Mineralogy and geochemistry of ferromanganese oxide deposits from the Chukchi Sea in the Arctic Ocean

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**ABSTRACT**

Abundant ferromanganese oxide deposits were recovered from the Chukchi Sea in the Arctic Ocean during the 7th Chinese Arctic Scientific Expedition in August 2016. Representative samples were collected to perform a mineralogical and geochemical analysis and elucidate their origin. Their mineral phases consist of todorokite, buserite, and birnessite, along with a small quantity of detrital minerals (quartz, feldspar, serpentine, kaolinite, and illite). Their elemental composition is rich in Ni and Mn compared to ferromanganese oxide deposits from other locations in the Chukchi Sea. The total rare earth element (REE) concentration varied from 138.95 to 207.23 μg/g with an average of 164.75 μg/g. The post-Archean Australian shale–normalized REE patterns have a slightly negative Ce anomaly and a positive Eu anomaly. The comprehensive geochemical and mineral data show that they have a mixed hydrothermal and diagenetic origin.

**Introduction**

Marine ferromanganese oxide deposits occur on the seafloors and in different forms (Hein et al. 1997). The interest in these deposits lies in the possibility to enrich many potentially economic elements and to understand the past environmental changes of the Earth (Hein et al. 2013; González et al. 2016). Such deposits are formed through three end-member processes: hydrothermalism, diagenesis, and hydrogenesis (Hein et al. 1997). Hydrogenetic deposits mainly consist of Fe vernadite and birnessite and are enriched in critical elements like Co, Te, and Mo, whereas hydrothermal and diagenetic deposits often contain todorokite, asbolane, and buserite and are concentrated in Ni, Cu, Zn, and Li (Marino et al. 2019 and references therein). The ferromanganese oxide deposits in the Pacific, Indian, and Atlantic oceans have been extensively explored (Hein et al. 1997; Hein and Koschinsky 2014), but ferromanganese oxide deposits in the Arctic Ocean still remain largely unexplored because of the remote location.

Ferromanganese oxide deposits in the Arctic Ocean were first reported and named “nodule” by Nordenskiöld in 1881. With the development of new technologies, such as ice-breakers and submarines, more and more Arctic ferromanganese materials including crusts and nodules have been collected in many places, including the Mendeleev Ridge (Baturin et al. 2014; Konstantinova et al. 2017), the Alpha Ridge (Stoffyn-Egli 1987), the Amerasian Basin (Brumley et al. 2013; Hein et al. 2017), the Barents Sea (Ingrí 1985), the Kara Sea (Bogdanov et al. 1995; Baturin 2011; Vereshchagina et al. 2019), the Chukchi Sea (Baturin and Dubinchuk 2011; Kolesnik and Kolesnik 2013, 2015), and other sites in the Arctic Ocean (Baturin and Dubinchuk 2011; Hein et al. 2017).

The ferromanganese oxide deposits found on the seabed of the Chukchi Sea exist as various types, including nodules, ore crusts, and imbricated ferromanganese materials (Kolesnik and Kolesnik 2015). Most of them are nodules with different shapes, such as discoid, cake, and platy (Kolesnik and Kolesnik 2013, 2015). These nodules are characterized by a relatively high iron content compared to the manganese concentration (Kolesnik and Kolesnik 2013, 2015), except for the samples studied by Baturin and Dubinchuk (2011), which had equal amounts of iron and manganese.
The high manganese end-members of the ferroman-
ganese oxide deposits were first collected during
China’s seventh exploration of the Arctic Ocean aboard
the Xue Long research vessel in August 2016. The
purpose of our study is to better understand the nature
and the origin of the materials from this expedition.
Therefore, we analyzed the petrological, mineralogical,
and chemical composition of four samples from one
dredge haul in the Chukchi Sea.

The Chukchi Sea is a marginal sea of the Arctic
Ocean with an average 77 m water depth (Mazarovich
and Sokolov 2003), as illustrated in Figure 1. The
bathymetry shows the latitudinal submarine rises that
develop in the central part of the Chukchi Sea
(Panteleev et al. 2010). The channels between them
modify the flow paths of the Chukchi seawater north-
wards. Examples include the Herald Canyon between
Wrangel Island and Herald Shoal, the central channel
between Herald Shoal and Hanna Shoals, and Barrow
Canyon between the Hanna Shoals and Alaska (Winsor
and Chapman 2004; Panteleev et al. 2010).

Geologically, the central rise is the Wrangel Herald
Arch, and the depressions next to the central rise are
the south Chukchi Basin and the north Chukchi Basin
(Hill et al. 2007; Khain and Polyakova 2007). Chukchi
Sea receives many sediment loads from the peripheral
continental rivers, the Pacific inflow, and sea ice trans-
port (Viscosi-Shirley, Pisias, and Mammone 2003;
Eicken et al. 2005). The thickness of sediments can
reach 20 to 22 km (Gusev et al. 2009). These geo-
morphic features are controlled by the graben rift sys-

tem that started in the Mesozoic (Shipilov 1989;
Shipilov and Senin 1992). Recent research shows that
neotectonics in this zone are still active (Astakhov et al.
[2008] and references therein).

Materials and methods

The ferromangetic oxide deposits were dredged using
an Agassiz trawl at site R11 (168°50′50″ W, 73°46′11″
N; waterdepth: 153 m) in the Chukchi Sea. Their spatial
concentration is low (about 0.04 kg/m²). The represen-
tative specimens analyzed in this study are presented in
Figure 2 and their macroscopic morphology can be
described as follows:

Sample R11-2 is dark gray and has a trapezoidal
shape with a size of 1.4 × 5.5 × 5.4 cm. The
upper surface is rough and shows attached fila-
mentous organisms. The bottom surface shows
rough, oolitic, and micro-botryoidal textures with
siliceous ooze attached on it. The sample can be
divided into two sublayers and the total thickness of the sublayers ranges from 0.2 to 0.6 cm. The nucleus is made of an altered sedimentary pebble. Sample R11-4 has a size of 10 × 8 × 1.5 cm and is similar to sample R11-2 in shape and color. The upper surface shows rough, oolitic, and micro-botryoidal textures and the bottom surface is similar to sample R11-2. The sample section shows a single layer with an average thickness of 0.4 cm. The core is also made of an altered sedimentary pebble.

Sample R11-6 is also dark gray and has a cauliflower-like shape with a size of 4.8 × 4 × 1.3 cm. The upper surface is rough with attached filamentous organisms, whereas the bottom surface is similar to sample R11-2. The sample can be divided into two sublayers with a total layer thickness from 0.2 to 0.7 cm. The core is similar to that of the other samples.

Sample R11-7 is gray with a size of 5 × 4 × 2 cm, and the ferromanganese oxides are wrapped around quartz sandstone. The total thickness of the layers ranges from 0.2 to 0.5 cm.

All samples studied were cut into two pieces: One part was polished for microscopy and the other was dried at 60°C and ground in an agate mortar to a 200 μm mesh. One part of the powered samples was used to conduct the mineralogical analysis and the other fraction was used for the chemical analysis.

The bulk mineralogical analysis of the powered samples was performed using an X-ray diffractometer with Cu-Kα radiation and a graphite monochromator with 0.02° steps for 2θ within 3° to 75°. The subsamples of R11-4 were dried at 60, 75, 95, 150, and 300°C for 24 hours to obtain information on the thermal stability of the Mn phases. The content of the major elements (Fe, Mn, Al, Ca, Mg, K, Na, Ti, and P) was determined by inductively coupled plasma–atomic emission spectrometry. The trace elements (Ba, Co, Cu, Ni, Cr, Sr, V, Zn, Zr, Li, Be, Sc, Ga, Ge, Rb, Nb, Mo, Cd, In, Cs, Hf, Ta, W, Ti, Pb, Th, and U) and rare earth elements (including Y, REEY) were determined using inductively coupled plasma–mass spectrometry. Chinese cobalt-rich crusts standards GSMC-1, GSMC-2, and GSMC-3 were used to calibrate the elemental concentrations of the samples measured. The analytical precision was generally better than 5 percent. The polished sections were observed using a reflective polarizing microscope. All tests were carried out at the First Institute of Oceanography, Ministry of Mineral Resources in the People’s Republic of China.

REEY plots were normalized to a post-Archean Australian shale (PAAS; Pourmand, Dauphas, and

![Figure 2. Morphology of the ferromanganese deposits analyzed.](image-url)
Ireland 2012). The Ce anomaly (δCe or Ce/Ce*) is calculated from Ce_{SN}/Ce_{SN}^* = Ce_{SN}/0.5La_{SN} + 0.5Pr_{SN} where Ce_{SN}, La_{SN}, and Pr_{SN} are the values normalized by PAAS.

Results and discussion

Mineralogy

The powder X-ray diffraction patterns of the samples analyzed are presented in Figure 3a. The manganese minerals of the representative samples were mainly composed of 10 Å and 7 Å manganate. Figure 3b shows the X-ray diffraction patterns of sample R11-7 heated at different temperatures. Compared with the X-ray diffraction pattern at 60°C, heating at 95°C slightly decreased the intensity of the reflection at 10 Å and slightly increased the one at 7 Å, which indicated the thermal instability of the 10 Å manganates. The X-ray diffraction pattern of the samples dried at 150°C also shows the reflection peaks at 10 Å and 7 Å, which demonstrates that thermally stable 10 Å manganates occur in this sample. After drying at 300°C, the reflections at 10 Å and 7 Å were still present, which also indicated that there were thermally stable manganese minerals in these samples.

In addition, the diffraction peaks at 4.27 Å, 3.34 Å, 1.82 Å, 1.54 Å, 1.37 Å, and 3.2 Å indicated that the samples included a small amount of detrital minerals.

Geochemistry

The chemical compositions of the samples are listed in Table 1. They have high Mn contents (11.22–25.57 wt%) and low Fe contents (10.30–16.73 wt%) with Mn:Fe ratios of 0.67 to 2.45. The Si and Al contents range from 9.25 to 9.89 wt% and 2.21 to 3.44 wt%, respectively. The Ti concentration varies between 0.12 and 0.21 wt%. The P content is from 0.74 to 1.28 wt% with an average Ca:P ratio of around 1.45.

The Ba content, varying from 1,339 to 2,517 μg/g, was the highest of the trace elements. The Sr contents were also relatively high, at an average of 760 μg/g. The combined Cu, Co, and Ni contents varied from 475 to 989 μg/g with a mean of 623 μg/g. The V, Zn, and Mo contents were also high.

The total REE contents vary between 139 and 207 μg/g with a mean of 165 μg/g. The Ce concentrations range from 48 to 74 μg/g with an average of 58 μg/g. The samples contain Y at a mean concentration of 32 μg/g. The PAAS-normalized REE_{Y} patterns show a slight negative Ce anomaly and a positive Eu anomaly (Figure 4) as well as slight REE depletions.

The elemental concentrations also vary along the growth direction, which can be seen in sample 7R11-7. The older part (innerlayers) has a lower Fe content (10.70 wt%) compared to the younger outerlayers.
(16.73 w%). The Mn content showed an opposite pattern; that is, it was higher in the older part. The Ba, Co, Cu, and Ni contents have the same trend as Mn.

### Mineralogy of the bulk deposits

The X-ray diffraction data of the samples studied showed that they mainly consist of different 10 Å and 7 Å manganates. Iron phase minerals were not detected because of their amorphous nature or because they were beyond the detection limit. The strengite reported in other nodules from the Chukchi Sea by Kolesnik and Kolesnik (2013) was not found in our samples.

The 10 Å manganates include the buserite (Na₂Mn₄O₁₀(OH)₂ · 21H₂O) and the todorokite ((Ca,K,Na,Mg,Ba,Mn)(Mn,Mg,Al)₂O₁₂ · 3H₂O) series (Usui 1992). It is difficult to distinguish them by X-ray diffraction at room temperature because of their overlapping peaks. However, at about 100°C, buserite can contract to 7 Å manganates from the release of weakly bound H₂O in the interlayers (Lee and Xu 2016 and references therein), but todorokite keeps a stable structure up to 400°C (Lee and Xu 2016). Our results show that the peak spacing at ~10 Å slightly decreases, but it does not disappear when the temperature increases, which indicates that both buserite and todorokite were present in samples. The vernadite ((Mn,Fe,Ca,Na)(OH)₂ · nH₂O) and asbolane ((Ni,Co)₂₃Mn⁴⁺(OH)₄ · nH₂O) reported in other

|  | 7R11-2 | 7R11-4 | 7R11-6 | 7R11-7 outer layer | 7R11-7 inner layer | Mean | Median |
|---|---|---|---|---|---|---|---|
| Ti (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Fe (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Mn (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Al (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Mg (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ca (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Na (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| K (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ti (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| P (wt %) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ba (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Be (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Cd (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Co (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Cr (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Cs (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Cu (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ga (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ge (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Hf (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| In (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Li (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Mo (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Nb (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ni (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Pb (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Rb (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| S (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Sr (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ta (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Tl (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Th (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| U (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| V (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| W (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Y (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Zn (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Zr (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| La (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ce (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Nd (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Sm (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Eu (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Gd (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Tb (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Dy (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ho (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Er (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Tm (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Yb (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Lu (µg/g) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
Chukchi sea nodules by Baturin and Dubinchuk (2011) were not detected because of their low levels, similar X-ray diffraction patterns, or the limitations of the methodology employed.

The 7 Å manganate in marine nodules is normally referred to as birnessite \((\text{Na,Ca})_{0.5}(\text{Mn}^{4+},\text{Mn}^{3+})_2\text{O}_4 \cdot 1.5\text{H}_2\text{O})\) (Hein, Koschinsky, and McIintyre 2005). It is almost destroyed at 200°C (Lee and Xu 2016). The 7 Å peak spacing was significantly reduced above 200°C, which indicates the presence of birnessite in our samples. Our data also indicate that these samples contain accessory minerals, such as kaolinite, serpentine, and illite, as well as quartz and feldspar, which is consistent with the enrichment in yellow detrital matter in these samples.

**Geochemistry of the manganese deposits**

Mn dominates over Fe in the nodules studied, with Mn:Fe ratios from 1.0 to 2.5, which is consistent with the data from other Chukchi Sea nodules presented by Baturin and Dubinchuk (2011) but higher than those of Kolesnik and Kolesnik (2013, 2015), who reported Mn:Fe ratios of 0.02 to 0.42. The collection of variable data indicates that both low-manganese and high-manganese ferromanganese deposits are developing in the Chukchi Sea. The Si:Al ratios of the deposits analyzed range from 4.09 to 4.19, which falls into the range expected for Chukchi Sea sediments (Astakhov et al. 2008). It indicates that Si can incorporate into the nodules as detrital grains, which is supported by the presence of kaolinite, illite, serpentine, quartz, and feldspar.

The ferromanganese deposits from the Chukchi Sea studied have higher Ni, Cu, P, Rb, and U contents than those of the Clarion–Clipperton Zone nodules (Kuhn et al. 2017). The Fe content is also slightly higher, whereas the Co and Mn contents are lower. This also occurred for nodules of the Peru Basin (Hein and Koschinsky 2014). This could be induced by their mineral compositions because todorokite (buserite) can accommodate Ni\(^{2+}\), Cu\(^{2+}\), and other cations in the vacant sites (Hein and Koschinsky 2014).

The ferromanganese deposits studied have a lower total REE\(_Y\) content than the diagenetic and hydrogenetic nodules in the Clarion–Clipperton Zone of the Pacific Ocean (Menendez et al. 2019) but a higher content than that for hydrothermal deposits (Pelleter et al. 2017). The PAAS-normalized REE patterns for the nodules are characterized by slightly negative Ce and positive Eu. This is consistent with the diagenetic and hydrothermal deposits (Bau et al. 2014). The negative Ce anomaly is attributed to the influence of the hydrothermal fluid and digenesis (Elderfield and Greaves 1981). This process is controlled by kinetics (Takahashi et al. 2007). The positive Eu anomaly is induced by the higher temperature of the hydrothermal fluid (>200–250°C; Yamaoka et al. 2017 and references therein).

**Origin of the manganese nodules**

Ferromanganese deposits occur extensively in different oceanic settings of the seafloor. Based on the transition elements and other indexes, three main genetic end-
members have been determined, namely, hydrogenetic, hydrothermal, and diagenetic (Takematsu, Sato, and Okabe 1989; Bau et al. 2014; Josso et al. 2017). In general, hydrogenetic deposits are characterized by the presence of vernadite, a high Co content, and slow growth rates (Halbach et al. 1981). Diagenetic deposits have higher Mn:Fe ratios and are richer in Cu, Ni, and 10 Å manganate (Buserite) and poorer in Fe, Co, and vernadite than hydrogenetic ones (Halbach et al. 1981; Jung and Lee 1999). Hydrothermal deposits have the highest growth rates up to 125,000 mm/Ma (Hein et al. 2008), with todorokite as the main manganese mineral (Usui and Someya 1997).

The todorokite (buserite) and birnessite in the ferromanganese deposits studied suggest that they were formed through hydrothermal processes (Yamaoka et al. 2017) and diagenetic processes (Wegorzewski and Kuhn 2014). Additionally, all samples show a boundary between the diagenetic and hydrothermal deposits (Bau et al. 2014; Figure 5). The evidence indicates the mixed diagenetic and hydrothermal origin of the ferromanganese oxide deposits studied here.

The diagenesis can be easily confirmed by the elemental distribution in the depth along the cores, including an Mn enrichment in surface sediments (Trefry et al. 2014). The hydrothermal source is more difficult to define because of the lack of geological and oceanological studies in the Chukchi Sea. However, there are indirect clues suggesting that this region located in the active graben rift system of the Chukchi Sea, which started in the Mesozoic (Shipilov 1989; Shipilov and Senin 1992). First, the noble metals in the surface sediments have a patchy distribution along the intersection zone of the submeridional and subtitudinal structures of the graben rift system in this area (Astakhov et al. 2008, 2010). Additionally, the extremely high methane content at the seabed and the active mud volcanoes in the Chukchi Sea prove the modern geological activity of the graben rift system (Astakhov et al. [2010] and references therein). Finally, the large heat flow found in the Herald Canyon of about 203 ± 28 mW.m² (O’Regan et al. 2016) is probably related to the heat refraction from the highly conductive underlying structures.

The exact enriching mechanism of noble metals in Chukchi Sea remains debatable, but it could have been formed in an environment similar to that of the Gakkel Ridge (Astakhov et al. 2008). Additionally, this active structure induces the magmatism and hydrothermal activity in the onshore counterpart of the Chukchi graben rift system. The isotopic data show that the mantle-derived melt and the surface water contributed to the hydrothermal system (Polyak et al. 2008, 2013). We therefore conclude that the source of the heat and the hydrothermal fluid results from the interaction between the deep earth materials and the surface water.

Conclusion
A large variety of ferromanganese oxide deposits are found on the Chukchi Sea shelf. Their main crystalline phases include todorokite (buserite) and birnessite, with small amounts of kaolinite, serpentine, illite, quartz, and felspar. Their chemical composition indicates an enrichment in manganese and cobalt compared to ferromanganese oxides from other regions of the Chukchi Sea. Their genesis is probably the result of combined diagenesis and hydrothermalism.

Figure 5. Binary discrimination diagrams for the ferromanganese deposits from the Chukchi Sea, after Bau et al. (2014).
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Disclosure statement

No potential conflict of interest was reported by the authors.

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