21. On the Metal Contents of Ocean Floor Nodules, Crusts and Massive Sulphides and a Preliminary Assessment of the Extractable Amounts

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Abstract

The metal contents of ocean floor nodules, crusts and massive sulphides was estimated and an assessment of their commercial extractability were conducted. The metals considered were iron, manganese, copper, nickel, cobalt, molybdenum, platinum, gold and silver. We found that significant metal amounts are located mainly in 5 regions of the world's oceans. Most of the tonnage of the studied metals are located at great depth, involving huge technological challenges. Only a smaller fraction (5-25%) of the detected amounts can be considered to be extractable under the most favourable of conditions. We found that the land-based metal resources appear to be more readily available for extraction. Despite huge optimism in the field, no profitable commercial operation has yet been started. It seems that based on an ore grade to metal price evaluation, that only cobalt or silver would perhaps be interesting on a commercial level.

Keywords: Ocean Seafloor Resources, Mining, Cobalt, Copper, Nickel, Molybdenum, Silver.

Introduction

There is a concern for the long-term sustainability of metal supply to the world, therefore mining the ocean seafloors have been proposed. Many authors have highlighted risks of resource depletion looming (Alonso, Frankfield, and Kirchain 2007, Bardi 2014, Meadows, Meadows, Randers, and Behrens 2004, Ragnarsdottir, Sverdrup, and Koca 2012, Sverdrup and Ragnarsdottir 2014). Metals on the seafloor (Manganese nodules, cobalt crusts, massive sulphide deposits) sometimes suggested as a calming message against metal resource scarcity concerns, a "solution-to-all-worries". We would like to inspect a bit closer how realistic this message is, and attempt to substantiate this to tonnage numbers for realistic extractable amounts. We have assessed the land-based resources extensively (Sverdrup and Ragnarsdottir 2014), and thus, the time has come to ask if there is some substance in mining the ocean seafloors and how much metal can we reasonably well expect to get out of it. Nodules are found on the deep ocean floors, cobalt crusts are associated with volcanism and seamounts, and massive sulphides with deep-sea brines, and deep sea hydrothermal wells associated with tectonic division lines, such as the mid-Atlantic Ridge.

Scope

To preliminarily assess the amount of extractable resources available on the seafloor in relationship to the resources available on land for some key infrastructural and technology metals; Iron, manganese, copper, nickel, cobalt, molybdenum, platinum group metals (PGM), silver and gold. We would consider the impact of setting different assumptions on the technical feasibility of actually doing the extraction from the Ocean floor, using literature descriptions of the available and potential future technology. The results will be used for helping set the right input resource sizes for iron, manganese, copper, nickel, cobalt, molybdenum, platinum group metals, gold and silver in the WORLD 6 model being developed by the authors (Ragnarsdottir et al. 2012, Sverdrup, Koca, and Ragnarsdottir 2015).

Methods

We made a literature review and extracted data from the published studies, assessments and evaluations. We compiled estimates of technically extractable amounts from the oceans, grading the resources according to estimated extraction costs and degrees of extractability. We made simple mass balances in tables and overview tables, using extractability estimates to gain recoverable resources from metal detected from any type of deposit. We focused on three types of deposits:

1. Manganese nodules on the main sea floor
2. Cobalt crusts on submerged seamounts
3. Massive sulphide deposits associated with black smokers and deep sea hydrothermal activity along mid-ocean ridges and tectonic separation- and subduction-zones

Figure 21-1 indicates the approximate location of the occurrence of ocean floor nodules, of cobalt crusts and of massive sulphide deposits (The map was modified after Boschen et al. (2013).) We used earlier land resource estimates by the authors for these metals (Alonso et al. 2007, Bardi 2014, Berger, Singer, Bliss, and Moring 2011, Ragnarsdottir et al. 2012, Sverdrup, Koca, and Ragnarsdottir 2013, Sverdrup, Olafsdottir, and Ragnarsdottir 2017a, Sverdrup and Ragnarsdottir 2014, 2016, Walther 2014)

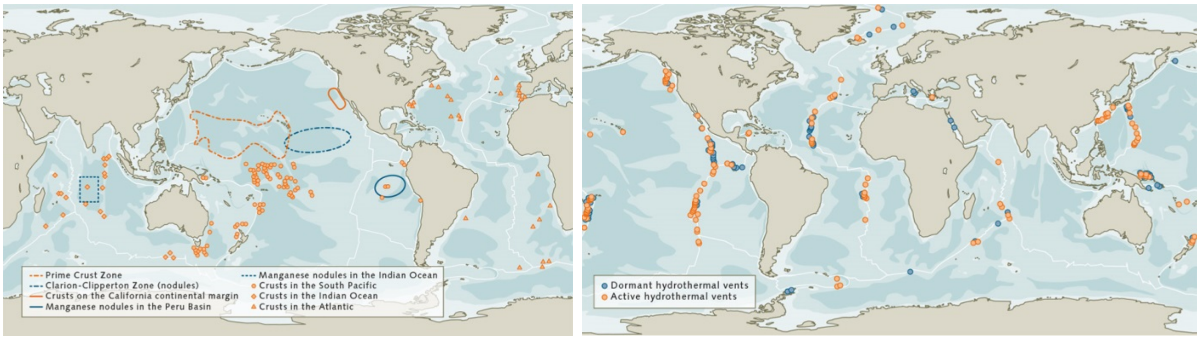

Figure 21-1: *Detected locations of ocean floor nodules, cobalt crusts and massive sulphides. As can be seen from the maps, these can be found in specific areas of the world's oceans, depending on their geological history. Figures from World Ocean Review 3, Maribus GmbH, Hamburg 2014, after Hein et al. 2014, 2015, and World Ocean Review 3, Maribus GmbH, Hamburg 2014, after GEOMAR (World Ocean Review 3 after Hein et al., 2014, 2015).*

Materials and data sources

A number of articles was reviewed the amount of resources and their locations in the World's Oceans: (Allsopp et al. 2013, Berger et al. 2011, Hoagland et al. 2009, Mudd, Weng, and Jowitt 2013, Schmidt 2015, World Ocean Review 3 after Hein et al. 2014, World Ocean Review 3 after Hein et al. 2014). Table 21-1 shows a general relationship between ore grade, the approximate production cost and minimum supply price to society, as well as the impact of price on the recycling in market supply adapted after (Phillips and Edwards 1976, Sverdrup et al. 2015). The cost estimates were generalized and approximated by the authors using literature data. The metal resources were stratified according to such an extraction cost scheme on the ocean floor. Hannington, Jamieson, Monecke, and Petersen (2014), Heinberg (2005) and Beaudoin et al. (2014) made efforts to estimate the size of the deposits and their average contents (ore grades). Roberts (2012) assesses the location and amount of metals in sulphides. Many samples have been taken from the sea floor. How well they actually cover the territory is only known on an overview level. We estimate that this is still sufficient for a preliminary estimate. Table 21-1 shows the general relationship between ore grade, the approximate production cost and minimum supply price to society for mining on land. We have added the approximate extraction cost for deep-sea mining and extraction as well. Figure 21-2 shows the development of copper ore grade with time (Data compiled by Sverdrup, Ragnarsdottir, et al. 2014 and Sverdrup, Olafsdottir, et al. 2017a). Most ores mined today have a copper ore grade of 1% or lower, whereas ocean floor massive sulphides have ore grades from 3-15% copper content.

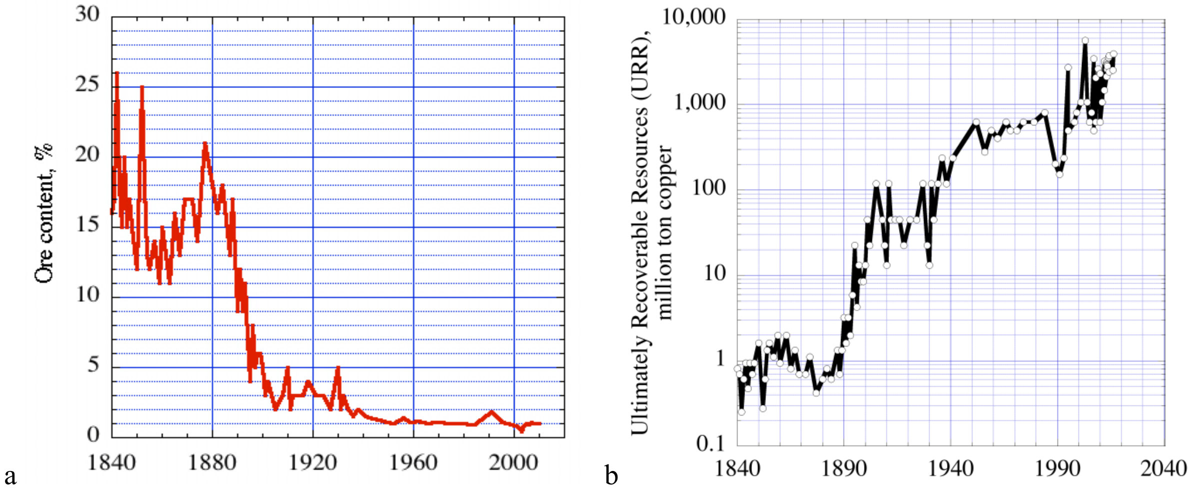

Figure 21-2: *Development of copper ore grade with time Diagram (a) shows the decline in ore grade observed for land-based copper deposits. Diagram (b) shows how the size of the recoverable copper resource is converging on round 4 billion ton of copper. This is what the human society can expect to be able to extract, and what it will have to make the best of.*

Ore grade	Metal content		Extraction yield, %	Land extraction cost, $/kg	Ocean floor extraction cost, $/kg	Land energy need, MJ/kg
	%	g/ton				
Rich	40-5	400,000-50,000	100	4-15	15-28	30
High	5-1	50,000-10,000	99	15-28	28-50	33-64
Low	1-0.2	10,000-2,000	98	28-50	50-100	120-160
Ultralow	0.2-0.04	2,000-400	91-95	50-100	100-160	400-600
Extralow	0.04-0.01	400-100	80-91	100-160	160-400	700-1,100
Trace	0.01-0.002	100-20	75-80	160-400	400-1,200	3,000-20,000
Rare	>0.002	20-4	55-75	>400	>1,200	>20,000

Table 21-1: *General relationship between ore grade, the approximate production cost and minimum supply price to society (Adapted after (Sverdrup, Koca, and Ragnarsdottir 2014a, Sverdrup et al. 2015, Sverdrup, Koca, and Ragnarsdottir 2017a, Sverdrup and Ragnarsdottir 2014, Sverdrup, Ragnarsdottir, and Koca 2014b).*

Diagram (a) shows the decline in ore grade in the land-based ultimately recoverable resource for copper. Several other metals (For example iron, nickel, zinc, gold, lead, molybdenum or platinum group metals) show similar patterns. Copper contents in nodules and cobalt crusts are normally lower (Table 21-2) than land-based ores at present, the content in massive sulphides are substantially higher. At the same time, the land-based ultimately recoverable resources of metals like copper, zinc and lead are converging on a fixed and finite number. The land-based resource is somewhere between 3.5 and 4 billion ton of copper (Figure 21-2b). In deep-sea mining, the mining extraction operation and actual hauling the material up and processing it out at sea cause larger costs than similar operations on land. Waste management will also be more expensive if the serious environmental damage is to be avoided. Most ores mined today have an or grade of 1% or lower (Figure 21-2), whereas ocean floor massive sulphides have ore grades from 3-15% copper content. The different types of metal resources are found at different depths in the oceans;

1. Manganese nodules on the sea floor are found from 1,800-4,000 meter depth
2. Cobalt crusts on submerged seamounts are found on 400-4,000 meter depth
3. Massive sulphide is found on 800-3,500 meter depth in connection with hydrothermal activities, but some deep trenches develop warm salt brines such as in the Red Sea.

These factors all combine to make the mining operations technically challenging and expensive. The southern and northern polar regions are, at the moment, blocked because of challenging ice conditions and the rough environment. The Southern Seas are also largely blocked because of their storm-infested very deep waters and risks of sea-ice. Part of the Penrhyn area in the Pacific Ocean is host to some of the largest coral reefs on the planet, and large-scale mining in significant parts of the area may not be such a good idea from an environmental point of view (Allsopp et al. 2013, Beckmann 2004, Smith and Heydon 2013).

Area	Size	Density	Amount	Fe	Mn	Cu	Zn	Ni	Co	PGM	Au	Ag
	mill. km^2	kg/m^2	billion ton	% weight						g/ton		
Deep sea nodules												
Clarion-Clipperton	9.0	2.3	21	18	22	0.2	0.4	0.4	0.5	5	1	10
Peru Basin	4.5	10	45	18	22	0.2	0.4	0.4	0.5	5	1	10
Penrhyn	0.75	25	19	18	22	0.2	0.4	0.4	0.5	5	1	10
Atlantic	0.20	25	4.8	18	22	0.2	0.4	0.4	0.5	5	1	10
Indian Ocean	0.75	5	3.8	18	22	0.2	0.4	0.4	0.5	5	1	10
Cobalt crusts												
Northeast Pacific	9.0	0.84	7.55	17.8	22.9	0.2	0.4	0.5	0.8	3	20	200
Southwest Pacific	4.5	0.7	3.2	18.1	21.7	0.1	0.2	0.5	0.8	3	20	200
Penrhyn	0.75	0.7	0.53	14.5	20.9	0.2	0.4	0.4	0.5	2	20	200
Atlantic	0.20	0.7	0.15	15.0	20	0.2	0.4	0.4	0.5	2	6	200
Indian ocean	0.75	0.7	0.53	17.0	22.3	0.23	0.4	0.5	0.6	2	20	200
Massive sulphides and brines												
Pacific CC+PB	13.5	0.22	3.000	10	0.2	3.5	13	0.1	0.7	1	3	150
Penrhyn	0.75	1.25	1.000	10	0.5	8.5	7	0.1	0.7	1	3	80
Atlantic	1.50	1.3	2.000	10	0.5	8.5	7	0.1	0.7	1	3	80
Indian Ocean	0.75	0.3	0.250	10	0.5	0.9	4	0.1	0.7	2	2	100

Table 21-2: *Area cover, metal ore density and contents of different metals in the different nodules, crusts and massive sulphides on the ocean floor. The estimates are very approximate.*

Area	Fe	Mn	Cu	Zn	Ni	Co	Mo	PGM	Au	Ag
	Million ton							Thousand ton		
Nodules										
Clarion-Clipperton	6,000	5,990	226	452	274	44	12	15	52	520
Peru Basin	8,145	9,765	450	900	587	94	26	30	104	1,040
Penrhyn Basin	3,420	4,180	203	406	247	40	10	15	48	480
Atlantic	864	1,056	10	20	62	10	3	4	12	220
Indian Ocean	1,080	1,078	41	82	49	8	2	-	1	10
Sum	19,509	22,069	930	1,860	1,219	196	53	64	217	2,270
Crusts										
Northeast Pacific	1,344	1,714	7.4	1.8	32	50	3.5	12	2	17
Southwest Pacific	2,870	3,668	15.8	4.0	68	107	7.7	24	4	34
Penrhyn	77	111	1.2	2.4	2.1	2.7	0.3	2	-	2
Atlantic	2	27	0.4	0.6	0.5	0.7	0.8	0.5	-	0.5
Indian ocean	90	118	1.3	0.4	2.2	2.9	0.3	3	-	2
Sum	4,383	5,636	26.7	9.2	104.5	163.3	12.6	41.5	6	55.5
Sulphides										
Pacific	300	150	60	405	6	21	21	6	60	600
Penrhyn	100	50	20	49	2	7	7	2	20	200
Atlantic	200	10	170	140	4	14	14	4	40	400
Indian Ocean	25	12	5	10	0.5	2	2	-	5	50
Sum	625	222	85	604	12.5	44	44	12	125	1,250

Table 21-3: *Estimated seafloor presence of metal resources, before assessment of technical extractability. The estimates are very approximate.*

Results

The results have been compiled in a series of Tables 21-2 to 21-4. Table 21-2 shows the area cover, metal ore density and contents of different metals in the different nodules, crusts and massive sulphides on the ocean floor. Table 3 shows the estimated seafloor metal resources, before assessment of technical extractability. Table 21-4 shows the estimated seafloor metal resources, coming to an assessment of technical extractability. We found that significant amounts are presently located in mainly 5 limited regions of the oceans for all the metals considered, two areas in the Pacific Ocean, One in the Atlantic Ocean and one in the Indian Ocean. Most of the tonnage of the interesting metals in nodules and black smokers are located at great water depth, from 1 km to more than 4 km depth, involving huge technological challenges. Only a smaller fraction (5-25%) of the detected amounts can be considered to be extractable under the most favourable of conditions (Allsopp et al. 2013, Mudd et al. 2013).

Area	Fe	Mn	Cu	Zn	Ni	Co	Mo	PGM	Au	Ag
		Million ton						ton		
Sum nodule	19,509	22,069	930	1,860	1,219	196	53	63,000	217,000	2,270,000
Sum crusts	4,383	5,636	27	9	105	163	13	41,500	6,000	55,500
Sum sulfides	625	222	85	604	13	44	44	12,000	125,000	1,250,000
Sum	24,517	27,727	1,042	2,473	1,337	403	110	116,000	348,000	3,505,000
Considering different extractability in the total picture of all extractable metal resources. The URR estimates are very approximate.										
Ocean, 25%	6,129	6,932	261	618	334	100	26	29,000	87,000	876,300
Ocean, 5%	1,226	1,386	53	124	67	20	6	5,800	17,400	175,260
Land	340,000	5,600	4,030	2,676	300	32	80	210,000	150,000	3,700,000
How much metal resources do we have on land and ocean floors? The estimates are very approximate										
URR low	341,226	6,986	3,823	2,800	367	52	86	215,800	167,400	3,900,000
URR high	346,129	12,532	4,291	3,294	634	132	106	229,000	237,000	4,576,000
% on land	99-98	81-41	98-96	96-81	82-49	62-24	94-79	97-91	90-66	87-95

Table 21-4: *Estimated seafloor metal resources, coming to assessment of technical extractability. The estimates are approximate.*

Discussion

Despite optimism in the field, no profitable commercial operation has yet been started. Considering the difficulty of mining, it seems that based on an ore grade to metal price evaluation, that only cobalt or silver would perhaps be interesting on a commercial level, with by-products of copper, gold, perhaps also molybdenum and nickel. There are few assessments of how much of the detected seafloor deposits that can actually be extracted. Many reports and prospects available are optimistic stories about new technologies aimed at potential investors and shareholders, and these do not constitute an objective assessment of real extractability. The extractability estimates in the scientific literature vary from 5% (Mudd et al. 2013) to 25% in the most optimistic views (Allsopp et al. 2013, Beckmann 2004). We have taken 5-25% as the minimum to maximum range. For iron (1-2% of the total resource is located on the sea floor), manganese (19-59% of the total resource is located on the sea floor), copper (2-8% of the total resource is located on the sea floor), molybdenum (6-21% of the total resource is located on the sea floor), PGM (3-9% of the total resource is located on the sea floor), gold (10-34% of the total resource is located on the sea floor), silver (13-42% of the total resource is located on the sea floor), the contribution from seafloor extraction will never be significant for any longer time. The resources on land for these metals are far larger than what is extractable from the sea floors. There are similar proportions for zinc and lead, however, these have so low market price at present that they do not support any deep-sea floor mining operations with the present cost situation. For some metals, the global fraction of the resources located on the ocean floor is significant; Manganese (19-59% of the total extractable resources in the ocean floor), cobalt (38-76% of the total extractable resources in the ocean floor), nickel (18-51% of the total resource is located on the seafloor), gold (10-34% of the total resource is located on the seafloor) and silver (13-42% of the total resource is located on the seafloor). This has been listed in Table 4. Considering the importance of cobalt, silver and nickel for production of new advanced technologies, the ocean floor resources provide interesting and significant backup resources for future global supply. It has been speculated about mining Rare Earth metals and phosphorus from the ocean floors, but at the moment, these are traded at prices where an extraction operation would be very far from profitable. Extractions from ocean floors are subject to the same consideration as is valid for the extraction of low-quality reserves and exotic sources of oil, a concept called EROI (Energy Return On Investment). For rare metals and materials, we would have the same limiting indicator; Utility Return On Investment (UROI). When the benefit from extracting the resource is less than the cost, energy use, effort and environmental damage cost, then it will not be extracted. If ocean floor mining is profitable or not in the future, depend completely on the future raw material prices and how the demand will develop in the time to come. To be able to pay for the extraction costs, as well as to do this in a manner that is not destructive to the oceans, several things are still needed. Firstly, the technology available at present is technically capable of extracting the ore, but at a high price so far. The technology has seen significant advances in the recent years. Secondly, many reports discuss the potential environmental impacts of ocean floor mining (Allsopp et al. 2013, Beaudoin et al. 2014, Beckmann 2004, Smith and Heydon 2013, World Ocean Review 3 after Hein et al. 2015). Unless special precautions are taken, significant impacts may be expected on marine ecosystems and water quality. Much work remains to ensure that the mining can be done environmentally sound and without causing irreversible damage to marine ecosystems and without causing deleterious damage to physical structures. This homework has definitely not been done yet, and the industry should use the time to solve this issue, rather than protesting against not being allowed to cause damage to nature.

Conclusions

The role of significant new resources for metals on the ocean floor to replace land supply seems limited for most metals. For some of the main metals in society (iron, copper, platinum group metals, gold, silver), the extractable amounts seafloor resources are significantly smaller than those on land and more expensive to extract. For some of the key technology metals in short supply and with small extractable resources, the ocean resources may be an interesting and significant source of metal. The metals cobalt, nickel and silver may be in this category, with additional side products of gold, copper or perhaps molybdenum and platinum group metals. There is a lot of manganese nodules available, but the manganese price is at present low, and would not pay for the effort to harvest them and to extract the manganese. The extraction of these resources may be commercially viable for the metals identified above, and they may under certain conditions contribute significant amounts to the total supply. Considering the difficulty of mining, it seems that based on an ore grade to metal price evaluation, that only cobalt or silver would perhaps be interesting on a commercial level in the near future.