MODULE EIA, LESSON 5
MINERALS MINERAL RESOURCES: SCIENTIFIC ASPECTS

LECTURE NOTES

Welcome to the second lesson of Module 2 of the Deep Dive Initiative from the International Seabed Authority. My name is Sven Petersen and I am a Senior Scientist at GEOMAR, Hemholtz Center for Ocean Research, a German research institution based in Kiel. I would like to introduce you to mineral resources of the deep sea and talk about a few scientific aspects regarding their formation, distribution and resource potential.

When talking about deep sea mineral resources, we have to consider three major resources. Manganese nodules that form around a nucleus and can be found in the sedimented abyssal plains. A large example of such a nodule is shown in the left-hand image.

Most manganese nodules are smaller than this one, commonly the size of potatoes or a salad. Secondly, cobalt-rich ferromanganese crusts that grow on the flanks of all volcanic edifices. And thirdly, seafloor massive sulfides or black smoker type deposits that form in areas with active volcanism, such as mid-ocean ridges or active volcanoes.

In the following lesson, I would like to give you some details about each of these resources. Our working area, the deep ocean, is a vast area. It covers over 360 million square kilometers, some 70% of the Earth's surface.

The ocean's topography is shown here in colors ranging from deep blue, meaning greater water depth, to light blue, shallower water depth, to orange and yellow on the continental slope. Of the ocean's area, some 41% are covered by exclusive economic zones, providing the coastal states with rights to the seafloor and the water column. These EZ are highlighted here by the thin white lines and slightly shaded in blue as well.

In addition to the exclusive economic zones, some areas fall under applications for the extension of the continental shelf, here shown in orange, which have been put forward by many countries in order to establish rights to resources at or below the seabed, mostly oil and gas. These applications for the extension of the continental shelf cover additional 8.3% of the ocean's area. This leaves barely 50% of the so-called area of the ocean, where the seabed is managed and regulated by the International Seabed Authority.

One of the main questions we would like to address as economic geologists is if the oceans can provide the raw materials necessary for future generations. As you will see during this lesson, the geological setting, resource potential, and environmental impacts of the three major resources in the deep sea are quite variable, and this variability has an impact on the legislative environment and corresponding regulations for seabed activities. Let's start with manganese nodules.

A typical image of a deep-sea nodule field is shown in the background, with a field of view of approximately 2 meters in the foreground. As already stated before, manganese nodules are found on the sedimented abyssal plains. They form on the sediment surface by growing around a nucleus, commonly a rock fragment or a shark tooth.

Growth rates are extremely slow, with less than 5-20 mm per million years. By no means a renewable resource. Nodules consist mainly of manganese and iron oxyhydroxides, but contain considerable copper, nickel, and cobalt, plus other metals.

Due to their large aerial extent and formation on the sediment surface, manganese nodules are a two-dimensional resource. Knowledge about the presence of manganese nodules is not new. In fact, the first manganese nodules were recovered in the Atlantic and Pacific Oceans during the famous Challenger expedition from 1872 to 1876.

The nodules were described in detail, as you can see on the left-hand image, and even their chemical composition was analyzed. But their presence was seen as a curiosity and nearly forgotten. An important process for nodule formation is sorption.

Manganese oxides form negatively charged colloids or particles that attract positively charged metals such as cobalt, nickel, and zinc, and others. Iron oxyhydroxides, in contrast, form positively charged aggregates that attract negative ions, as shown here in the upper image. The overall redox conditions can change over time, resulting in alternating layers of manganese-rich and iron-rich bands.

Nodules get most of the metals from the pore water of the sediment, which is called diagenetic, with addition of metals derived directly from seawater, called a hydrogenetic process. The proportions of these are variable on a regional scale. Globally, the areas where manganese nodules could form are quite large.

In this map, the calculated area that is likely to host manganese nodules is shown in purple colors. This calculation is based on the age of the oceanic crust. Only areas older than 10 million years are considered.

The sedimentation rate. Only areas with less than 2 cm per 1,000 years of sedimentation. The topography of the seafloor, only abyssal plains, excluding seamounts and ridges, are considered. And the water depth. As mentioned above, between 3,000 and 6,000 meters of water depth is the most commonly found water depth for manganese nodules.

The manganese nodule areas with greatest resource potential are shown in this map. Past research has mainly focused on the Clarion-Clipperton zone, an area spanning from Hawaii in the west to Mexico in the east. The Peru basin off the coast of South America and the so-called Penrhyn basin near the Cook Islands in the West Pacific.

Although manganese nodules can be found in every ocean basin, their geochemical composition varies on a regional scale with important differences in the concentration of cobalt, nickel and copper between the major oceans. Overall, highest contents of combined nickel plus copper plus cobalt have been found in the Pacific, commonly reaching over 2 weight percent. As you can see from the table, also the average concentrations of nickel and cobalt are higher in the Pacific than in the Atlantic or Indic.

The image on the left provides the average composition of manganese nodules in an area called the Clarion-Clipperton zone. I will show you its location on the next slide. You can see that the average combined nickel plus copper plus cobalt concentration in the CCZ reaches nearly 2.5 weight percent, a value commonly used to indicate economically interesting concentrations.

The image also shows that the most abundant metals in nodules are manganese over 28 weight percent and iron with 8 weight percent. The reminder of the nodules consists of silica, aluminum, sodium, calcium plus oxygen and hydrogen. The regional differences shown here also explain current exploration activities that focus on the Pacific Ocean.

We can clearly state that manganese nodules, due to their global distribution and its chemical composition, are a major resource when it comes to global future metal supply. The environmental impacts of mining activities will, however, also be very large. Fortunately, researchers commonly think outside the box or are simply surprised.

Here, Japanese researchers working in the EZ of Japan in 2016 discovered large areas covered with nodules in an area previously not considered to be of economic interest. While the geochemical composition is not known to me, the discovery of such new nodule fields clearly shows that we do not even know if we are in the right place when it comes to deciding where deep-sea mining might be done with the least environmental impact. The second deep-sea resource are ferromanganese crusts, such as the one shown in the upper left.

They form on the flanks of old seamounts. An example is given below the hand specimen. Those seamounts need to be old because ferromanganese crusts grow even slower than manganese nodules.

Commonly, growth rates between 1 and 5 mm per million years have been measured, with most of the metals coming directly from seawater, the hydrogenatic growth mentioned earlier with manganese nodules. Despite the fact that the crusts can form in all water depths, research has shown to date that highest cobalt and nickel concentrations can be expected close to the oxygen minimum zone in water depths ranging from 800 to 2,500 m. Since these crusts form a layer of only a few cm thickness on the hard substrate below, this resource is also a two-dimensional resource. Globally, the areas where ferromanganese crusts could form are provided here. Input parameters are again the age of the oceanic crust, the sedimentation rate, the topography of the seafloor, only seamounts and ridges are considered, and the water depth, here only depths between 800 and 2,500 m are considered. The old volcanic provinces and ridges, especially in the Atlantic and Pacific, are preferred locations for crust formation. Research to date has shown that the Western Pacific is the area with the greatest resource potential, with vast resources being present in the prime crust zone.

In a publication from 2013, Hein and co-authors have estimated that 7.5 billion tons of crusts occur in this prime crust zone alone. Global resource potential is more difficult to assess than for nodules. From an economic point of view, crusts need to have a certain thickness, commonly assumed to be a minimum of 4 cm for an economic recovery.

But how do you know variability without expensive sampling programmes? And I clearly have difficulties imagining mining equipment working in the difficult terrain in many crust areas, such as the one depicted in the right-hand image. And how do you separate that crust from the substrate efficiently and without dilution? Many technological difficulties still lie ahead. However, as with manganese nodules, the resource potential of ferromanganese crust is vast, with the environmental impact of mining activities probably comparable, but slightly smaller than that of nodule mining.

Based on previous research, resource potential of ferromanganese crust seems greatest in the Western Pacific. When comparing nickel and cobalt concentrations in crusts from the major oceans, it is apparent that those from the prime crust zone in the Western Pacific, with 0.4 weight percent nickel and more than 0.6 weight percent cobalt, are enriched over crusts from the Atlantic and Indic. However, a recent survey by Spanish colleagues documented nodules and crusts from the Galicia Bank off the coast of Spain that are strongly enriched in cobalt compared to other sites in the Atlantic.

Again, this highlights our limited knowledge about the true distribution and resource potential of ferromanganese crusts. Finally, the third resource are seafloor massive sulfides. These form divergent plate boundaries and young volcanics in all oceans.

They are typically associated with such nice black smokers as in this image from the Manos Basin in Papua New Guinea. These chimneys are especially enriched in copper and gold, averaging over 20 weight percent copper and 10 grams per ton of gold. This image nicely documents the common bias in sampling these sites and the lack of representative samples for this resource type.

In the background on the left-hand side, you can see a large amount that is composed of pyrite, an iron sulfide, and anhydride, a calcium sulfate, both minerals that are of no economic interest whatsoever. Publishing average geochemical analysis of the chimneys in the foreground will be misleading with respect to the overall chemical composition and resource potential of this site, because they are not representative of the deposit as a whole. In general, seafloor massive sulfides form in water depths ranging from a few hundred meters to roughly 5,000 meters.

The growth rates are much faster than for nodules and crusts, but still it would be misleading to call them renewable. The main metals of interest are the base metals copper and zinc, as well as the precious metals gold and silver. In contrast to nodules and crusts, the chemical composition of massive sulfides is very heterogeneous, even on regional or local scales.

In addition, most known sites are hydrothermally active, hosting chemosynthetic faunal communities that should be protected. And they are very often also quite small, mostly too small to be of economic interest. Seafloor massive sulfides are commonly forming mound-like deposits and therefore represent a three-dimensional resource.

This would imply a much smaller aerial environmental impact when compared to mining the same amount of metals, let's say 1 million tons, from nodules or crusts. The global distribution of known seafloor massive sulfides is shown here and nicely shows the relationship of this deposit type to mid-ocean ridges, where new oceanic crust is being formed. As stated before, the relation between the number of inactive, shown in orange, and active sites in red is mainly a result of the technology being used for exploration and does not reflect the true distribution.

It is very likely that many more inactive sites exist on the modern ocean floor, but these have not been found yet. Due to our preferred method of exploration for seafloor massive sulfides, which is searching for physicochemical anomalies in the water column, we currently know far more active deposits than inactive deposits, despite the fact that inactive deposits have been shown to be generally larger than active sites and therefore representing a larger potential. In summary, though, seafloor massive sulfides are a small resource and mining them is not likely to affect global metal supply.

When looking at this map of current exploration and mining contracts in the deep sea – the Atlantic is too deep in the Red Sea and the Solwara I deposit in Papua New Guinea, both within exclusive economic zones – it looks like a rush to the seafloor. But this would not be a good guide. We have to stand back and see what we truly have before making decisions.

If this decision is going forward to mine the seafloor, we currently lack the knowledge to decide where on the globe it can be done in the least harmful way, since exploration is clearly focused in areas where we already have information. Large areas are still not investigated. Here, due to the lack of data, future use of artificial intelligence might provide meaningful extrapolation.

With this I stop and hope that you found this lesson interesting and meaningful. Thank you for your participation.