On the discovery of ferromanganese nodules in the World Ocean

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Abstract: For a century, the discovery of ferromanganese (Fe-Mn) nodules in the World Ocean was universally and indisputably credited to the *Challenger* circum-global oceanographic expedition of 1872-1876, during which the first manganese nodules and crusts were dredged up from the sea floor in February-March 1873. A century later, a counterclaim appeared in the literature, crediting Nordenskiöld's expedition on *Sofia* in 1868, five years before the *Challenger* findings, for the discovery of Fe-Mn nodules in the ocean. This counterclaim, widely accepted without scrutiny, was based on the Gustaf Lindström (1884) chemical analysis of a single bottom sediment sample among 14 samples from two Arctic expeditions led by Nordenskiöld: *Sofia* 1868 and *Vega* 1878-1880. The Lindström (1884) report published as an eight-page brochure in Swedish remained almost unknown to the research community until now. A close examination of this report and other historical evidence revealed that the counterclaim of discovery by the *Sofia* 1868 expedition to the Kara Sea is invalid based on three notable facts: (1) *Sofia* never sailed in the Kara Sea; (2) the single bottom sediment sample with an extremely high content of Mn (24%), was collected in the Kara Sea during the *Vega* Expedition across the Northeast Passage; (3) the *Vega* sampling was in 1878, not in 1868. Meanwhile, five and a half years prior to the *Vega* sampling, the first Fe-Mn nodules and crusts were dredged up from the sea floor on 18 February and 7 March 1873 during the *Challenger* expedition. These findings have been promptly reported and published in May 1873. Thus, the credit for the discovery of ferromanganese nodules in the World Ocean firmly belongs to the *Challenger* expedition.

1. Introduction

Definition and description of Fe-Mn nodules and crusts. Deep-sea ferromanganese (Fe-Mn) ***nodules*** are typically round-shaped concretions, a few centimeters in diameter, enriched with Fe, Mn and other metals (thus often called *manganese* or *polymetallic* nodules) found predominantly on abyssal plains (3,000 to 6,000 m depth) throughout the World Ocean (Glasby, 2006; Hein and Koschinsky, 2014; Hein, 2016; Hein et al., 2017; Kuhn et al., 2017; Hein, Koschinsky, and Kuhn, 2020). Manganese nodules are defined by Hein (2016, p. 408) as follows:

> "Manganese and iron oxide mineral deposits formed on or just below the sediment-covered surface of the deep-ocean seabed by accretion (precipitation) of oxide layers around a nucleus, thereby forming nodules of various shapes and sizes and which contain minor but significant amounts of nickel, copper, cobalt, lithium, molybdenum, zirconium, and rare earth elements."

Unlike nodules that accrete around a nucleus, manganese ***crusts*** do not have such nuclei. Also, manganese crusts are found across a wider depth range, from 400 m to 7000 m, and are common on seamounts while nodules are common on abyssal plains.

<u>Discovery of Fe-Mn nodules and crusts.</u> For a century, the discovery of ferromanganese nodules in the World Ocean was universally and indisputably credited to the *Challenger* circum-global oceanographic expedition of 1872-1876 (e.g., Glasby, 1977; Baturin, 1988; Post, 1999; Baturin, 2000; Hein, 2016; Kuhn et al., 2017; Macdougall, 2019; Hein et al., 2020). Yet in 1978, a counterclaim appeared in a book review by Frank Manheim, crediting Nordenskiöld's expedition on *Sofia* in 1868, five years *<u>before</u>* the *Challenger* discovery in 1873, with the discovery of Fe-Mn nodules in the ocean. In his book review, Manheim (1978) wrote:

> "…it appears that the Challenger Expedition was not the first to find marine concretions. Lindstrom (1884) showed figures and reported analyses of nodules that were found east of Novaya Zemlya in the Kara Sea by the Sofia Expedition. The Sofia Expedition, under the scientific leadership of A. E. Nordenskiold, took place in 1868, and would therefore precede the Challenger deep sea finds by four years."

Mannheim's book review of 1978 is to the best of our knowledge the first known publication, in which Nordenskiöld's *Sofia* 1868 expedition is credited with the discovery of Fe-Mn nodules. This claim was repeated in a comprehensive report originally printed in 1989, updated and published online in 2014 (Manheim and Lane-Bostwick, 1989, p. 10):

> "The Challenger Expedition was not, as commonly assumed, the discovery voyage for marine ferromanganese concretions. That distinction seems to belong to a little-known and, from the scientific point of view, poorly documented Sofia Expedition of 1868, under leadership of the Swedish explorer, A.E. Nordenskiold (Manheim, 1978). The Sofia recovered nodules east of Novaya Zemlya in the Kara Sea, in less than 200m water depth. These were later analyzed chemically and reported by Lindstrom (1884)."

The above *counterclaim* of discovery was widely accepted by researchers and lay persons without any detailed examination of the original sources. The claim has been repeated in print and online ever since, apparently proliferating and propagating by way of "citation chain". A few examples are below:

> Ingri (1985, p. 101): "Since the Swedish Sofia expedition (1868) found ferromanganese nodules east of Novaya Zemlya in the Kara Sea…"
>
> Earney (1990, p. LX): "...marine nodules were not discovered until 1868, during the Sofia expedition led by A.E. Nordenskiöld; the nodules were recovered in the Kara Sea, east of Novaya Zemlya."
>
> Baturin (2000, p. 399): "Somewhat earlier [than *Challenger* in 1873], in 1868, during the Nordenskjold expedition on the Swedish vessel Sophia, some nodules were recovered from the Kara Sea bottom; however, this finding was considered insignificant and remained practically unknown (Manheim, 1965)."
>
> Glasby (2000, p. 356) and Glasby (2006, p. 393): "…these were the first marine Mn deposits to be discovered, during the 1868 Sofia expedition to the Kara Sea led by A.E. Nordenskiøld (Earney, 1990)."
>
> Malsow (2015, p. 1): "…the polymetallic manganese nodules … were discovered as early as 1868 by Swedish explorers (shallow water nodules) from the Kara Sea on board of the vessel Sophia."
>
> Neukirchen and Ries (2020, p. 246): "The nodules were discovered as early as 1868 in the Kara Sea."

> Ardron (2020, p. 3): "Nodules had been discovered a century earlier, in 1868 during the Swedish Nordenskold expedition in the Kara Sea. At the time, the discovery was deemed unimportant, went unpublished and therefore largely unknown (Baturin, 1999). As a result, Murray and Renard of the much better-known Challenger Expedition were for several decades (and frequently still are[7]) given credit for their (re-) discovery five years later, in 1873..."
>
> [7] E.g. The Geological Society website page on nodules, opens, "Deep-sea manganese nodules were first recovered in 1873 during the voyage of HMS Challenger. Yet their exploitation - until now - has remained uneconomic." https://www.geolsoc.org.uk/Geoscientist/Archive/May-2013/Treasures-from-the-abyss [Accessed Dec. 2019.]" [end of quote from Ardron (2020)]

Numerous Web sites repeat the same counterclaim. For example, the "*Manganese nodules*" article of www.Wikipedia.com states:

> "Polymetallic nodules were discovered in 1868 in the Kara Sea..." https://en.wikipedia.org/wiki/Manganese_nodule#:~:text=Polymetallic%20nodules%20were%20discovered%20in,most%20oceans%20of%20the%20world.

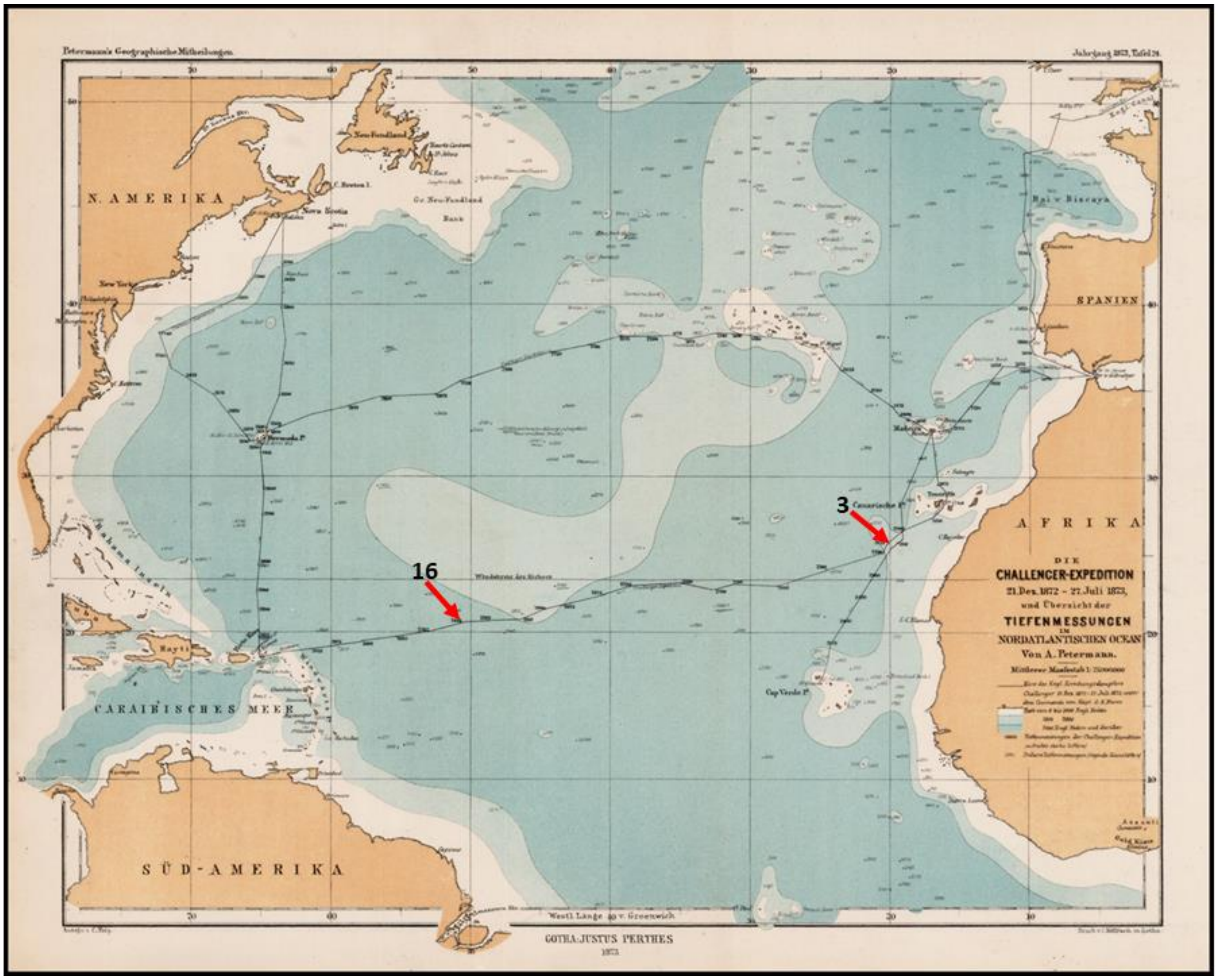
In this paper we show that this counterclaim is invalid; therefore, the credit for this discovery belongs to the *Challenger* expedition. The rest of this paper is structured as follows. Section 2 revisits the discovery of Fe-Mn nodules in the ocean by *Challenger* in 1873. Section 3 describes the 1868 expedition to Spitzbergen by Nordenskiöld on *Sofia*. Section 4 describes the 1878-1879 expedition across the Northeast Passage by Nordenskiöld on *Vega*. Section 5 presents a detailed analysis of the Lindström (1884) paper, complete with an English translation of the original Swedish-language text. Section 6 (Conclusions) sums up our findings.

2. Discovery of Fe-Mn nodules in the ocean by *Challenger* in 1873

The discovery of ferromanganese nodules in the ocean was made during the *Challenger* expedition in February-March 1873 and published in May 1873 in *Nature* (London). The first-ever sample of what was later identified as a Fe-Mn nodule/crust was dredged up from the sea floor on 18 February 1873 (Sta. 3) shortly after the expedition left Tenerife (Canary Islands), while the second critically important sample, which was immediately recognized as a manganese nodule, was dredged up on 7 March 1873 (Sta. 16), in the middle of the North Atlantic (**Figure 1**).

Fig. 1. The *Challenger* voyage across the North Atlantic (21 December 1872 – 27 July 1873) during the first seven months of the 1872-1876 circum-global expedition. Red arrows point to Stations 3 and 16, where the first ferromanganese crusts and nodules were dredged up from the bottom of the World Ocean. The map by August Heinrich Petermann, a renowned German cartographer (1822-1878).

[Fig. 1 is on the next page]



<u>Dredge haul of 18 February 1873</u> (Station 3, 25°45′N, 20°14′W, 1545 fathoms / 2825 m). This event is described by Wyville Thomson, the expedition's chief scientist, in his first letter from the *Challenger* published in *Nature* (London) on 8 May 1873 (Thomson, 1873a, p. 29):

> "On the 18th we sounded at 9 A.M. in 1,525 fathoms, lat. 25° 45′ N., long. 20° 12′ W, 160 miles S.W. of the Island of Ferro, and 50 miles to the west of the station of the day before, in 1,525 fathoms. The "Hydra" tube brought up no bottom, and we sounded again with a depth of 1,520 fathoms, and again no bottom. It thus seemed that we had got upon hard ground, and as the sounding of the following day gave 2,220 at a distance of only 19 miles, we had evidently struck the top of a steep rise. The dredge was lowered at 10 A.M. with 2,220 fathoms of line and 2 cwt. leads 300 fathoms before the dredge. At 5.30 P.M. the dredge was hauled up, and contained a few small pieces of stone resembling the volcanic rocks of the Canary Islands, and some large bases of attachment and some branches of the calcareous axis of an Alcyonarian polyp allied to *Corallium*. Some of the larger stumps were nearly an inch in diameter; the central portion very compact, and of a pure white colour: the surface longitudinally grooved, and of a glossy black. The pieces of the base of the coral which had been torn off by the dredge were in one or two cases several inches across and upwards of an inch thick, forming a thick crust from which the branches of the coral sprang. The crust was of a glossy black on the surface, showing a fine regular

granulation, and a fracture through the crust was of a uniform dark brown colour and semi-crystallised."

Figure 2 shows ***"the base of the coral"*** described by Thomson (1873a). This figure was published by Murray and Renard (1891, Plate III, Fig. 1) in the same volume with two chemical analyses (*ibid.*, p. 464, analyses 96 and 97) of this remarkable specimen that revealed extremely high concentrations of ferric oxide (31.60% and 40.71%, respectively) and manganese oxide (25.64% and 22.80%, respectively). Notably, the Thomson (1873a) description of the dredge haul of 18 February 1873 does not mention "manganese nodules" or "manganese concretions" yet; however, it describes ***"the base of the coral"*** as a ***crust***. Owing to the subsequent chemical analysis cited above, we know now that this was a ***ferromanganese crust***, the first-ever Fe-Mn crust dredged up from the bottom of the World Ocean. Clearly, the true meaning and importance of the dredge haul of 18 February 1873 was only recognized in retrospect, on 7 March 1873, when manganese nodules were dredged up from the ocean bottom as reported by Thomson in his 2nd letter from the *Challenger* published by *Nature* (London) on 15 May 1873 (Thomson, 1873b).

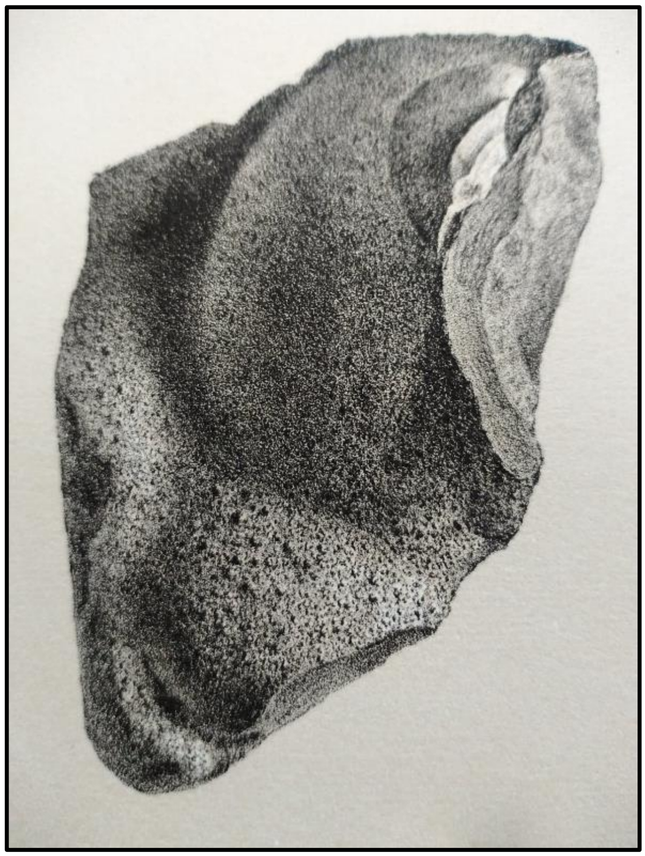


Fig. 2. Drawing of "the base of the black coral" described by Thomson in his first letter from the *Challenger* (Thomson, 1873a). The drawing and original caption below are from Murray and Renard (1891, Plate III):

"Fig. 1. Portion of a large flattened fragment from the North Atlantic (natural size). The original fragment was over a foot in diameter, and was evidently a piece torn from a much larger mass by the action of the dredge. The upper surface shows the usual rough mammillated appearance, being black and shining, while the interior is black-brown. To this nodule was attached a large branching Coral; at the upper right hand side of the figure a portion of the base of this Coral is seen to be attached to the nodule, and to be again covered by a slight coating of manganese. Station 3; 1525 fathoms. North Atlantic."

Note on morphological terminology: In the above caption, Murray and Renard (1891) twice used the word ***nodule***, whereas Thomson (1873a) thrice referred to the same specimen as a ***crust.*** The terminological discrepancy between Thomson (1873a) and Murray and Renard (1891) is thus hardly accidental and hence becomes significant, especially because according to Hein and Koschinsky (2014, p. 273), "Until the late 1970s, ferromanganese crusts (Fe–Mn crusts) and nodules (Fe–Mn nodules) were not distinguished and both were usually referred to as nodules."

Nonetheless, despite his clear preference for ***nodules***, Murray (1875) occasionally used the term ***incrustations*** alongside ***nodules*** (e.g., when he wrote (*ibid.*, p. 528): "The peroxide of manganese, in the form of minute grains, nodules, aggregations, or incrustations, occurs widely distributed in ocean-deposits."

<u>Comparison with modern geophysical and geochemical data.</u> In his first letter from the *Challenger* cited above, Thomson (1873a, p. 29) noted that "we had got upon hard ground, and … struck the top of a steep rise" while dredging at Sta. 3. The conclusion made by Thomson back in 1873, while lacking any bathymetric data except the *Challenger*'s own rudimentary soundings, is fully supported by the most recent high-resolution bathymetry (**<u>Figure 3</u>**), which makes evident that Sta. 3 took place over the crest of the southern ridge of The Paps Seamount in the southern Canary Islands Seamount Province. The Paps Seamount features rugged geomorphology, particularly the steep southern ridge (**<u>Fig. 3</u>**) with gully-incised slopes (Palomino et al., 2016, Fig. 4A). Such steep slopes are usually devoid of soft sediments swept clean by topographically induced currents. This is a typical environment conducive to the formation of Fe-Mn crusts similar to the one dredged up at Sta. 3 (**<u>Fig. 2</u>**).

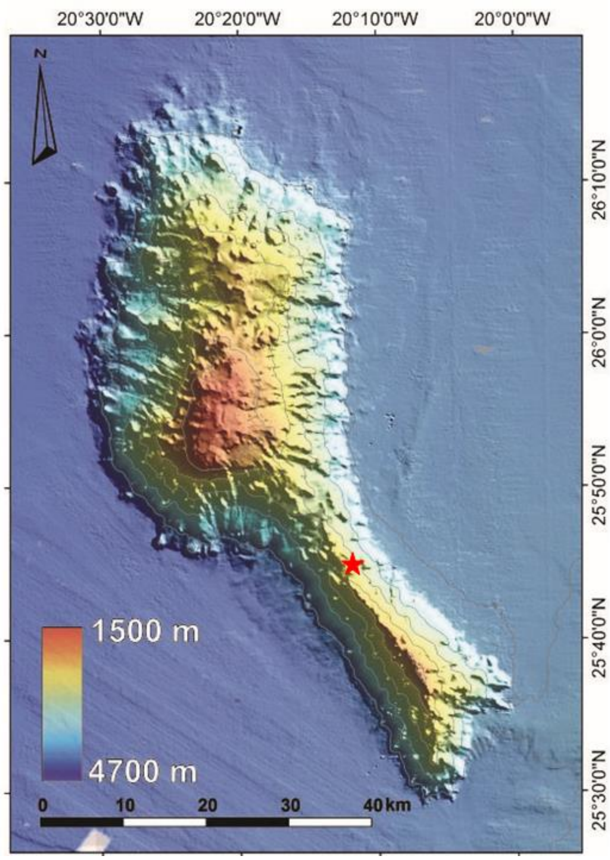


Fig. 3. The Paps Seamount bathymetry. Reproduced with permission after Palomino et al. (2016, Fig. 5A). Red star marks the *Challenger* Sta. 3.

The *Challenger*'s chemical analyses 96 and 97 of the Sta. 3 Fe-Mn crust (Murray and Renard, 1891, p. 464) can be directly compared with those by Marino et al. (2017) who presented results of the first comprehensive study of Fe-Mn crusts from the southern Canary Basin Seamount Province. The DR14 dredge by Marino et al. (2017) sampled the same crest of the southern ridge of the Paps Seamount at 25°39.25′N, 20°07.45′W, in 2221-2157 m depth as did the *Challenger* Sta.3 dredge at 25°45′N, 20°14′W, in 2825 m depth, just 10 nautical miles apart from DR14. The Fe-Mn contents of DR14 crusts (26.6%-19%, *ibid.*, Table 3) are not terribly different from those of the *Challenger* Sta. 3 crust (analysis 96: 31.60% -25.64%, respectively). Their Mn/Fe ratios are similar, 0.71 vs. 0.81, respectively.

<u>Dredge haul of 7 March 1873</u> (Station 16, 20°39′N, 50°33′W, 2435 fathoms / 4453 m). This event is vividly described by Thomson (1873b, p. 52) who is drawing a parallel with the dredge haul of 18 February 1873 (Station 3) by noting that the haul of 7 March 1873 contained

> "a number of very peculiar black oval bodies about an inch long, with the surface irregularly reticulated, and within; the reticulates closely and symmetrically granulated the

whole appearance singularly like that of the phosphatic concretions which are so abundant in the greensand and trias. My first impression was that both the [shark] teeth and the concretions were drifted fossils, but on handing over a portion of one of the latter to Mr. Buchanan for examination, he found that it consisted of almost pure peroxide of manganese. The character both of the exterior and interior of the nodule strongly recalled the black base of the coral which we dredged in 1,530 fathoms on the 18th of February..."

The subsequent chemical analysis of the Sta.16 manganese nodules (Murray and Renard, 1891, p. 465, analysis 98) revealed extremely high concentrations of ferric oxide (36.08%) and manganese oxide (29.32%) consistent with the analyses 96 and 97 of the Sta. 3 specimen (ferric oxide, 31.60% and 40.71%; manganese oxide, 25.64% and 22.80%; respectively).

Numerous findings of Fe-Mn nodules and crusts were made during the rest of the *Challenger* 1872-1876 expedition, especially in 1875, when the expedition worked in the Pacific. These findings were documented by John Murray (the expedition's naturalist) and John Young Buchanan (the expedition's chemist) in their preliminary reports to Wyville Thomson and promptly published in one of the most important and prestigious scientific periodicals of that time, the *Proceedings of the Royal Society of London* (Murray, 1875-1876; Buchanan, 1876).

3. *Sofia* 1868 expedition to Spitsbergen

The *Sofia* 1868 expedition to Spitsbergen was led by Adolf Erik Nordenskiöld. Two similar accounts of this expedition were published (Nordenskiöld and von Otter, 1868-1869; Nordenskiöld and von Otter, 1869; see also Leslie, 1879), with a detailed cruise map published once, in the former paper. This cruise map (**Figure 4**) reveals that during the 1868 expedition *Sofia* did not leave the Spitsbergen waters and did not venture into the southern Kara Sea, some 1500 km away.

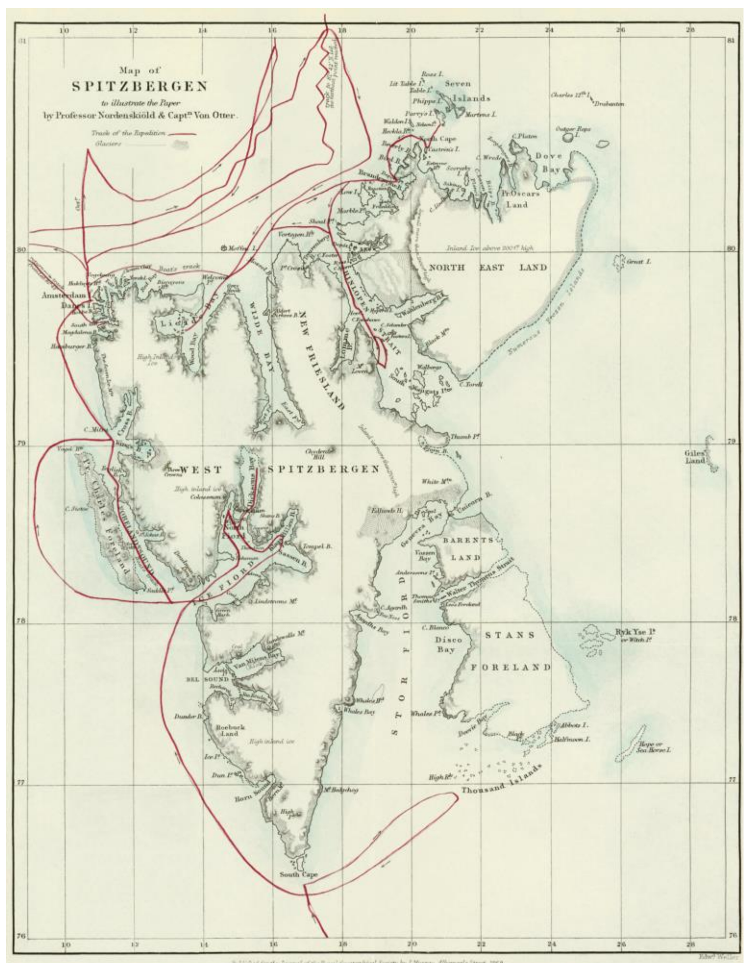


Fig. 4. *Sofia* 1868 expedition to Spitsbergen (Nordenskiöld and von Otter, 1869, map between pp. 131-132).

4. *Vega* Expedition across the Northeast Passage

The *Vega* Expedition 1878-1880 led by Adolf Erik Nordenskiöld completed the first sailing through the Northeast Passage and the first circumnavigation of Eurasia (Nordenskiöld, 1880, 1881; Nordenskiöld and Leslie, 1881; Nordenskiöld, 2012; Nordenskiöld (editor), 1882-1887; Leslie, 1879; Stuxberg, 1880). While crossing the Northeast Passage, *Vega* took 12 samples of rocks and bottom sediments, including one sample from the southern Kara Sea (**Figure 5**). The 12 samples collected by *Vega* were analyzed and reported in Lindström (1884) alongside two samples collected by *Sofia* off Spitsbergen in 1868. The joint publication of chemical analyses of samples taken in two different areas 10 years and 1500 km apart during two unrelated expeditions on two different ships is probably the explanation for the historical confusion that followed.

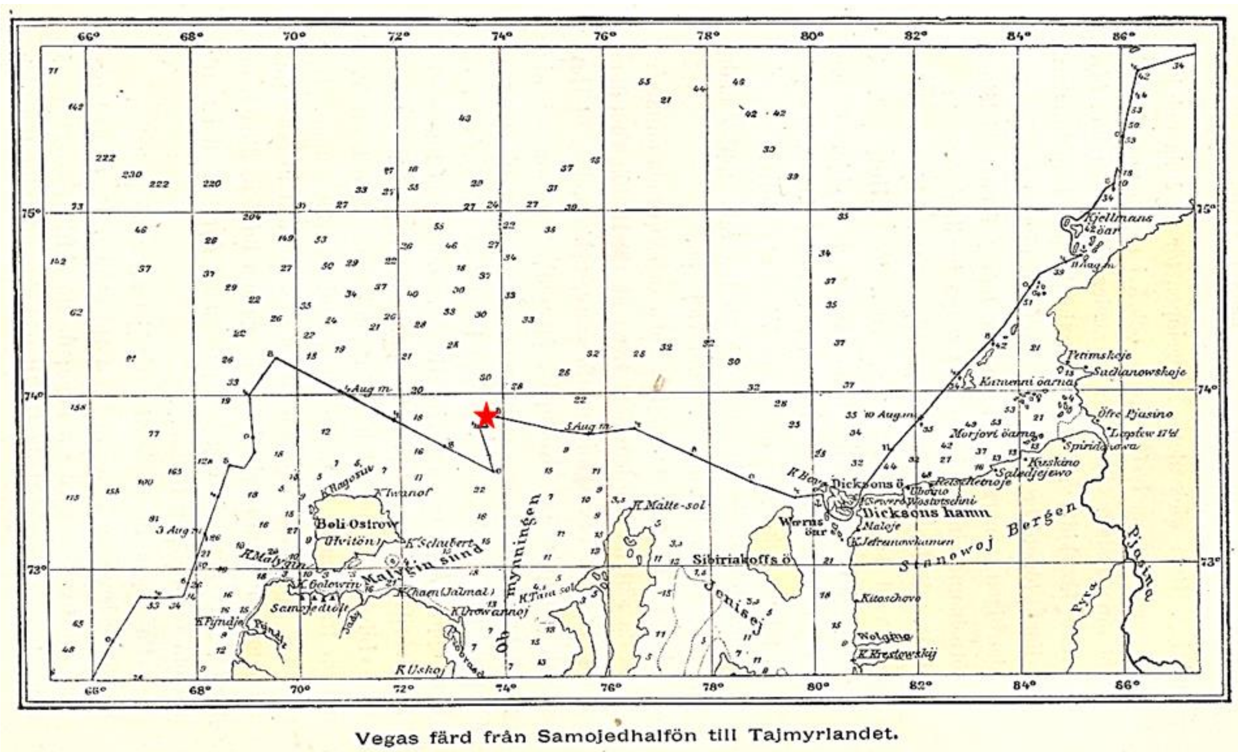


Fig. 5. Route of *Vega* in the Kara Sea in August 1878 (Stuxberg, 1890, p. 217). Red star marks the location of the bog iron ore formation analyzed by Lindström (1884, sample #3) (**Figure 6**).

5. Lindström (1884) paper

Gustaf Lindström was a chemist and mineralogist at the Swedish Museum of Natural History (Stockholm) for 44 years (Franzén, 2021). Lindström worked with A.E. Nordenskiöld and did chemical analysis on samples that Nordenskiöld brought back from Arctic expeditions. In 1884 Lindström published a brief account with results of chemical analysis of 14 rock and bottom sediment samples from two expeditions: (1) the *Sofia* expedition to Spitsbergen in 1868; (2) the *Vega* expedition through the Northeast Passage in 1878-1880. The Lindström analytical report has been printed by A.L. Normans Book Printing Company in Stockholm as 8-page brochure in Swedish (Lindström, 1884). Apparently, this brochure was not circulated widely as we could not find a single copy of this brochure in U.S. libraries. Fortunately, the Swedish Museum of Natural History (Stockholm) has a copy of this publication. We translated this brochure and made the English translation available in ***Supplementary Data***, complete with a scan of the original work and a searchable text (both in Swedish). The chemical terminology used by Lindström (1884) was checked against contemporary and modern publications in geochemistry.

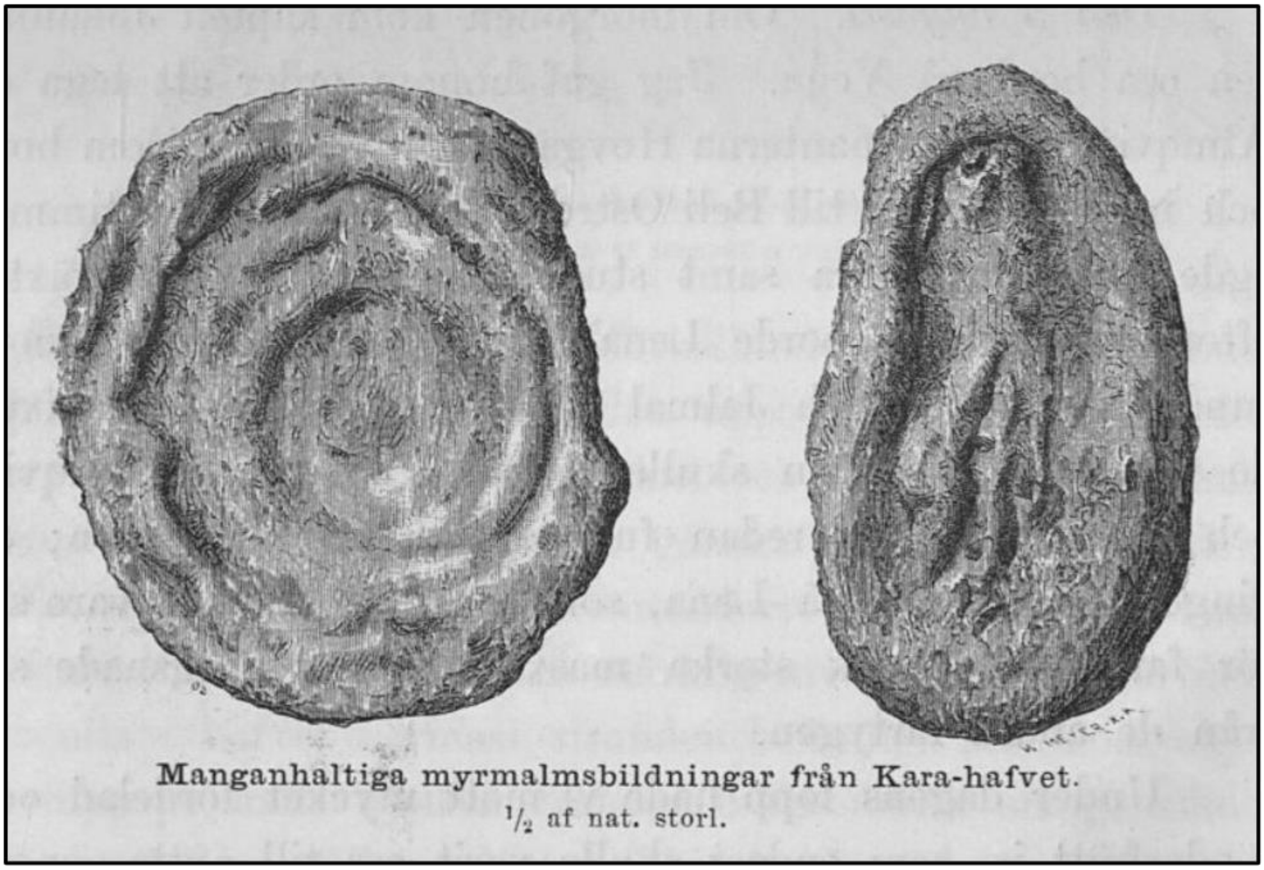


Fig. 6. Manganiferous bog iron-ore formation collected by *Vega* on 4 August 1878 northeast of Bely Island in the Kara Sea (bottom sediment sample #3 from Lindström, 1884, p. 4). Reproduced after Nordenskiöld (1881, p. 177) (cf. Nordenskiöld, 2012, p. 142, bottom).

The Lindström (1884) report is not cited in some of the most extensive sources on ferromanganese nodules, such as “Comprehensive Bibliography of Marine Manganese Nodules” (Glasby and Hubred, 1976), “Marine Manganese Deposits” (edited by Glasby, 1977; this book includes a chapter on shallow water nodules by Calvert and Price (1977), which did not cite the Lindström (1884) report), and “The Geochemistry of Manganese and Manganese Nodules in the Ocean” (Baturin, 1988). However, Lindström (1884) is included into the most exhaustive bibliography on manganese nodules by Meylan et al. (1976) published simultaneously with Glasby and Hubred (1976). Data (single sample) from Lindström (1884) was used by Senov (1937; reproduced by Gorshkova (1957, Table 2); see https://www.pangaea.de/?q=VEGA1878-1880), and Manheim (1965, Fig. 5 and Fig. 9). The Lindström (1884) report was not cited in the English-language literature, until Frank Manheim cited it in a brief book review (Manheim, 1978, p. 541.)

Samples 1 and 2 are bottom clay sediments collected during the *Sofia* cruise in 1868; they contain insignificant amounts of Mn. Samples 3 to 14 were collected during the *Vega* expedition 1878-1880, not from *Sofia* in 1868. The only sample (#3) with a large percentage of manganese oxide Mn_2O_3 (24.17%) was dredged on 4 August 1878 northeast of Bely Island in the Kara Sea (73.841340°N, 73.844950°E, water depth 50 m; https://www.pangaea.de/?q=VEGA1878-1880) while *Vega* was crossing the southern Kara Sea on her way to Dickson (presently Dikson) Island (**Figure 5**). This sample included a large (5 cm) flat Fe-Mn concretion of ***bog iron ore*** (*myrmalm* in Swedish; **Figure 6**). Regarding this and similar bog iron ore formations in the Kara Sea, Nordenskiöld (1881, pp. 175, 177) noted:

> "The bottom of the sea in the south and west parts of it consists of clay, in the regions of Beli Ostrov of sand, farther north of gravel. Shells of crustacea and pebbles are here often surrounded by bog-ore formations, resembling the figures on page 186. These also occur over an extensive area north-east of Port Dickson in such quantity that they might be used for the manufacture of iron, if the region were less inaccessible."

For a review of bog iron ores see pp. 343-348 in Ramanaidou and Wells (2014).

6. Conclusions

We have shown that, contrary to occasional claims in the literature, the *Sofia* expedition of 1868 was not the voyage of discovery of Fe-Mn nodules in the ocean for three reasons. First, in 1868 *Sofia* sailed around Spitsbergen and never entered the Kara Sea. Second, the only Fe-Mn concretion from the Kara Sea analyzed by Lindström (1884, sample #3) was collected by *Vega*, not *Sofia.* Third, the *Vega* sampling was in 1878, not 1868. The only *Vega* sample (#3) with extremely high concentration of Mn (>24%) was collected in August 1878. Meanwhile, five and a half years prior to the *Vega* sampling, the first Fe-Mn nodules and crusts were dredged up from the ocean bottom on 18 February and 7 March 1873 during the *Challenger* 1872-1876 circum-global oceanographic expedition. These findings have been promptly reported and published in May 1873. Thus, the credit for the discovery of ferromanganese nodules in the World Ocean firmly belongs to the *Challenger* expedition.

Supplementary data online:

(1) Lindström (1884) brochure scanned without OCR (optical character recognition).
(2) Lindström (1884) brochure manually re-typed into a Word document.
(3) English translation of Lindström (1884).
(4) Chemical terminology used by Lindström (1884).

Acknowledgments. We are indebted to librarians, information technology specialists, funding organizations, and publishers for making possible the digitization and online publication of the *Challenger* and *Vega* expedition reports and other books cited in this article and for making the online editions freely and easily accessible. Particular thanks go to digital libraries such as Google Books, JSTOR, and HathiTrust. The chemical terminology used in our translation of Lindström (1884) was checked and edited by Sc.D. Joseph Riskin (Haifa, Israel), Dr. Natalia Shulga (P.P. Shirshov Institute of Oceanology, Moscow, Russia), and Dr. Oleg Vereshchagin (St. Petersburg State University, Russia). Their comments are greatly appreciated. The high-resolution bathymetry of The Paps Seamount was kindly sent to us by Dr. Juan-Tomás Vázquez (Instituto

Español de Oceanografía). The original manuscript has been improved thanks to the comments by two anonymous reviewers. While working on this article, Igor Belkin was supported by the Zhejiang Ocean University.

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