doi: 10.13679/j.advps.2014.3.00192
September 2014 Vol. 25 No. 3: 192-203

Mineralogical study of surface sediments in the western Arctic Ocean and their implications for material sources

DONG Linsen, SHI Xuefa*, LIU Yanguang, FANG Xisheng, CHEN Zhihua, WANG Chunjuan, ZOU Jianjun & HUANG Yuanhui

The First Institute of Oceanography, SOA, Qingdao 266061, China

Received 13 May 2014; accepted 10 August 2014

Abstract Mineralogical analysis was performed on bulk sediments of 79 surface samples using X-ray diffraction. The analytical results, combined with data on ocean currents and the regional geological background, were used to investigate the mineral sources. Mineral assemblages in sediments and their distribution in the study area indicate that the material sources are complex. (1) Feldspar is abundant in the sediments of the middle Chukchi Sea near the Bering Strait, originating from sediments in the Anadyr River carried by the Anadyr Current. Sediments deposited on the western side of the Chukchi Sea are rich in feldspar. Compared with other areas, sediments in this region are rich in hornblende transported from volcanic and sedimentary rocks in Siberia by the Anadyr Stream and the Siberian Coastal Current. Sediments in the eastern Chukchi Sea are rich in quartz sourced from sediments of the Yukon and Kuskokwim rivers carried by the Alaska Coastal Current. Sediments in the northern Chukchi Sea are rich in quartz and carbonates from the Mackenzie River sediments. (2) Sediments of the southern and central Canada Basin contain little calcite and dolomite, mainly due to the small impact of the Beaufort Gyre carrying carbonates from the Canadian Arctic Islands. Compared with other areas, the mica content in the region is high, implying that the Laptev Sea is the main sediment source for the southern and central Canada Basin. In the other deep sea areas, calcite and dolomite levels are high caused by the input of large amounts of sediment carried by the Beaufort Gyre from the Canadian Arctic Islands (Banks and Victoria). The Siberian Laptev Sea also provides small amounts of sediment for this region. Furthermore, the Atlantic mid-water contributes some fine-grained material to the entire deep western Arctic Ocean.

Keywords **X-ray diffraction, western Arctic Ocean, minerals, surface sediments, sources**

Citation: Dong L S, Shi X F, Liu Y G, et al. Mineralogical study of surface sediments in the western Arctic Ocean and their implications for material sources. Adv Polar Sci, 2014, 25: 192-203, doi: 10.13679/j.advps.2014.3.00192

1 Introduction

The Arctic Ocean has played an important role in the environmental evolution of the Late Cenozoic and in present-day climate change[1]. The large area covered by sea ice has a high albedo that influences the global energy balance, and the Arctic water exchange with the Atlantic and the Pacific controls the oceanic global thermohaline circulation[2]. The sedimentary environment of the western Arctic Ocean is more complex, which is not only affected by the role of water bodies, but also by ice rafted deposition. In particular, the water exchange between the Arctic and the Pacific waters, and ice rafted deposition originating from the Canadian Arctic Archipelago seas and the Eurasian continental shelf ice (icebergs) in this region is very different compared with other areas.

Some proxies, e.g., mineralogy[3-9], element geochemistry[6,10] and stable isotopes[11-12], have been used to study the sources of Cenozoic sediments in the Arctic Ocean, to trace the river discharge, and the transport of sea ice and icebergs. However, previous mineralogical studies have focused on heavy minerals[3], ice-rafted detritus[4-5] and clay minerals[6-9].

Sediments in the Arctic Ocean (especially for deep water regions) are fine-grained, and there is little coarse detrital mineral material. Mineralogical analysis performed on

* Corresponding author (email: shixuefa@163.com)

bulk sediments using the X-ray diffraction (XRD) method is therefore particularly important and will provide significant insight on the transfer path, source, deposition process of sediments, and the reconstruction of the evolution of past oceanography[13].

Recent bulk mineralogy studies in the Arctic Ocean have mainly focused on the Eurasian Basin[13-15]. For example, Vogt et al.[14] suggested that the sediments in the Yermak Plateau are composed of quartz, feldspar, calcite, dolomite, and pyroxene. Combined with clay minerals and organic geochemistry, they further discussed the evolution of the Svalbard ice sheet. März et al.[15] proposed that sediments in the central Arctic Ocean contained quartz, phyllosilicates, plagioclase, K-feldspar, zeolite, amphibole, cordierite, and pyrite, and analyzed the sedimentary mechanisms of the Early–Late Quaternary.

Until now, no study has focused on the bulk mineralogy of surface sediments in the western Arctic Ocean. Here we present results of XRD analysis of the western Arctic Ocean surface sediments, to identify their mineral composition, carry out semi-quantitative calculations, and finally discuss the sediment transport mechanisms and sources.

2 Overview

2.1 Geological background

The western Arctic Ocean is surrounded by Alaska, Siberia, and the Canadian Arctic Archipelago.

The Alaska Peninsula is characterized by a variety of Jurassic to Cretaceous sandstones and shales, later intruded by granites, Tertiary to Recent acidic volcanic-plutonics, andesites and basalts[16-17].

The Siberian hinterland consists of distinct geologic terrains. From west to east, the region includes the Siberian platform, the Verkhoyansk Mountains, Kolyma-Omolon superterrain, Okhotsk-Chukotsk volcanic belt, and the Chukotka terrain[6]. The Precambrian Siberian platform consists of one of the largest flood basalts (Putoran) in the world[18]. The Verkhoyansk Mountains, located on the eastern Siberian platform, and its orogeny resulted in the deformation of the Devonian sediments grading eastward from shelf clastic sequences to deep-water shale deposits. The Kolyma-Omolon superterrain is mainly an amalgamation of continental fragments and island arc material bracketed by remnants of fore and back arc basins[6]. The western Okhotsk-Chukotsk volcanic belt contains acidic to intermediate rocks, whereas the eastern side mainly contains intermediate to basic rocks. The Chukotka terrain consists primarily of sedimentary rock[6,19].

The outcrops of the Canadian Arctic Archipelago are mainly composed of carbonate and clastic rocks[20].

2.2 Sediment input

Sediments from these landmasses are introduced to the continental shelf by coastal erosion, river discharge, and sea ice (icebergs) transport. Rivers draining to the western Arctic Ocean include the Mackenzie, Ob, Yenisei, Khatanga, Lena, Yana, Kolyma, and Indigirka rivers (Figure 1). In addition, the Yukon, Kuskokwim and Anadyr rivers draining to the Bering Sea can transport sediment to the Chukchi Sea by ocean currents[7]. The river discharge, sediment load and main lithological composition of the rivers basins are listed in Table 1. Coastal erosion is also an important source of Arctic Ocean sediments[21]. Sea ice (icebergs) in the central Arctic Ocean can transport marine sediments most likely originating from surrounding shallow shelf regions[22].

2.3 Ocean Currents

Ocean currents are an important factor influencing sedimentation in the Arctic Ocean. Pacific water flows northward via the Bering Strait into the Arctic Ocean. After moving through the Bering Strait, the Pacific water divides into three branches: Alaska Coastal Water, Bering Shelf Water and Anadyr Water (Figure 1). The Alaska Coastal Water flows eastward to north of Alaska. The Anadyr Water flows westward into the East Siberian Sea. The Bering Shelf Water flows northward along 170°W[35]. The Siberian Coastal Current generally flows eastward from the Laptev to the East Siberian and finally into the Chukchi Sea[6] (Figure 1).

There are two major surface current systems in the Arctic Ocean; the Transpolar Drift (TPD) and the Beaufort Gyre (BG). These two surface currents control the movement of sea ice and icebergs in the Arctic Ocean. Sea-ice drift regimes are strongly affected by the Arctic Oscillation (AO) during the Holocene. During a negative AO, a strong high-pressure system dominates the Beaufort Sea, which promotes a robust anti-cyclonic Beaufort Gyre and restricts the TPD to the Siberian side of the Arctic Ocean[36]. In contrast, during a positive AO, low atmospheric pressure dominates the Arctic and the TPD moves closer to North America[36].

In addition, intermediate currents can also transport sediment to the Arctic, especially fine-grained silts and clays[37]. Atlantic water enters the Arctic Ocean via two branches: the Fram Strait and the Barents Sea. There, the Barents Sea branch reaches the southern Canada Basin and the Northwind Ridge beyond the Chukchi Cap[38] (Figure 1).

3 Materials and methods

A total of 79 sediment samples were recovered from the western Arctic Ocean during the second, third and fourth Chinese National Arctic Research Expeditions (CHINARE) in the summers of 2003, 2008 and 2010, respectively. The samples include 44 stations in the Chukchi Sea, four stations on the Chukchi Plateau, two stations on the Northwind Ridge, five stations on the Alpha Ridge, 22 stations in the Canada Basin, and two stations in the Makarov Basin (Figure 1).

Each sample was dried and pulverized, and then passed through a 200 mesh sieve. Samples were X-rayed from 3 to 65 degrees (2θ) with Cu K-alpha radiation (40 kV, 100 mA)

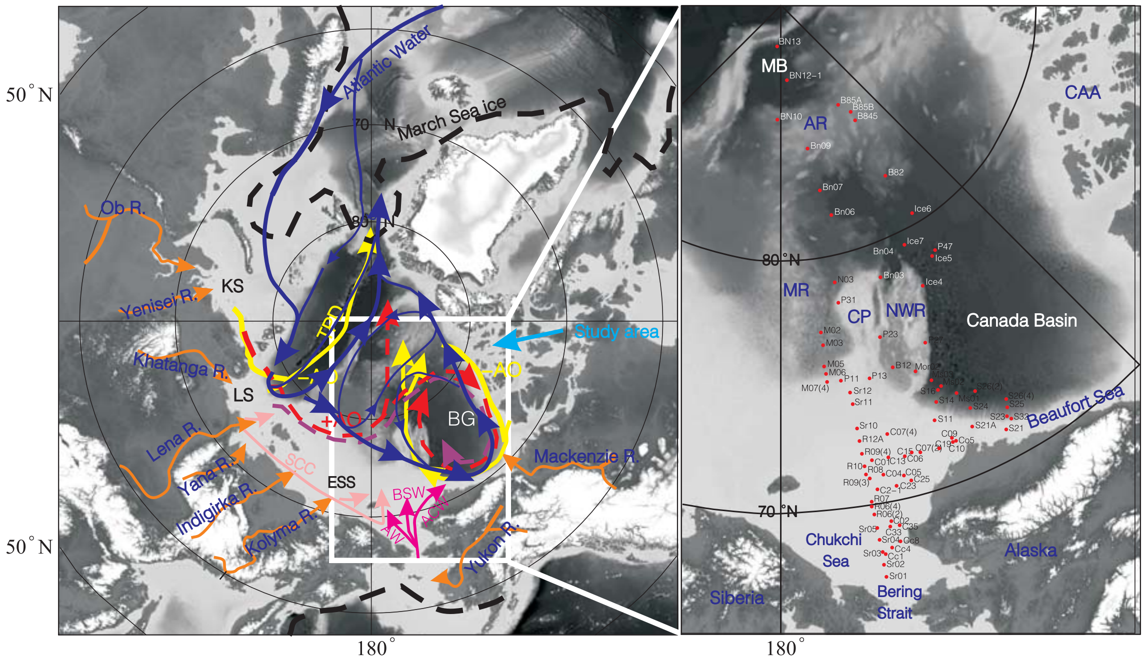


Figure 1 Location of the study area, rivers, currents[6,36,38-39], sea ice extent[40] of the north polar region, and surface sampling stations. KS—Kara Sea; LS— Laptev Sea; ESS— East Siberian Sea; MB— Makarov Basin; MR—Mendeleev Ridge; AR—Alpha Ridge; CP—Chukchi Plateau; NWR—Northwind Ridge; SCC—Siberian Coastal Current; ACW—Alaska Coastal Water; BSW— Bering Shelf Water; AW—Anadyr Water; TPD—Transpolar Drift; BG—Beaufort Gyre; +AO—Positive Arctic Oscillation; −AO—Negative Arctic Oscillation. The TPD and the BG depict endmember extremes for a strong −AO phase (solid yellow drift arrows) and a strong +AO (dashed red arrows for Kara Sea ice and dashed maroon arrows for Laptev Sea ice).

Table 1 River discharge, sediment load, and main rock types of the drainage basins

Rivers	River discharge/ ($km^3 \cdot a^{-1}$)	Sediment load/ (10^6 t $\cdot a^{-1}$)	Main rock types of drainage basins
Ob	427[23]	16.5[24]	Granites, Sandstones, limestones[25]
Yenisei	636[23]	5.9[24]	Mainly flood basalts[26]
Khatanga	101[27]	1.4[27]	Mainly flood basalts[28]
Lena	525[27]	21[27]	sedimentary rocks, Metamorphic rocks (Paleozoic−Mesozoic sedimentary rocks), balasts [3]
Yana	31[27]	3[27]	Sandstones, shales [29]
Indigirka	57[30]	13.7[21]	Sandstones, shales [29]
Kolyma	120[30]	16.1[21]	Sandstones, shales [29]
Mackenzie	298[23]	127[31]	Carbonate rocks, shales, siltstones[32]
Yukon	210[33]	54[33]	Paleozoic−Mesozoic metasedimentary, metavolcanic rocks, including carbonates, geosynclinal elastic sediments, and granites[16]
Kuskokwim	60[33]	8.2[33]	
Anadyr	68[33]	3.6 [33]	Cretaceous−Tertiary volcanic, and granitic and granodioritic rocks[34]

using a D/max2500 Diffractometer (XRD), 1-degree slits, a step size of 0.02 degrees (2θ), and 2 degrees per minute. The test instrument was corrected[41] before the experiment and all samples were tested under the same conditions. Peak areas were estimated from XRD traces using Jade6.0 software and semi-quantitative estimates of bulk mineral percentages were calculated following Cook et al.[42]. The windows (2θ), range of spacings (A), and intensity factors of minerals based on Cook et al.[42] are listed in Table 2.

4 Results

4.1 Mineral content of the bulk sediment

The XRD data were converted into weight percent minerals. In the western Arctic Ocean, the major minerals (content >5%) are quartz, K-feldspar, plagioclase, and mica. Some typical minerals used for tracing sources were also identified, including amphibole, pyroxene, calcite, dolomite, kaolinite,

Table 2 Minerals actively analyzed in diffraction data analysis

Mineral	Window (2*θ*, CuKα radiation)	Range of D-Spacing (*A*)	Intensity Factor[a]
Amphibole	10.30−10.70	8.59−8.27	2.5
Analcite	15.60−16.20	5.68−5.47	1.79
Anatase	25.17−25.47	3.54−3.50	0.73
Anhydrite	25.30−25.70	3.52−3.46	0.9
Apatite	31.80−32.15	2.81−2.78	3.1
Aragonite	45.65−46.00	1.96−1.97	9.3
Augite	29.70−30.00	3.00−2.98	5
Barite	28.65−29.00	3.11−3.08	3.1
Calcite	29.25−29.60	3.04−3.01	1.65
Chlorite	18.50−19.10	4.79−4.64	4.95
Clinoptilolite	9.70−9.99	9.11−8.84	1.56
Cristobalite	21.50−22.05	4.13−4.05	9
Dolomite	30.80−31.15	2.90−2.87	1.53
Erionite	7.50− 7.90	11.70−11.20	3.1
Goethite	36.45−37.05	2.46−2.43	7
Gypsum	11.30−11.80	7.83−7.50	0.4
Halite	45.30−45.65	2.00−1.99	2
Hematite	33.00−33.40	2.71−2.68	3.33
Kaolinite	12.20−12.60	7.25−7.02	2.25
K-Feldspar	27.35−27.79	3.26−3.21	4.3
Magnetite	35.30-35.70	2.54−2.51	2.1
Mica	8.70−9.10	10.20−9.72	6
Montmorillonite	4.70−5.20	18.80−17.00	3
Palygorskite	8.20−8.50	10.70−10.40	9.2
Phillipsite	17.50−18.00	5.06−4.93	17
Plagioclase	27.80−28.15	3.21−3.16	2.8
Pyrite	56.20−56.45	1.63−1.62	2.3
Rhodochrocite	31.26−31.50	2.86−2.84	3.45
Quartz	26.45−26.95	3.37−3.31	1
Sepiolite	7.00−7.40	12.60−11.90	2
Siderite	31.90−32.40	2.80−2.76	1.15
Talc	9.20−9.55	9.61−9.25	2.56
Tridymite	20.50−20.75	4.33−4.28	3
Gibbsite	18.00−18.50	4.93−4.79	0.95

Notes: [a]The intensity factors are determined in 1:1 mixtures with quartz by obtaining the ratio of the diagnostic peak intensity of each mineral with the intensity of the diagnostic peak of quartz, which is assigned a value of 1.00. The detection limit in weight percent of the minerals in a siliceous or calcareous matrix can be obtained by multiplying the intensity factor by 0.12.

and chlorite. In addition, goethite, phillipsite, aragonite, halite, anatase, pyrite, siderite, and anhydrite were identified from the XRD spectra (Figure 2). All data were converted into weight percent. Table 3 lists the percentages of the major and typical minerals.

4.2 Distribution of minerals

The mineral distribution styles, based on the ArcGIS inverse distance weighting interpolation method, are shown in Figure 3. Quartz is generally the most abundant mineral in the sediments. The quartz content surrounding Alaska in the Chukchi Sea is high, up to 45%, and the quartz in the Alpha Ridge and the northernmost Canada Basin is also relatively high. As a whole, the quartz content of the Chukchi Sea is higher than that of the Arctic Ocean deep sea (including the Alpha Ridge, Northwind Ridge, Canada Basin, and Chukchi Plateau). Feldspar is also fairly common with K-feldspar concentrations of up to 13.04% in the study area. The K-feldspar content near the Siberian shelf is higher than that on the Alaskan shelf. The K-feldspar concentrations in the Canada Basin are the lowest. The distribution of the plagioclase concentrations, 2.82%–20.49%, is similar to K-feldspar. The mica concentrations in the Canada and Makarov basins are high, up to 22.99%. Those in Chukchi Sea, the Northwind Ridge, Chukchi Plateau, and Alpha Ridge are relatively low. Amphibole concentrations in the Chukchi Sea range from 0 to 1.51%, and in the deep Arctic Ocean from 0 to 1.25%. The high values for amphiboles are mainly concentrated in the Chukchi Sea near the East Siberian Sea. Pyroxene concentrations in the southern tip of the Canada Basin, Northwind Ridge, Chukchi Plateau, Alpha Ridge, and Makarov Basin are very high (maximum of 4.1%), and those in the other areas are low. Calcite and dolomite concentrations are very high in the Canada Basin, up to 11.1% and 13.04%, respectively, and those in the Chukchi Sea are very low. Kaolinite concentrations range from 0.47% to 4.81%, and have no significant variations in the study area. Chlorite concentrations in the Chukchi Sea vary from 0 to 4.67%, whereas those in the other areas are very low.

The feldspar to quartz ratio (F/Qz) of the bulk fraction is applied as a proxy of sediment chemical weathering intensity, and it has been used to investigate sediment sources and climate change[43]. The distribution of F/Qz is shown on Figure 4. Fk/Qz, Fp/Qz and (Fk + Fp)/Qz showed the same trend, with greater ratios in the area close to the East Siberian Sea than those in the areas surrounding Alaska, indicating a relatively low weathering intensity.

4.3 Cluster Analysis

To investigate the regional coherence of the mineral compositions of the study area, we performed a cluster analysis (Figure 5) using the Squared Euclidean distance metric and identified six mineral assemblages types, except at R08 and Bn03, which were two abnormal stations.

The average mineral composition of each mineral assemblage is shown in Table 4. Mineral assemblage I is further divided into I_a, I_b, and I_c. Type I_a is located at the two ends of the Chukchi Sea. Quartz concentrations in the Chukchi Sea surrounding Alaska are very high (I_{a1}), and low near the Siberian Sea (I_{a2}). Compared with other mineral

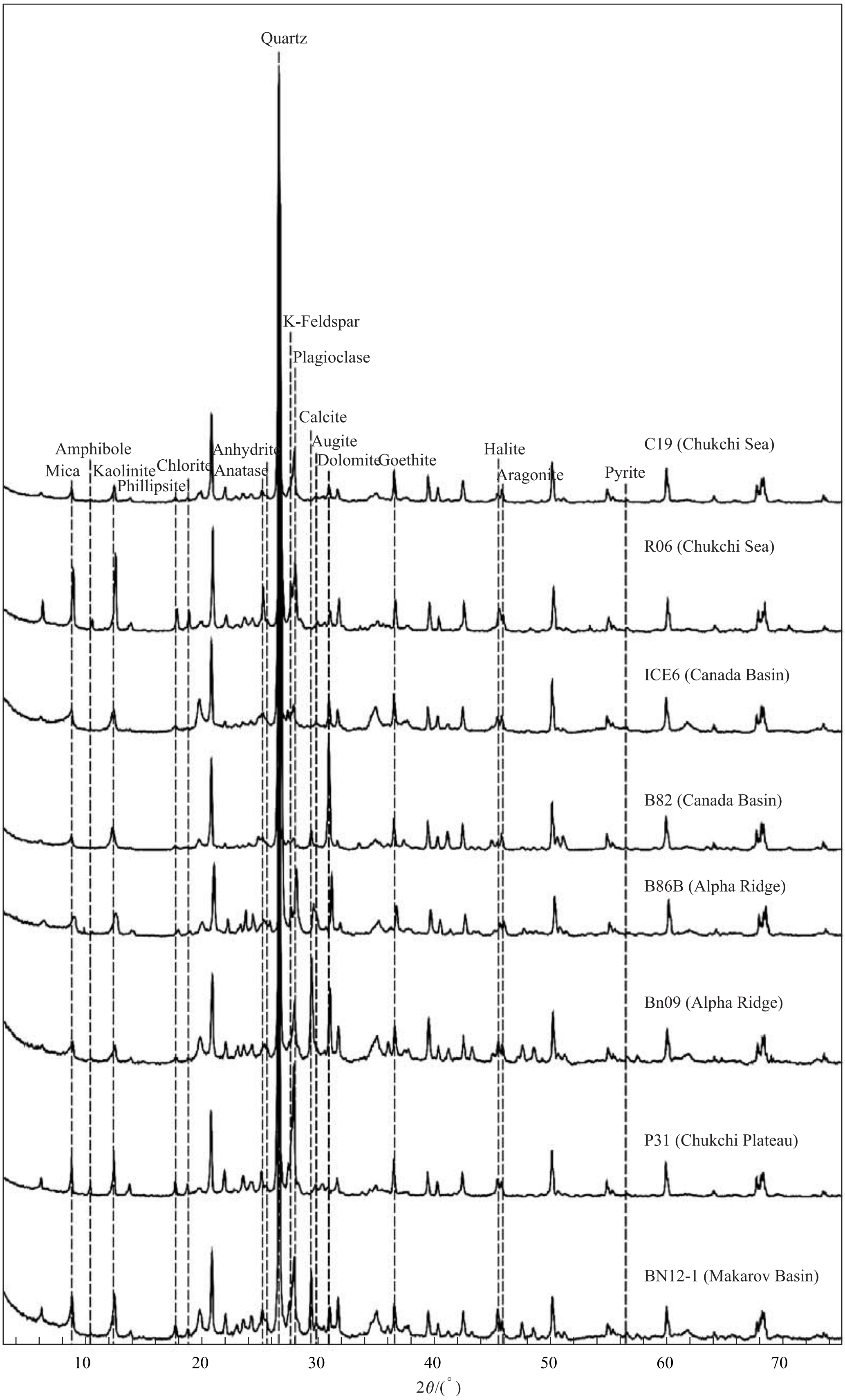
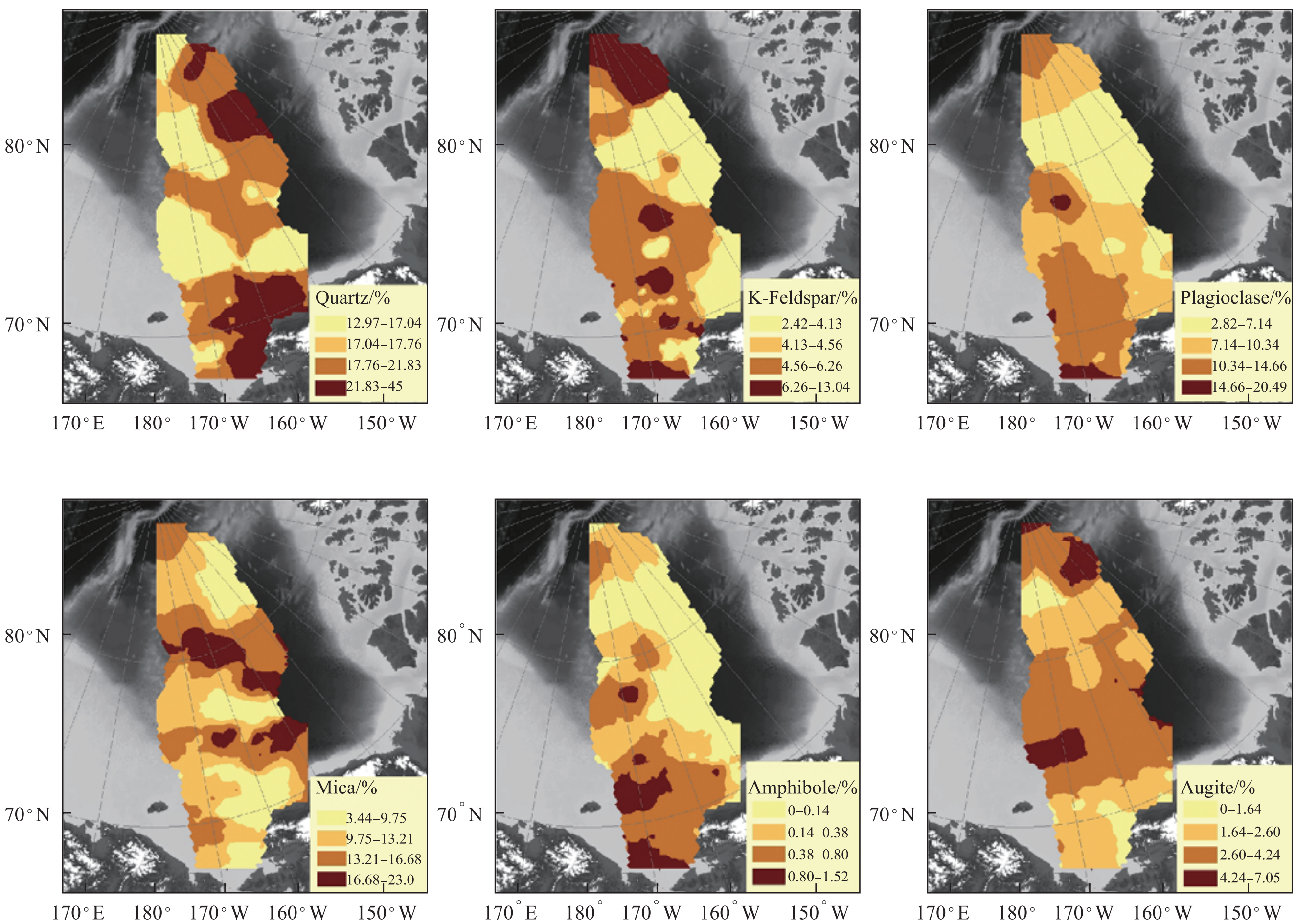


Figure 2 Multiple X-ray diffraction diagrams of typical samples in the western Arctic Ocean.

Table 3 Composition of primary and representative minerals of sediments in the western Arctic Ocean

Mineral area	Quartz/%		K-Feldspar/%		Plagioclase/%		Mica/%		Amphibole/%	
	Min-max	Mean	Min-max	Mean	Min-max	Mean	Min-max	Mean	Min-max	Mean
Chukchi Sea	12.97−45	21.50	2.5−13.04	5.21	5.14−20.49	11.60	3.44−18.05	10.86	0−1.51	0.64
Chukchi Plateau	18.22−21.25	19.27	4.43−8.15	6.05	6.66−18.71	11.41	5.93−13.43	9.67	0−1.25	0.31
Northwind Ridge	16.76−19.78	18.27	3.55−6.04	4.8	6.08−9.47	7.78	5.62−18.58	12.1	0−0	0
Canada Basin	13.59−24.83	16.93	2.42−7.16	4.29	2.82−10.99	6.68	8.09−22.99	15.43	0−0.71	0.2
Alpha Ridge	17.16−24.33	19.83	4.25−10.73	7.21	7.14−10.53	9.58	6.7−11.85	10.05	0−0.52	0.22
Makarov Basin	14.21−15.32	14.76	6.74−6.97	6.85	11.70−11.98	11.84	13.79−16.78	15.28	0−0.42	0.21

Mineral area	Augite/%		Calcite/%		Dolomite/%		Kaolinite/%		Chlorite/%	
	Min-max	Mean	Min-max	Mean	Min-max	Mean	Min-max	Mean	Min-max	Mean
Chukchi Sea	0−5.43	2.55	0−2.75	0.27	0.19−12.89	1.70	0.48−7.81	5.03	0−4.67	2.43
Chukchi Plateau	1.32−4.41	2.96	0−11.1	3.98	0.43−11.27	3.89	3.05−5.08	4.26	0.63−3.46	1.98
Northwind Ridge	3.76−4.31	4.04	0−9.6	4.8	0.83−6.24	3.53	3.91−5.53	4.72	1.14−1.45	1.30
Canada Basin	1.72−4.72	3.06	0−7.29	1.79	0.26−13.04	3.31	4.06−7.28	5.72	0.58−4.58	2.18
Alpha Ridge	0−7.05	3.03	0.76−8.69	4.76	1.02−5.35	4.01	3.33−5.77	4.39	1.3−1.68	1.48
Makarov Basin	3.13−5.1	4.11	3.5−4.33	3.91	1.53−1.83	1.68	3.97−5.75	4.86	1.7−1.89	1.8



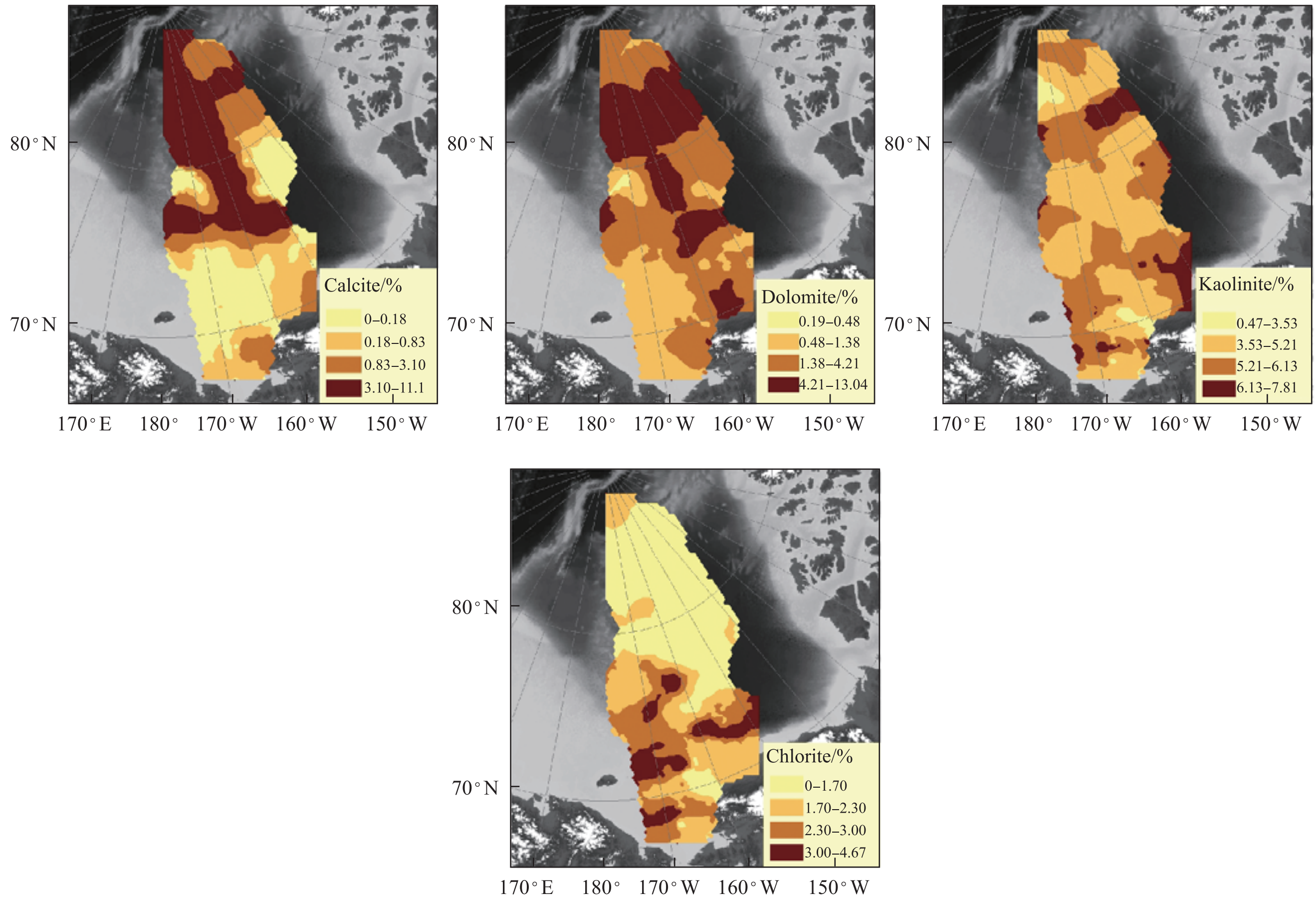


Figure 3 Distribution of primary and representative minerals of sediments in the western Arctic Ocean.

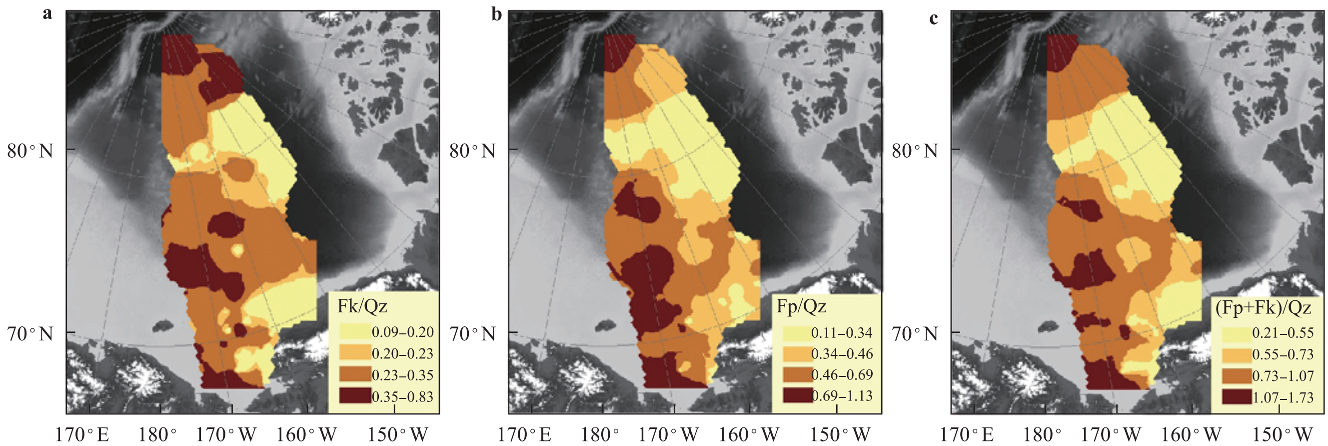


Figure 4 Variation of the ratios of Fk/Q (**a**), Fp/Q (**b**), and Fk+Fp/Q (**c**) of sediments in the western Arctic Ocean.

assemblages, the plagioclase content is relatively high, which is very similar to the type I_c mineral assemblage. The type I_c mineral assemblage is also found in the western Chukchi Sea. The I_b mineral assemblage, distributed in southern (I_{b1}) and central (I_{b2}) Canada Basin, is characterized by high mica, and low quartz and plagioclase concentrations. The carbonate content in the southern basin is slightly higher than that in the central basin. The type II mineral assemblage is characterized by high concentrations of calcite and dolomite, with average concentrations of 6.08% and 5.66%, respectively. The concentrations of quartz and dolomite are very high in the type III mineral assemblage located in northern Alaska, with a mean of 25.85% and 6.8%, respectively. Type IV contains more plagioclase and K-feldspar, with mean concentrations of 9.81% and 18.39%, respectively, located mainly in the area near the Bering Strait. The calcite and dolomite content in the type V mineral assemblage is relatively high, with an average content of 5.18% and 3.72%, respectively, which is

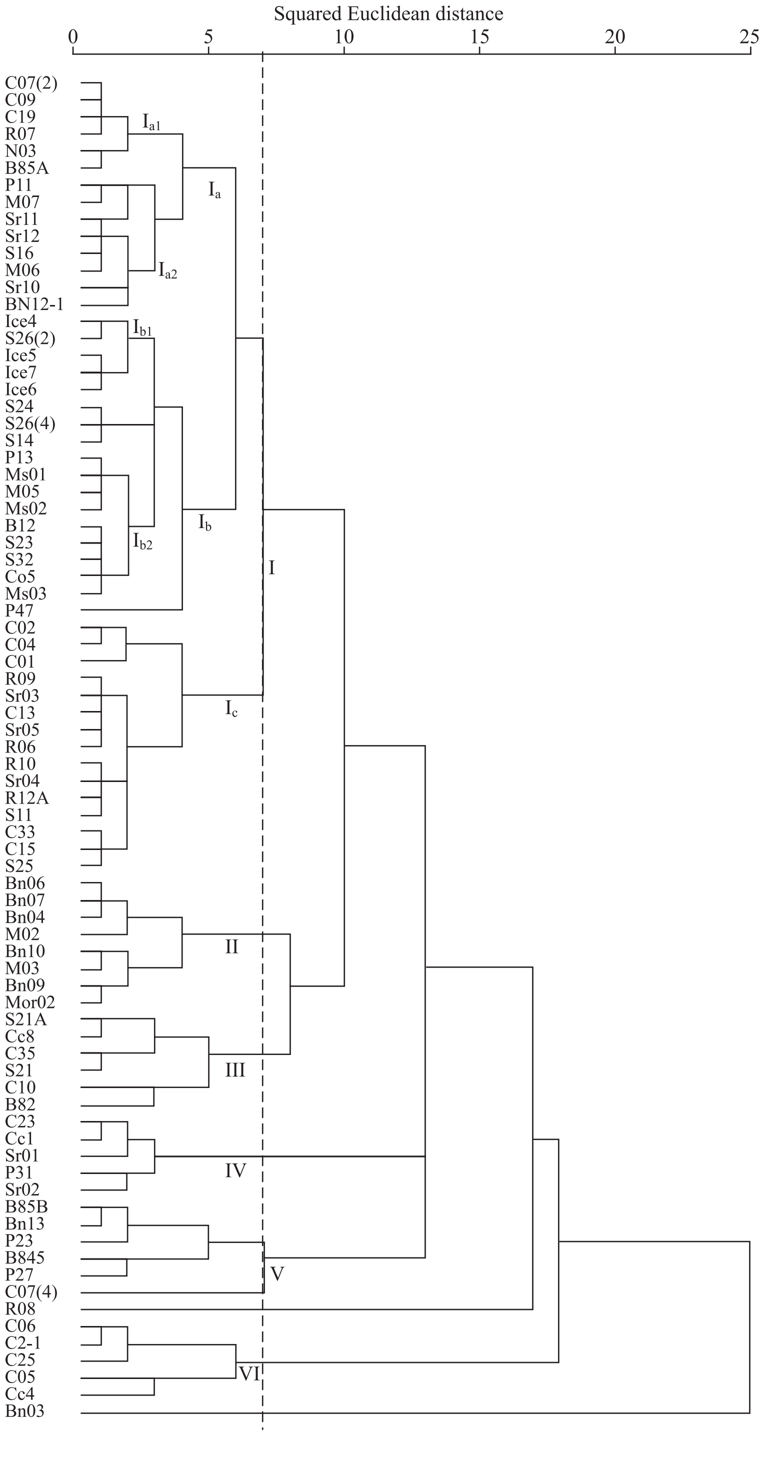


Figure 5 Q-cluster analysis of the bulk mineral assemblages in the study area.

slightly lower than type II. The type IV mineral assemblage is characterized by high concentrations of quartz, with a mean of 36.74%, located near Herald Shoal. The mineral assemblage distributions are shown in Figure 6.

5 Discussion

Because there are some differences in the hydrology and potential material sources of sediments between the Chukchi Sea shelf and the deep sea region of the western Arctic Ocean, the study area is divided into two parts for the convenience of discussion.

5.1 Chukchi Sea

Chukchi Sea, located on the western Arctic shelf where

Table 4 The mineral composition of different assemblage types

Type		Quartz /%	K-Feldspar /%	Plagioclase /%	Mica /%	Amphibole /%	Augite /%	Calcite /%	Dolomite /%	Kaolinite /%	Chlorite /%
I	I_{a1}	**23.62**	4.98	**11.36**	10.13	**0.41**	2.73	0	1.14	3.81	1.64
	I_{a2}	15.41	5.89	**11.53**	12.26	**0.47**	4.4	0	0.41	4.89	2.93
	I_{b1}	16.61	3.76	7.51	**16.47**	0.18	3.18	1.00	2.1	6.5	2.25
	I_{b2}	18.19	4.05	4.93	**16.81**	0	3.46	0.05	1.77	4.06	1.52
	I_{c}	18.48	4.55	**12.70**	12.69	**0.81**	2.59	0.046	1.2	6.18	3.03
II		16.39	4.60	7.37	13.31	0.35	2.26	**6.08**	**5.66**	4.91	1.65
III		**25.86**	2.95	7.15	9.44	0.39	1.36	1.47	**6.8**	5.47	1.93
IV		18.48	**9.81**	**18.39**	10.1	1.05	2.12	0.21	0.88	4.70	2.4
V		19.1	8.35	9.53	8.7	0.175	4.7	**5.18**	**3.72**	4.36	2.03
VI		**36.74**	4.65	8.99	3.95	0.45	1.36	0	0.594	1.83	0.99

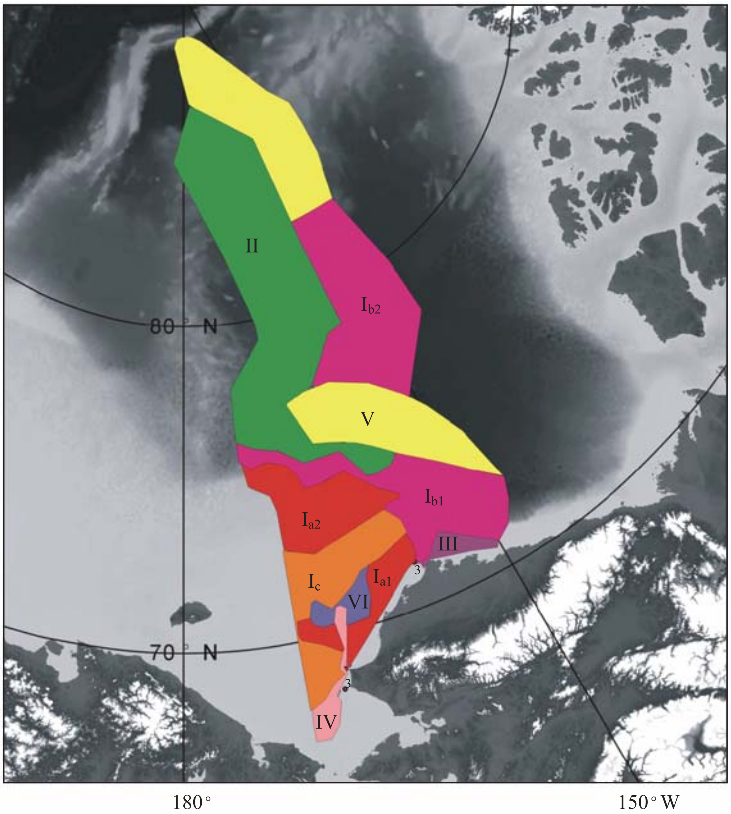


Figure 6 Distribution of the surface sediment mineral assemblages in the study area.

many rivers discharge, is characterized by a complex system of currents, and the sediments in the sea must have another material source. The sea receives a considerable volume of sediment originating from rivers, coastal erosion, ocean currents, and melting sea ice. The Arctic rivers transport large amounts of material towards the ocean. The flow of Pacific water into the Arctic Ocean includes Alaska Coastal Water, Bering Shelf Water and Anadyr Water, and these three branches transport material from the Bering Sea to the Chukchi Sea. Rivers draining into the Bering Sea mainly include the Yukon and Kuskokwim rivers of Alaska, and the Anadyr River of the Chukotka Peninsula.

The Yukon and Kuskokwim rivers drain sediments into the eastern Bering Sea, and the sediments are then transported to the Chukchi Sea shelf by the Alaska coastal currents flowing through the Bering Strait. Ortiz et al.[44] proposed that sediments in the Barrow Canyon area of the Chukchi-Alaskan margin were mainly from the Yukon River and some other small rivers of Alaska.

The main rock types in the drainage basins of the Yukon and Kuskokwim rivers are shale, sandstone, and granite[16] with high quartz concentrations. Combined with the ocean currents and mineral assemblages in the study area, we propose that the I_{a1}-type mineral assemblages originate from the Yukon and Kuskokwim river discharge, and are then transported to the Chukchi Sea shelf by the Alaska coastal currents. VI-type minerals should also be affected by the sediments of these two rivers. Eberl et al.[45] analyzed the mineral composition of the Yukon rivermouth sediments by semi-quantitative XRD analysis. The plagioclase content varied by 22%, the K-feldspar was approximately 13%, and the silica content was up to 50%. The content of calcite and dolomite was less than 1%, and the composition of the Yukon rivermouth sediments was most similar to the I_{a1}-type sediments in the Chukchi Sea in our study. The feldspar content in our results was relatively low, which may be due to instability during transport.

Type IV sediments with high plagioclase and K-feldspar content were located near the Bering Strait in the Chukchi Sea, and the main rock types in the Anadyr River drainage basin were volcanic, granite, and granodiorite rocks[34], with high plagioclase and K-feldspar content. Therefore, we propose that the IV sediments are from the Anadyr River discharged to the western Bering Sea and transported northward through the Bering Strait into the Chukchi Sea. I_{a2} and I_c type sediments also contain significant amounts of plagioclase and K-feldspar that originated from the Anadyr River, and the Laptev and East Siberian seas, and was then transported to the Chukchi Sea shelf by the Siberian coastal current flowing through the Long Strait.

The Siberian hinterland consists of acidic to basic and sedimentary rocks, and the region can supply either light minerals, such as K-feldspar, plagioclase and quartz, or some heavy and clay minerals. The surface sediments in the western Laptev and Kara seas have a high smectite and pyroxene content[46]. The pyroxene-rich assemblages are closely related to the Yenisei and Khatanga river sources[47], originally from the Permian flood basalts of the Siberian Trap[3].

The sediment of the eastern Laptev and the East Siberian seas are characterized by high amphibole content[46], which was mainly transported by the Lena and Yana rivers. Moreover, the sea-ice from the Byrranga Mountains contains large amounts of mica transported into the Laptev Sea[3] and these minerals, released from melting sea-ice, can be transported by the Siberian coastal current from the Laptev Sea to the East Siberian Sea, and then finally into the Chukchi Sea[48]. Chlorite is derived from physical weathering of metasedimentary and igneous rocks, which are widespread in Siberia[49]. As a result, the Chukchi Sea near the Siberian mainland contains large amounts of chlorite[49-50]. III-type mineral assemblages contain large amounts of dolomite, which may be affected by the Mackenzie River discharge, because the drainage basin of the river contains a lot of carbonate rocks[31].

5.2 Deep sea in the western Arctic Ocean

The mineral assemblages in the deep sea region of the western Arctic Ocean include types I_b, II and V. In the Arctic Ocean, in particular, in the deep sea region with lower deposition rates, sediments are mainly transported by sea ice and icebergs. Darby et al.[51] suggested that all the coarse fraction and almost all of the fine fraction in the central Arctic Ocean are from ice-rafted deposition. Type II and V sediments in the clockwise Beaufort Gyre are characterized by large amounts of calcite and dolomite, most likely originating from the Canadian Arctic Archipelago. This hypothesis has been confirmed by several other studies. For example, Polyak et al.[52] identified the sediment composition and potential sources of the fine-grained ice-rafted component in cores from the Mendeleev Ridge. They proposed that the detrital carbonates in the ice-rafted sediments derived from the Banks and Victoria islands and may originate from the Canadian Arctic Islands. In addition, Phillips et al.[5] suggested that the erratics (up to 70%) are dolostones and limestones in the southern Amerasia Basin and hypothesized that they originated from the carbonate-rich Paleozoic terrains of the Canadian Arctic Islands.

The type I_{b1} sediments are located in moderate water depth, such as the Chukchi Plateau and the Northwind Ridge. These areas were affected either by the Beaufort Gyre and the Transpolar Drift, or the Atlantic waters. Type I_{b2} sediments are located in the central Canada Basin. These two types contain little calcite and dolomite, indicating that the influence from the Beaufort Gyre on these regions is relatively small. Moreover, compared with other mineral assemblages, they contain a relatively higher quantity of mica, which may be derived from the Byrranga Mountains and finally transported into the Laptev Sea[5]. Therefore, we suggest that type I_{b1} and I_{b2} sediments were most likely transported from the Laptev Sea during the positive Arctic Oscillation. The major source of quartz in the western Arctic Ocean is the Laptev Sea[53]; however, considerable amounts of quartz may also originate from sections of the Canadian Archipelago (the central Queen Elizabeth Island), upstream of the Beaufort Gyre[53]. In addition, some clay material may be carried by Atlantic waters from the Eurasian Shelf [8,37].

6 Conclusions

Data on the mineral composition of the surface sediments provide important information on the depositional environment, oceanic circulation patterns, and sources in the western Arctic Ocean and can be summarized as follows:

(1) The major minerals (content >5%) of the surface sediments in the western Arctic Ocean are quartz, plagioclase, K-feldspar, and mica. Other typical minerals include calcite, dolomite, pyroxene, hornblende, kaolinite, and chlorite, which can be used to trace sediment sources.

In addition, the XRD spectra of bulk sediments identified goethite, phillipsite, aragonite, halite, anatase, pyrite, siderite, and anhydrite. Six mineral assemblages were found. Among them, the class I mineral assemblage was further divided into I_{a1}, I_{a2}, I_{b1}, I_{b2}, and I_c. The quartz content of types I_{a1} and VI is high; I_{a2} and I_c are characterized by high plagioclase and hornblende content; I_b is rich in mica and poor in quartz and plagioclase; types II and V contain large amounts of calcite and dolomite; type III is characterized by high dolomite content only; and type IV contains high concentrations of plagioclase and K-feldspar.

(2) The mineral assemblages of the Chukchi Sea are I_{a1}, I_{a2}, I_c, III, IV, and VI. Type IV is located near the Bering Strait in the Chukchi Sea and originates from the Anadyr River discharge into the western Bering Sea and is then transported northward through the Bering Strait into the Chukchi Sea. Types I_{a2} and I_c are located in the western Chukchi Sea and are also affected by the Anadyr River, and the Laptev and East Siberian seas. The original sediments were transported to the Chukchi Sea shelf by the Siberian coastal current flowing through the Long Strait. Type I_{a1} and VI are distributed in the eastern Chukchi Sea, and the sediments were derived from the Yukon and Kuskokwim rivers in Alaska, and then transported by the Alaskan coastal currents flowing through the Bering Strait. Type III is distributed in northern Alaska and the Mackenzie River is the main source.

(3) The mineral assemblages in the deep sea region of the western Arctic area include I_{b1}, I_{b2}, II, and V. Types II and V are characterized by high calcite and dolomite content, and are mainly affected by the Beaufort Gyre. The main sources for the region are the Banks and Victoria islands, and the region may also be influenced by the Laptev Sea sediments. Type I_{b1} is distributed in the northern Chukchi Sea and the southern Canada Basin, and contains low concentrations of carbonate minerals, indicating that type I_{b1} is little affected by the Beaufort Gyre. Type I_{b2} has a low calcite and dolomite content, indicating that I_{b2} is almost unaffected by the Beaufort Gyre. The main source of types I_{b1} and I_{b2} is the sea ice from the Laptev Sea sediments. In addition, some of the fine-sized material may be transported by the Atlantic water.

Acknowledgments The samples used in this study were collected by the second, third and fourth Chinese Arctic Research Expedition and were provided by the Polar Sediment Repository of Polar Research Institute of China(PRIC). Special thanks are extended to Dr Quanshu Yan for the help in grammar of this paper. This work was jointly supported by the National Natural Science Foundation of China (Grant nos. 41306205 and 40176136), the Polar Science Strategic Research Foundation of China (Grant no. 20120306), and the Chinese Polar Environment Comprehensive Investigation & Assessment Programmes (Grant no. CHINARE 2014-03-02).

References

1 Aagard K, Darby D, Falkner K, et al. Marine science in the Arctic: a strategy. Fairbanks, AK: The Arctic Research Consortium of the United States (ARCUS), 1999.

2 Smith L M, Miller G H, Otto-Bliesner B, et al. Sensitivity of the Northern Hemisphere climate system to extreme changes in Holocene Arctic sea ice. Quat Sci Rev, 2002, 22(5-7): 645-658.

3 Peregovich B, Hoops E, Rachold V. Sediment transport to the Laptev Sea (Siberian Arctic) during the Holocene-evidence from the heavy mineral composition of fluvial and marine sediments. Boreas, 1999, 28(1): 205-214.

4 Darby D A, Bischof J F. A statistical approach to source determination of lithic and Fe oxide grains: an example from the Alpha Ridge, Arctic Ocean. J Sedim Res, 1996, 66(3): 599-607.

5 Phillips R L, 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, 172(1-2): 91-115.

6 Viscosi-Shirley C, Mammone K, Pisias N, et al. Clay mineralogy and multi-element chemistry of surface sediments on the Siberian-Arctic shelf: implications for sediment provenance and grain size sorting. Contin Shelf Res, 2003, 23(11-13): 1175-1200.

7 Chen Z H, Shi X F, Han Y B, et al. Clay mineral distributions in surface sediments from the western Artic Ocean and their implications for sediment environment s. Adv Mar Sci, 2004, 22(4): 446-454.

8 Zhang D Y, Gao A G, Zhang D J. Clay minerals in surface sediments from the Chukchi Sea and Canadian Basin . Adv Mar Sci, 2008, 26(2): 171–183.

9 Yurco L N, Ortiz J D, Polyak L, et al. Clay mineral cycles identified by diffuse spectral reflectance in Quaternary sediments from the Northwind Ridge: implications for glacial–interglacial sedimentation patterns in the Arctic Ocean. Polar Res, 2010, 29(2): 176–197.

10 Chen Z H, Gao A G, Liu Y G, et al. REE geochemistry of surface sediments in the Chukchi Sea. Sci China (Series D), 2003, 46(6): 603–611.

11 Chen Z H, Li C X, Meng X W, et al. Samarium—neodymium isotopic characteristics of the clay—size fraction in surface sediments from the western Arctic Ocean and their implications for sediment sources and transport pattern. Acta Oceanol Sin, 2011, 33(2): 96-102.

12 Asahara Y, Takeuchi F, Nagashima K, et al. Provenance of terrigenous detritus of the surface sediments in the Bering and Chukchi Seas as derived from Sr and Nd isotopes: implications for recent climate change in the Arctic regions. Deep-Sea Res II, 2012, 61-64: 155-171.

13 Vogt C. Bulk mineralogy in surface sediments from the eastern central Arctic Ocean//Stein R, Ivanov G, L Evitan M, et al. Surface-sediment composition and sedimentary processes in the Central Arctic Ocean and along the Eurasian Continental Margin. Reports on Polar Research, 1996, 212: 159-171.

14 Vogt C, Knies J, Spielhagen R F, et al. Detailed mineralogical evidence for two nearly identical glacial/deglacial cycles and Atlantic water advection to the Arctic Ocean during the last 90, 000 years. Glob Plan Change, 2001, 31(1–4): 23–44.

15 März C, Vogt C, Schnetger B, et al. Variable Eocene-Miocene sedimentation processes and bottom water redox conditions in the Central Arctic Ocean (IODP Expedition 302). Earth Plan Sci Lett, 2011, 310(3-4): 526-537.

16 Beikman H M. Geologic Map of Alaska. Scale 1: 2 500 000. US Geological Survey, Arlington. 1980.

17 Naidu A S, Han M W, Mowatt T C, et al. Clay minerals as indicators of sources of terrigenous sediments, their transportation and deposition: Bering Basin, Russian-Alaskan Arctic. Mar Geol, 1995, 127(1-4): 87-104.

18 Sharma M, Basu A R, Nesterenko G V. Temporal Sr-, Nd- and Pb-isotopic variations in the Siberian flood basalts: implications for the plume-source characteristics. Earth Plan Sci Lett, 1992, 113(3): 365-381.

19 Fujita K, Cook D B. The Arctic continental margin of eastern Siberia// Grantz A, Johnson L, Sweeney J F. The Geology of North America, the Arctic Ocean Region, Vol. 10. Boulder, Colorado: Geological Society of America, 1990: 289–304.

20 Okulitch A V. Geology of the Canadian Archipelago and North Greenland//Trettiln H P. Geology of the Innuitian orogen and Arctic

Platform of Canada and Greenland. Geology of Canada, Vol. 3. Ottawa: Geological Survey of Canada, 1991: 435-458.

21 Timokhov L A. Regional characteristics of the Laptev and the East Siberian seas: climate, topography, ice phases, thermohaline regime, circulation//Kassens H, Hubberten H W, Priamikov S M, et al. Berichte zur Polarforschung, 1994, 144: 15-31.

22 Darby D A, Bischof J F, Jones G A. Radiocarbon chronology of depositional regimes in the western Arctic Ocean. Deep-Sea Research II, 1997, 44 (8): 1745-1757.

23 Holmes R M, McClelland J W, Peterson B J, et al. Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas. Estuaries Coasts, 2012, 35(2): 369-382.

24 Gordeev V V, Shevchenko V P. Chemical composition of suspended sediments in the Lena River and its mixing zone. Russian–German Cooperation: Laptev Sea System//Kassens H, Hubberten H W, Priamikov S M, et al. Berichte zur Polarforschung, 1995, 176: 154-169.

25 Gordeev V V, Rachold V, Vlasova I E. Geochemical behaviour of major and trace elements in suspended particulate material of the Irtysh river, the main tributary of the Ob river, Siberia. Appl Geochem, 2004, 19(4): 593-610.

26 Wahsner M, Müller C, Stein R, et al. Clay-mineral distribution in surface sediments of the Eurasian Arctic Ocean and continental margin as indictor for source areas and transport pathways—a synthesis. Boreas, 1999, 28(1): 215-233.

27 Rachold V, Eisenhauer A, Hubberten H W, et al. Sr isotopic composition of suspended particulate material (SPM) of East Siberian rivers – sediment transport to the Arctic Ocean. Arct Alp Res, 1997, 29(4): 422–429.

28 Nalivkin D V, Markovskiy A P, Muzylev S A, et al. Geological Map of the Union of Soviet Socialist Republics, Scale 1: 2 500 000. Moscow: The Ministry of Geology of the USSR, 1965.

29 Suchet P A, Probst J L, Ludvig W. Worldwide distribution of continental rock lithology: Implications for the atmospheric/soil CO2 uptake by continental weathering and alkalinity river transport to the oceans. Global Biogeochem Cycles, 2003, 17(2): 1038, doi: 10.1029/2002GB001891.

30 Ivanov V V, Piskun A A. Distribution of river water and suspended sediment loads in the deltas of rivers in the basins of the Laptev and East-Siberian Seas//Kassens H, Bauch H A, Dmitrenko I A, et al. Land-Ocean Systems in the Siberian Arctic: Dynamics and History. Berlin: Springer-Verlag, 1999: 239-250.

31 Macdonald R W, Solomon S M, Cranston R E, et al. A sediment and organic carbon budget for the Canadian Beaufort shelf. Mar Geol, 1998, 144(4): 255-273.

32 Amon R M W, Rinehart A J, Duan S, et al. Dissolved organic matter sources in large Arctic rivers. Geoch Cosmoch Acta, 2012, 94: 217–237.

33 Milliman J D, Farnsworth K L. River discharge to the coastal ocean: a gloal synthesis. Cambridge: Cambridge University Press, 2011: 292.

34 USSR. Academy of Sciences, Geological Institute and Institute Of Oceanology, 1970. Tectonic Map of the Pacific Segment of the Earth. Moscow, 1970.

35 Weingartner T. Chukchi Sea Circulation. http://www.ims.uaf.edu/chukchi/, 2001.

36 Darby D A, Ortiz J D, Grosch C E, et al. 1,500-year cycle in the Arctic Oscillation identified in Holocene Arctic sea-ice drift . Nature Geosci, 2012, 5(12): 897-900.

37 Winkler A, Wolf-Welling T, Stattegger K, et al. Clay mineral sedimentation in high northern latitude deep-sea basins since the Middle Miocene (ODP Leg 151, NAAG) . Intern J Earth Sci, 2002, 91(1): 133-148.

38 Nørgaard-Pedersen N, Mikkelsen N, Kristoffersen Y, et al. Arctic Ocean record of last two glacial-interglacial cycles off North Greenland/Ellesmere Island—implications for glacial history. Mar Geol, 2007, 244(1-4): 93-108.

39 Wang R J, Xiao W S, Li W B, et al. Late Quaternary ice-rafted detritus events in the Chukchi Basin, western Arctic Ocean. Chin Sci Bull, 2010, 55(4-5): 432-440.

40 Dyck S, Tremblay L B, de Vernal A. Arctic sea-ice cover from the early Holocene: the role of atmospheric circulation patterns. Quat Sci Rev, 2010, 29(25-26): 3457-3467.

41 Fang X S, Shi X F, Cheng Z B, et al. Mineralogy of surface sediment in the eastern area off the Ryukyu islands and its geological significance. Mar Geol Quat Geol, 2013, 33(3): 57-63.

42 Cook H E, Johnson P D, Matti J C, et al. Methods of sample preparation and X- ray diffraction data analysis, X-ray mineralogy laboratory//Kaneps A G. Init Repts, DSDP XXVIII, 1975: 997-1007. http://www.deepsea drilling.org/28/volume/ds dp28-appen dix-IV.pdf.

43 Yang Z S, Zhao X H, Qiao S Q, et al. Feldspar/Quartz (F/Q) Ratios as a chemical weathering intensity indicator in different grain size-fractions of sediments from the Changjiang and Huanghe Rivers to the seas. Period Ocean Univ China, 2008, 38(2): 244-250.

44 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. Glob Plan Change, 2009, 68(1-2): 73-84.

45 Eberl D D. Quantitative mineralogy of the Yukon River system: Variation with reach and season, and sediment source unmixing. US Geological Survey, Boulder, Colorado, 2003.

46 Schoster F, Behrends M, Müller 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. Intern J Earth Sci, 2000, 89(3): 486-495.

47 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, 23(1), PA1S06, doi: 10.1029/2007PA001497.

48 Münchow A, Weingartner T J, Cooper L W. The summer hydrography and surface circulation of the east Siberian shelf sea. J Phys Oceanogr, 1999, 29(9): 2167-2182.

49 Chamley H. Clay sedimentology. Berlin: Springer-Verlag, 1989.

50 Naidu A S, Creager J S, Mowatt T C. Clay mineral dispersal patterns in the north Bering and Chukchi Seas. Mar Geol, 1982, 47(1): 1-15.

51 Darby D A, Ortiz J, Polyak L, et al. The role of currents and sea ice in both slowly deposited central Arctic and rapidly deposited Chukchi–Alaskan margin sediments. Glob Plan Change, 2009, 68(1-2): 58-72.

52 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, Palaeoclimatol, Palaeoecol, 2004, 203(1–2): 73-93.

53 Bischof J, Clark D L, Vincent J S. Origin of ice-rafted debris: Pleistocene paleoceanography in the western Arctic Ocean. Paleoceanography, 1996, 11(6): 743-756.