Technology developments in the exploration and evaluation of deep-sea mineral resources

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Manganese nodules, Co-rich crusts, and Seafloor massive Sulfides (SMS) are commonly seen as possible future resources that could potentially add to the global raw materials supply. At present, a proper global assessment of these resources is not possible due to a severe lack of information regarding their size, global distribution, and composition. The sizes of the most prospective areas that need to be explored for a global resource assessment are vast. Future deep-sea minerals exploration has to provide higher-resolution data and at the same time needs to cover large areas of the seafloor in a fast and cost-efficient manner. While nodules and crusts are 2-dimensional occurrences and an assessment of their distribution at the seafloor itself seems sufficient, seafloor massive sulfides are 3-dimensional sites and a proper resource assessment will always require drilling. Here the development of methods to image the subseafloor and to recognize economically interesting sites prior to drilling is of importance.

Manganese nodules

Manganese nodules occur widely on the vast, sediment-covered abyssal plains at depths of about 3,000–6,500 m. They are mineral concretions made up largely of manganese and iron that form around a hard nucleus and incorporate metals from the sediment and seawater. As manganese nodules form directly on the seafloor, these deposits can be regarded as a 2-dimensional resource. The greatest concentrations of metal-rich nodules occur in the Clarion-Clipperton Zone (CCZ), which extends from Hawaii to Mexico. Nodules are also concentrated in the Peru Basin, near the Cook Islands, and at abyssal depths in the Indian and Atlantic Oceans. The abundance of nodules and, therefore, the quantities of associated metals are moderately well known for the CCZ, the Central Indian Ocean Basin and the Cook Islands EEZ, but poorly known for other areas of the global ocean (HEIN & *al.*, 2013). Nevertheless, over the past 15 years 17 contracts for manganese nodule exploration have been approved by the International Seabed Authority, of which 16 have been signed and 1 is pending signature. Most (16) are located in the CCZ, covering 1.2 million km^2, and one is in the Central Indian Ocean (77,000 km^2).

On a local scale, the nodule abundance varies from 0 to up to 30 kg/m^2 within a few hundreds of meters depending on parameters such as overall sedimentation rate, burial of organic material, local bathymetry, near-bottom currents, and nodule size. Common approaches to map manganese nodule occurrences in the deep-sea rest on vessel-based hydro-acoustic backscatter and deep-towed side scan sonar data-sets. These techniques can monitor large regions but lack a resolution sufficiently high to identify variations in nodule density, the most important parameter for controlling the resource. Ground truthing is commonly done visually by towed video sleds and by point sampling using box corer or similar devices. Both methods only provide limited spatial coverage and might not be representative for larger areas. Also, recent photo surveys have shown that decimetric-sized blocks of volcanic rocks occur in between manganese nodules in certain areas of the CCZ (PEUKERT, 2016), and such blocks may hinder mining activities. Such blocks are not recognizable in ship-based or deep-towed survey data. This is just one example why we need to explore large areas of the seafloor with higher resolution. The need to also better understand the areal distribution of faunal communities makes photo surveys the tool of choice. Since submersibles and ROVs are slow and areal coverage is limited, only AUV photo surveys seem to be able to provide such large scale coverage. There is, however, a conundrum as

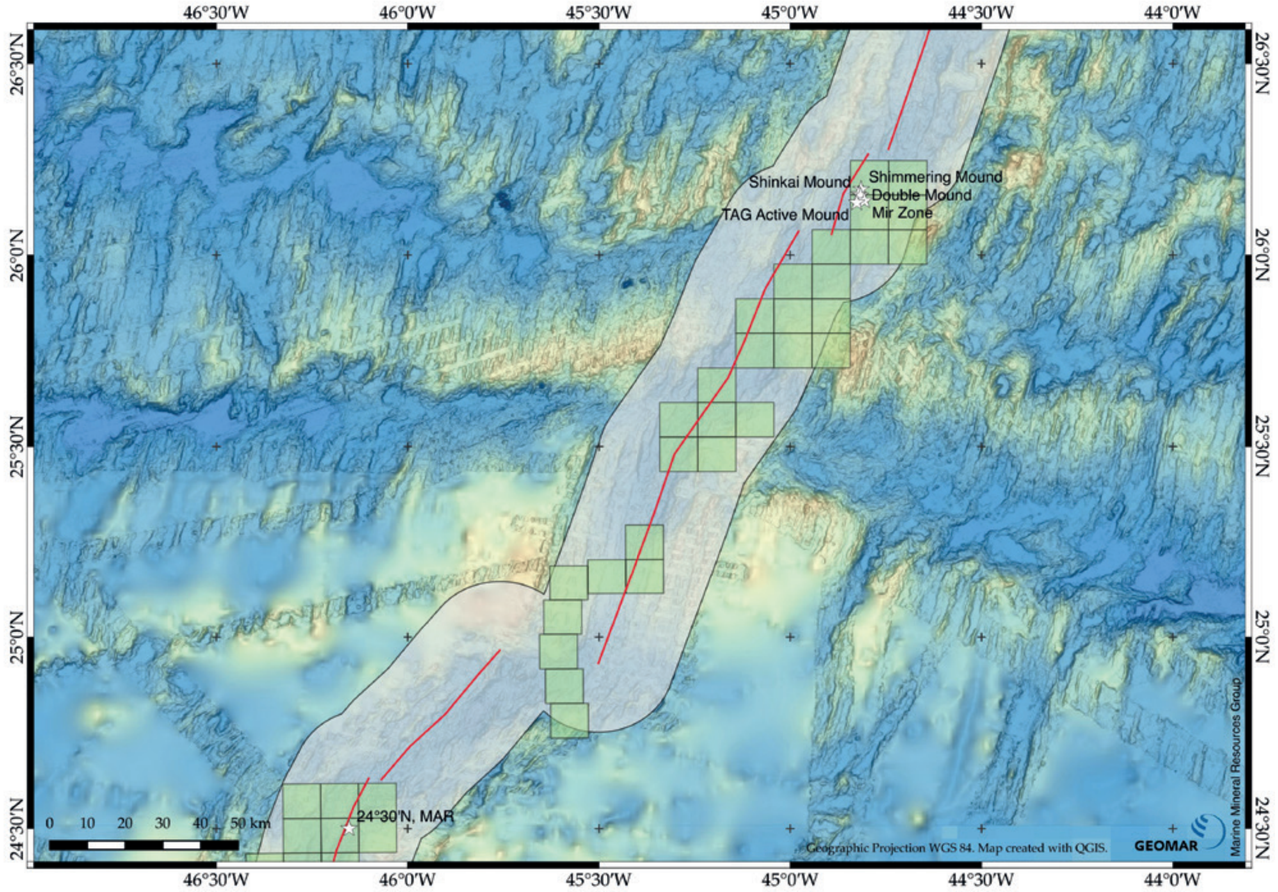

Figure 1: Regional bathymetry of the central Mid-Atlantic Ridge between 24°30 and 26°30 showing the location of the French exploration license blocks for massive sulfides in the area (green squares). Each square is 100 km² in size. The spreading axis is indicated by the red line. The white area shows the increase in the area that could be prospective for massive sulfides assuming a corridor of only 20 km on both sides of the spreading axis. White stars indicate the location of known active and inactive massive sulfide occurrences. Background bathymetry compiled from MGDS using GMRT v3.2 (RYAN & al., 2009).

current AUVs can either fly at a low speed (ca. 1kn) very close to the seafloor (1-3 m) providing high-resolution images (mm/pixel) with a limited areal coverage or they map large areas at higher speed (2.5 – 3.5 kn) and at higher altitudes (5-10 m) with a more limited image resolution (cm/pixel). The latter will only allow the recognition of megafauna, but is sufficient to calculate nodule abundance and will hence be useful for a proper resource assessment. Recent AUV surveys in the CCZ and the Peru Basin used a newly developed camera and LED lighting system developed in order to fly at higher altitudes and at greater speed (KWASNITSCHKA & *al.*, 2016). During these surveys several 100,000 images were obtained per cruise (MARTINEZ-ARBIZU & *al.*, 2015; GREINERT & *al.*, 2015) and were than mosaicked using newly developed image analyses software needed to handle large amounts of images (SCHOENING & *al.*, 2013). Overall, this setup, flying at a speed of ca. 3.5 kn, was able to cover 25,000-160,000 m² per hour, much more than previous surveys (KWASNITSCHKA & *al.*, 2016).

With a combination of several methods from regional mapping using hydroacoustic vessel-based backscatter to local exploration using deep-towed side-scan sonar, automated image analysis of AUV-based photo surveys, and seafloor sampling, it will be possible to produce predictive maps of prospective nodule areas. In order to provide a meaningful global resource estimate, however, exploration needs to cover vast areas of the ocean floor. A recent estimate of the global prospective areas for manganese nodule formation in sediment deep-sea basins indicates that 38 million km² would need to be explored (PETERSEN & *al.*, 2016). This is based on water depth, sediment thickness, sedimentation rate, topography, and the age of the underlying crust. Using a single AUV during a couple of cruises is certainly not the way forward in exploration. A reliable global resource estimate would certainly need increased exploration activities outside the CCZ, most likely using fleets of AUVs mapping simultaneously in order to effectively cover larger areas. New technologies to extend battery lifetime and to communicate between AUVs need to be developed to further enhance exploration.

Seafloor Massive Sulfides (SMS)

SMS, also known as black smoker deposits, are occurrences of metal-bearing minerals that form on and below the seabed as a consequence of the interaction of seawater with a heat source below the seafloor, mainly at volcanically active oceanic spreading centers and along volcanic arcs (HANNINGTON & *al.*, 2005). The majority of all SMS occurrences that are presently known are small, 3-dimensional bodies that are not of interest to the mining industry. Some deposits contain metals such as Cu, Zn, Au, and Ag that are of economic interest. Other trace elements, that are important for a variety of industry uses (Bi, Ga, Ge, In, Te), can be enriched at certain sites and may be considered as possible by-products (MONECKE & *al.*, 2016). A growing interest in SMS over the past few years resulted in six national exploration licenses, covering 10,000 km^2 each, that have been issued by the UN International Seabed Authority (ISA) since 2011. Each contractor has to explore 10,000 km^2 within the 15-year runtime of the contract. Actually, the need to define areas that are not economically interesting is more pressing, as 50% of the 100 license blocks have to be returned to ISA after eight years - hopefully areas that do not contain large and economically interesting SMS deposits.

Current geochemical prospecting technologies have mainly been developed for the search for active hydrothermal systems (e.g. hydrothermal vents and associated black smokers) that can easily be traced through physical and chemical anomalies in the water column (temperature, chemical variations of elements such as Mn, Fe, redox potential, and/or the particle concentration in the water column). Such plume surveys have been a primary tool for exploration of SMS systems, but they only identify active, and therefore mostly young and small hydrothermal systems.

Providing reliable global resource estimates for SMS is not possible: we simply do not know how much of the metal that is released by high-temperature fluid convection over a given length of a ridge axis and over a specific geological time frame is actually deposited as massive sulfides. There are no systematic surveys for massive sulfide abundance on a ridge segment scale and back in time (away from the ridge axis). The amount of sulfide along the neovolcanic zone has been estimated to be 600 millions of tonnes globally (HANNINGTON & *al.*, 2011). However, this estimate was based on the current knowledge of the vent sites at the time and is likely underestimating the resource potential of inactive sites. For example, in a recent survey within known vent sites at the Endeavour Segment, AUV-based high-resolution bathymetry was used to identify extinct sulfide chimneys and mounds. There, in only eight 18-hour dives, the number of chimneys and mounds present was quadrupled (JAMIESON & *al.*, 2014). This is especially noteworthy, since this vent site has seen well over one hundred submersible and ROV dives over the past 30 years and is considered to be one of the best studied submarine hydrothermal fields on Earth.

There is now ample evidence from recent seafloor surveys that much larger, but inactive or extinct sulfide deposits (eSMS) occur away from the ridge axis where long-lasting fluid flows along stable fault systems allow for the accumulation of massive sulfides over large time spans (McCAIG & *al.*, 2007). The hypothesis is that large eSMS deposits can be found in a strip of a few tens of kilometers away from mid-ocean ridges at only a few meters below a sediment or lava carapace. The potential to find extinct sulfide deposits that far from the ridge axis opens up a vast area of the seafloor for future exploration. Extending the exploration effort to only 20 km on each side of the ridge axis results in a prospective area of 3.2 million km^2 (Fig. 1). Also, since the entire oceanic floor was once formed at a mid-ocean ridge and is likely to have formed SMS deposits during the entire time, the true global resource potential is probably much bigger. However, without a distal signature, *e.g.* a geochemical or geophysical anomaly that is detectable over hundreds of meters or even kilometers away from deposit, and with only poorly constrained geophysical properties, inactive deposits are difficult to locate or evaluate. We actually do not know the fate of seafloor massive sulfide occurrences after they formed. Do they oxidize quickly, releasing the metals back to the pore water? Without a better understanding of their size, structure, and distribution, the global resource potential of eSMS remains uncertain.

Knowledge about the regional and local spatial controls of sulfide deposition are currently also still lacking. This is largely a reflection of the lack of high-resolution investigations away from the spreading centers. However, large inactive deposits have been discovered in the past few years, especially at slow-spreading ridges. These include the Krasnov, Semyenov, and Petersburg sites in the Central Atlantic (CHERKASHOV & *al.*, 2010; SHILOV & *al.*, 2012) that are estimated to contain up to 14 million tonnes of sulfides in the case of the Semyenov cluster and the Krasnov occurrence (CHERKASHOV & *al.*, 2010). As stated above, these extinct sites cannot be found with traditional exploration technologies that are looking for geochemical or geophysical tracers in the water column. Russian scientists used time-consuming deep-towed platforms for their discoveries. Techniques to identify such deposits time and cost efficiently on a regional scale are still lacking. High-resolution AUV-based mapping of the bathymetry with associated magnetic and self-potential sensors seems to be the only way to survey larger areas fast, efficiently, and cheap. A recent AUV survey of the TAG Hydrothermal Field mapped the bathymetry over an area of 47 km^2 combining 13 AUV missions into a single map and identified a number of eSMS in the area (PETERSEN & *al.*, 2016b; Fig. 2). It should be noted, however, that a coverage of 47km^2 during a single cruise is only a fraction of the 10,000 km^2 that each contractor has to survey in 15 years. Clearly, for a global resource estimate, even using only the 20 km corridor around the spreading axis as the prospective area, other means are necessary. As with manganese nodules, fleets of AUV, working in tandem, seems the only choice.

Even worse, we currently also lack the ability to identify buried deposits (beneath a few meters of sediments or lava), thereby further underestimating the resource potential of explored areas. This currently limits our efforts to explore further off-axis, as the deposits are buried under increasing sediment cover. The sediments themselves may, however, provide a far-field halo around inactive deposits at a scale comparable to that of plume mapping.

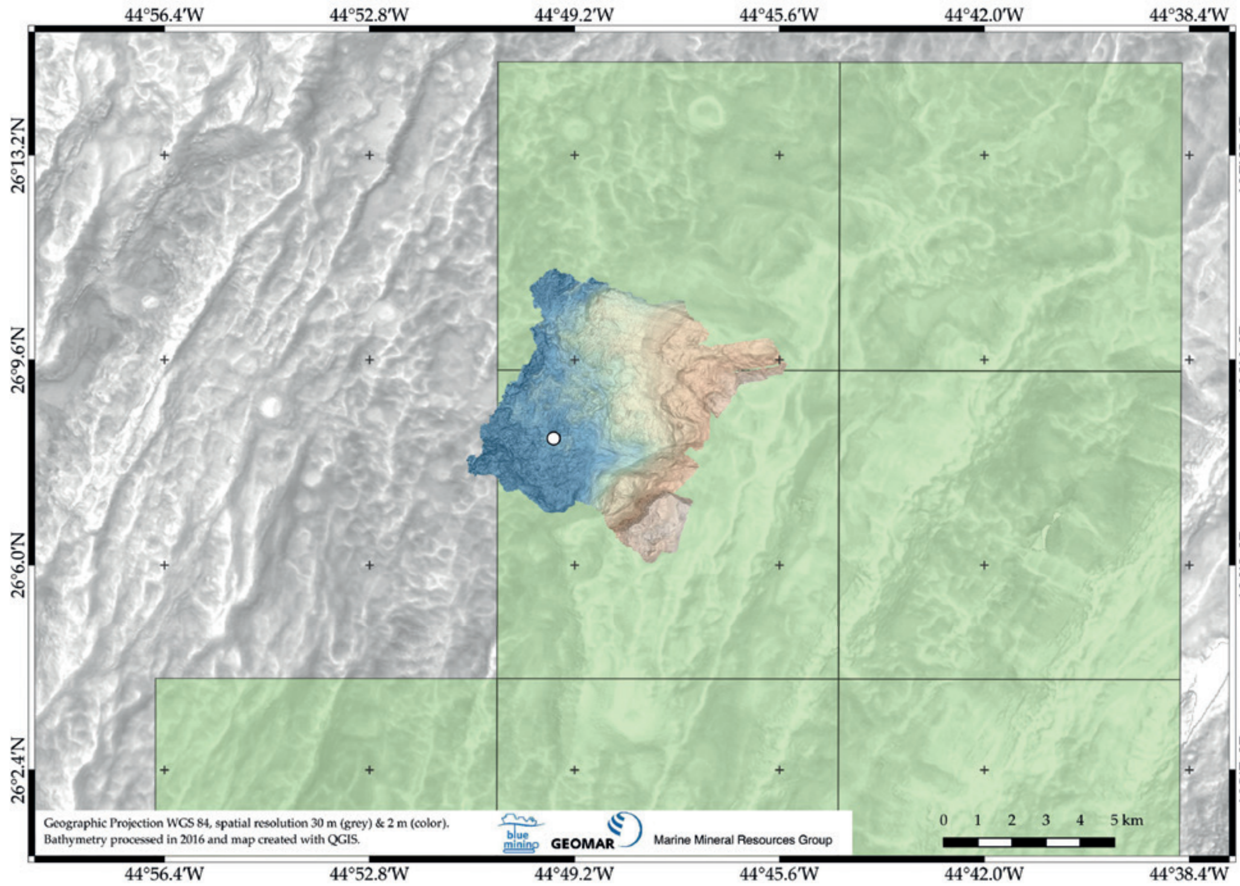

Figure 2: Location of the recently acquired AUV bathymetry in the TAG Hydrothermal Field during cruise RV Meteor M127 in 2016 and the French exploration license blocks for massive sulfides (green squares; each 100km2 in size). Note the size of the AUV map (47 km^2) compared to the license blocks. One hundred blocks need to be explored during the runtime of the contract. Note also, that less than 24 hours of shiptime were used for handling the AUV (launch and recovery for 13 missions) and the ship was free to do other science while the AUV was mapping. The TAG active mound is indicated by the white dot. Background shows texture-shaded ship-based multibeam bathymetry from M127 gridded at 30 m.

Although sediment geochemistry has been a standard tool in marine geology for over a century, there have been few modern advances to adapt this technique to the search for marine minerals. This contrasts with the search for ore deposits on land, where exploration geochemistry has achieved a high degree of sophistication, including the application of ultra-sensitive tracers such as mobile metal ions and pore-fluid gases. Depth profiles of metals in the sediments can potentially be used to estimate the age of a source (and how far away it might be, based on spreading rates), but few sensitive mineralogical, geochemical or isotopic vectors have been tested that could be traced back to metal sources more than 1-2 km distant or at depth below the sampled core. Gravity coring and ship-based analytics (e.g. portable XRF, PIMA, portable XRD) in combination with structural interpretation of AUV-based high-resolution self-potential, magnetics, and bathymetry data may open up a new frontier in exploration technology.

As stated above, SMS deposits are 3-dimensional bodies and therefore any resource estimate must build on depth information. Tonnage calculations reported for most known seafloor deposits, however, are only based on interpretation of visual surface information of the outcrop thickness and lateral extension as well as on distribution of Fe-staining at the surface. In many cases, these estimates are considered to overestimate their size and tonnage (HANNINGTON & *al.*, 2011). Drilling is currently the only technology that provides depth information of SMS deposits and has only been performed for few deposits. With the exception of a those sites, little is known about the interiors of most SMS deposits. Several lander-type drill rigs are currently being used globally. However, obtaining representative samples from up to 50 m below the seafloor in rough topography is still challenging. Since drilling is very expensive, there is a pressing need to develop or modify existing technologies to gain subsurface information. In order to prevent coring of waste rock or sulfides lacking the commercial metals of interest (Cu, Zn) in-situ logging tools are needed in order to terminate holes in time and to reduce the costs of the assessment. Geophysical tools such as seismic and marine electromagnetics (EM) could also provide information about the interior. Due to the rough morphology reflection seismic data collected at the sea surface will be heavily disturbed by side echoes and diffraction events. Refracted seismic events from Ocean Bottom Seismometers (OBS) may be used to further improve reflection seismic images. Such techniques have so far mainly been applied to crustal scale investigations and need to be tested for their potential to investigate eSMS deposits.

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