.20	0.02	**–0.54**	0.18	–0.25	AF00-02
Illite	–0.14	**–0.56**	0.15	**0.35**		**–0.81**	–0.31	$N = 39$
Kaolinite	0.30	**0.70**	**–0.33**	**–0.35**			0.01	
Chlorite	0.14	**0.33**	–0.05	–0.24				
Smectite	**–0.45**	0.20	–0.22	0.09	–0.26	0.09	**–0.39**	AF00-08
Illite	**–0.41**	**–0.75**	**0.34**	**0.54**		**–0.95**	**–0.57**	$N = 36$
Kaolinite	**0.44**	**0.76**	–0.27	**–0.59**			**0.47**	
Chlorite	**0.65**	0.31	–0.19	**–0.36**				
Smectite	–0.30	–0.10	0.02	0.07	**–0.69**	**0.36**	0.12	AF00-23
Illite	0.11	–0.33	0.08	0.08		**–0.87**	**–0.62**	$N = 36$
Kaolinite	–0.07	**0.46**	–0.11	–0.13			**0.46**	
Chlorite	0.23	**0.35**	–0.09	–0.12				
Smectite	–0.15	–0.13	0.18	–0.03	**–0.64**	**0.37**	–0.22	AF00-28
Illite	0.09	–0.24	–0.17	0.26		**–0.90**	**–0.40**	$N = 50$
Kaolinite	0.02	**0.30**	0.15	**–0.30**			**0.28**	
Chlorite	–0.11	**0.33**	–0.03	–0.18				
Smectite	**0.43**	0.04	–0.23	0.10	**–0.73**	**0.52**	**0.35**	AF00-34
Illite	–0.21	0.11	0.11	–0.14		**–0.93**	**–0.83**	$N = 21$
Kaolinite	–0.03	–0.12	0.08	0.04			**0.73**	
Chlorite	0.22	–0.19	–0.19	0.24				
Smectite	–	–	–	–	**–0.92**	**0.78**	**–0.68**	AF00-37
Illite	–	–	–	–		**–0.86**	**0.41**	$N = 23$
Kaolinite	–	–	–	–			**–0.57**	

(–) Measurement was not carried out.

strate opposite trends. One can see a regular decrease of kaolinite and increase of illite downward the section, and this trend is most prominent at station AF00-23. Distinct regularities in the distribution of chlorite and smectite are missing.

Cores AF00-34 and AF00-37 are located on the continental slope in the shelf zone of the East Siberian Sea. Since sedimentation rate is higher, a smaller stratigraphic interval is recorded here. In sediments from core AF00-34, the distribution of clay minerals along the section is extremely irregular. Here, illite and kaolinite continue to show opposite trends, but both minerals show a weak correlation with the sand fraction. Correlation between kaolinite and chlorite is direct and sufficiently significant. Distribution of clay minerals is more stable at station AF00-37. One can see a regular decrease of kaolinite and smectite, but the content of illite increases within the upper 40-cm interval. Sediments are represented here by probably Holocene brown aleuropelites. They are underlain by bluish gray aleuropelites with a sufficiently monotonous distribution of clay minerals. The content of chlorite decreases toward the section base.

RESULTS

Most scientists believe that the terrigenous material (clay minerals included) is transported to the AO mainly by currents, ices, and icebergs. Other researchers assume the predominance of local sources for bottom sediments on the Mendeleev Ridge (Kaban'kov et al., 2004, 2008). The coarse-grained material is often used as a marker of ice (iceberg) drift material. It is known that the icebergs can transport diverse (in dimension) particle ranging from pelites to boulders. In contrast, the present-day Arctic ice usually contains a fine-grained silty–clayey material (Nürnberg et al., 1994), although the anchor ice can entrap coarser particles (Darby et al., 2011; Lisitsyn, 1994; and others.). Recent studies revealed the following interesting fact: the size of terrigenous particulates frozen in ice commonly does not exceed 30–60 μm, whereas the anchor ice can often accommodate a coarser material if, of course, the latter was present on the seafloor (Darby et al., 2011). Fraction coarser than 0.25 mm (fine-grained sand) is a more or less reliable marker of iceberg rafting (Spielhagen et al., 2004; Darby et al., 2011; and others.). However, particles of this dimension are also transported by the anchor ice. Hence, application of only grain size distribution data can sometimes provoke incorrect conclusions. In this paper, sand and gravel are considered separately, because we assume that high contents of the sand fraction in sediments on the Mendeleev Ridge, which were not subjected to the impact of gravitites, also indicate the presence of icebergs. This is suggested, in particular, by the reverse correlation between sand and foraminifers, which is atypical of the anchor ice, and their significant positive correlation with the fraction coarser than 0.25 mm ($r = 0.61$ for core AF00-08).

Thus, the mechanism of material transport can be established with a certain degree of reliability by the correlation of contents of clay minerals and sand–psephite fractions. Most interesting is core AF00-08 confined to the Mendeleev Ridge, because this area lacks turbidite flows that distort the sedimentary record. Table 3 shows that the kaolinite group minerals at station AF00-08 have a significant correlation with not only sand and gravel (positive), but also pelite (negative) fractions. In contrast, the illite group minerals have a significant positive correlation with the pelite fraction and negative correlation with the sand. These data suggest the compositional similarity of gravel/sand and kaolinite, as well as illite and pelite, provenances. Significant correlation is also recorded for the kaolinite–sand and illite–sand pairs in sediments of core AF00-02. Such trends are also typical of sediments in the remaining cores, but they are statistically less expressed (Table 3).

The above-mentioned direct correlation between sand and kaolinite in sediments of the Amerasian Basin is known long ago. For example, according to (Dalrymple and Maass, 1987), sandy clays from the upper portion of the Alpha Ridge are marked by high concentrations of kaolinite because of its delivery by icebergs owing to the glacial erosion of Mesozoic rocks of islands in the Canadian Arctic archipelago. We completely support this interpretation. High correlation between the contents of coarse fractions and kaolinite definitely testify to the delivery of these minerals by icebergs splitting off from the Laurentian ice sheet during its degradation. The presence of kaolinite-bearing rocks and weathering crusts in this area was mentioned above. Other provenances are less probable. Since the Franz Josef Land is located far away, it could hardly serve as the source of kaolinite if we do not assume a considerable ice circulation in the past that needs a serious argumentation. The above-mentioned weathering crusts in the Russian segment of the eastern Arctic are not major suppliers of kaolinite into the AO, as suggested by the distribution of this mineral in recent sediments of the East Arctic shelf (Kosheleva and Yashin, 1999; Wahsner et al., 1999). The northern coast of Alaska, one of the sources of the kaolinite group minerals (Naidu and Mowatt, 1983), could hardly serve as an important provenance during deglaciations, because this area was not subjected to glaciations. Most probably, kaolinite transported from this area to the Amerasian Basin together with currents and ices created the background concentrations. The decrease of kaolinite in the lower half of the section is consistent with the coarse fractions. This pattern of sand distribution along the section is known well for sediments in the Lomonosov, Alpha, and Mendeleev ridges (Jakobsson et al., 2000; Krylov et al., 2011; Spielhagen et al., 2004). The phenomenon mentioned above is likely related to more stable conditions: for example, the AO could be covered with pack ices.

In connection with our assumptions about correlation between the sand fraction and kaolinite, as well as modes of their transport, we should mention the following alternative opinion: the glacial/iceberg drift plays a subordinate role, whereas local sources of sedimentary material are primary (Kaban'kov et al., 2004, 2008). The local nature of coarse-clastic material is quite probable for the Akademik Fedorov Rise area (Kaban'kov et al., 2004), but we do not think that this particular situation can be extrapolated over the entire ridge system in the AO, particularly the southern Mendeleev Ridge (Kaban'kov et al., 2008). The predominance of local sources of sedimentary material is refuted by the data on great thickness of sediments and by the virtually complete absence of acoustic basement exposures on the surface (except rare outcrops on steep slopes) over the entire length of seismic sections across the Alpha and Mendeleev ridges (Bruvoll et al., 2010, 2012). It is evident that the Cenozoic history of these ridges was dominated by accumulative rather than erosional processes.

However, we should mention the results of organogeochemical investigations of sediments from core AF00-08 that suggest the catagenetic maturity level of organic matter and the complete absence of humic organic matter (Petrova et al., 2010). At the same time, an appreciable portion of humic organic matter is recorded in bottom sediments from the deep-water zone of the AO in both depressions and rises (Schubert and Stein, 1997). Bottom sediments in core AF00-08 from Upper Paleozoic–Lower Mesozoic rocks of the Siberian Craton are closest in terms of organogeochemical parameters. The organic matter dispersion in these rocks reached the level of mesocatagenesis (Petrova et al., 2010). The lack of humic organic matter suggests at least that delivery of the Quaternary terrigenous material to the core AF00-08 area from Eurasia was negligible. This observation can be used as argument in favor of local primary sources of sedimentary material (Kaban'kov et al., 2004). However, these results do not rule out the possibility of discharge from the Canadian Arctic archipelago dominated by Paleozoic carbonates. In any case, this phenomenon needs further investigations.

According to an earlier work devoted to clay minerals in sediments of the Alpha Ridge (Dalrymple and Maass, 1987), high contents of smectite are often recorded in beds enriched in the sand fraction (as in the case of kaolinite), suggesting prevalence of the iceberg-mediated delivery of smectite. In our case, correlation between the sand fraction and smectite content is not statistically confirmed, although a significant correlation between kaolinite and smectite is observed for cores AF00-23, AF00-28, AF00-34, and AF00-37 (Table 3). Nevertheless, Fig. 3 shows that peaks of sand and smectite coincide in some cases. In the case of station AF00-08, this observation can likely indicate the iceberg-mediated input of this mineral during the formation of specified beds.

Minerals of the illite and chlorite groups prevail in the studied sections. Probably, their relatively intense input is typical of both glacial and interglacial intervals. In cores AF00-02 and AF00-08, illite has a significant positive correlation with the pelite fraction and negative correlation with the sand fraction (Table 3), suggesting the predominant delivery of this mineral by currents and ices. Obviously, illite and kaolinite in our cores behave as antagonistic components. In contrast, chlorite is often concentrated in sandy beds. This fact confirms a significant positive correlation of chlorite with sand in sediments of stations AF00-02, AF00-23, and AF00-28 (Table 3). Since the cores mentioned above were recovered from basins subjected to the influence of turbidites (this fact is particularly important for stations AF00-23 and AF00-28), we cannot affirm confidently that icebergs played an essential role in the delivery of chlorite.

CONCLUSIONS

Study of clay minerals in six cores recovered from different morphostructural zones of the Mendeleev Ridge revealed that they are mainly represented by the following species (in decreasing degree): illite (average content 60%), chlorite (21%), kaolinite (12%), and smectite (5%).

For studying specific features of Late Quaternary sedimentation, most interesting is core AF00-08 located at the Mendeleev Ridge summit, because this core was not subjected to the influence of turbidite flows. Correlation between the distribution of clay minerals and psephite–psammite fractions is the most informative parameter.

The majority of studied sections are characterized by a significant positive correlation between kaolinite and sand fraction. The maximum correlation is recorded in core AF00-08 ($r = 0.76$). Assuming the sand as an indicator of material transported by icebergs, we can conclude that kaolinite was mainly delivered from zones subjected to glaciation. Most probably, the provenances were likely represented by islands of the Canadian Arctic archipelago. Background concentrations of kaolinite were likely delivered from Alaska.

Illite is statistically assigned to beds enriched in the pelite fraction, testifying to its predominant delivery by ices and currents.

Minerals of the smectite and chlorite groups are less informative for the cores studied in the present work. However, coincidence of their peaks with high contents of the psammite–psephite fractions in core AF00-08 indicates that these minerals were transported by icebergs during the formation of specified beds.

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REFERENCES

Andreeva, I.A., Basov, V.A., Kupriyanova, N.V., and Shilov, V.V., Age and formation conditions of bottom sediments in the Mendeleev Rise area (Arctic Ocean), in *Tr. NIIGA-VNIIOkeangeologiya*, 2007, vol. 211, pp. 131–152.

Backman, J., Jakobsson, M., Lovlie, R., et al., Is the central Arctic Ocean a sediment starved basin?, *Quater. Sci. Rev.,* 2004, vol. 23, pp. 1435–1454.

Belov, N.A. and Lapina, N.N., *Donnye otlozheniya Arkticheskogo basseina* (Bottom Sediments of the Arctic Basin), Leningrad: Morsk. Transp., 1961.

Biscaye, P.E., Mineralogy and sedimentation of recent deep-sea clays in the Atlantic Ocean and adjacent seas and oceans, *Geol. Soc. Am. Spec. Bull.*, 1965, no. 76, pp. 803–832.

Bischof, J. and Darby, D., Mid- to Late Pleistocene ice drift in the western Arctic Ocean: Evidence for a different circulation in the past, *Science*, vol. 277, pp. 74–78.

Bjork, G., Jakobsson, M., Rudels, B., et al., Bathymetry and deep-water exchange across the central Lomonosov Ridge at 88–89° N, *Deep-Sea Res. I*, 2007, vol. 54, pp. 1197–1208.

Bruvoll, V., Kristoffersen, Y., Coakley, B.J., and Hopper, J., Hemipelagic deposits on the Mendeleev and Alpha submarine ridges in the Arctic Ocean: Acoustic stratigraphy, depositional environment and inter-ridge correlation calibrated by the ACEX results, *Mar. Geophys. Res.*, 2010, vol. 31, pp. 149–171.

Bruvoll, V., Kristoffersen, Y., Coakley, B.J., et al., The nature of the acoustic basement on Mendeleev and northwestern Alpha ridges, Arctic Ocean, *Tectonophysics*, 2012, vol. 514–517, pp. 123–145.

Clark, D.L., Whitman, R.R., Morgan, K.A., and Mackey, S.D., Stratigraphy and Glacial-Marine Sedimentation of the Amerasian Basin, Central Arctic Ocean, *GSA Spec. Pap.*, 1980.

Dalrymple, R.W. and Maass, O.C., Clay mineralogy of late Cenozoic sediments in the Cesar cores, Alpha ridge, central

Arctic Ocean, *Can. J. Earth Sci.*, 1987, vol. 24, pp. 1562–1569.

Darby, D.A., Kaolinite and other clay minerals in Arctic Ocean sediments, *J. Sediment. Petrol.*, 1975, vol. 45, pp. 272–279.

Darby, D.A., Polyak, L., and Bauch, H.A., Past glacial and interglacial conditions in the Arctic Ocean and marginal sea—A review, *Progr. Oceanogr.*, 2006, vol. 71, pp. 129–144.

Darby, D.A., Myers, W.B., Jakobsson, M., and Rigor, I., Modern dirty ice characteristics and sources: The role of anchor ice, *J. Geophys. Res.*, 2011, vol. 116, p. C09008.

Gorbunova, Z.N., Highly dispersed minerals in sediments of the Kara Sea, *Oceanology*, 1997, vol. 37, no. 5, pp. 763–769.

Grantz, A., May, S.D., Taylor, P.T., and Lawyer, L.A., *Canada Basin*, in *The Geology of North America: The Arctic Ocean Region*, Grantz, A., Johnson, G.L., and Sweeney, J.F., Eds., Colorado: *Geol. Soc. Am.*, 1990, pp. 379–402.

Gusev, E.A., Maksimov, F.E., Novikhina, E.S., et al., Issue of the stratigraphy of bottom sediments on the Mendeleev Rise (Arctic Ocean), *Vestn. St. Petersb. Univ.,* Ser. 7: Geol. Geogr., 2012, issue 4, pp. 102–115.

Ivanov, G.I., Wahsner, M., Ponomarenko, T.V., et al., Distribution of clay minerals in surface bottom sediments in the St. Anna Trough, *Rep. Polar Res.,* 1999, no. 342, pp. 172–182.

Jakobsson, M., Lovlie, R., Al-Hanbali, H., et al., Manganese and color cycles in Arctic Ocean sediment constrain Pleistocene chronology, *Geology*, 2000, vol. 28, pp. 23–26.

Jokat, W., Seismic investigations along the western sector of Alpha ridge, central Arctic Ocean, *Geophys. J. Int.*, 2003, vol. 152, pp. 185–201.

Kaban'kov, V.Ya., Andreeva, I.A., Ivanov, V.N., and Petrova, V.I., Geotectonic nature of the central Arctic morphostructure system and geological significance of bottom sediments for its identification, *Geotectonics*, 2004, no. 6, pp. 31–42.

Kaban'kov, V.Ya., Andreeva, I.A., Krupskaya, V.V., et al., New data on the composition and origin of bottom sediments in the southern Mendeleev Rise (Arctic Ocean), *Dokl. Earth Sci.*, 2008, vol. 419, pp. 641–643.

Kalinenko, V.V., Clay minerals in sediments of the Arctic seas, *Lithol. Miner. Resour.*, 2001, no. 4, pp. 413–424.

Kim, B.I. and Slobodin, V.Ya., Main stages of the evolution of East Arctic shelves of Russia and Canadian Arctic in the Paleogene and Neogene, in *Geologiya skladchatogo obramleniya Ameraziiskogo subbasseina* (Geology of the Folded Framing of the Amerasian Subbasin), St. Petersburg: Sevmorgeologiya, 1991, pp. 104–116.

Kosheleva, V.A. and Yashin, D.S., *Donnye osadki Arkticheskikh morei Rossii* (Bottom Sediments in the Arctic Seas of Russia), St. Petersburg: VNIIOkeangeologiya, 1999.

Krupskaya, V.V., Krylov, A.A., and Sokolov, V.N., Clay minerals as indicators of sedimentation conditions at the Cretaceous–Paleogene–Eocene boundaries on the Lomonosov Ridge (Arctic Ocean), *Probl. Arkt. Antarkt.*, 2011, no. 2, pp. 23–35.

Krylov, A.A., Andreeva, I.A., Vogt, C., et al., A shift in heavy and clay mineral provenance indicates a middle Miocene onset of a perennial sea ice cover in the Arctic Ocean, *Paleoceanography*, 2008, vol. 23.

Krylov, A.A., Waiel, D., Sapega, V.F., et al., Clay minerals as indicator of depositional environment of upper Quaternary sediments in the St. Anna Trough (Kara Sea), *Oceanology*, 2008, vol. 48, pp. 85–94.

Krylov, A.A., Shilov, V.V., Andreeva, I.A., and Miroly-ubova, E.S., Stratigraphy and depositional environment of upper Quaternary sediments on the northern Mendeleev Rise (Amerasian Basin of the Arctic Ocean), *Probl. Arkt. Antarkt.*, 2011, no. 2, pp. 7–22.

Lapina, N.N., *Metodika izucheniya veshchestvennogo sostava donnykh otlozhenii (na primere Severnogo Ledovitogo okeana)* (Method for Studying the Lithology of Bottom Sediments: Evidence from the Arctic ocean), Leningrad: NIIGA, 1977.

Levitan, M.A., Wahsner, M., Nürnberg, D., and Shelekhova, E.S., Average composition of clay mineral assemblages in the surface layer of bottom sediments in the Arctic Ocean, *Dokl. Akad. Nauk*, 1995, vol. 344, no. 3, pp. 364–366.

Lisitsyn, A.P., *Ledovaya sedimentatsiya v Mirovom okeane* (Glacial Sedimentation in the World Ocean), Moscow: Nauka, 1994.

Lisitsyn, A.P., Unresolved problems in the Arctic oceanology, in *Opyt sistemnykh okeanologicheskikh issledovanii v Arktike* (Experience of Oceanographic System Studies in the Arctic), Lisitsyn, A.P. et al., Eds., Moscow: Nauchn. Mir, 2001, pp. 31–75.

Logvinenko, N.V., *Petrografiya osadochnykh porod* (Petrography of Sedimentary Rocks), Moscow: Vyssh. Shkola, 1984.

Moran, K., Backman, J., Brinkhuis, H., et al., The Cenozoic palaeoenvironment of the Arctic Ocean, *Nature*, 2006, vol. 441, pp. 601–606.

Naidu, A.S. and Mowatt, T.C., Sources and dispersal pattern of clay minerals in surface sediments from the continental-shelf areas off Alaska, *Geol. Soc. Am. Bull.*, 1983, vol. 94, pp. 841–854.

Naidu, A.S., Creager, J.S., and Mowatt, T.C., Clay mineral dispersal patterns in the North Bering and Chukchi seas, *Mar. Geol.*, 1982, vol. 47, pp. 1–15.

Norgaard-Pedersen, N., Spielhagen, R.F., Thiede, J., and Kassens, H., Central Arctic surface ocean environment during the past 80000 years, *Paleoceanography*, 1998, vol. 13, pp. 193–204.

Nürnberg, D., Wollenburg, I., Dethleff, D., et al., Sediments in Arctic Sea ice: implications for entrainment, transport and release, *Mar. Geol.*, 1994, vol. 119, pp. 185–214.

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

Ortiz, J.D., Polyak, L., Grebmeier, J.M., et al., Provenance of Holocene sediment on the Chukchi-Alaskan margin based on combined diffuse spectral reflectance and quantitative X-ray diffraction analysis, *Global Planet. Change*, 2009, vol. 68, pp. 73–84.

Petrova, V.I., Batova, G.I., Kursheva, A.V., and Litvinenko, I.V., Geochemistry of organic matter in bottom sediments on the central rises of the Arctic Ocean, *Geol. Geofiz.*, 2010, vol. 51, pp. 113–125.

Petschik, R., Kuhn, G., and Gingele, F., Clay mineral distribution in surface sediments of the South Atlantic: Sources, transport, and relation to oceanography, *Mar. Geol.*, 1996, vol. 130, pp. 203–229.

Phillips, R.L. and Grantz, A., Regional variations in provenance and abundance of ice-rafted clasts in Arctic Ocean sediments: Implications for the configuration of late Quaternary oceanic and atmospheric circulation in the Arctic, *Mar. Geol.*, 2001, vol. 172, pp. 91–115.

Polyak, L., Curry, W.B., Darby, D.A., et al., Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge, *Palaeogeogr.*, *Palaeoclimat., Palaeoecol.*, 2004, vol. 203, pp. 73–93.

Polyak, L., Bischof, J., Ortiz, J.D., et al., Late Quaternary stratigraphy and sedimentation patterns in the western Arctic Ocean, *Global Planet. Change*, 2009, vol. 68, pp. 5–17.

Schoster, F., Behrends, M., Muller, C., et al., Modern river discharge and pathways of supplied material in the Eurasian Arctic Ocean: Evidence from mineral assemblages and major and minor element distribution, *Int. J. Earth Sci.,* 2000, vol. 89, pp. 486–495.

Schubert, C. and Stein, R., Lipid distribution in surface sediments from the eastern central Arctic Ocean, *Mar. Geology*, 1997, vol. 138, pp. 11–25.

Shelekhova, E.S., Nürnberg, D., Vasner, M., et al., Distribution of clay minerals in the surface layer of sediments in the southwestern Kara Sea, *Okeanologiya*, 1995, vol. 35, pp. 435–439.

Slobodin, V.Ya., Kim, B.I., Stepanova, G.V., and Kovalenko, F.Ya., Differentiation of the Aion borehole section based on the biostratigraphic data, *Stratigrafiya i paleontologiya mezo-kainozoya Sovetskoi Arktiki* (Stratigraphy and Paleontology of the Meso-Cenozoic in the Soviet Arctic), Leningrad: Sevmorgeologiya, 1990, pp. 43–58.

Spielhagen, R.-F., Baumann, K.H., Erlenkeuser, H., et al., Arctic ocean deep-sea record of northern eurasian ice sheet history, *Quat. Sci. Rev.*, 2004, vol. 23, pp. 1455–1483.

Stein, R., *Arctic Ocean sediments. Processes, proxies, and paleoenvironment*, Amsterdam: Elsevier, 2008.

Stein, R., Grobe, H., and Wahsner, M., Organic carbon, carbonate, and clay mineral distributions in eastern central Arctic Ocean surface sediments, *Mar. Geol.,* 1994, vol. 119, pp. 269–285.

Viscosi-Shirley, C., Mammone, K., Pisias, N., and Dymond, J., Clay mineralogy and multi-element chemistry of surface sediments on the Siberian-Arctic shelf: Implications for sediment provenance and grain size sorting, *Cont. Shelf Res.*, 2003, vol. 23, pp. 1175–1200.

Vogt, C., Regional and temporal variations of mineral assemblages in Arctic Ocean sediments as climatic indicator during glacial/interglacial changes, *Rep. Polar Res.*, 1997, no. 251, p. 309.

Vogt, C. and Knies, J., Sediment dynamics in the Eurasian Arctic Ocean during the last deglaciation: The clay mineral group smectite perspective, *Mar. Geol.*, 2008, vol. 250, pp. 211–222.

Vogt, C. and Knies, J., Sediment pathways in the western Barents Sea inferred from clay mineral assemblages in surface sediments, *Norw. J. Geol.*, 2009, vol. 89, pp. 41–55.

Wahsner, M., Ivanov, G., and Tarasov, G., Marine geological investigation of surface sediments in the Franz-Josef Land area and the St. Anna Trough, *Rep. Polar Res.*, 1996, no. 212, pp. 172–184.

Wahsner, M., Muller, C., Stein, R., et al., Clay-mineral distribution in surface sediments of the Eurasian Arctic Ocean and continental margin as indicator for source areas and transport pathways—a synthesis, *Boreas*, 1999, vol. 28, no. 1, pp. 215–233.

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