



# Sustainability in Mineral Resource Extraction: Best Practices On-Shore and Challenges Off-Shore

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## 1. Introduction

Sustainable development in the mineral resource industry can be defined as policy in developing, operating and re-naturing mining projects, which integrates economic, environmental, efficiency, safety and social considerations in order to improve the lives of the current generation and to ensure that future generations will have adequate resources and opportunities (e.g. Hendrix 2006, Lawrence 2011). The question may be asked, if the extraction of non-renewable resources can be sustainable at all, as today's extracted resources are unavailable for future generations. This question could be answered theoretically, taking an inter-temporal approach to assess different net values of extracting resources over time. In this context, an extraction could be said to be sustainable, if it follows Hotellings rule (e.g. Gaudet 2007). This rule states that the most socially and economically profitable extraction path of a non-renewable resource is one along which the price of the resource, determined by the marginal net revenue from the sale of the resource and increases at the rate of interest. In other word, the time of extraction should be defined carefully taking into account macro-economic developments and needs of future generations; the question should be asked: Would an extraction at a later point in time create more net social value? Since our ability to predict the future is limited, this is a quite difficult question and cannot be answered with a high degree of confidence. Therefor the optimal time of extracting mineral resources is certainly an almost philosophical question, which shall not be further discussed here. Instead, this paper focuses on sustainable extraction principles and practices, which involve a holistic approach integrating all interdependent factors in order to determine the net social value of a project (Figure 1).

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**Figure 1:** Interdependency of factures defining sustainable mining practices (after AUGOV 2011).

The first part of this paper critically reviews best practice in on-shore mining related to sustainability factors. The second part reveals challenges for an extraction in a deep sea environment.

## 2. Sustainability – best practices on-shore

According to figure 1, a mining project operated according to sustainable best practices needs to balance out economic, safety, environmental, resource efficiency and community related aspects. To be more general, it should consider all stakeholders interests, which are effected by the mining project. At this point it is worth mentioning that mineral resource extraction projects are temporary projects. Thus, impacts of interests of stakeholders need to be taken in account during the project execution and after mine closure. The next paragraphs present selected examples for best practices related to the mentioned factors defining sustainability. Although far from a complete review, it provides impressions of current practice and highlights policies of companies committed to sustainable mineral resource extraction.





## 2.1 Impact on Environment

No doubt, mineral resource extraction has a tremendous impact on the environment. Open pit mines cover areas of several km<sup>2</sup>, contaminate water, impact biotopes, emit dust and noise and light pollution. Responsible mining companies understand this impact and undertake enormous measures in order to mitigate the impact or create an equivalent compensation. The following three examples are related to German lignite mining activities and illustrate that these measures can even increase the biodiversity.

To guarantee a safe and economic development of the Inden mine, the relocation of the Inde River was inevitable. For this purpose, RWE took a far-sighted planning and designing process that considered all concerns ranging from nature conservation all the way to mine development. In a project time of 8 years, a new artificial bended river bed was created on the dump site, which was assessed after completion to exhibit a higher ecological quality and biodiversity than before (see figure 2). Approximately 24 Mio. Euro were invested, 400.000 trees and shrubbery were planted, 7 new bridges constructed. It was designed according to old maps, showing the original river bed, before mining activities started some 100 years ago (RWE, 2005).



**Figure 2:** the relocated Inde River (from RWE, 2005).

Other examples can be stated from the central German mining area around the city of Leipzig. Large swathes of the Leipzig region are currently taking on a whole new appearance on what could be termed the biggest construction site anywhere in Europe! The barren landscapes which just twenty years ago were still scarred by mining and industry are giving way to a veritable lake district evolving around the city of Leipzig. In total, 22 new lakes with a total surface area of almost 70 square kilometres are emerging. This will usher in many uses to which the lakes, rivers and canals can be put, especially for tourism and recreation. An important role will be played by the attractive network of waterways connecting Leipzig to the lakes in the district round about. The combination of Leipzig's big city attractions with a wide range of water-based activities is an enormous boost for the region's development and makes Leipzig New Lakeland a truly unique destination (rvp-West Sachsen, 2013).

During Operation the impact on environment is mainly due to the use of area and space, dust and noise pollution as well as water contamination. Mitigation actions include dust suppression systems, sound encapsulation of noise emitters or mine water treatment. The last measure is necessary in lignite mines as the acidity of the mine water may increase if it contacts oxidized pyrite. For mitigation large mine water treatment plants are built, which are to improve the mine water quality to the level of drinking water with a capacity of 45 to 60 m<sup>3</sup>



**Figure 3:** New Lake Land around Leipzig (LMBV 2013).



**Figure 4:** Mine Water treatment plant at United Schleenhain mine, MIBRAG (MIBRAG 2013).



per hour (Figure 4).

## 2.2 Impact on the Community

Living next to a mining area comes certainly with both, advantages as well as disadvantages. Advantages include employment opportunities and interesting career paths related to the mineral resource extraction or the improved infrastructure around the area. However, there are as well negative aspects.

One of the largest impacts is certainly the necessity to relocate whole townships. This happened in the past decades in lignite mining in Germany several times. Figure 5 shows a local protest sign against the relocation of the village of Holzweiler, near Erkelenz, North Rhine-Westphalia. The last examples are the towns of Heuersdorf in Saxony and Grossgrimma in Saxony-Anhalt, which were relocated between 1992 and 2005. It is obvious that your home has a social and emotional value, which is not payable in Euro. Thus relocation is not a project, which one decides and then it will be executed. It needs a lot of discussions between all involved (these are not always nice and objective discussions), involves large compromises and probably some mining history and tradition to be successful.

One remarkable activity in this context was the relocation of the “Emmaus” Church from Heuersdorf to the town of Borna in the year of 2007 (Figure 6). This 750 year old church was transported 12 km in 6 days allowing future generations to meet in or to visit this church. This extraordinary example stands for the need to mitigate as well the impact on cultural and religious goods.



**Figure 5.** Local protest against relocation (“Yes to your Homeground. Stop Rheinbraun. We remain here!”) in the village of Holzweiler, near Erkelenz (North Rhine-Westphalia). The village is intended to be relocated because of the expansion the Garzweiler open pit lignite mine. Source: <http://de.wikipedia.org/wiki/Rheinbraun>



**Figure 6.** Relocation of the Emmaus Church (MIBRAG, 2007).

Although relocation is a very seldom and hard impact, living next to mines means impact due to dust, noise and light pollution as well due to temporary reduction of property value. These impacts need of course to be minimized, mitigated or balanced out by the mining company. In order to shape the life next to a mine as comfortable as possible, it requires a good “neighbour”-relationship, open discussions and common goals and the will from both parties.

## 2.3 Safety

Safety for all staff as well as for the neighbouring community has to have highest priority. There is no compromise against safety: if any activity during mineral resource exploration has the potential to be unsafe, it is not acceptable. A deeper discussion here is skipped, as it could fill whole books.

## 2.4 Resource Efficiency

A mine also has to be efficient in the way the resource is managed and extracted. Mining engineers, geologists and metallurgists collaborate to optimize resource extraction. We will not discuss this in more depth here. Rather the focus of discussion is placed on the complex utilization of the resource or recovery. A non-sustainable practice, observed in some operations, is to go for the good and easy ore, also known as “high grading”. In order to improve the short-term economic result, only the mineral resource is mined, which results in the highest profit. This practice comes with the fact, that lower grade areas or more difficult to mine areas are left behind at the time of mining and cannot be accessed anymore (or only with enormous financial effort) by future generations. This development may be especially triggered by high commodity prices or high turnover of managers. Incentive or bonus systems for managers are still often based on annual performance, dividend, etc. Long-term strategic goals involving sustainability effects are often missing. However, recovering additional ore comes with long-term benefits, such as extension of the mine life and a decrease in relative fixed costs as the ratio of waste rock to ore (stripping ratio) decreases. These effects are not captured in nowadays mostly used evaluation techniques such as the net present value (NPV). In fact the timely discounting of value decreases the perception of value in future years, which is contrary to a sustainable practice. Here further research and change of practices is necessary in order to incorporate the value of sustainability in evaluating mining projects. In the opinion of the author (J. Benndorf), there is still room for improving the mind-set and the policies of mining companies as well as governmental procedures to monitor the resource efficiency. Good examples can be seen in coal mining, where a small scale mobile fleet recovers remaining coal, which is not selectively mineable by large mining systems (Chatwick, 2008).

## 2.5 International Guidelines and Procedures

In Europe the environmental and social impact is regulated by the Environmental Impact Assessment Directive (EIA Directives 85/337/EEG and the amendment 97/11/ EC of the European Union) and implemented by national law. It focusses on the assessment of impact on objects to be protected, including:

- human beings, animals, plants,
- soil, water, air, climate,
- landscape,
- cultural and other objects as well as
- utilization of ground and real estate.

Figure 7 shows the general procedure of environmental impact assessment (Achieng Ogola, 2007). One of the most important aspects of this process is the involvement of the public (or stakeholders) at an early stage as well as at a decision making stage. The communication of mining activities, the understanding of the stakeholders' value and holistic approach considering all relevant aspects towards impacts are essential for a responsible extraction of mineral reserves. During the step of mitigation and impact management state-of-the-art techniques in geo-environmental engineering, geo-engineering and subsidence prediction, operations management and mine scheduling, re-naturation, as well as continuous monitoring of emissions and other impacts are required. The two geoscience departments at the Faculty of CEG, TU Delft are involved in several leading edge projects for a continuously improved environmental impact management, not only in large mineral extraction projects but as well in all other projects impacting objects to be protected.

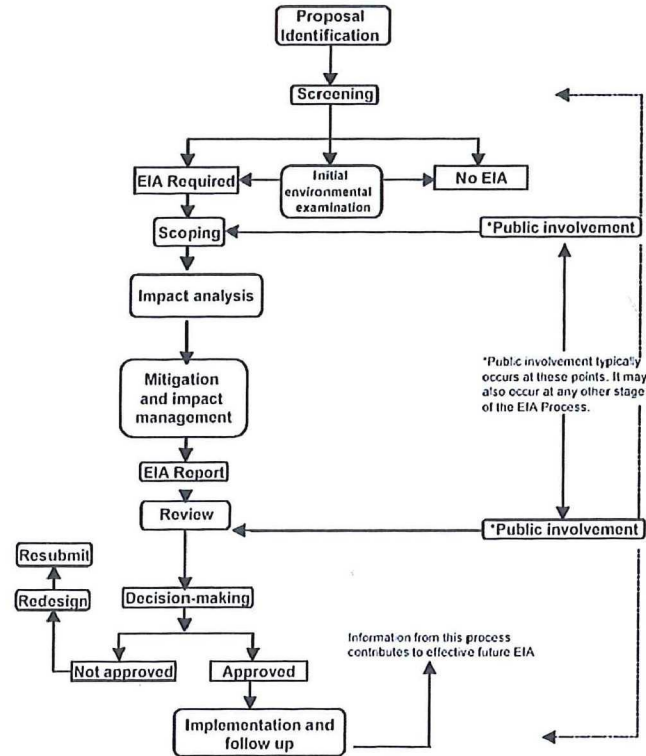


Figure 7. Environmental Impact Assessment General Procedures (Achieng Ogola, 2007).

## 2.6 Discussion

The discussed examples clearly indicate best practices for a sustainable mineral resource extraction on-shore. However, best practices means as well that there are companies or regions on this world, where mineral resource extraction is not done in a responsible way. It needs to be the mission in educating students and professionals around the world to treat responsibly our non-renewable resources. For this, it is important for all mining company CEO's, managers and miners to maintain or develop a sustainable mind-set which balances out the micro-economic considerations with the inter-temporal impact on nature and human being of mineral resource extraction.

## 3. Challenges Offshore

### 3.1 Introduction

Mining offshore is completely different from mining onshore. You have no direct access to the deposit. The deposit is in a completely different environment, where you cannot go without specialized equipment. The environment is quite unforgiving: there is strong corrosive action from seawater, and ambient pressures are high to very high, whereas temperatures are low, even close to zero degrees Celsius.

But with respect to the deep sea, there is also another question which is important. Who owns the deep sea? No-one? Or does it belong to everyone? Can you do out there whatever you like? Or can you not? Who supervises those matters, or does no-one do that?

### 3.2 Legal Matters

The latter question is the most easy to answer. In 1982 a conference was held resulting in the United Nations Convention on the Law of the Sea (UNCLOS). As a consequence of UNCLOS, the Exclusive Economic Zone, or EEZ has been established. This is an area of 200 (nautical) miles (approximately 370 km) offshore from coastlines where coastal states have exclusive rights. (This holds of course only there where possible. The countries should be far enough apart).

Also it was established that the area outside the EEZ's (called the High Sea), and its resources are to be considered "The Common Heritage of Mankind". This effectively means

that it belongs to **everyone**, so also to you, the reader of this paper, or, for instance, to someone in Bangladesh.

The treaty became effective on November 16, 1994, after ratification by 158 states (including The Netherlands). This comprises almost all coastal states. The treaty holds for all seas on the world, and for all mineral resources (including oil and gas). Also UNCLOS led to the establishment of the **International Seabed Authority (ISA)**, which supervises mining outside the EEZ's. The ISA, headquartered in Kingston, Jamaica, has at its disposal not only ships, but also has access to aerial photographs and satellite images.

UNCLOS therefore sets rules for deep sea mining, including environmental issues (UNCLOS, 1982, article 194). These latter rules concern among others discharge of toxic or harmful substances, from land, from ships, or by atmosphere. Also rules for emergency situations and accidents (involuntary discharges etc.) are set.

Although little is known of life on the ocean floor, it most likely exists, even in places where it was thought not possible (as with the life forms around Black Smokers). Although most of the ocean floor will be largely devoid of larger life, except probably life in a bacterial stage, a lot more research is necessary to get a good overview of the available life forms, and how mining affects them.

### 3.3. Deep Sea Mineral Deposits.

Well, what do we know about the deep sea and its minerals deposits? Quite a lot. There has been a lot of research in the past 10 years, and many deposits have been sampled. On the other hand, that is still just a fraction of what is probably present. Nevertheless it has been established that there are some very interesting minerals deposits.

#### 3.3.1. Types of Deep Sea Deposits

##### a) Ores related to magmatic processes

This category consists of ores related to submarine volcanism/magmatism. Such magmatic systems predominantly occur along Mid-Oceanic Ridges: elongated, submarine volcanic mountain chains.

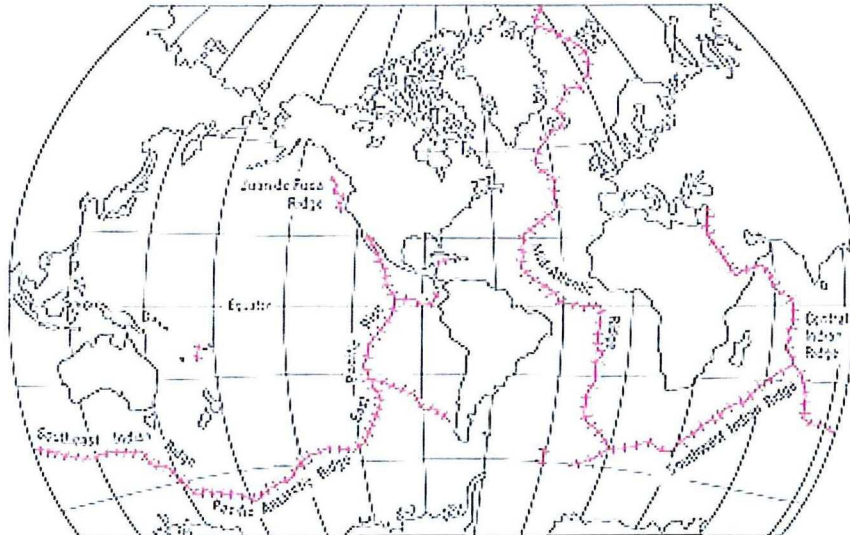


Figure 8: Mid-Oceanic Ridges. (Image: © USGS)

Aqueous fluids, seeping through the seabed are heated by the influence of submarine magmatism. These fluids (called hydrothermal) are enriched in minerals by leaching them out of the rocks, and the typically contain iron, copper, zinc, sulphur, and possible gold and silver. Also mixing with magmatic fluids is possible.

Via faults these hydrothermal fluids can reach the surface of the seabed. There they cool, leading to deposits of copper and zinc sulphides. This happens at depths of 4 – 6 km

### Black Smokers

Reaction of these solutions with seawater also leads to the formation of  $\text{CaSO}_4$ -rich cones and chimneys, which may be several meters in height. The solutions that come out of these cones and chimneys are black, due to the heavy load of tiny sulphide crystals. When these structures were first sighted (Corliss et al., 1979), researchers saw an analogy with chimneys venting black smoke. They were therefore termed Black Smokers. Sulphides occur near to (but also inside) the chimneys, and form together with collapsed chimneys the so-called submarine massive sulphide deposits. Such deposits (varying in size from a few thousand tonnes to 5 million tonnes) are very rich in metals, and the larger ones are in potential lucrative to mine (Hannington et al., 2011).

A fascinating detail is that close to these chimneys, depths where no light penetrates anymore, life occurs. These ecosystems function on basis of chemosynthesis (with sulphur), instead of on photosynthesis. There one can find a furthermore not occurring type of tubeworm: the so-called Giant Tubeworm (*Riftia Pachyptila*), with lengths up to 2.5 m. Also several species of adapted (a.o. blind) sea creatures occur. Before the discovery of the Black Smokers in 1979 these life forms were unknown.

This immediately puts the focus on what we know about life in the deep sea: probably little! On the other hand, life most likely only occurs there, where there are a lot of nutrients available, like around the Black Smokers. Other places of the deep sea may possibly host only bacterial life. But still: what environmental damage will mining do? What kind of species that are not even known yet, will perish? And the surface of the sea afterwards looks still the same. On land you immediately see the effects of mining. At sea you do not.

### Hydrothermally formed phosphorites

Phosphorites are another type of submarine ores, which are partly related to hydrothermal processes. Phosphorites are rocks which contain at least 20% of phosphate. Besides a hydrothermal origin, phosphorites can have a biological origin, or originate from diagenetically altered limestones. Presently phosphorites are mined only on land, where they have put in place by geological (tectonical) processes.

### REY-muds

Two years ago, Japanese investigators (Kato *et al.*, 2011) found a new type of deposit: Rare Earth Element-and Yttrium-rich (REY) muds. These muds consist of metal containing clay, zeolitic clay, and red deep sea clay. These muds occur in the South-Eastern and Northern Pacific Ocean. Analysed mud contains in total 0.2 – 0.3 weight percent REY. Thicknesses up to 10 m have been observed. These muds are also rich in vanadium, cobalt, nickel, zinc, molybdenum and manganese. The deposits are possibly linked to hydrothermal activity of mid-oceanic ridges. The researchers are however cautious: fluctuations in thickness are very well possible, and much more research is necessary to say anything about potential reserves. Exploitation is still far away.

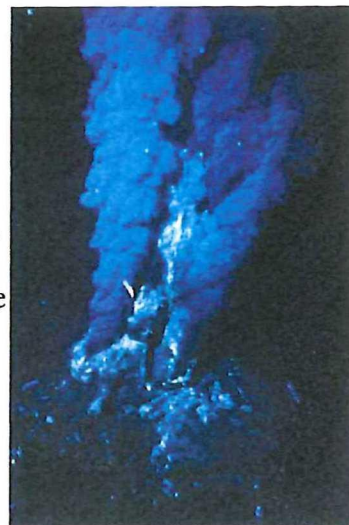


Figure 9. Black Smoker.  
(Image: © Wikipedia)



Figure 10. Specimens of the Giant Tubeworm, *Riftia Pachyptila*, near a Black Smoker.  
(Image: © Wikipedia)



b) Ores related to geochemical processes in seawater.

**Manganese Nodules**

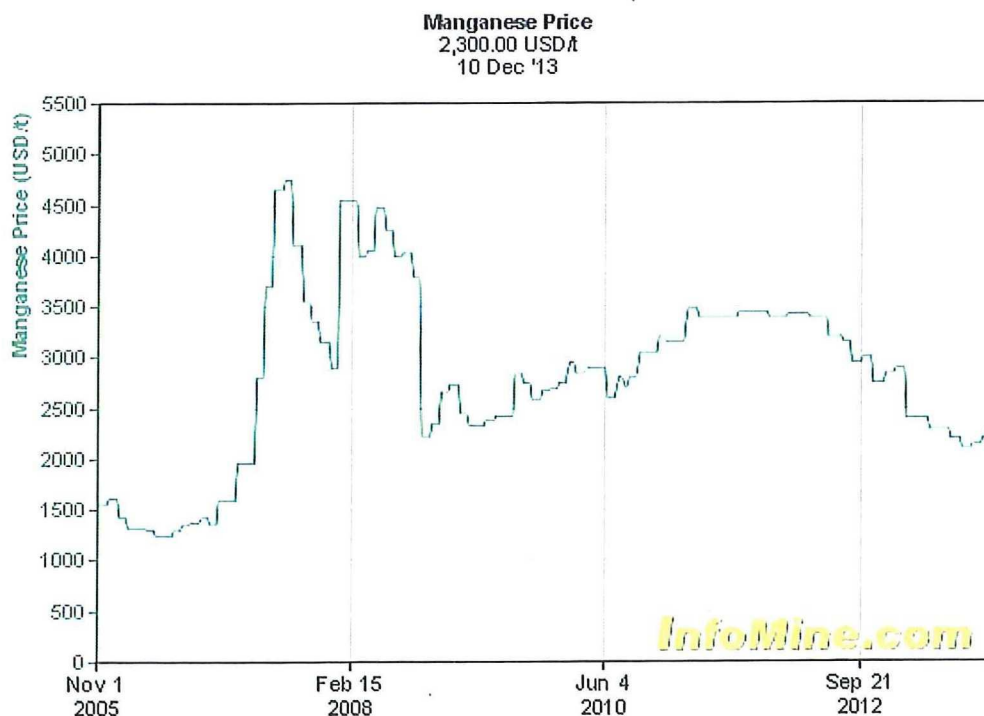
The most important ores from this group are the so-called manganese nodules. They form at the ocean floor, where very low sedimentation is necessary ( $< 7 \mu\text{m}/\text{year}$ ). Excrements and remains of surface organisms eventually reach the seafloor. These contain small amounts of metals. Submarine volcanism also contributes to the concentration of metals in seawater. Dissolved iron and manganese precipitate as iron and manganese oxides in concentric layers around solid particles, like sand grains, or shark teeth. So a nodule (or ball) is formed. They also contain cobalt copper and nickel, and have approximately the size of potatoes. An often used synonym is: polymetallic nodules. Their growth rate is very low. They form over millions of years.



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**Figure 11.** Left: A manganese nodule. (Image © Wikipedia. Right: They are comparable in size to potatoes.)

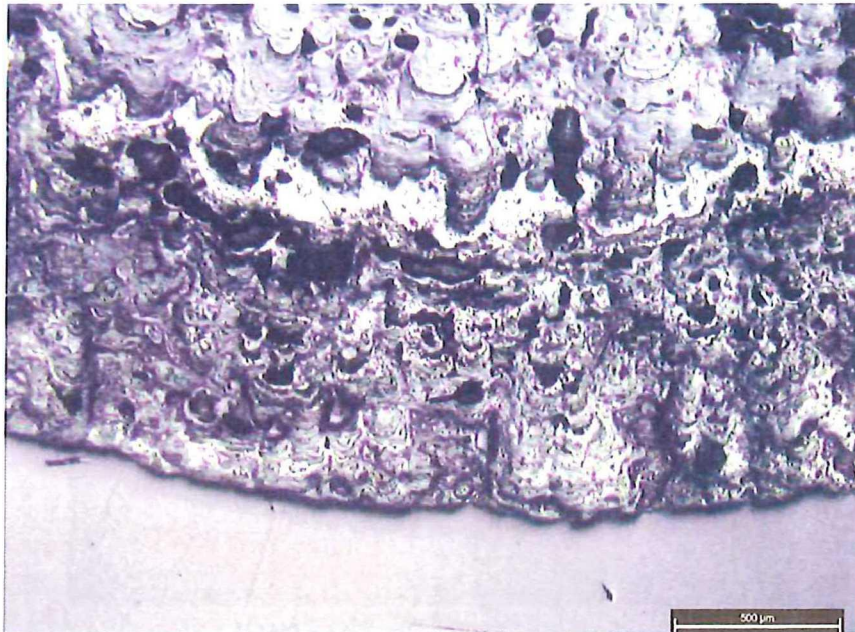
The nodules occur world-wide, but occur on some places more than on others. The reason for this is not well known. Usually the nodules are found at depths of 4 – 6 km. In the 1970's, it was for a little while attempted to mine them, but exploitation was stopped. Mining appeared uneconomical. The price of manganese varies quite strongly, and this makes exploitation of manganese nodules uneconomical even on longer term.



**Figure 12.** Manganese prices, 2005 – 2012 in USD/tonne. Data from Infomine.com.





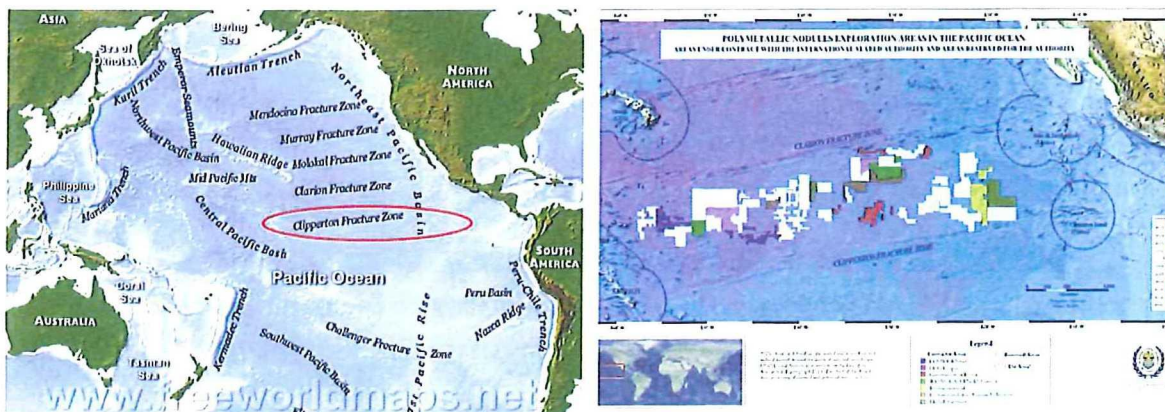


**Figure 13.** Microstructure of the rim of a manganese nodule. Scale bar is 500µm.

Nodules of economic interest have been found in three areas:

- North central Pacific Ocean
- Peru Basin in the southeast Pacific
- Centre of the north Indian Ocean.

The most promising of these deposits in terms of nodule abundance and metal concentration occur in the Clipperton Fracture Zone of the eastern equatorial Pacific between Hawaii and Central America.



**Figure 14.** The Clipperton Fracture Zone. Top: location of the Clipperton Zone. Bottom: Exploration areas for polymetallic nodules. Sources:

Left: <http://www.freeworldmaps.net/ocean/pacific/pacific-ocean.jpg>

Right: [http://www.soest.hawaii.edu/oceanography/faculty/csmith/MPA\\_webpage/MPAindex.html](http://www.soest.hawaii.edu/oceanography/faculty/csmith/MPA_webpage/MPAindex.html)

### Cobalt-rich crusts on seamounts

Slopes of submarine mountains (seamounts) and volcanoes at depths of 800 – 2500 m in the Pacific Ocean are often covered by a crust of cobalt, titanium, cerium, manganese and nickel. The most important metal is cobalt, followed by manganese. These deposits also were precipitated from seawater, possibly under the influence of bacteria. Hydrothermal activity is a possibility for the origin of the metals. The formation times are probably tens of millions of years.

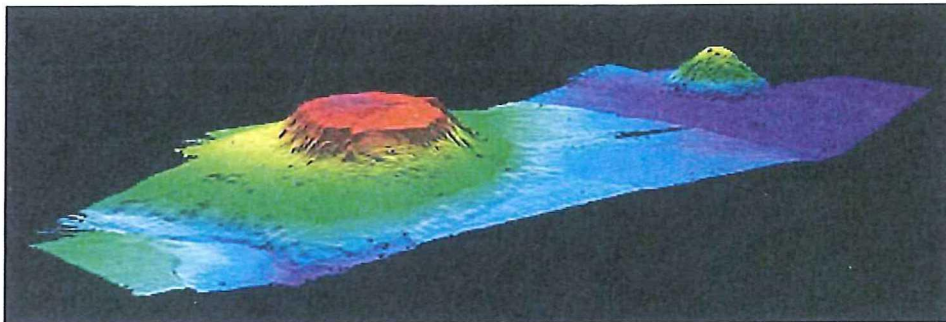
The crusts are in average about 2.5 cm thick. The middle of the Pacific Ocean seems the most suitable for mining. However, the small thickness of the crusts makes mining technically problematic.



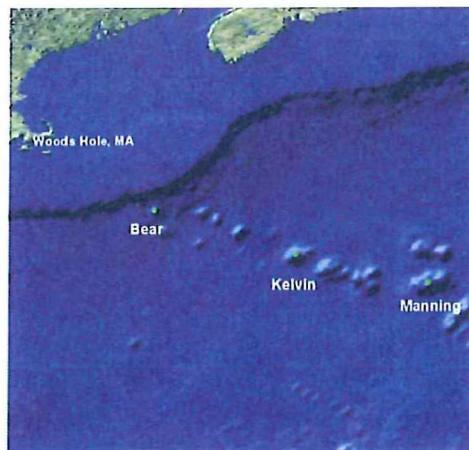
**Figure 15.** Close-up of central Pacific Basin. The image shows that the Hawaiian Islands (marked with white arrow in the right of the image) are the youngest portion of a long chain of seamounts.

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The linear arrangement of many seamounts (Figure 15) indicates that they formed because the plate moved over a stationary site of magma upwelling, a so called mantle “Hot Spot”. Seamounts are submarine volcanoes that may finally build above the water level (e.g. Hawaii), in which case they are called islands. If seamounts eventually rise above sea level (two reasons: build-up of material in a cone, upwelling mantle pushes up the plate), they are subject to wave erosion and colonization by reefs, with both processes tending to create a flat top on the original volcanic cone. Later, when the oceanic plate cools down and the island finally drowns this leads to flat-topped seamounts, so called Guyots.



**Figure 16.** 3-D depiction of Bear Seamount (N-Atlantic), with Physalia Seamount in the background.



**Figure 17.** Location of Bear Seamount, offshore near Woods Hole, MA, USA.

*c) Deposits related to subduction processes.*

This is about submarine hydrothermal manganese deposits which occur at a number of island arcs (Tonga-Kermadec ridge, Ogasawa trench, Bonin trench, Mariana trench and the Bismarck Archipelago). Due to dewatering of sediments subject to subduction, large volumes of solutions are released (Glasby, 1988). These solutions are rich in manganese, which precipitates as hydrothermal manganese deposits. The depth on which they occur varies from 110 – 8350m. Often these deposits have a spatial relationship with seamounts that occur at subduction zones. The manganese crusts are rather thin (centimetres to sometimes a decimetre). This makes mining technically difficult, and expensive. As the price of manganese is quite unstable, this leads to further difficulties regarding mining of these deposits.

*d) Deposits related to sedimentary processes.*

Placers or placer deposits occur world-wide and are relatively high concentrations of valuable, weathering resistant minerals. These minerals have a high density, in comparison to rock forming minerals. Examples are diamond, monazite, zircon and garnet. The concentrations form by means of by sedimentation processes. The material is supplied from very nearby landmasses. They are exploited usually by dredging methods.

Diamond placers occur along the shoreline of Namibia (on land as well as on sea). Most of the diamond is won at sea.

Submarine tin placers (with cassiterite,  $\text{SnO}_2$ ) occur near China, Thailand, Burma, Malaysia (Kinta Valley), and Indonesia (Bangka en Belitung – the latter name was reformed under influence of Dutch pronunciation into Billiton). The countries mentioned above produce approximately 80% of the world tin supply.

### 3.4. Discussion

With respect to submarine mining, one must also consider that if this going to be carried out at a site, one should take everything there is, also the lesser value material. It is unlikely that, even with future higher prices, one can go back to mine remaining ore that was in the past was left behind, because it was below cut-off grade. With higher prices it may be above the cut-off grade, as was valid during active mining. Going back and take the remaining low-grade ore, however, may be too expensive.

Also it is important to consider that in case of technical difficulties, or breakdowns; downtime of equipment will be substantial. In a mine, one can send a crew of dedicated technicians to stranded mining equipment, which can (quite often) fix it on the mine site. However, in the deep sea, you have to haul the equipment to the surface, repair it (if possible), and lower it down again, which may take hours for the hauling and lowering, and perhaps even longer for the repair. In case of spare parts not available on the accompanying ships, even longer delay is unavoidable. This makes deep sea mining logistically difficult, and costly. Weather may play a role too. Although storms will have little effect on the ocean floor, it may become difficult for accompanying surface vessels.

Considering the often quite thin, but (possibly) extensive ore deposits, new methods of mining will have to be developed.

Although most seafloor deposits seem to be highly concentrated, most likely some processing will have to take place on the accompanying ships, to produce a concentrate which can be shipped in an economically feasible way to land-based processing and extraction plants. This, apart from technical difficulties with respect to processing on board of a ship, also leads to the problem of tailings, of which it may very well be possible, that they cannot be discharged at the mining site, because of pollution and international law (UNCLOS). Certainly with froth flotation this will be an issue.

Anyway, very close surveillance of the mining site with respect to pollution seems necessary, to avoid or minimize environmental damage. Also this will make off-shore mining costly.



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