# Chapter 1
# Deep-Sea Mining: Historical Perspectives

**David S. Cronan**

**Abstract** The seeds of deep-sea mining were sown during the post-war boom. The massive use of raw materials and the wholescale destruction of both property and material during that war created a demand for raw materials that some thought could not be met from conventional sources. Amongst these was a group of University of California Professors who met at the Scripps Institution of Oceanography in 1957 and who initiated a programme on the evaluation of mining manganese nodules (Mero 1965). John Mero was appointed Chief Investigator of this project and went on to produce several papers on the subject (Mero 1959, 1960, 1962), and his now-classic book 'The Mineral Resources of the Sea' (1965) painted a very optimistic picture of deep-sea mining.

It was arguably the publication of Mero's book that initiated interest in the whole business of deep-sea mining. However, Mero was not the first person to recognise the future potential of manganese nodules. John Young Buchanan, ship's chemist during the Challenger Expedition (1873–1876) mentioned their possible future value in a letter to his father (Glasby 1977). Additionally, Dunham (1964) mentioned the possibility of potentially economic hydrothermal minerals occurring on the seafloor, several years before they were actually discovered.

The deep-sea minerals of interest in this Introduction are manganese (polymetallic) nodules, cobalt-rich ferromanganese oxide crusts and hydrothermal polymetallic sulphide deposits (PMS).

**Keywords** Deep-sea minerals · Nodules · Crusts · Sulphides · Historical perspective

D. S. Cronan (✉)
Imperial College, London, UK
e-mail: david.cronan64@alumni.imperial.ac.uk

 
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## 1 Manganese or Polymetallic Nodules

Industrial and political interest in manganese nodules commenced soon after the publication of John Mero's book in 1965 and has lasted to the present day, with one or two ups and downs. It was the work of Mero that engendered serious consideration being given to mining them and at least partly to the declaration by the Maltese Ambassador to the UN that the resources of the deep-sea floor should be 'the common heritage of mankind' (1967) which in turn helped lead to and underpinned the third Law of the Sea Conference and the ensuing Law of the Sea Convention in 1982. Mero (1965) considered that if only 10% of the nodule deposits on the ocean floor were to be mined, enough metals to last for thousands of years at the then rates of consumption would be recovered. He also said that the nodules were growing ocean wide at a rate faster than the metals that they contained could be consumed, which on a worldwide basis was probably true. However, subsequent work showed that only a very small proportion of all the nodules on the deep-sea floor would be mined for reasons of their grade and that those were amongst the most slowly growing, at rates of only up to a few tens of millimetres per million years.

Another point that Mero (1965) made was that manganese nodule mining could lead to the closure of environmentally polluting mines on land, a theme that was subsequently developed in regard to comparisons with nickeliferous laterite mining, its nearest terrestrial equivalent, which is a great despoiler of mainly tropical areas. This and other points in favour of deep-sea mining were made by Heydon (2012) who stated that 'in contrast to terrestrial mining, deep sea mineral extraction involves minimal overburden stripping…decreased extraction waste, no societal displacement, minimal production infrastructure, no need to build roads and railways for haulage, no blasting, no acid mine drainage and no deforestation'. Mero himself never seemed to have considered the possibility of marine environmental damage, something that has recently generated much interest and concern (Sharma 2019). Nevertheless, Mero's lasting legacy is that with only limited data he outlined the manganese nodule compositional regions of the Pacific, which remain more or less unchanged to this day in spite of many more data now being available.

Commercial interest in nodule mining commenced in the mid-1960s and by the 1970s several consortia had been formed to mine in the Clarion Clipperton Zone (CCZ) in the Pacific, which resource estimates suggested contains about 7.5 billion tonnes of Mn, and respectively 340, 265 and 78 million tonnes of Ni, Cu and Co. Large sums were spent by Industrial Consortia in exploring for future mine sites in the CCZ but most became inactive in the late 1970s and 1980s. Later, several National Consortia sponsored by countries such as France, Japan, Korea and others were formed, some of which are still active.

In the Indian Ocean, the National Institute of Oceanography, Goa, started an exploration programme for nodules in 1981 using the R.V. Gaveshani after desk-based studies on published data to identify the best areas. The first nodules were picked up from 4800 m depth on 26 January of that year on the S.W. Carlsberg Ridge. Exploration for nodules in the prime area of the Central Indian Basin identified from published data commenced in 1982. Work continued to the identification of a mine site (Qasim and Nair 1988). Indian national manganese nodule programme has been described by Valsangkar (2003) and Sharma (2010), amongst others.

In terms of the physical and chemical attributes of the nodules, by the 1970s both the abundance and distribution of nodules had been found to be very variable on an ocean wide scale and also locally on the scale of a kilometre or less (Glasby 1977). It was also realised by then that nodule distribution depends on a number of processes including the availability of nuclei on the seafloor and the rate of accumulation of the associated sediments. It was found that low sedimentation rates favour high nodule abundance. Nodules were first found to be most abundant in the CCZ (Horn et al. 1972) and later to be locally almost as abundant in the Central Pacific Basin (Usui and Moritani 1992). Subsequent research in the South Pacific found nodule distribution and abundance to be more irregular than in the North Pacific largely because of its greater topographic and sedimentological diversity, but that nodules were particularly abundant around the Cook Islands and especially in the Penrhyn Basin where abundances can locally exceed 50 kg/$m^2$ (Glasby et al. 1974; Cronan 1987, 2006; MMAJ 1995).

Early geochemical work on nodules (see Verlaan and Cronan, 2021 for a recent review) found that they represent a continuum exhibiting a compositional mixing from diagenetic end-members enriched in Mn, Ni and Cu to hydrogenous end-members enriched in Fe and Co. The diagenetic deposits were thought to derive their Mn, Ni and Cu in part from sediment pore waters by recycling these metals from decaying organic material. Hydrogenous deposits were thought to get their metals from normal seawater or non-metal-enriched sediment pore waters. Nickel- and Cu-rich nodules of resource interest in the CCZ fall near the diagenetic end-member in composition and are enriched in these metals up to about 3% combined but are relatively low in Co. In contrast, Co-rich nodules of resource interest in the Penrhyn Basin are hydrogenous and contain up to about 0.6% Co (Pautot and Melguen 1979). Early geochemical work on nodules also showed that some contained enrichments of many minor and rare elements up to 100 times or more over their crustal abundances (Cronan 1976). Most of these elements were for a long time thought to be of little economic interest, but in the early 2000s some of them were found to be required in emerging technology industries. Koschinsky et al. (2010) identified not only the Rare Earth Elements (REE) in this regard but also Li, Te, Pt, V, Mo and W.

One of the issues that exercised the early workers on the economics of nodule mining was the question of what reserves and resources were. After considerable discussion, Archer (1979) suggested that reserves should be defined as the recoverable elements in mineral deposits that are economically workable in the locally prevailing circumstances. By contrast, resources would then be those elements in deposits that may be workable at some time in the future. Resources may become reserves with changing economic and technological circumstances. On this basis, Archer proposed that marine mineral resources should be defined as mineral occurrences on the seafloor that are likely to become workable in the next 20 or 30 years.

General recognition of Exclusive Economic Zones (EEZs) as potential sites of marine minerals dates from the early 1980s and was given publicity by the declaration by President Reagan of a very large EEZ around the United States. EEZs are areas within 200 nautical miles of coastal states in which those states can exert jurisdiction over resources. Areas beyond 200 miles come under the jurisdiction of the International Seabed Authority (ISA). Since the early 1980s, many states have sought to exercise control over the marine resources adjacent to their coasts. However, it was realised early on that most EEZs were not deep-sea areas and thus, with one or two exceptions, would not contain typical deep-sea minerals such as manganese nodules. Indeed, it was found that the only EEZs that did contain nodules in sufficient amounts to be of economic interest in the foreseeable future were those around certain of the island states in the South Pacific (Exon 1983), most notably the Cook Islands. Glasby et al. (1974) were amongst the first to point out the importance of nodules in that part of the S W Pacific Basin that would later become part of the EEZ of the Cook Islands. This resulted in many subsequent cruises for nodule exploration in the CI EEZ, most notably by the Metal Mining Agency of Japan (MMAJ) from 1985 onwards in collaboration with CCOP/SOPAC, the then principal marine minerals authority in the South Pacific. Cronan (2013) has summarised the results of those cruises. Essentially, the North Penrhyn Basin nodules are rich in Ni and Cu, and the South Penrhyn Basin nodules are rich in Co, Ti and REE.

Between the mid-1980s and the commencement of the twenty-first century, interest in mining manganese nodules declined, and the deep-sea mining that was expected to happen in the twentieth century never occurred. There were several reasons for this. First, the prices of the main metals in the nodules either decreased or remained relatively static during the last quarter of the twentieth century. Second, the oil price increase in the mid-1970s added greatly to the processing costs for nodules. Third, the 1982 Law of the Sea Convention was widely regarded by the embryonic deep-sea mining industry as being unsatisfactory. Fourth, increasing environmental awareness in the 1970s and 1980s produced an added constraint for deep-sea mining.

Increasing metal prices at the start of the twenty-first century led to a resurgence of interest in nodule mining. This was capitalised on by the ISA who permitted contractors to work in the reserved areas of the mine sites that they had licensed and which had to be relinquished by the licensees under the provisions of the Law of the Sea Convention. One of these was Nauru Ocean Resources Inc. (NORI), and there were several others. By 2011, it had been granted exploration licenses in four parts of the CCZ between 115 and 130° west which was explored by its sub-contractor Deep Green Resources.

## 2 Cobalt-Rich Crusts

During the 1960s and 1970s, cobalt-rich crusts were rarely differentiated from manganese nodules when it came to resource estimates. It was not until the work in the early 1980s of Halbach, Hein and their co-workers (Halbach et al. 1982; Hein et al.

1985) that they came to be considered as a separate class of ferromanganese oxide deposits. Interest in the economic potential of Co-rich ferromanganese oxide crusts lay initially in their Co content and to a lesser extent in their Mn, Ni and Pt and later their REE content.

Once they had been recognised as a separate class of deposits from nodules, some of their specific attributes were enumerated (see Verlaan and Cronan, 2021 for a recent review). First, crusts largely occur in shallower water than nodules, in general on seamounts more than 2000 m shallower than most nodule deposits of economic interest and sometimes just within a few hundred meters of the sea surface. Second, they usually contain much more Co than nodules. Third, they often occur in EEZs as the seamount chains on which they are mainly found frequently contain islands. Most of our initial knowledge on Co-rich crusts came from the central Pacific. They were found to be mainly present on non-sedimented seamount slopes between 1000 and 3000 m depth and were especially well developed on and near the tops of guyots. The composition of the deposits was found to exhibit considerable variations, Mn from about 15–30%, Fe from 7–18%, Co up to about 2% and averaging 0.8% in the richest areas of the western central Pacific. Crust thicknesses were found to range from less than 1 cm to over 8 cm, with an average thickness of around 2.5 cm. Growth rates were found to be around 10 mm per million years. Geological stability was found to be necessary for the crusts to develop properly as slumping and erosion on seamounts can destroy or abrade crusts.

A study of the distribution of Pacific crusts in relation to latitude showed that their maximum thickness fell within 15° of the equator. Several elements in them were also found to exhibit a latitudinal variation (Hodkinson and Cronan 1991). Manganese, Co, Ni, Mo and Cd were found to be highest at low latitudes; Fe and Cu showed the opposite. Several elements also showed a relationship with depth. Manganese, Co, Ni, Mo, V, Zn and Pb all decreased with increasing depth whereas Fe showed the opposite.

Platinum was also recognised as an element of potential economic importance in the crusts (Halbach and Puteanus 1984). It generally occurred in concentrations of between 0.1 and 1 ppm but could be as much as 3 ppm. This is not much less than the Pt content of Sudbury ores (3.3 ppm) but much less than in the Bushveld Pt ores (7–10 ppm). Maximum Pt values were generally found to occur in crusts from less than 1500 m water depth.

Concerns about World Cobalt supplies developed strongly in 1978 when the principal supplier, Zaire, was aggressively invaded. The Co price increased dramatically as a result. In view of this, it is not surprising that interest in Co-rich crusts as resources commenced in the early 1980s. One Co-rich crust mining operation with an output capacity of 1 m tonnes per year would have met a significant part of US Cobalt demand, together with part of its Mn, Mo, Ni, V and Pt demand, had it taken place.

## 3 Hydrothermal Deposits

Potentially economic submarine hydrothermal deposits (PMS) were first discovered in the Red Sea in the 1960s (Miller et al. 1966) and were found to consist largely of sulphides of Fe, Cu and Zn. The Red Sea deposits were originally thought to be a unique isolated occurrence but were later realised to be the result of the hydrothermal activity that occurs all along the World Mid-Ocean Ridge System. Most of the other occurrences that occur on mid-ocean ridges, or at volcanically active ocean margins where they are also found, do not exhibit either the diversity or metal concentrations exhibited by the Red Sea deposits.

Most submarine hydrothermal deposits were thought to be largely formed by seawater penetrating into hot volcanic rocks and leaching metals from them thereby becoming transformed into mineralising brine which rises back to the seafloor to precipitate the metals. However, magmatic contributions to the deposits could never be ruled out.

On mid-ocean ridges, active hydrothermal venting was discovered in the Galapagos region by Oregon State University workers in 1979 (Corliss 1979). The hydrothermal mineral composition was found to depend on several factors including temperature of leaching, the composition of the rocks being leached and the amount of circulating seawater. Soon after, small amounts of gold, silver and other valuable metals were found in mid-ocean ridge sulphides (Herzig and Hannington 2000), and it was realised not long after their discovery that to be of serious economic value seafloor polymetallic sulphides should contain recoverable amounts of precious metals.

Later, submarine hydrothermal deposits were found at ocean margins both in back-arc basins and on volcanic island arcs, especially in the S W Pacific (Cronan 1983). These were found to be more compositionally variable than the mid-ocean ridge varieties. The best-studied and economically most valuable hydrothermal mineral deposits discovered were found to occur in the Bismarck Sea off Papua New Guinea (Binns and Scott 1993). One such deposit is the Solwara-1 deposit about 50 km from Rabaul. It is composed of mounds and chimneys and contains base metal sulphides plus Au and Ag and until recently was being developed for mining.

## 4 Recent Trends

The licensing of parts of the ISA reserved areas for commercial manganese nodule exploration has already been mentioned. Recently, the Red Sea hydrothermal muds programme has been reactivated (Hamer 2018). Although the Solwara-1 Project in the Bismarck Sea closed down in 2019, continued commercial interest in other hydrothermal mineral deposits, some licensed for exploration by the ISA on mid-ocean ridges, remains. The recent resurgence of interest in deep-sea minerals is due to not only the twenty-first century increase in commodity prices but also perceived future mineral shortages caused by traditionally mineral exporting countries becoming large importers of minerals to fuel their own industrial development. This phenomenon is particularly true in the case of REEs because they are needed for emerging ‘green’ and ‘technology’ applications. If any single group of elements can be held responsible for the resurgence of interest in marine minerals in the twenty-first century, it is arguably the REEs. However, deep-sea minerals will probably not be mined just for these elements, but REE and other rare elements will probably comprise an increasing proportion of the perceived value of deep-sea mineral deposits in the future.

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**David S. Cronan** is one of the longest serving marine minerals researchers. He studied at Durham, Oxford and London (Imperial College) Universities, obtaining his Ph.D. with a thesis on manganese nodules in 1967. He became interested in submarine hydrothermal deposits in the 1970s and worked in both the Red Sea and on mid-ocean ridges. One of his major contributions in the 1980s was the elucidation of the distribution of hydrothermal deposits in the arcs and back-arc basins of the SW Pacific, including, jointly with G. P. Glasby and Karin Knedler, the discovery of the first hydrothermal deposit to be found on the Tonga-Kermadec Ridge. Also in the 1980s he led the Aitutaki-Jarvis transect cruise in the Eastern Pacific which elucidated the long-sought relationship between manganese nodule composition and the calcium carbonate compensation depth. Like many academics, in his fifties he was drawn more and more into University administration but gave all that up on his 60th birthday in 2002 to concentrate on research again. Since then he has mainly worked on the behaviour of manganese nodules and other deposits in the SW Pacific in collaboration with SPC SOPAC and has written a substantial series of papers on the nature and variability of these deposits. He has published more than 150 scientific papers, given more than 50 conference presentations, written two books on marine minerals and edited two more .