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Clay minerals in Arctic Kongsfjorden surface sediments and their implications on provenance and paleoenvironmental change

SHI Fengdeng[1, 2], SHI Xuefa[2, 3*], SU Xin[1], FANG Xisheng[2, 3], WU Yonghua[2, 3], CHENG Zhenbo[2, 3], YAO Zhengquan[2, 3]

[1] School of Ocean Sciences, China University of Geosciences (Beijing), Beijing 100083, China

[2] Key Laboratory of State Oceanic Administration for Marine Sedimentology and Environmental Geology, The First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China

[3] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China

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Abstract

Kongsfjorden is a typical fjord on the edge of the ice cap of the Arctic Svalbard-Barents Sea. Its inner bay is connected with a modern glacier front along the direction of the fjord axis with a significant gradient change in the parameters of hydrology, sedimentation, and biology. In summer, ice and snow melt-water and floating ice collapse continuously and thus transport the weathering products on the surrounding land into the sea. Thus Kongsfjorden is regards as a natural laboratory for the study of unique sedimentation in polar fjords under modern glacial-sea water conditions. In this study, fifty-two surface sediments were collected in Kongsfjorden for clay mineral analysis to study the sediment source and sediment-transport process. Our results indicate that clay minerals in the surface sediments from Kongsfjorden are mainly composed of illite, chlorite, and kaolinite, and no smectite is found. Rocks from different periods exposed extensively in the surrounding areas of Kongsfjorden provide an important material basis for clay minerals in the Kongsfjorden. Kaolinite may be mainly derived from the fluvial deposits, weathered from reddish sandstones and conglomerates during the Carboniferous Period. Illite is mainly derived from Proterozoic low-grade and medium-grade metamorphic phyllite, mica schist, and gneiss. While chlorite is mainly from Proterozoic low-grade metamorphic phyllite and mica schist. In the direction from the fluvio-glacial estuary to the sea of the glacier front of Kongsfjorden, illite increase gradually, and the content of kaolinite declines gradually. However, the change pattern of chlorite is insignificant, which may be related to the provenance. Kongsfjorden detritus is mainly transported by the fluvio-glacial streams and icebergs into the sea and deposited in the inner bay. Coarse sediments are rapidly deposited in the glacier front, estuary, and near-shore areas. Clay fraction begins to deposit significantly by 200–400 m after flowing into the sea, which due to the crystal behavior of clay minerals, hydrodynamic condition and flocculation. Kaolinite and chlorite on the south of the bay near the Blomstrandhalvøya Island is mainly affected by ice-rafted detritus and thus can reveal the trajectory of transportation by the floating ice while entering the sea.

Key words: Arctic Pole, Kongsfjorden, clay mineral, provenance, sedimentation

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1 Introduction

Kongsfjorden is a typical fjord developed on the edge of the ice cap of the Arctic Svalbard-Barents Sea. It is located at 78°40′–79°00′N, 11°20′–12°30′E in Ny-Ålesund on the northwest shore of the Svalbard Archipelago. The Svalbard Archipelago was totally covered by the ice cap of Svalbard-Barents Sea during the ice age of the Late Weichselian period (Landvik et al., 1992). The ice cap front of the Svalbard-Barents Sea gradually receded to the west shore of the archipelago (Landvik et al., 1998; Lehman and Forman, 1992) and formed a series of extremely deep fjords at the entrance to the sea given the increase in temperature since the last deglacial period. Thus, Kongsfjorden was formed during this period. Given that it is in the alternate zone of the ocean and the mainland ice cap, the hydrological, sedimentary, and biological gradient changes along the fjord axis are significant and provide a long-term sequence, high-resolution record for the study of changes in climate and environment (Syvitski and Shaw, 1995; Gilbert, 2000). Kongsfjorden has become a natural laboratory for the study of global climate change in the Arctic region.

Scientists' research has focused on the response of the hydrological and biological environment to global climate change (Halldal and Halldal, 1973; Lydersen and Gjertz, 1986; Ito and

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*Corresponding author, E-mail: xfshi@fio.org.cn

Kudoh, 1997; Ingvaldsen et al., 2001; Hop et al., 2002; Svendsen et al., 2002; Kwasniewski et al., 2003; Basedow et al., 2004; Cottier et al., 2005; Jiang et al., 2005; Lefauconnier et al., 1999; Ji et al., 2014), and less attention has been paid to the process of sedimentary environment changes (Zajączkowski, 2002, 2008; Shi et al., 2011). The sedimentary environment of the Arctic region is extremely sensitive to global climate changes. Particularly in the past 100 years, a large area of the Svalbard Archipelago glacier has receded because of continuous global warming (Nordli et al., 1996; Ziaja, 2001). With increased glacier activity, the amount of freshwater and terrestrial detritus transported to the fjord increases accordingly (Elverhøi et al., 1995; Svendsen et al., 2002; Zajączkowski et al., 2004; Wlodarska-Kowalczuk et al., 2007), which results in high turbidity of water bodies near glaciers or estuaries (Syvitski, 2002). The existence of high turbidity of water bodies has resulted in the suppression of biological primary productivity in the bay (Keck, 1999), and much plankton has been killed by osmotic impulsive forces (Zajączkowski and Legeżyńska, 2001). The high deposition rate of terrestrial detritus affects the composition and diversity of benthic fauna (Wlodarska-Kowalczuk and Pearson, 2004). The changes in the sedimentary environment in modern fjords, such as the widespread occurrence of high turbidity in water bodies, seriously affect the near-shore ecosystem and hydrological (halocline) situation in the fjords. Therefore, understanding the modern sedimentation process in the Arctic fjord areas at high latitudes is important to global research on climate change.

Kongsfjorden is an ideal place for the study of the modern sedimentation process in the Arctic region. Its inner bay remains connected to the front of modern glaciers at present. In summer, ice and snow meltwater and floating ice collapsed continuously to transport the products of weathering and denudation on the surrounding land into the sea (Shi et al., 2011). Howerer, the questions such as the provenance, transportation and distribution of the sediments after entering the sea need to be answered to understand the modern sedimentation process in the Arctic Kongsfjorden region. Clay minerals, as the main component of marine sediments, are relatively stable. Most of them are from the weathering products of land rocks (Ehrmann et al., 1992). The climate is extremely cold in the Arctic high-latitude areas. In the mostly frozen natural environment, the physical weathering effect on the rocks is strong, but the chemical weathering effect is weak, which is conducive to the preservation of clay minerals. Moreover, clay minerals are highly sensitive to the hydrodynamic force condition because of their unique fine-grain flaky texture. The condition simplifies the identification of the source of the detritus materials and their transportation route from the clay minerals in the marine sediments rather than from other components, which reflects the characteristics of the rocks and climate in the source area. Thus, researchers can understand the sedimentation process and the rules on the movement of detritus materials after entering the sea (Naidu et al., 1971, 1982, 1995; Naidu and Mowatt, 1983; Chamley, 1989; Nürnberg et al., 1994; Stein, 1994; Petschick et al., 1996; Gingele and Leipe, 1997; Viscosi-Shirley et al., 2003; Stein et al., 2004; Chen et al., 2004; Zhang et al., 2008; Li et al., 2012a; Dong et al., 2014).

The establishment of the Arctic Yellow River Station in July 2004 in Ny-Ålesund region of the Svalbard Archipelago provided an effective scientific research platform for Arctic geological research in China. This study selected fifty-two surface sediments collected in Kongsfjorden for clay mineral analysis and research during the summer investigation of the Arctic Yellow River Station in 2007 and 2008. Combined with the geological data of the region, the source, formation cause, and transportation process of clay minerals in the sediments was identified, and sediments distribution rules and the main influencing factors of the clay minerals in Kongsfjorden were revealed, thereby enriching the understanding of the sedimentation effect in the polar region.

2 Regional geological background

Owing to the poor vegetation coverage and the lack of soil layer in the study area, numerous rock strata was exposed with extensive strata developed in each period from the Proterozoic to the Quaternary period (Dallmann et al., 1999; Hjelle, 1993). Figure 1 (Hjelle, 1993) shows that the commonly exposed bedrock in the north shore of Kongsfjorden comprises gneiss and granites with remnants of schist and limestone beds, in which limestone is susceptible to severe metamorphism into marble. The degree of metamorphism of the schist and gneiss is gradually increasing to the north, and the schist produced in the south contains much chlorite and white mica. Moreover, the schist produced in the north is mainly composed of biotite, hornblende, and garnet. In the Blomstrandhalvøya Island, Lovénøyane archipelago, and north of the Blomstrandbreen, some red conglomerates and sandstones of Devonian without metamorphism are visible and distributed in a north-south banding zone. In Brøggerhalvøya at the south shore of Kongsfjorden, the exposed bedrock in the southeast contains garnet, hornblende, and micacite of layered marble from the early and middle Proterozoic, and the exposed bedrock in the north contains phyllite of lamellar quartzite from the late Proterozoic. The exposed bedrock in the west and north contains sedimentary rock from the middle and late Permo-carboniferous periods. A set of fluvial sedimentary facies dominated by reddish sandstone and conglomerate developed in the middle Carboniferous, and the uniquely developed lamellar limestone, dolomite with more fossils and gypsum and anhydrite interlayer were found in the late Permo-carboniferous period. Lower Carboniferous strata can be seen only in the northwest of Kulmodden. Approximately 200–250 m thick sandstone overlies were found on the eroded surface of bedrock, and a set of 3 m thick shale deposits were found in the lower part of the bedrock, mixed with impure coal seams. During the transition from the Cretaceous period to Palaeocene epoch, affected by the oblique extrusion of Greenland, a series of thrust evidence from SSW to NNE appears in this region, and old strata are often pushed over by new strata (Hjelle and Lauritzen, 1982). Paleogene strata are exposed in the west and the small areas south of Ny-Ålesund (4.5 km^2), surrounded by lower Permo-Carboniferous rocks. The exposed bedrock in the Ossian Sarsfjellet area at the east of Kongsfjorden is dominated by schist. The metamorphic grade increases, with limestone transforming into marble, because of its closeness to the east of the fjord. The exposed bedrock further to the east is dominated by gneiss with a small amount of gray granite because of the strong metamorphic effect in Stemmeknausane. Gneiss is also exposed in two small mountains towards the south. Middle and upper Permo-carboniferous strata in other moutains in the east and north of Kongsvegen glacier are mainly exposed. The rock stratum is essentially horizontal because of the intense tertiary folding and faulting effect in the western belt. The mountains are of Pyramid type. The Kroner is typical. Horizontally distributed Permo-Carboniferous strata cover the Devonian strata that are subjected to minor folds lower than 1 000 m. Black Jurassic rocks intruded prevalently and formed cliffs on mountain ranges (Hjelle, 1993).

Many glaciers developed on both sides of Kongsfjorden and the leading edge of basin. Brøggerbreen, Midtre Lovénbreen, Austre Lovénbreen, Pedersenbreen, and Uversbreen belong to Valley glacier. Blomstranbreen, Conwaybreen, Kongsbreen, Kronebreen and Kongsvegen belong to tidewater glacier. A large number of tillites are found near these glaciers. The study area is covered with ice most of the year. The warming on the surface in summer leads to the partial melting of ice and snow and forms a series of small seasonal glacial-meltwater rivers on both side of Kongsfjorden.

3 Material and methods

Fifty-two surface sediment samples analyzed in this study were acquired by boat and comprised the Chinese 4th and 5th Arctic Summer Expedition of the Yellow River Station in 2007 and 2008 (Fig. 1). The sample collection method was clamshell grab. Surface sediment samples were sampled in 0–2 cm layers.

X-ray diffraction method (XRD) for oriented thin section of clay grade mineral (<2 μm) was used for clay mineral analysis (Li et al., 2012b). Samples were prepared as follows. Roughly 1 cm^3 of the sample was taken to remove organic matter with 30% of H_2O_2. Approximately 0.5% HCl was used to remove carbonate, and the sample was washed repeatedly with deionized water until deflocculation occurred. Particles less than 2 μm were sucked with a needle tubing for centrifugation based on the settling time determined by the Stokes sedimentation principle. The scraping method was used to prepare sample-oriented slices to dry naturally. AD/max-2500 type rotating target X-ray diffraction instrument (Japan) was used to for XRD inspection. The preparation and testing of samples were conducted in a test center at the Key Laboratory of State Oceanic Administration for Marine Sedimentology and Environmental Geology.

4 Results and discussion

4.1 *Content and distribution characteristics of clay minerals*

The evaluation of clay minerals only considers four types: kaolinite, illite, chlorite and smectite. The evaluation and calculation are in accordance with the literature (Li et al., 2012b). Table 1 presents based on comprehensive identification and semi quantitative calculation of various maps and curves. Clay minerals in surface sediment mainly consist of illite, chlorite and kaolinite, and no smectite was observed.

Illite is a type of clay mineral with the highest content in the study area. The changing range is 69%–78% with a mean value of 74.4%. Its distribution follows a certain rule, as shown in Fig. 2a. Illite is gradually increasing from the south shore of Kongsfjorden to the north. The content of illite is also increasing gradually from the leading edge of glacier at the east of Kongsfjorden to the ocean. The content of illite shows decreasing and then increasing trends in a small area near the south of Blomstrandhalvøya Island.

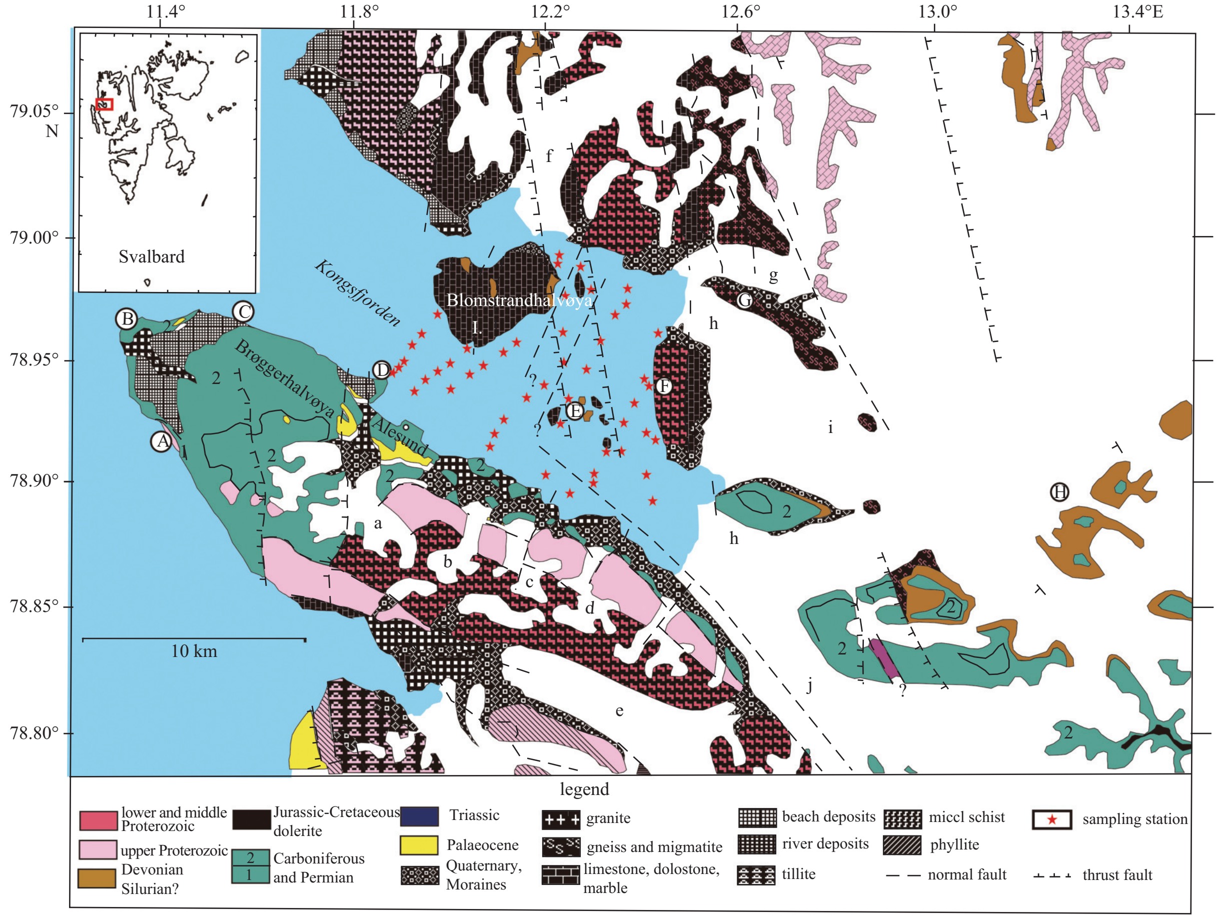

Fig. 1. The geological map of Ny-Ålesund area (modified from Hjelle, 1993). The name of place: A. Kulmodden, B. Kvadehuken, C. Kongsfjordneset, D. Brandalpynten, E. Lovénøyane, F. Ossian Sarsfjellet, G. Stemmeknausane, and H. Tre Kroner. The name of glacier: a. Brøggerbreen, b. Midtre Lovénbreen, c. Austre Lovénbreen, d. Pedersenbreen, e. Uversbreen, f. Blomstranbreen, g. Conwaybreen, h. Kongsbreen, i. Kronebreen, and j. Kongsvegen.

Table 1. Statistics of clay mineral contents in the surface sediments, Kongsfjorden

Content	Illite	Kaolinite	Chlorite	Smectite
Sample number	52	52	52	52
Max/%	78	17	21	0
Min/%	69	9	11	0
Average/%	74.4	12.7	12.9	0

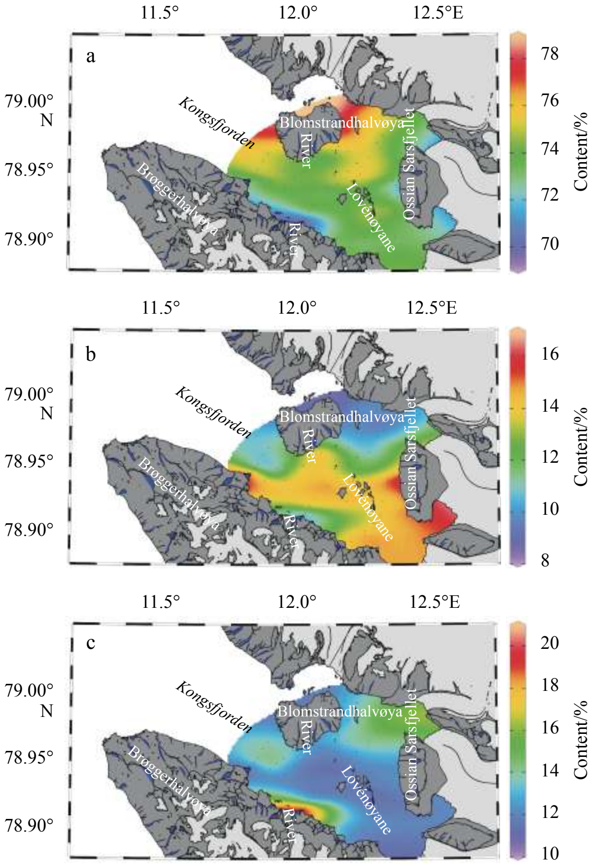

Fig. 2. The distributions of clay mineral content in the surface sediments. a. Illite, b. kaolinite and c. chlorite. This figure was generated with "Ocean Data View" (Schlitzer, 2015).

The content of kaolinite in the surface sediment in the study area is 9%–17%, with a mean value of 12.7%. Figure 2b shows that two high-value areas are found in Kongsfjorden for the content of kaolinite. The content of kaolinite is gradually decreasing in the entrance of glacier rivers and tide water glacier slightly to the south Ossian Sarsfjellet mountain. The content of kaolinite is also decreasing gradually from the estuary of glacial-melt water formed by Midtre Lovénbreen, Austre Lovénbreen, and Pedersenbreen at the south shore of Kongsfjorden to the ocean. The content of kaolinite shows increasing and then decreasing trends in a small area near the south of Blomstrandhalvøya Island.

The chlorite content in the surface sediment in the study area is within 11%–21%, with a mean value of 12.9%. Figure 2c shows that the chlorite content gradually decreasing from the estuary of glacial-melt water formed by the Midtre Lovénbreen, Austre Lovénbreen, and Pedersenbreen at the south shore of Kongsfjorden, and the west and east of Ny-Ålesund to the ocean. The chlorite content also decreases from the Conwaybreen on the north of Kongsfjorden and the leading edge near Kongsbreen to the ocean. However, the change in the chlorite content is not obvious in other areas.

4.2 *Provenance and environmental significance indicated by clay minerals*

4.2.1 *Illite*

Illite generally emerges from feldspar, mica, and other aluminosilicate minerals under the condition of weathering and K^+ removal at low temperatures and weak alkaline environment. Its major cations are composed of Si, Al, and K. The crystallinity of illite is determined by half band width at 10 Å diffraction peak (Li et al., 2012b). The previous division standard of the degree of crystallization is adopted (Diekmann et al., 1996): the degree of crystallization is divided into four types: very good, good, moderate and bad. The ranges of crystallinity values are <0.4, 0.4–0.6, 0.6–0.8 and >0.8. Low crystallinity value of illite indicates a high degree of crystallinity. Such a result indicates that the land provenance area is weak in hydrolysis and shows dry and cold weather conditions. The parameter is consistently used to trace provenance areas and transport paths (Krumm and Buggisch, 2010). The chemical index of illite is determined by using 5 Å/10 Å peak area ratio. A ratio of more than 0.5 indicates that illite with rich Al is characterized by strong hydrolysis. A ratio of less than 0.5 indicates that illite with rich Fe-Mg, which is the product of physical weathering (Esquevin, 1969). Figure 3 shows that via calculation, the crystallinity value of illite in surface sediments in Kongsfjorden is 0.30–0.43, with a mean value of 0.39. Based on the previous division standard, the crystallinity of illite can be judged as very good–good. The chemical index is within

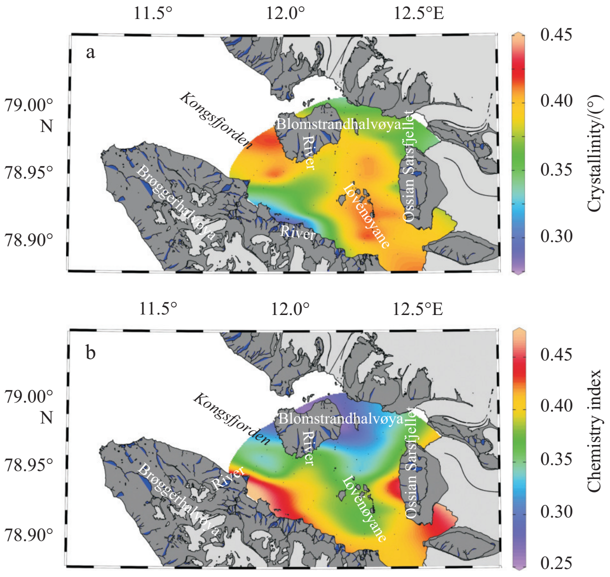

Fig. 3. The distributions of illite crystallinity and chemistry index in the surface sediments of Kongsfjorden. a. Illite crystallinity ($\Delta 2\theta$, °) and b. illite chemistry index. This figure was generated with "Ocean Data View" (Schlitzer, 2015).

0.26–0.46, with a mean value of 0.37, which can be determined as illite with rich Fe-Mg. This result indicates that the provenance area has dry and cold weather conditions, which is consistent with the modern environment. Thus, illite in the study area is the product of the strong physical weathering of rocks.

Illite in the ocean is mainly from land (Shi, 1995). Low and intermediate metamorphic rocks from the Proterozoic era are widely exposed around Kongsfjorden and mainly include phyllite, mica schist, and gneiss, which contain rich feldspar, mica and other aluminosilicate minerals. The rocks provide an important physical basis for the formation of illite. Moreover, the natural environment characteristics of dry and cold climate and weak leaching action in the provenance area are conducive to the formation and conservation of illite. Thus, illite is a clay mineral with the highest content in the study area. Svalbard is also considered the main source area of the Arctic Ocean illite (Stein et al., 1994).

4.2.2 *Kaolinite*

Previous studies have mentioned that kaolinite is generally recognized to be formed by two pathways: hydrothermal alteration and surface weathering (Zhu, 1987; Yang, 1988). Warm and humid climatic conditions and dense vegetation cover on the surface are necessary to produce weathering. The soil medium is acidic, and leaching is powerful. Thus, K, Na, Ca, Mg can be separated from aluminosilicate minerals. Feldspar and mica minerals are weathered into kaolinite. No signs of hydrothermal activity are found on the seafloor. Measured pH values in surface sediments in Kongsfjorden that are more than 8 (Zhu et al., 2014), indicating a marine alkaline environment. Thus, the basic conditions for forming kaolinite minerals are not available in the modern submarine environment. Moreover, the source of its material is transported from the land to the sea by geological agents such as glaciers and rivers. Based on the current surface environment in the study area, the annual average temperature is roughly −5.8°C and the average annual precipitation is up to 400 mm (Hisdal, 1998). The plant species are relatively rare and dominated by polar tundra plants. No natural condition for the formation of kaolinite appears possible. Determining whether strong chemical weathering is needed to produce kaolinite is necessary. Xia and Xie (2007) analyzed 16 elements in lake sediments (49.5 cm long, drilling to the bedrock) from L1 drilling hole in the Blomstrandhalvøya Island in Arctic Ny-Ålesund and the calculated component variance index. The researchers found that component variance index in sediments was significantly higher than the indices of feldspar and clay minerals and close to the component variance index of primary rock (Xia and Xie, 2007). This result indicates that the content of clay minerals produced after the weathering effect in the study area is far less than the content of the primary mineral. Thus, in the study, the chemical weathering is weaker in the primary stage. These results show that kaolinite is not produced by weathering. Moreover, kaolinite can be converted from other clay minerals. Generally, illite can be converted into smectite under the condition of continuous weathering and K^+ removal (Tang et al., 2002). In hot and humid climates, chemical weathering is thorough and can be further decomposed into kaolinite (Tang et al., 2002). No smectite is found in sediments in the study area. These results indicate a lack of smectite materials in the provenance area. Moreover, the results indicate that the weak chemical weathering in the modern environment in this area is insufficient to make Na, K and other strongly active alkali metals well leached. The metals only stay in the formatting stage of illite. Therefore, the kaolinite minerals in the study area are unlikely to be formed under modern environmental conditions. Given frequent glacial events during the historical period in the area, the erosion and transport of glaciers cause fewer sediments older than 700 years to be conserved in the study area (Jones and Birks, 2004). Moreover, kaolinite minerals are easy to be destroyed during metamorphism or deep burial. A correlation analysis revealed a significant negative correlation with illite and chlorite content, which indicates that the sources were different (Fig. 4). Kaolinite in this area is inferred to be the product of sedimentary rocks that have been kaolinized or contain kaolinite that was formed before the Quaternary after physical weathering, similar to the origin of kaolinite in the Arctic and Antarctic continents (Zhang et al., 2008; Blakemore and Swindala, 1958). Based on the study conducted by regional geology (Hjelle, 1993), the kaolinite present in this area likely originated from the fluvial facies that were dominated by reddish sandstone and conglomerate in the middle Carboniferous. The reason is that the Svalbard archipelago at that time is at the same latitude as the North African desert today. The climate is hot and the area is near the ocean. Moreover, strong leaching property helps the formation of kaolinite. Rock stratum from this era is widely exposed in the coast of the cape between Brandalpynten and Kongsfjordneset, the east of Kvadehuken, near Brøggerbreen, and around Kongsvegen. Given extremely strong etching from Brøggerbreen, Kongsvegen, and Kronebreen and other

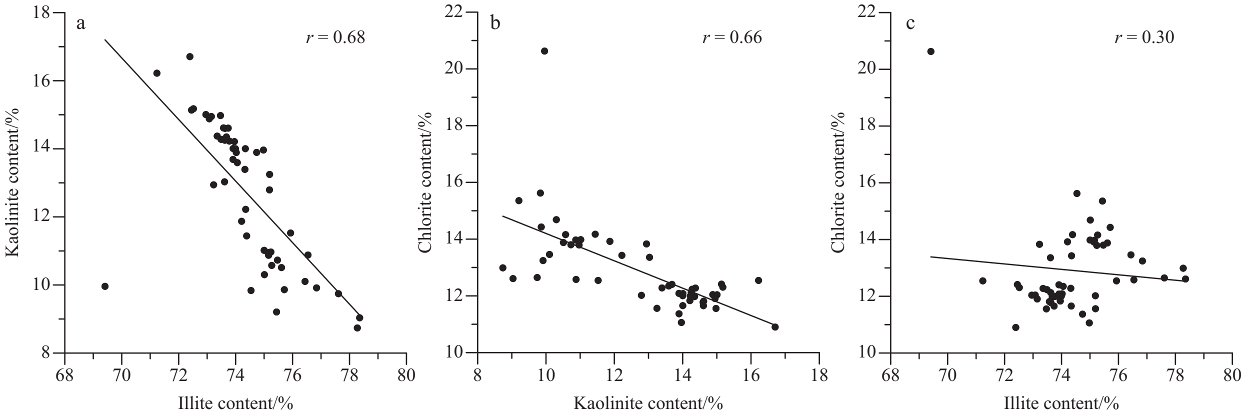

Fig. 4. Correlation diagrams between clay minerals in the surface sediments of Kongsfjorden. a. Kaolinite versus illite, b. chlorite versus kaolinite and c. chlorite versus illite.

modern glaciers, sedimentary rocks from this period are often broken into the muddy matter, which brings a red color to many rivers and streams near Ny-Ålesund and the rivers south of Ossian Sarsfjellet. The particles are then transported into the fjord. Kaolinite minerals are deposited in these estuaries with relatively high content (Fig. 2b).

4.2.3 *Chlorite*

Chlorite is usually formed in alkaline and less leaching environments. Under weathering effect, Fe^{2+} in water magnesium layer is easily oxidized. Thus, it can only be preserved when the chemical weathering is inhibited (Rateev et al., 2010). Chlorite can be used to indicate cold climatic conditions (Griffin et al., 1968). The chlorite content is the highest in the Antarctic Ocean, land, and Arctic and subarctic seas. Chlorite is generally formed from metamorphic rock in terrigenous areas by intense physical weathering and weak chemical weathering under cold and dry climatic conditions. Previous studies have shown that the origin of chlorite is complicated. Its formation is related to low-temperature hydrothermal action, epimetamorphism and sedimentation (Pan et al., 1993). Several studies have reported that chlorite can be transformed from gibbsite when volcanic material is subjected to intense chemical weathering (Shi, 1995). Volcanic material must be present in the study area if it is transformed from gibbsite. Moreover, volcanic material can easily form smectite under the weathering effect. However, no smectite is found in this area. A significant negative correlation was found between chlorite and kaolinite content, and a weak negative correlation was observed between chlorite and illite content, which indicate that the sources were different (Fig. 4). Moreover, no volcanic material is found in regional rock formations. Therefore, chlorite is unlikely to be changed from gibbsite. The schist produced in the south of the north shore of Kongsfjorden contains many chlorite minerals due to the low degree of metamorphism. The typical mineral combination in the phyllite exposed in the south shore of Kongsfjorden contains chlorite. Therefore, combined with cold and dry environments in the study area, the chlorite in this area mainly comes from low-grade metamorphic phyllite and mica schist in the Proterozoic era that surrounds Kongsfjorden. Chlorite formed under physical weathering can be preserved in the glacier environment after these rock formations are subjected to glacial erosion. Finally, it is carried into the sea by glaciers or glacial meltwater rivers. Figure 2c shows that high chlorite content area that emerges in the south and north of Kongsfjorden is closely related to the provenance.

4.3 *Transportation and deposition process of clastic (clay) materials*

Glacier volume shows an obvious decline after the end of the little ice age in the Svalbard archipelago. The ice layer becomes thin constantly in front of the ablation zone and then shrinks backward at the end of the glacier tongue (Hagen et al., 2003; Ai et al., 2013). Further studies have shown that glaciers with persistent recession are usually small in size (<10 km^2) and low in altitude (<500 m) (Xu et al., 2007). Many clastic materials in the glacier recession are transported and deposited by glaciers and rivers. Two different types of glaciers are found in Kongsfjorden: valley glacier and tidal water glacier. Differences are observed in the abilities and means of the clastic material transportation between them.

Valley glaciers were developed in Brøggerhalvøya on the south shore of Kongsfjorden. The flow rate of such glaciers is extremely low because of the effects of low temperatures. For example, the flow rates of Austre Brøggerbreen, Midre Lovénbreen, and Austre Lovénbreen are only 2 m, 4.5 m and 7 m, respectively (Svendsen et al., 2002). Pro-talus ramparts or rock glaciers are formed from some broken glacier materials generally found near the glaciers, which are distributed in the area in which Quaternary moraine is deposited in Fig. 1. The moving rate of these rock glaciers is extremely low, at roughly 3–4 cm or less per year (Sollid and Sørbel, 1992). Regardless of valley glaciers or rock glaciers previously formed, the ability of this type of glacier in the study area to directly transport fragmentary materials is weak because of the very low flow rate. The clastic materials are mainly transported and deposited via rivers on land. The study area is covered by glacier and snow for most of the year. The transportation mainly happens in summer.

A large amount of firn and meltwater in a small area of valley glacier at the low altitude flow out from the sides or bottom of the glacier. Moreover, after passing through the leading edge of the glacier or cutting terminal moraine dam and rock glacier, the terrain becomes wide and slow, and a series of small braid-shape rivers exists at the coast of Kongsfjorden. These glacial-melt water rivers show seasonal activity. No permanent deep-incised valley is found, except for the Bayelva River. A wide glacial-melt water deposition plain can be formed (Fig. 5). Coarse fluvial deposits are prevalent and vegetation development is rarely found. Many clastic materials are deposited after glacial-meltwater enters the ocean. The analysis on the grain size of surface sediment in Kongsfjorden shows that sediments in Kongsfjorden contain gravel, sand, silt, and clay components, and is dominated by silt and clay components. The distribution of gravel, sand, and clay has highly significant characteristics. From the south shore of Kongsfjorden to the north, the contents of gravel and sand fragments gradually decreased, and that of clay increases. It is closely related to onshore glacial-melt water river input (Shi et al., 2011).

Four tidal glaciers, namely Kronebreen, Kongsvegen, Blomstranbreen, and Conwaybreen developed on the north shore of Kongsfjorden and the leading edge of the basin. Polythermal Kongsbreen formed by Kronebreen and Kongsvegenr in the front of glaciers is the largest and most active in this area (Lefauconnier et al., 1994). The maximum amount of glacial meltwater occurs in July, and the flow rate is up to 138 m^3/s (Zajączkowski and Legeżyńska, 2001). Statistics indicate that roughly 1.4 km^3 of fresh water is discharged into Kongsfjorden annually (Svendsen et al., 2002). The amount of meltwater discharged into glaciers is roughly 0.33 km^3 (Beszczyńska-Möller et al., 1997). The glacier meltwater flows out from inside the glacier and directly into the fjord along the glacier cliff (Zajączkowski, 2008). In the area around Kongsvegen glacier, many rocks are broken and transported to the fjords because of highly intense glacier erosion. Roughly 2 million tons of sand, mud and gravel are transported annually by glacial meltwater rivers to the inland basin near the front of the glacier. This amount is equivalent to 2 000 tons of materials per square kilometer of glacier (Hjelle, 1993). However, Blomstranbreen and Conwaybreen are inactive. Only a small amount of turbid water is discharged yearly (Svendsen et al., 2002). Two types of sediment are generated in the fjord given different transportation modes and sedimentary differentiation abilities. First, ice-edge fan deposits dominated by lamellar sand and gravels occur in the front of glacier. Second, massive argillaceous deposits dominated by silt and clay occur in the leading edge of the glacier (Shi et al., 2011). Icebergs formed after disintegration are another major geological agent for transport and deposition of sediment in the leading edge of the tidal glacier in

Fig. 5. Sandur and braided drainage systems in the Ny-Ålesund.

Fig. 6. Small iceberg strand in the Kongsfjorden.

summer. Kronebreen only releases small-scale icebergs to the fjord and they transport from the basin under the effect of the southeast wind (120°) prevailed in Ny-Ålesund (Svendsen et al., 2002). Large icebergs consistently strand in the east area of Lovénøyane island or on the boundary line between the basin and central fjord and the north between Lovénøyane and Blomstrandhalvøya island. These icebergs consistently carry much clastic matter (Fig. 6). A particular type of sediment that contains more fine gravels may occur in the transportation process.

Fine clay component is mainly composed of clay minerals compared with gravel, sand, and silt components.Therefore, the clay minerals are easily transported and difficult to deposit after carried by rivers or glaciers into the sea. They are the main component that constitutes suspended matter in water. The sediment trap placed in the fjord show that the concentration of the total suspended matter begins to increase in April and reaches the maximum in July. The deposition process ends in the middle of September. Suspended particles remain for approximately 30 days in the fjord (Svendsen et al., 2002). The basin of Kongsfjorden is covered by sea ice in winter. Sea ice begins to subside by April of each year as the weather becomes warmer. Sea ice is completely melted in July. Glaciers and rivers enter an active phase at this time. The seasonal variation in freshwater input creates a stable stratification in summer and weak stratification in winter. The upper layer circulation in summer is confined to a shallow surface layer (Svendsen et al., 2002). A large number of terrigenous clastic materials are transported to the sea. In mid-September, the weather turns cold and the handling process ends. The concentration of suspended particles is increased to the maximum, and terminal time of deposition process is consistent with the beginning and ending times of the transport of terrigenous material into the sea by glaciers and rivers. The concentration of suspended particles has a significant peak in the spatial distribution at the leading edge of the glacier. The deposition is extremely fast. The deposition rate is up to the maximum in a place 200–400 m distant to the leading edge of glacier (Svendsen et al., 2002). During the Chinese 6th Arctic Yellow River Summer Expedition in August 2009, a LISST-100B field laser particle size analyzer was used to make cross-section measurements on the concentration of suspended matter in the water of Kongsfjorden from the leading edge of the glacier, basin, and middle fjords to outside fjords. The concentration of the total suspended matter decreased regularly from the basin, and middle fjord to outside fjord, and the subsurface showed the maximum in the vertical direction (unpublished data). Generally, the transport process of clay minerals in waters can be indicated by the change in the concentration of the total suspended matter. However, the deposition process of clay minerals from water bodies is highly complicated and restricted by many factors. First, clay minerals with fine particles are highly sensitive to hydrodynamic forces. Thus, clay minerals are not easy to deposit. Second, the sedimentation of clay minerals mainly depends on flocculation. In the position of Kongsfjorden roughly 10 m close to the glacier, brackish water is mixed with more saline water to produce flocculation. The flocculation in the middle and outside fjord is mainly produced in 20 m position (Syvitski, 1980). Moreover, clay minerals differ in their crystal behavior. Thus, debris, flakes, granules and plates occur. The deposition rate also varies with different crystal forms. The hydrodynamic force is relatively strong in the leading edge of the glacier and the estuary of glacial meltwater. A strong surface current meandered along the glacier front with a maximum speed exceeding 1 m/s (Svendsen et al., 2002). Affected by diluted water, the surface salinity is lower and the flocculation is weaker. The flocculation at the position roughly 10 m below the surface is produced by mixing brackish water with more saline water. The sedimentation of kaolinite minerals in even-grained or thick plate is relatively fast, which form a high-value region of kaolinite distribution. The hydrodynamic condition is relatively weak in the area far from the estuary and the leading edge of the glacier. The speed of the brackish current, measured in July 1999 in the constriction between the inner and middle basin, ranges from 10 to 30 cm/s (Svendsen et al., 2002). Given that the influence of diluted water is relatively small, the salinity of the surface is increased and the flocculation is significantly enhanced. Patch or flaky illite deposits gradually form a high-value region of illite distribution. Chlorite is easier to deposit than illite and can easily form a high-value area on the leading edge of the glacier and the estuary of glacial meltwater with abundant provenance given a larger grain size than illite. ^{210}Pb dating technique is used to measure the deposition rate of a series of columnar sediments from the leading edge of the glacier to the outside (Svendsen et al., 2002). The result shows that deposition rate is significantly reduced from the basin (20 000 g/(m^2·a)) and middle fjord (1 800–3 800 g/(m^2·a)) to the outside fjord (200 g/(m^2·a)). ^{137}Cs test result, which is closely related to clay minerals, provides good verification. ^{137}Cs in the basin is maximum, namely, >60 cm; 10 cm in middle fjord and <5 cm in the outside fjord (Papucci et al., 1998). The most intensive turbulent eddies with diameters of a few meters were commonly found in close proximity to direct outflows from the front of Kongsbreen. Sharp fronts that separate waters with different concentrations of suspended matter were clearly visible at the surface. Patches of strong turbulent mixing were distinguishable (Svendsen et al., 2002). These results indicate that, not only gravel, sand, silt, but also other fine-grained components can be identified in the inner bay. Fine clay component are mainly deposited in this place. A small area on the south side of Blomstrandhalvøya Island in Kongsfjorden (Ω-shape area in Fig. 2c) is the place in which small icebergs produced from the disintegration of Conwaybreen and Kongsbreen tidal glaciers pass through into the sea in summer. Moreover, some large icebergs are stranded in this area (Fig. 6). The icebergs gradually melt under the action of warm seawater. A type of mixture that contains fine gravel appears in its surface sediments (Shi et al., 2011), which is considered fragmentary matters in different sizes that fall from icebergs, and are formed when deposition rate of the unloading materials is extremely high. The distribution of illite and kaolinite here is highly regular in this area. The content of kaolinite in the outside fjord is increased and then decreased. However, the change in the content of illite is the opposite. This behavior is related to the unloading of a large quantity of fragmentary matter that is carried by icebergs in entering the sea or stranding. With the difference in crystallization behavior, the sedimentation of kaolinite is fast and that of illite is relatively slow. Thus, the changes in their contents are different in spatial distribution. The abnormal changes in the contents of two types of clay minerals in the middle of the fjord can reveal the melting place of icebergs and the trajectory of the transportation by the floating ice when entering the sea, which provides a new means of thinking for studying the route of the glacier to enter the sea in historical periods.

5 Conclusions

Through systematical analysis of the characteristics of clay mineral components in surface sediment samples from Arctic Kongsfjorden, and a combination of rock types and weathering conditions in the surrounding area of Kongsfjorden, the cause of clay mineral formation and sediment-transport process have been discussed in this paper. The following conclusions are presented:

(1) The combination of clay minerals in the surface sediments from Kongsfjorden is dominated by illite, which is followed by chlorite and kaolinite. No smectite is observed.

(2) Rock strata widely exposed in the area surrounding Kongsfjorden in each period provide an important material basis for the formation of various clay minerals in the surface sediment of Kongsfjorden. Among the strata, kaolinite is from fluvial facies with micro-red sandstone and conglomerate mainly from the middle Carboniferous period. Illite is mainly from low and intermediate metamorphic phyllite, mica schist, and gneiss in the Proterozoic era. Chlorite is mainly from low-grade metamorphic phyllite and mica schist in the Proterozoic era.

(3) Clastic materials are mainly transported into the sea through two geological agents: glaciers and rivers. The gravel, sand, and silt components in the sediments are deposited successively under mechanical sedimentary differentiation. A clay component is mainly composed of clay minerals with fine particles (<2 μm). The component can be easily moved and is difficult to deposit after entering the sea. Its distribution in surface sediments of Kongsfjorden is regular. The content of illite is gradually increased in the leading edge of the glacier in Kongsfjorden, the estuary of glacial-melt water to the sea. Moreover, the content of kaolinite is gradually decreased, and the change in the content of chlorite is not obvious. The content in the process of deposition is restricted by hydrodynamic conditions, flocculation, crystal behavior and provenance. The abnormal changes in the contents of kaolinite and illite in a small scope in the south of Blomstrandhalvøya Island in Kongsfjorden reveal the trajectory of the transportation by the floating ice while entering the sea, which provides a new approach for studying the route of the glacier in entering the sea during historical periods.

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