Increased Terrigenous Input from North America to the Northern Mendeleev Ridge (Western Arctic Ocean) Since the Mid-Brunhes Event

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Abstract

Mid-Brunhes Event (MBE) occurred at approximately 420 ka between Marine Isotope Stage 11 and 12, and is considered the most pronounced climatic shift during the last ~800 kyrs. On the other hand, it is unclear if the MBE was global, despite being observed in the high-latitude Northern Hemispheric cryosphere in terms of climate systems. A 5.35-m long gravity core ARC5-MA01 was obtained from the northern Mendeleev Ridge in the western Arctic Ocean to track the paleoenvironmental changes in terms of the terrigenous sedimentation in response to the glacial-interglacial climate changes across the MBE. Geochemical proxies (biogenic opal, total organic carbon, C/N ratio, carbon isotope of organic matter, and calcium carbonate) of MA01 suggest that the terrigenous input was generally higher during the interglacial periods. Based on a mineralogical examination, most of the terrigenous input was attributed to the abundance of dolomite and the increased kaolinite content from North America. In particular, most paleoceanographic proxies showed that the terrigenous input from North America was enhanced distinctly during the post-MBE interglacial periods. These results suggest that the MBE in the western Arctic Ocean was a global climatic shift closely linked to cryospheric development in North America during the middle Pleistocene.

Introduction

The glacial-interglacial (G-IG) changes paced by the variations in the orbital parameters were the most pronounced climate fluctuations during the Quaternary, which is highlighted by the onset of Northern Hemisphere glaciation¹. The global terrestrial, marine, and ice archives clearly showed that climatic variations during the recent one-third of the Quaternary (~800 kyrs) are predominated by 100-kyr G-IG cycles, particularly during the last four cycles^{1,2}. A distinct global climatic shift, called the Mid-Brunhes Event (MBE), occurred at Marine Isotope Stage (MIS) 11/12, which coincides with the largest fluctuation in amplitudes of benthic $\delta^{18}\text{O}$ values over the Quaternary^{1,3}. During the interglacial periods since the MBE, the Antarctic ice core records showed warmer air temperatures and higher atmospheric CO_2 concentrations, compared with those in earlier interglacial periods^{4,5}. Lang and Wolff (2011)⁶ suggested, based on the diverse paleoclimatic data collected from south of ~60°N, that the MBE was a global event related to the stronger interglacials and terminations during the last ~450 kyrs. In contrast, the climatic amplitudes during the glacial periods remain less pronounced.

Although climate change during the MBE has been reported worldwide from the terrestrial, marine, and ice core records, only a few studies have been conducted in the Arctic Ocean where the climatic changes fluctuated more severely than the other oceans⁷. For example, based on the Mg/Ca ratios in ostracodes from the western Arctic Ocean sediments, Cronin et al. (2017)⁸ reported that the thermal maximum events during the transitions from the interglacial to glacial periods since the MBE were related to the inflow of warm Atlantic Water, i.e., enhanced Arctic amplification. Xiao et al. (2020)⁹ suggested that preservation of calcareous microfossils improved across the MBE in the western Arctic Ocean. This phenomenon is related to the decrease in organic matter export and/or weakened bottom water ventilation along with the development of perennial sea ice. In general, the climatic shift across the interglacial-terminations since the MBE was intensified, but the climate changes during the glacial periods across the MBE are poorly resolved. Such a lack of information is typical of the Arctic Ocean, where calcareous microfossil preservation is poor during the glacial periods¹⁰.

This study examined the geochemical and mineralogical proxies of core ARC5-MA01 (hereafter MA01) in terms of terrigenous sedimentation to reveal the paleoenvironmental changes by orbital-scale glacial activities during the last ~840 kyrs in the northern Mendeleev Ridge of the western Arctic Ocean. Our results revealed an increase of North American terrigenous input to the western Arctic Ocean since the MBE, supporting a global climatic amplification since the MBE.

Results

The geochemical results of MA01 clearly show the G-IG cyclic variations during the last ~840 kyrs (Figs. 1 and 2). Biogenic opal contents (from 1.2 to 7.4% with an average of 3.1%) were higher during interglacial periods (Fig. 2 and Table 2). Total organic carbon (TOC) contents (from 0 to 0.55%) increased from the glacial periods (*ca.* 0.06%) to the interglacial periods (*ca.* 0.08%) (Fig. 2 and Table 2). In particular, TOC contents were higher and more variable since MIS 11. C/N ratios are higher during the interglacial periods (*ca.* ~1.6) than during the glacial periods (*ca.* ~1.1). Their variations are similar to TOC contents, following higher fluctuations since MIS 11 (Fig. 2). Similar to the biogenic opal and TOC contents, the interglacial $\delta^{13}\text{C}_{\text{org}}$ values (-23.9‰ on average) are higher than the glacial values (-24.5‰ on average) (Fig. 2 and Table 2). Interestingly, CaCO_3 content (0.4 to 26.2%) associated with dolomite increases since

MIS 16 (Fig. 2). Its average content was higher during the interglacial periods, together with greater fluctuations since MIS 11 (Fig. 2 and Table 2).

Table 1
List of cores in this study and reference cited.

Core site	Area	Latitude	Longitude	Water depth (m)	Reference
ARC5-MA01	Mendeleev Ridge	82° 01.86' N	178° 57.60' E	2,295	This study , Xiao et al., 2020 ⁹
HLY0501-JPC6	Chukchi-Alaskan margin	72° 30.71' N	157° 02.08' W	673	Ortiz et al., 2009 ²⁴
MR09-03 PC04	Chukchi Slope	74° 26.30 N	165° 44.30' W	370	Park et al., 2017 ¹³
MR09-03 PC01	Chukchi Slope	75° 28.10' N	165° 40.40' W	558	Park et al., 2017 ¹³
MR08-04 PC1	Northwind Ridge	74° 48.50' N	158° 31.85' W	998	Rella and Uchida, 2011 ¹⁶
ARC4-BN05	Canada Basin	80° 29.04' N	161° 27.90' W	3,156	Dong et al., 2017 ¹⁹
ARC5-ICE6	Makarov Basin	83° 37.69' N	161° 45.84' E	2,901	Xiao et al., 2021 ²¹
PS2178-5	Makarov Basin	88° 01.50' N	159° 42.20' E	4,008	Schubert and Stein, 1997 ¹¹
PS2185-6	Lomonosov Ridge	87° 32.20' N	144° 55.60' E	1,052	Schubert and Stein, 1997 ¹¹
PS2174-5	Amundsen Basin	87° 29.10' N	91° 32.60' E	4,427	Schubert and Stein, 1997 ¹¹

Table 2

Statistical summary of geochemical and mineralogical results of MA01 for interglacial and glacial periods during the last ~840 ky and post-MBE (after 424 ka) and pre-MBE (before 424 ka).

		B-opal (%)	TOC (%)	C/N	$\delta^{13}\text{C}_{\text{org}}$ (‰)	CaCO_3 (%)	PF (#/g/10 ³)	>154 mm (%)	Kaolinite (%)	Smectite (%)	Illite (%)	Chlorite (%)
Interglacial (MIS 1, 3, ..., and 21)	Average	3.2	0.08	1.6	-23.9	3.6	0.98	2.4	16	7	58	20
	Min	1.2	0.00	0.0	-25.6	0.4	0	0.3	11	1	38	17
	Max	7.4	0.55	15.4	-22.8	26.2	9.61	17.4	29	14	65	25
	Std.	1.0	0.10	2.0	0.7	4.0	1.73	2.6	4	2	5	2
Glacial (MIS 2, 4, ..., and 20)	Average	3.0	0.06	1.1	-24.5	2.4	0.10	2.4	14	6	60	20
	Min	1.2	0.00	0.0	-25.7	0.5	0	0.3	11	2	47	15
	Max	5.0	0.35	7.8	-23.2	12.1	2.14	30.1	23	16	65	23
	Std.	0.7	0.06	1.3	0.6	2.4	0.39	3.5	2	3	4	2
Post-MBE interglacial (MIS 1, 3, ..., and 11)	Average	3.1	0.14	2.7	-23.9	5.6	1.92	3.7	18	7	56	20
	Min	1.2	0.00	0.0	-25.6	0.4	0	0.5	12	1	38	17
	Max	7.4	0.55	15.4	-22.8	26.2	9.61	17.4	29	14	64	25
	Std.	1.0	0.11	2.3	0.7	4.7	2.02	2.9	5	3	6	2
Post-MBE glacial (MIS 2, 4, ..., and 10)	Average	2.7	0.10	2.1	-24.5	3.5	0.30	4.3	16	5	59	21
	Min	1.2	0.03	0.6	-25.7	0.7	0	0.5	13	2	47	19
	Max	4.6	0.35	7.8	-23.2	11.7	2.14	30.1	23	8	65	23
	Std.	0.8	0.07	1.6	0.8	3.0	0.65	5.5	3	2	5	1
Pre-MBE interglacial (MIS 13, 15, ..., and 21)	Average	3.2	0.03	0.5	-24.0	1.6	0	1.2	13	7	60	20
	Min	1.6	0.00	0.0	-25.2	0.7	0	0.3	11	2	56	17
	Max	7.1	0.19	3.9	-23.4	8.7	0.01	9.8	17	10	65	24
	Std.	0.9	0.03	0.5	0.5	1.3	0	1.5	1	2	2	1
Pre-MBE glacial (MIS 12, 14, ..., and 20)	Average	3.1	0.03	0.7	-24.4	1.9	0	1.5	13	7	60	20
	Min	2.0	0.00	0.0	-25.2	0.5	0	0.29	11	3	51	15
	Max	5.0	0.16	4.1	-23.7	12.1	0.01	7.02	18	16	64	23
	Std.	3.2	0.03	1.6	-23.9	3.6	0.98	2.43	16	7	58	20

C/N ratio is positively correlated with TOC content during the interglacial periods ($r^2=0.88$), particularly strong during the glacial periods ($r^2=0.97$) (Fig. 3). It is also positively correlated with CaCO_3 content between the interglacial ($r^2=0.70$) and glacial ($r^2=0.60$) periods (Fig. 3). Modest correlation is observed between TOC and CaCO_3 contents ($r^2=0.55\sim0.59$), regardless of the G-IG cycles (Fig. 3). On the other hand, $\delta^{13}\text{C}_{\text{org}}$ values are very poorly correlated with either C/N ratio ($r^2<0.01$) or TOC content ($r^2<0.01$). Nonetheless, several low $\delta^{13}\text{C}_{\text{org}}$ values ($<-25\text{‰}$) coincide with the peaks of CaCO_3 content during MIS 16, 13, and 8 to 7 (Fig. 2).

The relative contents of the four major clay minerals show that illite (38-65%, average 59%) was the most abundant. The other clay minerals (kaolinite, chlorite, and smectite) occupied 15% (11-29%), 20% (15-25%), and 6% (1-16%) on average, respectively (Fig. 4 and Supplementary Fig. S1). Despite the low resolution, the clay minerals of MA01 appeared to show G-IG cyclic variations during the last ~840 kyrs (Fig. 4). Although the variation pattern seems similar among kaolinite, smectite, and chlorite, it is noticed that smectite and kaolinite contents increased during the interglacial periods, particularly since MIS 11, similar to the pattern of geochemical proxies (Fig. 5). These variations were differentiated more clearly between the glacial and interglacial periods since the MBE (Fig. 5; Table 2).

Based on carbonate quantification, most TIC consists of dolomite during the last ~840 kyrs (Figs. 2 and 4). The calcite accounts partly for TIC during the warm periods since MIS 7, corresponding to the peaks of planktonic foraminiferal abundance (Fig. 4). In addition, CaCO_3 peaks associated with dolomite peaks during MIS 16, 13, 7, 5, and 3 coincide with the intervals of high kaolinite contents and coarse fractions (Fig. 4).

Discussion

Glacial-interglacial changes of geochemical and mineralogical proxies in the northern Mendeleev Ridge during the last 840 kyrs

The geochemical proxies of core MA01 were characterized by G-IG cycles and, particularly, by the long-term change during the last ~840 kyrs (Fig. 2). The biogenic opal content, representing the primary productivity of the surface seawater, is low (3.1% on average), which was attributed to the year-round sea ice cover in the central western Arctic Ocean^{11,12}. Such a low biogenic opal content is similar to those in the cores from the central-to-eastern Arctic Ocean (~2-4% on average)¹¹ and the Chukchi Rise (3.7-4.4% on average)¹³ located northwest and southeast to the Mendeleev Ridge, respectively. In the Northwind Ridge, based on foraminiferal assemblages, Polyak et al. (2013)¹² reported that the perennial sea ice condition was established at ~0.8 Ma. This is consistent with the overall low primary productivity in the present study, suggesting that the northern Mendeleev Ridge was covered dominantly with perennial sea ice during the last ~840 ka. Despite low, the biogenic opal content in this study was slightly different between glacial and interglacial periods, particularly higher (up to ~7.4%) during MIS 5, 7, and 13 (Fig. 2). Such difference between the glacial and interglacial periods was also reported from the central Arctic Ocean¹¹ and the Chukchi Rise¹³. Schubert and Stein (1996)¹¹ attributed that the low biogenic opal content during the glacial periods was attributed to both the reduced marine productivity and the increased input of terrigenous sediments. The lower biogenic opal content in the northern Mendeleev Ridge during the glacial periods can be explained in a similar reason to Schubert and Stein (1996)¹¹. Thus, based on the occurrence of planktonic foraminiferal tests in MA01 which is in line with the G-IG variability of the biogenic opal content during the last ~840 kyrs (Figs. 2 and 4), the surface water conditions in the northern Mendeleev Ridge were different between the glacial and interglacial periods.

TOC content and C/N ratio also represent the G-IG changes in the surface water conditions in the northern Mendeleev Ridge (Fig. 2 and Table 2). Similar to the biogenic opal content, the TOC content exhibited G-IG variability characterized by a high and low content during interglacial and glacial periods, respectively. Despite the generally low C/N ratios due to the low TOC content and, thus, its dominant effect on total nitrogen¹⁴, the strong positive correlation ($r^2=0.88$ for interglacial periods and $r^2=0.97$ for glacial periods) between TOC contents and C/N ratios indicates that higher TOC contents were attributed to higher contribution of terrestrial organic matter than the enhanced surface water productivity in the northern Mendeleev Ridge (Figs. 2 and 3). The strong contribution of terrestrial organic matter in the northern Mendeleev Ridge is supported by the generally low $\delta^{13}\text{C}_{\text{org}}$ values (Fig. 2). Previous studies also reported a higher input of terrestrial organic matter during the glacial periods in the western Arctic Ocean^{15,16}. Yamamoto and Polyak (2009)¹⁵ suggested that the increased input of terrestrial organic matter during the cold periods in the southern Mendeleev Ridge was associated with the more efficient transport of glaciogenic fine-grained particles from the continent to the western Arctic Ocean. In the Chukchi Borderland, the increase in TOC content was mostly associated with the low coarse-grained (>150 μm) fraction during the cold periods, whereas the marine production of organic carbon more likely increased during the warm periods¹⁶. In contrast, our record from the northern Mendeleev Ridge shows higher TOC content during the interglacial periods rather than the glacial periods (Figs. 2 and 4).

Rella and Uchida (2011)¹⁶ reported that TOC content was negatively correlated with CaCO_3 and coarse fraction contents in the Chukchi Borderland. For example, the high TOC content was accompanied by a low CaCO_3 and coarse fraction contents, which resulted from the transport of terrestrial organic matter from CaCO_3 -poor areas such as Siberian margins and/or the less CaCO_3 transport to the Chukchi Borderland. In contrast, the geochemical results of this study showed that CaCO_3 content was positively correlated with TOC content ($r^2=0.55-59$) and C/N ratio ($r^2=0.60-70$) (Fig. 3). Hence, CaCO_3 and TOC contents are mainly terrigenous in origin, similar to studies in the eastern-central Arctic Ocean^{11,17}. Such terrigenous contributions are evidenced by the peaks of the coarse fraction and dolomite contents (Figs. 2 and 4). This suggests that the inorganic carbon components, consisting mostly of dolomite, originate mainly from the Canadian Arctic Archipelago and Mackenzie watershed^{9,13,18,19}. Thus, the terrigenous input in MA01 was sourced mainly from northern North America. These findings suggest that the regions far from the continental shelf in the western Arctic Ocean are affected more by sediment deposition from North America than the Siberian margin. Such increased terrigenous input requires an enhanced Beaufort Gyre in the western Arctic Ocean, leading to the transport of more sediments from North America to the northern Mendeleev

Ridge²⁰. Thus, the geochemical and bulk mineral results of MA01 indicate that sediment transport from North America to the western Arctic Ocean, which generally stagnated during the glacial periods, was activated during the deglacial and stadial periods.

The strong G-IG variabilities were also observed in the variation of the major clay mineral compositions of MA01 (Fig. 4 and Supplementary Fig. S1). The overall predominance of illite is in good accord with previous studies in the western Arctic Ocean^{13,19}. Nonetheless, the other minor clay minerals have been used for the provenance studies^{13,19,21}. Smectite content in the western Arctic Ocean is very low due to its long distance from the main source areas in the eastern Arctic margins^{13,19,22}, although the content is relatively high in the central-western Arctic Ocean^{21,23}. Similar to this study in the northern Mendeleev Ridge, the very low smectite content was reported from the Chukchi Rise (7-9% on average)¹³ and the Canada Basin (3% on average)¹⁹ in the western Arctic Ocean. Despite the low content, the smectite content of MA01 seems different between the glacial and interglacial periods since the MBE (Fig. 4).

In the Chukchi-Alaskan Slope, chlorite was used as a proxy for the Pacific inflow through the Bering Strait²⁴. On the other hand, chlorite is also distributed abundantly in the East Siberian margin¹⁴. Due to the wide distribution of chlorite along the continental margins of the western Arctic Ocean, its G-IG cycles were less detectable in the Chukchi Rise¹³ and Canada Basin¹⁹ and the northern Mendeleev Ridge of this study area (Fig. 4 and Table 2). In comparison, kaolinite in the western Arctic Ocean reflects a specific source area, i.e., northern Canada and Alaska²⁵. Moreover, its content was fairly variable among the clay mineral assemblage in the Chukchi Rise and Canada Basin^{13,19}. Similarly, the kaolinite content of MA01 showed strong G-IG variability (Figs. 4 and 5; Table 2). Recently, Xiao et al. (2021)²¹ argued that the kaolinite was transported from Franz Joseph Land in the Barents Sea to the Makarov Basin at several glacial/deglacial events including MIS 6 and 4/3. However, no prominent kaolinite peak was observed at these events in MA01 (Fig. 4), presumably due to the different sedimentation regimes between the northern Mendeleev Ridge and the Makarov Basin. The distinct kaolinite peaks of MA01 coincided with the detrital carbonate peaks (e.g., calcite, dolomite, and XRF-Ca/Al) indicative of the enhanced terrigenous input from North America during MIS 16, 13, 7, 5, and 3 (Figs. 2 and 4). This suggests that the clay-sized particles were also delivered with the coarse fraction from North America to the northern Mendeleev Ridge.

Park et al. (2017)¹³ attributed the high kaolinite content in the Chukchi Rise to more terrigenous input from North America. The terrigenous input was more active during the deglacial period than the peak glacial period when the terrestrial glaciation and sea ice were most intensive^{13,26}, which strongly reduced sediment transportation to the western Arctic Ocean^{27,28}. Accordingly, in the northern Mendeleev Ridge, the terrigenous input increased during the deglacial periods and/or interglacial periods when more terrigenous sediments could be transported efficiently from North America via iceberg and/or sea ice in open water condition.

Increased terrigenous input to the northern Mendeleev Ridge since the MBE and its paleoenvironmental implications

The geochemical and mineralogical results of MA01 show an amplification of G-IG contrast across the MBE (Fig. 5 and Table 2). Particularly, TOC and CaCO₃ contents, C/N ratio, and kaolinite content associated with the dolomite peaks were distinctly high during the post-MBE interglacial periods, suggesting the enhanced terrigenous input from North America (Figs. 2, 4, and 5 and Table 2). The terrestrial and marine records as well as modeling results suggest that the continental ice sheets in North America grew remarkably during the late Quaternary^{29–32}. In the northern North Atlantic, glaciogenic marine sediments were observed since the Pliocene-Pleistocene transition, while the detrital carbonate sediments from North America started to appear since MIS 16³³. Similarly, in the western Arctic Ocean, detrital carbonate occurred distinctly since MIS 16, indicating an expansion of the North American ice sheets^{9,34}. Hence, the sediment input that originated from North America to the western Arctic Ocean increased during the middle Pleistocene as a result of the development of the North American ice sheets. Such increased terrigenous input to the northern Mendeleev Ridge was evidenced by our multiproxy results that were characterized by the more distinct G-IG fluctuation since the MBE (Fig. 5 and Table 2), while the first extensive development of the North American ice sheets occurred at MIS 16 (Fig. 4).

Many records regarding the climatic shift during the post-MBE (since MIS 11) are distinguished by the strong interglacial conditions represented by warmer seawater temperatures, higher atmospheric CO₂ concentrations, and smaller ice volume^{1,4–6,35}. One possible explanation to the MBE is the gradual removal of continental regoliths in the Northern Hemisphere during the Quaternary^{36,37}. Regolith removal, resulting from the repeated glaciation, facilitated silicate weathering of the freshly exposed bedrocks, accelerating the removal of atmospheric CO₂ concentration, which enhanced global cooling by positive feedback^{36–38}. Clark et al. (2006)³⁶ reported that the long-term climate change superimposed G-IG cycles during the Quaternary is closely linked to the increase in ice volume since the early

Pleistocene. This successive climatic evolution eventually occurred globally as the change in G-IG cycles from ~41 kyrs to ~100 kyrs during the middle Pleistocene (~700 ka)³⁶. Based on the geochemical and mineralogical proxies of MA01, such climatic changes related to the ice sheet development on North America occurred first in the northern Mendeleev Ridge at MIS 16 (~640 ka) and fluctuated distinctly since the MBE (Figs. 2, 4, and 5). Hence, these results support the regolith removal hypothesis because the terrestrial-origin sediment deposition increased since the MBE as a result of the development of the North American ice sheets adjacent to the western Arctic Ocean. The remaining question is why more terrigenous sediments were deposited during the interglacial periods in the northern Mendeleev Ridge of the western Arctic Ocean.

The cooling in the northern Mendeleev Ridge across the MBE can be found not only by the increase in terrigenous input but also by the change in the surface water conditions. Although the cause of the changes in calcareous microfossil abundance in the central-to-western Arctic Ocean remains unclear^{38,39}, distinct G-IG contrast of surface water conditions are inferred by biogenic opal content and planktonic foraminiferal abundance of MA01 since MBE (Figs. 2, 4, and 5). The G-IG contrast was particularly amplified since MIS 11 with a decrease (2.7% on average) of biogenic opal content during the glacial periods (Fig. 5; Table 2), which indicates post-MBE colder glacial conditions. Such productivity difference seems to be related to the difference in seawater temperature and sea ice cover between the glacial and interglacial periods. Cronin et al. (2019)⁴⁰ suggested that perennial sea ice developed during the interglacial period across the MBE based on the calcareous microfossil assemblages representing the faunal transition in the western Arctic Ocean. The thick perennial sea ice conditions were settled during the glacial periods⁴⁰, corroborating the gradual cooling regime across the MBE in the northern Mendeleev Ridge. Based on the changes in the microfossil abundance in the central-western Arctic Ocean, Marzen et al. (2016)³⁹ reported that the sea-ice related productivity increased during the interstadial periods since the MBE, with modulation by ~100 kyrs of G-IG cycles. This suggests that the climate variability was more sensitive in the central-western Arctic Ocean during the strong interstadials compared to the global climate variability³⁹. Due to the high sensitivity to climate change, not only 100 kyr cycle of the G-IG contrast but also shorter (<20 kyrs) stadial/interstadial variations were recorded in the northern Mendeleev Ridge, leading to more terrigenous input during the interglacial periods. Such high sensitivity to climate change from global cooling eventually occurred as a distinct G-IG contrast in the northern Mendeleev Ridge since the MBE. Continuous regolith removal during the Quaternary has been accelerated since the middle Pleistocene³⁷. Such conditions supplied more terrestrial sediments to the northern Mendeleev Ridge in the western Arctic Ocean during the warmer and more extended post-MBE interglacial periods and multiple stadial/interstadial transitions.

Conclusions

In this study, diverse geochemical and mineralogical proxies of MA01 were analyzed to track paleoenvironmental changes in terms of the terrigenous sediment deposition related to the glacial history during the G-IG climatic changes over the last ~840 kyrs. The overall features of the geochemical and mineralogical results in the northern Mendeleev Ridge accorded with the previous results reported in other regions of the western Arctic Ocean. On the other hand, the partial difference from the central-western Arctic Ocean was attributed to the regional difference in the depositional environment. The most significant differences between the glacial and interglacial periods were the terrigenous input from North America and the sea surface conditions during the post-MBE. This finding aligns well with the regolith removal hypothesis, which has been proposed as one of the primary causes of global cooling and the completion of ~100 G-IG world during the Pleistocene. This study suggests that the post-MBE G-IG contrast in the northern Mendeleev Ridge resulted from global cooling and internal positive feedback, both of which are closely related to the cryospheric development in North America. Strong G-IG contrast during the post-MBE was observed in the northern Mendeleev Ridge. Nevertheless, diverse regional effects should be considered using other paleoceanographic proxies to understand better the paleoenvironmental history in the western Arctic Ocean.

Materials And Methods

A 5.35 m-long gravity core MA01 was taken from the northern Mendeleev Ridge (178°58'E 82°02'N, 2,295 m deep) by R/V Xue Long during scientific cruise CHINARE-V in 2012 (Fig. 1). Core sediments were subsampled at 2 cm intervals at Tongji University (China) and ground after freeze-drying at Pusan National University (Korea) for laboratory analyses. Xiao et al. (2020)⁹ reported the color reflectance, bulk elemental composition, coarse fraction (>150 µm), foraminiferal abundance, AMS ¹⁴C dating, and paleomagnetic inclination of MA01. The stratigraphy of MA01 was determined to be ~840 ka by lithostratigraphic and biostratigraphic regional correlations and tuning of Mn content to the global climate variability⁹. We note that, the tuning-based stratigraphy before MIS 6 is

tentative due to the lack of identifiable stratigraphic marker to constrain the Mn variability⁹. This study used the same age model to interpret the data of MA01.

Geochemical measurements

Geochemical properties were analyzed on a total of 271 samples. Biogenic silica (Si_{BIO}) content was measured using the molybdate blue spectrophotometer following the wet-alkaline sequential extraction method modified from DeMaster (1981)⁴¹. The biogenic opal content was calculated by multiplying Si_{BIO} by 2.4⁴². The analytical error of biogenic opal content is less than $\pm 1\%$.

Total inorganic carbon (TIC) content was measured using an UIC CO_2 Coulometer CM5014. The analytical error of TIC was $\pm 0.1\%$ as a relative standard deviation. CaCO_3 content was calculated by multiplying TIC contents by 8.333 (C to CaCO_3 ratio). Total carbon (TC) and total nitrogen (TN) contents were measured using an elemental analyzer (Flash 2000). The analytical errors were less than $\pm 0.1\%$ and $\pm 0.01\%$, respectively. TOC content was calculated as the difference between TC and TIC and C/N ratio was calculated by TOC/TN.

Carbon isotope of sediment organic matter ($\delta^{13}\text{C}_{\text{org}}$) was measured from 82 horizons using Europa Scientific 20-20 Elemental Analyser-Isotopes Ratio Mass Spectrometer (IRMS) at Iso-Analytical Ltd (UK). The expressed conventional delta notation is per mil deviation from the Vienna Pee Dee Belemnite (V-PDB) for the carbon isotope. Precision for carbon isotope was $\pm 0.1\text{‰}$.

Clay mineral analysis

Major clay mineral compositions (smectite ($17\text{\AA}$), illite ($10\text{\AA}$), kaolinite, and chlorite ($7.1\text{\AA}$)) of fine-grained sediments were measured for 90 samples. Organic matter of bulk sediments was removed using 6% hydrogen peroxide solution. After wet-sieving through a $63\text{ }\mu\text{m}$ mesh, clay particles ($<2\text{ }\mu\text{m}$) were extracted using a settling technique based on Stoke's Law. The extracted clays were applied on glass slide into orientation⁴². The air-dried slides were scanned using X-ray diffractometer (XRD; SIEMENS/BRUKER D5005) at Gyeongsang National University (Korea) and repeated after ethylene glycol-saturating at 60°C during 24 hours⁴⁴. The relative contents of the four major clay minerals were calculated semi-quantitatively according to the scheme reported by Biscaye (1965)⁴⁵. The proportion of kaolinite and chlorite was determined from their peak areas ($3.58\text{\AA}$ and $3.54\text{\AA}$), respectively⁴⁶.

Quantitative analysis for carbonates

The contents of carbonate minerals (calcite and dolomite) were quantified for the 14 selected samples based on the prominent peaks of coarse fraction and TIC content. The bulk sediment powders were analyzed using the same XRD. According to the assumption that the carbonate minerals of the Arctic Ocean sediments consist mostly of calcite and dolomite³⁴, TIC content was divided simply into calcite and dolomite proportions as below.

$$\text{calcite (\%)} = \frac{\text{RI}_{\text{calcite}}}{(\text{RI}_{\text{calcite}} + \text{RI}_{\text{dolomite}})} \times \text{TIC} \times 8.333$$

$$\text{dolomite (\%)} = \frac{\text{RI}_{\text{dolomite}}}{(\text{RI}_{\text{calcite}} + \text{RI}_{\text{dolomite}})} \times \text{TIC} \times 7.67$$

where RI represents relative intensity of calcite ($3.04\text{\AA}$) and dolomite ($2.89\text{\AA}$).

Declarations

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Author Contributions

B.K.K. designed the research plan and was responsible for the experimental plan and data acquisition. K.P. is responsible for obtaining the laboratory experiments, interpreting analytical data, and writing the draft with the assistance of all authors. R.W. and W.X. provided the sediment samples and previous data in addition to the discussion with L.P. and H.G.C.

Competing interest: The authors declare that they have no competing interests.

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Figures

Figure 1

Geographic map showing the locations of cores in this study (ARC5-MA01) and referenced sites in the text (Table 1). The black arrows represent large-scale surface circulation system; clockwise Beaufort Gyre in the western Arctic Ocean and Transpolar Drift flowing from the Siberian shelves into the Fram Strait. BeS=Beaufort Sea; CS=Chukchi Sea; ESS=East Siberian Sea; LS=Laptev Sea; KS=Kara Sea; BaS=Barents Sea; ChB=Chukchi Borderland; CaB=Canada Basin; MB=Makarov Basin; AB=Amudsen Basin; NB=Nansen Basin; MR=Mendeleev Ridge; AR=Alpha Ridge; LR=Lomonosov Ridge; GR=Gakkel Ridge.

Figure 2

Downcore variation of the geochemical results (biogenic opal, TOC, C/N, $\delta^{13}\text{C}_{\text{org}}$, and CaCO_3) of core ARC5-MA01 along with global benthic $\delta^{18}\text{O}$ values¹ and North American ice volume (m.s.l.e.)³⁰. Marine isotope stages (MIS) are indicated with blue shadings of glacial periods.

Figure 3

Cross-plots between the geochemical results of core ARC5-MA01. (a) C/N vs. TOC, (b) C/N vs. CaCO₃, and (c) TOC vs. CaCO₃ with their correlation coefficient (r^2) during the glacial (red) and interglacial (black) periods, respectively.

Figure 4

Downcore variation of mineralogical (four major clay minerals; kaolinite, smectite, illite, chlorite, and calcite and dolomite contents) results, XRF Ca/Al ratio, planktonic foraminiferal (P.F.) abundance⁹, and coarse-grained (>154 μm) fraction⁹ of core ARC5-MA01 along with global benthic δ¹⁸O values¹ and North American ice volume (m.s.l.e.)³⁰. Marine isotope stages (MIS) are indicated with the blue shadings of glacial periods. Please refer to the supplementary Fig. S1 for detailed downcore variations of the major clay mineral contents.

Figure 5

Box-Whisker plots showing the normalized intensity values of the geochemical (biogenic opal, TOC, C/N, $\delta^{13}\text{C}_{\text{org}}$, and CaCO_3), planktonic foraminifera (P.F.), and mineralogical (kaolinite, smectite, illite, and chlorite) data of core ARC5-MA01 for (a) the last ~840 kyrs, (b) the post-MBE, and (c) the pre-MBE, respectively. The interquartile ranges multiplied by a factor of 1.5 are indicated as error bars. Red and blue boxes represent the interglacial and glacial periods, respectively.

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