Seabed Mining, Mineral Extraction & Methane Hydrates

SUBSEA ENGINEERING OPPORTUNITY
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Scottish Enterprise

Contents

1. Introduction

This report is part of a series of reports considering the opportunities for the Scottish oil and gas (O&G) subsea supply chain in other subsea and related markets. The reports are a desk review considering the international activity of each of the sectors including where there is current activity and where there is the potential for activity based on published targets and available resource and opportunity. The reports also consider the particular synergies of the given sector and the subsea oil and gas supply chain. These opportunities cover areas where there is a direct cross over and also where there are opportunities for collaboration to provide innovative solutions.

Seabed mining (SBM) is the extraction of minerals from deposits on the seafloor, and this report is particularly interested with Deep Sea Mining (DSM) which occurs at water depths in excess of 500 m. Mineral extraction does occur in shallower water, such as the extraction of materials for construction, but the industry for this is well established, and as such the report will focus on DSM.[1,2]

Deep sea mineral deposits largely occur around hydrothermal vents, ocean plate boundaries and metal rich muds where over thousands of years deposits are laid containing metals such as gold, silver, copper, nickel, cobalt and manganese as well as rare earth elements (REEs).[3]

Interest in DSM first started in the 1960s, but at that point it was uneconomical and technically unfeasible. With modern advances in subsea technology, including deep water applications, and the reducing resources of minerals on land combined with an increase in demand for these minerals, DSM is rapidly gaining interest.[4] DSM is, however, yet to occur at a commercial scale, although there is a pilot project in planning by the Canadian company Nautilus Minerals, off the coast of Papua New Guinea; although the project has faced a number of obstacles not only from the environmental community but financially too.[5] The environmental concerns about the impact of DSM is largely around the lack of evidence on the potential impacts that the mining techniques could have, such as the impact of plumes generated by disturbing the seabed. This presents an opportunity in terms of research to develop exploitation regulations on an international scale as well as to use innovative technology to maximise economic benefit, but minimise environmental impact.

This report will also cover the extraction of methane hydrates. Methane hydrate deposits are found where there are suitable high pressure, low temperature conditions and an abundance of methane. The methane is largely generated biogenically from the breakdown of organisms in a zone below approximately 10 m below the seabed, where the sediment is no longer oxygenated, to a depth of approximately 3,000 m where the methanogenic bacteria no longer live. The methane then rises through the seabed through fissures etc. and when the correct conditions are present in the gas

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[1] Study to investigate state of knowledge of deep sea mining, Final Report, Annex 5: Ongoing and planned activity, Ecorys, 2014

[2] KASM, What is Seabed Mining, accessed March 2018 http://kasm.org.nz/seabed-mining/what-is-seabed-mining/

[3] Managing impacts of deep-sea resource exploitation: the MIDAS project, Research Highlights, 2016

[4] Parliamentary office of Science and Technology, Deep-sea mining, POSTnote 508, 2015

[5] Nautilus Minerals website, accessed February 2018, http://www.nautilusminerals.com/irm/content/overview.aspx?RID=252

hydrate stability zone (GHSZ) methane hydrate forms. The deposits are largely found on the continental shelfs where there has been rich biological activity which over time is broken down to form methane and carbon dioxide (CO_2).

The extraction of methane hydrates is yet to be commercially achieved, but Japan and China have each carried out pilot projects, with research occurring particularly in the USA and Germany. Methane hydrates are thought to be a plentiful resource, with estimates of approximately 10,000 trillion cubic feet. Their main benefit is that they exist across most of the globe at the edges of the continental plates, therefore providing countries that do not have other indigenous hydrocarbon resources with a homegrown natural gas supply.

2. Subsector overview

2.1. Deep Sea Mining (DSM)

Deep sea mining (DSM) is the activity of extracting minerals from the seabed at depths more than 500m. The attraction of DSM, given the difficultly and expense of offshore activities, particularly in deep water situations, is around the concentration of the minerals in the deposits, as well as the availability compared to dwindling terrestrial resources. An example is the Solwara 1 area, Papua New Guinea, where the seafloor massive sulphides (SMS) contain 7% copper, approximately ten-fold more than terrestrial deposits (at 0.6%)[6].

The main deep-sea minerals of interest are polymetallic nodules; seafloor massive sulphides; and cobalt rich ferromanganese crusts. Table 1 provides an overview of these deposits including the depth they are likely to be found at; where in the ocean floor topology they are likely to be found; and where the main areas of interest and exploration have been.

Table 1: Main deep-sea mineral deposits of interest. Source. ISA

Deposit	Situation	Depth	Main area of exploration
Polymetallic Nodules (Manganese Nodules)	Nodules from mm diameter to 20 cm, largely 5-10 cm, on or just below the seabed. Concentric layers of iron and manganese form around a 'seed' such as a shark's tooth or fragment of previous nodule.	Main concentration 4,000 – 6,000m Although can be found at any depth.	North central Pacific Ocean, the Peru Basin in the south-east Pacific Ocean and the centre of the north Indian Ocean[7]
Seafloor Massive Sulphides (SMS) or Polymetallic Sulphides	Form around 'black smokers' where hot water (400degC) from the below the crust is discharged and mixes with the cooler seawater precipitating sulphides which fall onto the chimneys and nearby seabed.	Up to depths of 3,700m	At the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise (likely to occur at other ocean rifts e.g. Mid-Atlantic Ridge and the Central Indian Ridge but there has been less exploration of these areas.)[8]
Cobalt-rich Ferromanganese crusts	Found in seamounts (underwater mountains) where the minerals have precipitated out of the seawater, likely due to bacterial activity, and layered onto the surface	400m -4,000, main concentration 800 – 2,500m depth.	Most exploration in the Pacific Ocean, however the Atlantic and Indian ocean are likely to also have deposits.[9]

[6] Nautilus Minerals, Fact Sheet, 2016.
[7] International Seabed Authority, Polymetallic Nodules Factsheet
[8] International Seabed Authority, Polymetallic massive sulphides and cobalt-rich ferromanganese crusts: Status and prospects, 2000
[9] International Seabed Authority, Cobalt-rich crusts Factsheet

2.1.1. Regulation

Under the United Nations Convention on the laws of the seas (UNCLOS) seabed mining activity is governed by the national government of the relevant state when activity is within the Exclusive Economic Zone (EEZ) this is to 200 nautical miles from the coast. Or when outside the EEZ, seabed mining is governed by the International Seabed Authority (ISA). Even when exploration or extraction activity happens within the EEZ, if the state has ratified UNCLOS the state regulations must be in line with the UNCLOS provisions.[10] The Mining Code covers all the regulations associated with seabed mining. To date there are only regulations published for prospecting and exploration, and these differ depending on the type of deposit that is being sought, e.g. polymetallic nodules or seafloor massive sulphides.[11]

Licences are granted firstly for the exploration of an area to see if there is resource available. Under ISA rules, these licences are granted state or to a company or consortium with backing from a national government. The exploration licences are valid for 15 years with an option for a single five-year extension. By 2018, there were 28 exploration licences awarded in international waters. Exploration licences vary on the mineral deposit to be explored, examples of some of the regulations are below:

- *Polymetallic nodules*
  As the least complex mining opportunity, the rules relating to polymetallic nodules are the most developed. From a prospecting area, the licence holder must split the area of interest into two blocks of roughly equal commercial value, with each block not exceeding 150,000 km^2. The ISA then chooses one of these blocks to make a 'reserved area' which can be given at a later date to a developing country. The licence holder then performs exploration work on the other block, and within eight years, but relinquish up to 75,000 km^2 back to the ISA. The remining section is then available, subject to the appropriate licences, for mining activities. The rules also have specific requirements around environmental impact assessments (EIAs), as well as the testing of equipment and methodologies and regular reporting.[10]
- *Cobalt-rich ferromanganese crusts*
  Exploration licences, outwith EEZs are issued by the ISA and cover a specified area of seabed. The size of the area depends on the mineral deposit in question, for example licences for colbalt crusts are issued for up to 150 cells 'colbalt crust blocks'. Each cell is no more than 20 km^2 and either square or rectangular. They are then grouped in clusters of five blocks across an area not exceeding 550 km by 550 km.[12]

Post exploration the next phase is to exploit the resource. Exploitation licences are also granted by the ISA, although this has yet to happen. The guidelines around exploitation licences including how environmental considerations are handled are still being developed. This creates an opportunity for them to be developed before any harm is done to the environment, but also means that there could be a delay in licences being processed if the appropriate regulations are not in place.

[10] World Ocean Review 3, Environment and Law, 2014.
[11] International Seabed Authority website, accessed April 2018
[12] Regulations on prospecting and exploration for Cobalt-rich ferromanganese crusts in the area, International Seabed Authority, 2012

Within a country's EEZ, it is the responsibility of the national government to authorise the exploration and exploitation. It is much harder to find information on this as there is no central repository for this information. However, we do know that the Government of Papua New Guinea have issued an exploitation licence to Nautilus Minerals to exploit Seafloor Massive Sulphides (SMS), with mining expecting to commence in Q3 2019. More details on countries involved in DSM is available in section 4 below.

Methane hydrate reserves are largely within EEZ boundaries and so will be under the jurisdiction of the relevant coastal state.

2.1.2. Technology

The technology used in deep-sea mining (DSM) is a combination of traditional mining, underwater mining and oil and gas technology. With equipment such as dredgers, remotely operated vehicles (ROVs), risers, rock cutters and production support vessels all required.

The stages of DSM can be summarised as[1,13]:

- *Prospecting, exploration and appraisal*
  Including the application for an exploration licence, environmental impact assessments, geotechnical and geophysical surveys, etc.

- *Resource assessment, mine planning*
  This stage includes the collection of samples to assess the resource, it could also include a pilot stage mine, at 1/10-1/5 the scale of the project, as well as detailed planning about how the activity will be undertaken.

- *Extraction, lifting and surface operations*
  This is the 'operation' stage where the mining takes place, once the material is mined it is transported up to the production support vessel (PSV) as a slurry through risers, it is processed on the PSV and waste material is returned to the seabed.

- *Offshore and onshore logistics*
  This includes the vessel logistics, the deployment of the remote or autonomous vehicles, the offloading of the mined minerals and supply of the PSV for necessary components. For example, any fluids required for processing.

- *Metallurgical processing*
  This is the final extraction of the minerals from the mined activity and can be done on or offshore, and will be dependent on the processes required. A certain level of extraction will occur either subsea or on the vessel as the amount of waste material being transported should be kept to a minimum.

[13] Abramowski, T., Value chain of deep sea mining, Deep sea mining value chain: organization, technology and development, Edition:1, Interoceanmetal Joint Organisation, 2016.

- *Distribution.*
  The distribution of the minerals is not a subsea process.

A more detailed analysis of the technology will be covered in section 3.

2.2. Methane Hydrates

Methane Hydrates (also known as Methane Clathrate) are another subsea resource, which occur where methane gas is trapped inside ice. The deposits are formed spontaneously at low temperatures and high pressures, largely in the deep ocean (>400m deep) and at the continental margins. They are known to the O&G industry as a problem when they form in the same conditions inside pipelines. In a deep ocean context however, they are a potential significant resource, with estimates that global deposits of methane hydrates are between 100,000 and 5,000,000 trillion cubic feet (Tcf), or possibly ten-times that of natural gas deposits and 15x that of shale deposits. Considering the most accessible deposits, these could produce around 10,000 Tcf which would add 60% to global recoverable gas reserves. Additionally, compared to global gas demand of approximately 100 Tcf it is a potentially important resource[14,15,16,17]

At present, the Methane Hydrate resource is almost entirely unexploited as although it is hugely abundant there are no technically proven methods for extraction. The furthest forward in this respect are the Japanese, who have run a pilot project to extract their reserves. In nations with indigenous O&G reserves there are no drivers for exploiting this reserve given the technical difficulties and costs. For countries, such as Japan, who rely heavily on imported hydrocarbons, the local methane hydrate reserves provide a potential home-grown hydrocarbon source. These countries without their own subsea expertise and supply chain in O&G exploitation will need to seek support from nations such as Scotland with experience and technology.

Methane hydrates are a dense resource with 1 m^3 of the product bearing 164 m^3 of methane gas. Unlike natural gas and oil reserves which are found in porous rock formations under the seabed. Methane hydrates are formed in the sediment where there are the appropriate conditions of pressure, temperature and abundance of methane. The gas hydrate stability zone (GHSZ) as it is known varies depending on the water depth and thickness of the Earth's crust (affect on temperature) and can vary in thickness from a few metres to 800 m thick. As the extraction of the methane from the hydrate can change the stability of the structure and the sediment that it is found in is often less stable than the rock formations that produce oil and gas the 'wells' can fill with sand impeding further extraction. The environmental and geological consequences of methane extraction from hydrates are not yet understood, and releases of large quantities of methane gas

[14] DeHaemer, C., Methane Hydrates - More Energy than All Other Fossil Fuels Combined, Wealth Daily, 2012
[15] O'Driscoll, B. and Allen, S., Unconventional Gas, Parliamentary Office of Science and Technology, POSTNOTE 374, 2011
[16] Subsea UK, Subsea Technology and Engineering, 2014
[17] USGS, Gas Hydrates Primer, The U.S. Geological Survey Gas Hydrates Project, 2014

into the water column during extraction operations could also pose a significant environmental issue. [18]

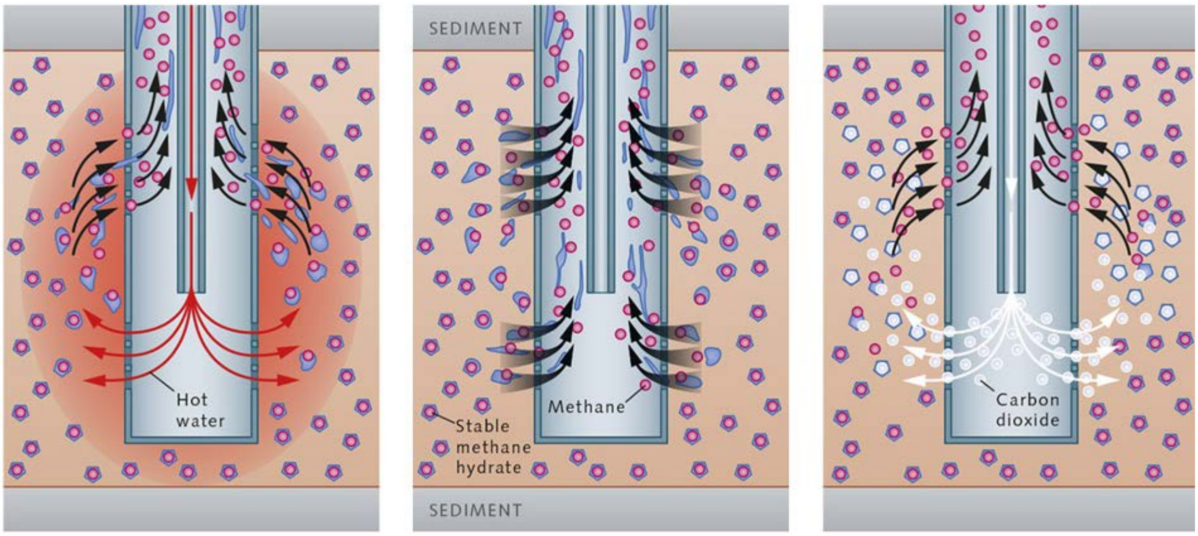

Figure 1: Three proposed methods of methane extraction from methane hydrates. a) water circulation where hot water changes the temperature of the area releasing the methane gas, b) depressurisation where the well being drilled releases the pressure in the methane hydrates propagating the release of the methane gas and c) carbon dioxide injection where CO_2 is introduced to the formation and exchanges with the methane in the hydrate's molecular cage. Source WOR3

Proposed methods for the dissolution of the methane from the hydrate, as shown in Figure 1, include the use of hot water which increases the temperature and breaks down the hydrate; depressurisation of the formation which releases methane gas from the hydrates and injection of carbon dioxide into the formation which more readily attaches to the water molecules forming carbon dioxide hydrates. All methods have their challenges, and none have been proven at scale, the most success so far is through the injection of carbon dioxide. The gas exchange is slow in this method and research is being conducted to speed up this process. An added benefit is that this method sequesters carbon dioxide and can use CO_2 captured from industrial processes.[18,19]

Although this is a new sector with the technical solutions still being developed, the cost of production is hard to define, although estimates show that current costs of methane hydrate produced gas is between US$30-US$50 per million British thermal units (MMBTUs). It has been estimated that the costs could come down to US$4.70 – US$8.60 per MMBTU once efficient processes are implemented.[20] It is worth noting that for some countries, such as Japan with no other indigenous hydrocarbon resources, the price of producing methane from gas hydrates is not comparable to the cost of producing natural gas from conventional methods, but against the cost of imported liquid petroleum gas (LPG). Coupled with the cost is the benefit of security of supply by removing the reliance on imported resources.

[18] World Ocean Review 3, Methane Hydrate Formation, 2014.
[19] Janicki. G., Schlüter, S., Hennig, T. and Deerberg, G., Simulation of subsea gas hydrate exploitation, *Energy Procedia* **59** (2014) pp82 – 89
[20] Oil Field Magazine, Methane hydrates: a business opportunity for NOCs in the Middle East and large IOCs?, 2015

3. Subsea engineering needs

The subsea engineering needs of deep sea mineral mining (DSM) and the extraction of methane hydrates have significant synergies with the subsea O&G supply chain. The section below covers the technology crossover, covering the stages of a project as described above.

3.1. Prospecting, exploration and appraisal

At this initial stage, the aim is to find a suitable resource, that can be economically extracted and secure the licences required for exploration (prospecting isn't a licensed activity, but notice must be given to the ISA of any activities). To do this survey vessels are required that use a mixture of side scan sonar, multibeam echo sounders, photography and video survey including lights, seismic profiling, and sampling techniques such as grabbers, draglines and box corers, with deeper samples taken by coning, probing or drilling.[13,21] These techniques are carried out from the ship or using ROVs and AUVs, both bottom crawling and in the water column. The data gathered by these surveys must then be analysed to understand the potential resource available. Many, if not all, of these techniques are employed during the prospecting stage of O&G exploration, where the rock strata, bathymetry and seabed conditions are needed to be known. As well as the techniques, the ability to analyse the data is another significant crossover. The management of such projects including the vessel operations is yet another area of synergy.

Further, tighter grid, sampling will take place once prospecting has identified potential specific areas of exploration. Sampling includes techniques and equipment such as grabbers, draglines and box corers, with deeper samples taken by coning, probing or drilling.[13,21]

3.2. Exploitation

As there are yet to be any exploration activities for deep-sea mineral deposits, the below is based on assumptions about the activities, as well as information from the proposals of the first planned project, Solwara 1, by Nautilus Minerals in Papua New Guinea. There is an expectation that the techniques will be a crossover between terrestrial and shallow water mining techniques and subsea O&G operations.

The exploitation of a resource will depend on the deposit targeted, e.g. polymetallic nodules are on or just below the seabed surface and therefore can be gathered through a form of trawling, subject to environmental considerations. SMS and Cobalt-crusts require to be cut or crushed from the structures and are part of and therefore will require different technologies.

The general principle for all three is that remotely operated or autonomous vehicles, known as seafloor production tools (SPTs), must be deployed from a vessel, such as a production support vessel (PSV) which itself must have accurate station keeping abilities as well as launch and recovery systems

[21] Seabed Technology Brochure, International Seabed Authority

(LARS) for the subsea vehicles.

The SPTs, examples shown in Figure 2, include mining tools, which cut or drill the rock and a collection vehicle which is connected via risers to the PSV. The risers must be resistant to abrasive materials as they will contain a slurry of water and the crushed rock.[22]

Onboard the vessel there will need to be some form of processing, such as a dewatering plant, and either storage capacity, or further processing equipment where the minerals (in some cases such as SMS only 30% of the mined rock) are extracted. It is likely it will be a combination of storage and processing as some of the extraction techniques are very involved chemical processes, which are more likely to be undertaken onshore, but given limited storage capacity, and also dependent on distance from shore, there will be a drive to do some processing on the vessel. Any by-products, e.g. water from the dewatering plant, that are returned to the seabed or water column must be done in accordance to regulations and the evacuations monitored.[21]

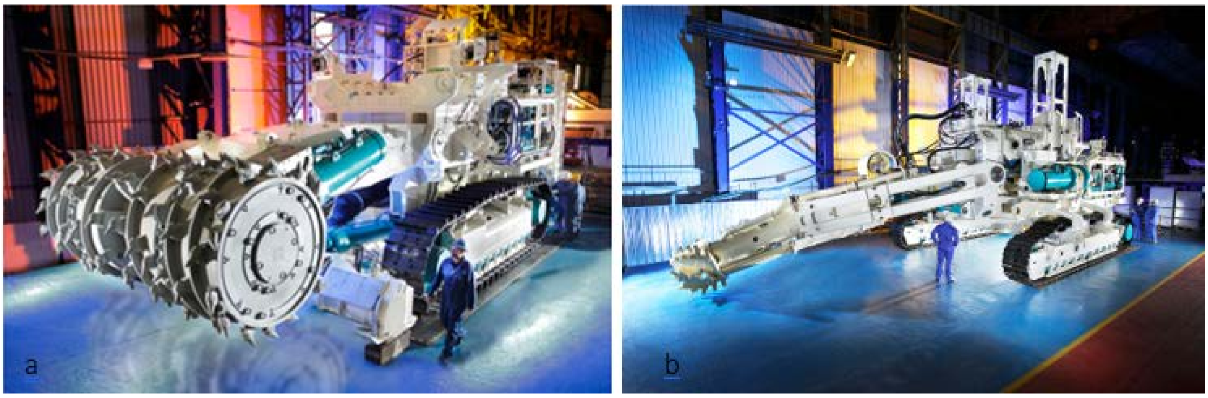

Figure 2: Two of Nautilus Minerals' SMD built three seafloor production tools (SPTs) they are a) Bulk Cutter and b) Collecting Machine. Source: Nautilus Minerals

As shown in Table 1, the depths the minerals are found at vary, however, the anticipated range is between 800m and 5000m. The deepest of these are beyond current ultradeep O&G activity (which is up to about 3000m deep) however, the technology for transporting the mined material from the seafloor to the PSV is analogous to the movement of hydrocarbons from subsea wells to an FPSO. Lessons, expertise and technology can therefore cross here.

The onshore elements, such as further processing of the minerals and distribution, will not be addressed in this report.

Synergies with oil and gas are therefore in:[16, 23]

- The design and manufacture of ROVs and AUVs and the associated tooling
- Station keeping production support vessels
- Risers with associated buoyancy and inspection tools
- Launch and recovery systems (LARS)

[22] Nautilus Minerals, Technology, Seafloor Production Tools, website accessed 2018

[23] Oil Industry News, Deep Sea Mining, 2017

- Separation techniques
- Slurry pumps
- Umbilicals
- Subsea power
- Environmental monitoring
- Telemetry
- Technology suitable for ultradeep conditions

3.3. Challenges

DSM is yet to be commercially achieved, although there is progress being made and 2018 is likely to see the first exploitation happening. There are a number of challenges that need to be addressed to ensure the future of this sector. These are outlined below and each provides an opportunity for the subsea O&G supply chain to engage and help develop innovative solutions for the sector.

- *Environmental impact*
  The biggest challenge for DSM is the potential environmental impact of the mining activities. The ISA have developed a precautionary approach with the regulations with clauses specifically relating to the protection of the environment. An impact which requires mitigation is the creation of sediment plumes as the seafloor is disturbed. These plumes have a negative impact on the seafloor flora and fauna. The movement of sediment also exposes previously covered minerals to the water, causing oxidation reactions and leaching heavy metals into the ecosystem. Where the heavy metals are dissolved into water they pose a threat to the animals living in this environment as they can pass through e.g. gills, or may be ingested when they adsorb onto the surface of particulates. A research project funded by the European Commission has looked into the potential impacts of DSM, drawing on the expertise of both ocean scientist and the seabed mining industry. MIDAS, the Managing Impacts of Deep-sea resource exploitation project lasted for three years from 2013 to 2016.[24]
  Solutions that minimise the disruption to the seafloor sediment can help minimise plume impacts. Plumes also occur where waste water and products are expelled from the PSV, separation, filtering and monitoring to ensure the least impact will be important here.
  There is a potential opportunity for innovation in mining techniques to be as selective as possible in selecting rocks to be cut, rather than cutting and crushing whole rock formations. can come through a combination of developing techniques for identifying the mineral deposits including data analysis as well as subsea techniques and selectively harvesting the deposits through innovative SPTs.

- *Seafloor Production Tools*
  Due to the early stage of the sector, technology has not had a chance yet to be proven at scale. A review of DSM technology carried out by the European Commission in 2014 showed that current technology has, in all but a couple of examples, yet to reach technology readiness level (TRL) 5, defined as ‘technology validated in (an industrially) relevant

[24] Research Highlights, MIDAS, 2016

environment'.[25] Given the age of this study it is worth noting that from 2013-2015 the number of DSM technology patents filed increased by 100 percent, showing that there is an increase in activity, however, technology has still had limited demonstration in real world situations.[26]

- *Water depth*
  The mineral deposits under investigation are found in ultradeep waters, and Annex 2 shows the water depth at the ISA licensed exploration sites. The sites for polymetallic nodules are almost exclusively at a water depth of 4,000 – 5,000 m, with SMS and cobalt-rich ferromanganese crusts at shallower, but still ultradeep sites, in the range 1,000 – 4,000 m. These depths, particularly for the polymetallic nodules, are deeper than current O&G activity. The increased pressure at these depths therefore needs to be taken into consideration when designing and developing equipment for working on the seafloor. The challenges of these depths lend themselves to robotics and autonomous activity, a strength that has been developed in the O&G supply chain. Subsea telemetry will also be important to ensure reliable communication between subsea equipment and between the seafloor activity and the PSV.

- *Seafloor processing*
  The development of SPTs could also include the advancement of more processing on the seafloor to minimise the amount of material that needs to be transported to the PSV. Due to complex chemical extractions, it is unlikely that all of this could occur subsea, however, there is scope to consider opportunities to submerge some of the activity, particularly for the deeper sites, given the distance that transportation must occur at. Given the distance from shore is, at least for ISA licensed exploration, over 200 nm from the coast, maximising offshore activity to reduce the amount of waste material transported onshore, is advantageous.

3.4. Methane Hydrates

The technology for the development of methane hydrate extraction has an even greater crossover with subsea oil and gas extraction than DSM. Many of the techniques and equipment needed will either be a direct cross over or an adaptation of O&G technology.

Methane hydrate are yet to be commercially extracted, although pilot operations have taken place in Japan and China in 2017.[27] As the deposits are found below the seabed drilling, akin to O&G well drilling will take place to reach the appropriate layer. The methane hydrate layers are not as deep as many oil and gas reserves. As the extraction process is yet to be proven, the section below is an estimation of the types of technology that maybe a cross over with the methane hydrates industry.

[25] Ecorys, Study to investigate state of knowledge of Deep Sea Mining, 2014
[26] Recent Advances in Deep Sea Mining and Exploration – High-Tech Materials TechVision Opportunity Engine (TOE), Frost and Sullivan, 2016
[27] ARS Technica, Japan, China have extracted methane hydrate from the seafloor, 2017

- *Project management and design*
  Project management of explorative and exploitative subsea activities, including offshore logistics, asset management, HSE and HR.
  This stage also includes, with support from the survey work discussed next, the front-end engineering design (FEED) of the project equipment.

- *Surveys*
  Firstly, for surveys for prospecting, initial desk based prospecting can be done through simulations using temperature and pressure profiles to understand where there are likely to be the conditions suitable for methane hydrate formation. In-field surveys can then take place using multibeam echo sounders; multichannel seismic; 3-d seismic; deep-towed streamers; and methane sensors. A key indicator of methane hydrate deposits is the leakage of methane bubbles from the seabed. These can be identified through the survey techniques as well as the sub-bottom profiling to gain an understanding of where the deposits are likely to occur. The research vessels, data packages and equipment used for this are all used within the O&G industry for prospecting, although small modifications, such as receiver spacings on the multichannel seismic, may need to be changed to allow for finer resolution, or looking for other markers such as methane bubbles as part of the multibeam echo sounder survey.
  Secondly, once prospecting has identified areas for further investigation, more detailed survey techniques can be deployed such as ocean bottom seismometers, coring and electromagnetics. Again, modifications may need to be made from O&G practices such as the ability to maintain the temperature and pressure of the methane hydrate in the core sample to preserve its integrity.[18]
  Lastly, there will be a requirement for EIAs, and continued monitoring during and after operations.

- *Extraction*
  The extraction processes, examples shown in Figure 1, are yet to be fully understood. They have yet to be carried out at commercial scale, and all three options present challenges either economically or technically.[18] It is anticipated that as a well is required, there will be similarities with O&G extraction equipment, including drill rigs, subsea production infrastructure; subsea processing systems including filtration; the use of ROVs and/or AUVs for manipulation, tooling and inspection; flow assurance techniques; risers; production support vessels; etc.
  Assuming further analogies to the subsea O&G sector, the produced gas may be collected and offloaded by a floating production, storage and offloading (FPSO) type vessel, or linked directly to pipelines to shore. Early days are likely to be linked to the least infrastructure option, due to the cost of pipelines, etc. and therefore until a significant, economically accessible resource is discovered it will be likely transported onboard vessels.

The challenges for methane hydrate extraction are similar to DSM in terms of finding a technically and economically viable solution to extracting the resource, as well as minimising any environmental impact. Potential environmental impacts from methane hydrate extraction include:[28]

[28] MH21 Research Group, Methane hydrate development and environment, accessed March 2018

- Leakage of methane onto the seafloor and the potential then for this to be released into the environment. This could further intensify climate change as methane is a potent greenhouse gas.
- Seafloor subsidence, due to the removal of the methane hydrate, could destabilise the sediment. The likelihood of this occurring will depend on the extraction method and the structure of the sediment.
- Submarine landslides, will depend on the topology of the seabed above and adjacent to the resource.
- Processing of production water, the use of water for extraction, will need to be cleaned and disposed of, and may happen onshore or in-situ and back into the water column. Release of water in such a way can cause plumes, as well as the need to ensure that the water is cleaned to the appropriate level.

https://www.mh21japan.gr.jp/english/mh21-1/5-2/

4. Global market with locations of interest

Deep sea mining and methane hydrate extraction are global opportunities, and the maps in Figure 3 and Figure 4 highlight the global opportunity respectively. Figure 3, however only shows part of the story as it only includes exploration licences outwith national EEZs, and does not show other potential areas that are yet to be explored.

Deep-sea mining is expected to be worth £40bn to the UK by 2043[29] and estimates are that within Europe the mineral resources between 500 – 1,000 m are worth €100 billion.[30] Although there are no definitive figures on the overall value of the industry it will be a significant prize for many countries and companies. The DSM industry is already looking to the O&G sector for technology, and there is a real opportunity for the Scottish supply chain to make an impact in this sector.

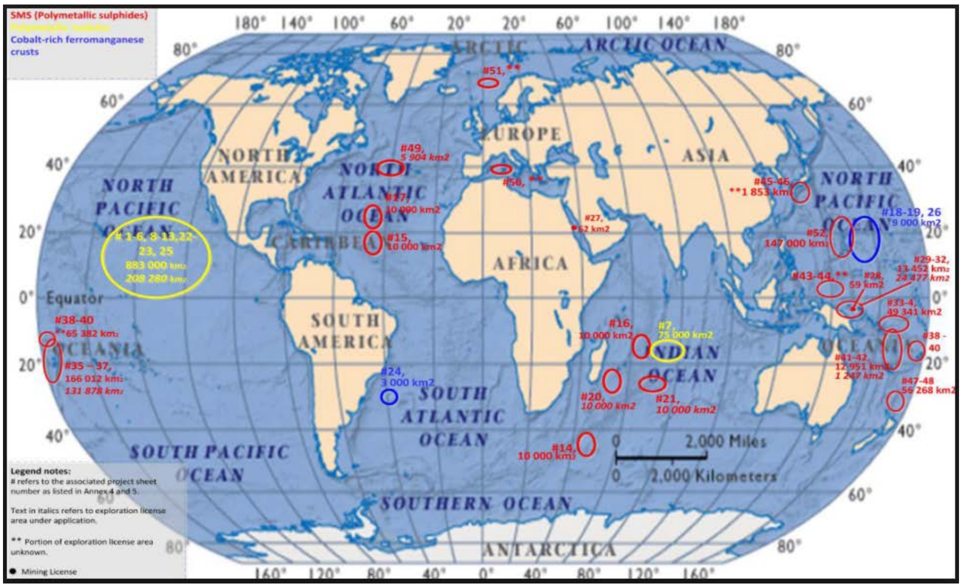

Figure 3: Map showing location of exploration licences in international waters. Source: Ecorys

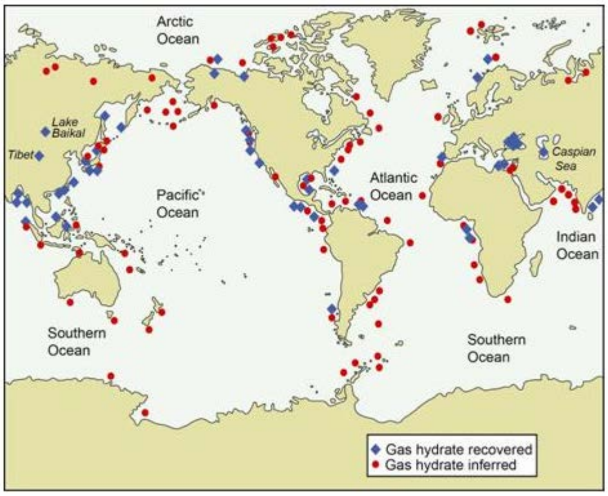

Figure 4: Map showing the locations of methane hydrate resources, both recovered and inferred. Source: US Geological Survey

[29] Parliamentary office of Science and Technology, Deep-sea mining, POSTnote 508, 2015
[30] Subsea World News, Trelleborg supplies mining hoses for Vamos, 2017

4.1. Deep sea mining activity – international waters

Deep sea mining (DSM) activity in international waters is regulated by the International Seabed Authority (ISA), they have, up to 2018, awarded 29 exploration licences, but are yet to award an exploitation licence. The licences granted to date are summarised by deposit type, also showing location, water depth and sponsor state in the table in Annex 2. Colour coding in the table shows that 17 of the 29 licences are for polymetallic nodules, this is likely to be due to these deposits being seen to be easier to mine, 16 of which are in the Clarion Clipperton Fracture Zone (CCZ). The contract dates highlight that there has been a steady interest in gaining exploration licences mainly since 2010, although a handful of licences have already exceeded their 15-year span and are into the five-year extension period.

Financing of the exploration is in most cases by the national government, who either directly or indirectly are supporting the activity. There are a few exceptions, such as the UK, Singapore and Belgium where the activity is being financed by an industrial partner. In these cases, as part of the licence contract they declare that they have sufficient funds to cover the exploration activities. Costs range for exploration activity, but examples are shown to be in excess of US$10 million (£7.4 m).[1]

4.2. Deep sea mining – EEZ activity

There is less published data on activity within the EEZs as there is no central repository for information, however the information we have is outlined in Annex 3. Up to 2014 there were 26 licences granted or under application by national governments, of which two are DSM exploitation licences, these include:

- In Papua New Guinea, the Solwara 1 project in the Bismarck Sea (Nautilus Minerals Inc.)
- In Saudi Arabia and Sudan, the Atlantis II project in the Red Sea (Diamond Fields International)

The licences and applications are dominated by two companies, Nautilus Minerals Inc. and Neptune Minerals (including its subsidiaries). Between them they hold 20 of the 26, with ten to each of the companies. Other licences and applications are held by government funded organisations in Japan, South Korea as well as two other private companies. [1]

All EEZ licences and applications, both exploitation and exploration, are concerned with mining polymetallic sulphides, also known as seafloor massive sulphides, (SMS). There is further subsea mining activity in Namibia and New Zealand, however in water depths of less than 500 m these are not considered deep-sea mining.[1]

Legislatively, within the EEZ boundary, DSM activity falls under the regulations of the relevant coastal state. The ISA holds a National Legislation Database, where individual countries regulations can be accessed.[31] Countries that have ratified UNCLOS are obliged to have regulations in line with these prescriptions.

[31] International Seabed Authority, National Legislation Database, accessed March 2108 https://www.isa.org.jm/national-legislation-database

4.2.1. Deep sea mining – company highlights

There are two major companies involved in DSM currently, the Canadian Nautilus Minerals and the American Neptune Minerals.

- *Nautilus Minerals Inc*
  Nautilus is a Canadian company, headquartered in British Columbia. The company's major shareholders include: MB Holding Company LLC and Metalloinvest Holding (Cyprus) Limited. The company has raised significant capital through its shareholders, amounting to US$270 million (£200 m).[1]
  For the Solwara 1 project off the coast of Papua New Guinea, the company has links with suppliers including: Soil Machine Dynamics (SMD) and United Engineering Services LLC for their seafloor production tools (SPTs); GE Oil and Gas for the subsea slurry lift pump; Technip USA for the riser and lifting system; and Fujian Mawei Shipbuilding Ltd. and Marine Assets Corporation for the production support vessel (PSV). This highlights the immediate crossover opportunities with subsea oil and gas supply chain.[26]
- *Neptune Minerals*
  Neptune is an American company that is taking a precautionary approach, which it refers to as 'BABY STEPS'. It has a principle of adapting technology rather than designing new technology for the exploration and exploitation, including using grab technology for harvesting deposits.[26,32]

4.3. Methane hydrates

The interest globally in Methane hydrates is largely from Japan, China and the USA. Other countries include: South Korea, Taiwan, India, Vietnam and New Zealand. It is estimated that US$1 billion (£740 m) has been spent on research worldwide.[16]

As Figure 4 shows there is a global distribution of methane hydrate deposits with a resource of between 100,000 and 5,000,000 Tcf. The sections below provide a brief overview of current activity in the countries most involved in methane hydrates extraction.

4.3.1. Japan

Japan does not have indigenous hydrocarbon resources and as a result are the largest global net importer of LNG (30-35% of total export), having had a larger requirement due to the change in energy policy following the Fukushima disaster in 2011. LNG import prices were as high as US$18.11/MMBtu (July 2013), but since the O&G downturn it is now US$9.40/MMBtu (April 2018) with a low point of US$5.86/MMBtu in May 2016.[33]. The urgency to find an alternative has reduced, but there is still an impetus.

Methane hydrate resources are estimated to be 39 Tcf in Japan[34]

[32] Neptune Minerals website, accessed April 2018
[33] Japan Liquefied Natural Gas Import Price, YCharts, accessed May 2018.
[34] World Ocean Review 3, 2014.

They have the largest EEZ and are keen to make use of methane hydrates to provide a homegrown source of hydrocarbons. Not having their own O&G sector also means that the Japanese have a limited experience in subsea engineering, with their global interests more involved with downstream aspects and LNG. They will eventually want to have their own market, but Scottish expertise can be used to help build that.

There is a Japanese consortium established in 2001, called the 'Research Consortium for Methane Hydrate Resources in Japan' or MH21 which includes operators, large industrials, government and academia. In addition, the Japan Methane Hydrate Operating Co., Ltd. (JMH) was established in 2014. JMH includes 11 private companies who have an interest in methane hydrate extraction. They include companies such as Japex, Mitsubishi, Chiyoda, INPEX and others with O&G exploration and production and offshore engineering experience. They have capital of 300 million Japanese Yen (£2 m).[35]

Pilot tests have been carried out in Japan in 2013 and again in 2017 at the Daini Atsumi Knoll between Atsumi Peninsula and Shima Peninsula off the Japanese coast. The 2013 production test by JOGMEC involved the drill ship 'Chikyu', and extracted the methane using the depressurisation method. A flow of 700,000 cubic feet of methane gas was extracted daily for six days during the trial.[36] The trial however encountered problems with sand clogging the subsea filtration system on the sixth day. This is an issue that will need to be overcome for future demonstrations and production.[37]
Japan did an offshore flow test in 2015 flaring the methane that was released, but abandoned the trial as subsea filtration was an issue and the system clogged with sand.

Scottish-based companies Wood., Aker Solutions, Baker Hughes and Expro are all involved in methane hydrate activities in Japan.

4.3.2. China

China has an interest in methane hydrates as a potential source of gas, and the government have an active programme pursuing it from 2016 – 2020, with commercial extraction anticipated for 2030. The estimates of resource are equivalent to 80 billion barrels of oil, approximately 25 times the Chinese energy consumption.[38] A potential benefit that these large gas reserves could have would be in the displacement of coal plants, thus facilitating a positive carbon reduction impact.

A pilot project was conducted in 2017 in the South China Sea by China's Ministry of Land and Resources and the China National Petroleum Corp and produced 10 MMcf over 60 days using the depressurising technique. Further exploration has been agreed with a pilot to be built in the Guangdong province.[38,39]

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[35] JMH, company profile, accessed April 2018.
[36] Japex website, Research of Methane Hydrate in Japan, accessed April 2018
[37] Cryanoski, D., Japanese test coaxes fire from ice, Nature, 496, 2013.
[38] Hepeng Jia, China opens up new energy front as it succeeds in tapping gas hydrates, 2017
[39] Reuters, CNPC, Guangdong Sign Strategic Deal on S. China Sea Methane Hydrate, 2017

4.3.3. United States of America

The USA have an interest in methane hydrates. In 2013 the US Department of Energy provided almost US$5 million for seven projects to further the national understanding of methane hydrates. Projects including research to understand the formation of methane hydrates, optimisation of sampling techniques, dissociation of methane from the hydrate and a project jointly with universities in Germany and Norway, looking at the specificities of methane hydrates in arctic conditions.[40] Activity so far in the US has been research based with no pilot production projects, and these are perceived not to be likely until the late 2020s. Methane hydrate reserves in the US are predominately in the Gulf of Mexico as well in Alaska, of these the more northerly deposits are predominately in shallower waters.[41]

4.3.4. Other countries

There is also active research in a number of countries in Europe, including Germany, particularly on the gas exchange method of production; Norway, in the Svalbard region; and in the UK including by the University of Birmingham. This is currently focused on research and not at the stage of pilot production projects.[41,42]

[40] US Department of Energy, Energy Department Expands Research into Methane Hydrates, a Vast, Untapped Potential Energy Resource of the U.S., 2013.
[41] Colman, Z., Should the World Tap Undersea Methane Hydrates for Energy?, Scientific American, 2017.
[42] Janicki. G., Schlüter, S., Hennig, T. and Deerberg, G., Simulation of subsea gas hydrate exploitation, *Energy Procedia* **59** (2014) pp82 – 89

Annex 1: List of Acronyms

AUV	Autonomous Underwater Vehicle
CCZ	Clarion Clipperton Fracture Zone
CO_2	Carbon Dioxide
COMRA	China Ocean Mineral Resources Research and Development Association
DSM	Deep Sea Mining
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
FEED	Front-end Engineering Design
FPSO	Floating production storage and offloading
GHSZ	Gas Hydrate Stability Zone
Ifremer	Institut français de recherche pour l'exploitation de la mer
ISA	International Seabed Authority
JMH	Japan Methane Hydrate Operating Co., Ltd.
JOGMEC	Japan Oil, Gas and Metals National Corporation
O&G	Oil and Gas
PSV	Production Support Vessel
ROV	Remotely Operated Vehicle
SBM	Seabed Mining
SMS	Seafloor Massive Sulphides
SPT	Seafloor Production Tool
Tcf	Trillion standard cubic feet
TRL	Technology Readiness Level
UNCLOS	UN Convention on the Law of the Sea

Annex 2: Overview of licences awarded by the International Seabed Authority

Table 2: Summary of the exploration licences granted by the ISA up to 2018. Source: ISA

Sponsoring State	Contractor	Location	Deposit Type	Depth	Date of contract
China	China Minmetals Corporation	Clarion Clipperton Fracture Zone (CCZ)	Polymetallic nodules		2017-2032
Cook Islands	Cook Islands Investment Corporation	CCZ	Polymetallic nodules	5,000 m	2016 - 2031
UK	UK Seabed Resources Ltd.	CCZ (II)	Polymetallic nodules	4,800 m	2016 - 2031
Singapore	Ocean Mineral Singapore Pte Ltd.	CCZ	Polymetallic nodules	4,000 – 5,000 m	2015 - 2030
UK	UK Seabed Resources Ltd.	CCZ (I)	Polymetallic nodules	4,000 m	2013 - 2028
Belgium	Global Sea Mineral Resources NV	CCZ	Polymetallic nodules	5,000 m	2013 - 2028
Kiribati	Marawa Research and Exploration Ltd.	CCZ	Polymetallic nodules	5,000 m	2015 - 2030
Tonga	Tonga Offshore Mining Limited	CCZ	Polymetallic nodules	5,000 m	2012 - 2027
Nauru	Nauru Ocean Resources Inc.	CCZ	Polymetallic nodules	4,000 – 5,000 m	2011 - 2026
Germany	Federal Institute for Geosciences and Natural Resources of Germany	CCZ	Polymetallic nodules	4,200 – 4,800 m	2006 - 2021
India	Government of India	Indian Ocean	Polymetallic nodules	5,000 – 5,700 m	2002 – 2017 ext. 2022
France	Institut français de recherche pour l'exploitation de la mer (Ifremer)	CCZ	Polymetallic nodules	5,000 m	2001 – 2016 ext. 2021
Japan	Deep Ocean Resources Development Co. Ltd.	CCZ	Polymetallic nodules	5,000 m	2001 – 2016 ext. 2021
China	China Ocean Mineral Resources Research and Development Association (COMRA)	CCZ	Polymetallic nodules	5,000 – 5,300 m	2001 – 2016 ext. 2021
Korea	Government of the Republic of Korea	CCZ	Polymetallic nodules	3,000 – 6,000 m	2001 – 2016 ext. 2021
Russia	JSC Yuzhmorgeologiya	CCZ	Polymetallic nodules	5,000 m	2001 – 2016 ext. 2021

Bulgaria, Cuba, Czech Republic, Poland, Russia, Slovakia	Interoceanmetal Joint Organisation	CCZ	Polymetallic nodules	4,000 – 5,000 m	2001 – 2016 ext. 2021
Poland	Government of the Republic of Poland	Mid-Atlantic Ridge	Polymetallic Sulphides		2018 - 2033
India	Government of India	Central Indian Ocean	Polymetallic Sulphides	3,000 m	2016 - 2031
Germany	Federal Institute for Geosciences and Natural Resources of Germany	Central Indian Ocean	Polymetallic Sulphides	2,600 – 3,300 m	2015 - 2030
France	Ifremer	Mid-Atlantic Ridge	Polymetallic Sulphides	3,400 m	2014 - 2029
Korea	Government of the Republic of Korea	Central Indian Ocean	Polymetallic Sulphides		2014 - 2029
Russia	Government of the Russian Federation	Mid-Atlantic Ridge	Polymetallic Sulphides		2012 - 2027
China	COMRA	Southwest Indian Ridge	Polymetallic Sulphides		2011 - 2026
Korea	The Republic of Korea	Western Pacific Ocean	Cobalt-rich Ferromanganese		2018 – 2033
Brazil	Companhia De Pesquisa de Recursos Minerais	Rio Grande Rise, South Atlantic Ocean	Cobalt-rich Ferromanganese	1,000 – 5,000 m	2015 – 2033
Russia	Ministry of Natural Resources and Environment of the Russian Federation	Magellan Mountains, Pacific Ocean	Cobalt-rich Ferromanganese	2,000 – 2,300 m	2015 – 2030
Japan	Japan Oil, Gas and Metals National Corporation (JOGMEC)	Western Pacific Ocean	Cobalt-rich Ferromanganese	3,000 – 4,000 m	2014 – 2029
China	COMRA	Western Pacific Ocean	Cobalt-rich Ferromanganese	2,000 – 2,300 m	2014 – 2029

Annex 3: Overview of DSM licences issued by national governments

Table 3: Overview of DSM licences granted by national governments for polymetallic nodules, SMS and cobalt-rich ferromanganese crusts up to 2014. Source: Ecorys

Contractor	General location	Type of deposit	Depth	Contract duration
Exploitation Licence				
Diamond Fields International	Red Sea	Polymetallic Sulphides (SMS)	1,900 – 2,200 m	2010 - 2040
Nautilus Minerals Inc.	Manus Basin, Papua New Guinea	SMS	1,600 m	2011 – 2030
Exploration Licence				
Nautilus Minerals Inc.	Papua New Guinea	SMS	1,030 – 2,590 m	Granted
Nautilus Minerals Inc.	Papua New Guinea	SMS		Granted
Nautilus Minerals Inc.	Papua New Guinea	SMS	1,500 – 2,000 m	Under application (as of 2014)
Neptune Minerals	Papua New Guinea	SMS		2012 – 2014
Nautilus Minerals Inc.	Solomon Islands	SMS		2011 - 2014
Bluewater Metals (Neptune Minerals Subsidiary)	Solomon Islands	SMS		2007 – 2014
Nautilus Minerals Inc.	Tonga	SMS	965 – 2,360 m	Granted
Neptune Minerals	Tonga	SMS		2008 – 2014
Korean Institute of Ocean Science and Technology (KIOST)	Tonga	SMS		2008 – 2014
Nautilus Minerals Inc.	Fiji	SMS		2014 – 2016
Bluewater Metals (Neptune Minerals Subsidiary)	Fiji	SMS		2012 – 2014
Korean Institute of Ocean Science and Technology (KIOST)	Fiji	SMS		2011
Nautilus Minerals Inc.	Vanuatu	SMS	1,000 – 3,000 m	Granted
Bismarck (Neptune Minerals Subsidiary)	Vanuatu	SMS		2011 - 2014 & 2012 – 2015
Neptune Minerals	Federated States of Micronesia	SMS		Under application (as of 2014)
Neptune Minerals	Palau	SMS		Under application (as of 2014)
JOGMEC	Izu & Ogasawara Island Chain and SW Okinawa Islands, Japan	SMS		2008
Neptune Minerals	Japan	SMS		Under application (as of 2014)
Nautilus Minerals	Bay of Plenty, New	SMS		Under application

Inc.	Zealand			(as of 2014)
Neptune Minerals	Gisborne, New Zealand	SMS	1,000 – 1,800 m	Under application (as of 2014)
Nautilus Minerals Inc.	Azores	SMS		Under application (as of 2014)
Neptune Minerals	Tyrrhenian Sea, Italy	SMS	500 – 1,000 m	Under application (as of 2014)
Nordic Ocean Resources AS (NORA)	Norwegian sector of the Mid-Atlantic Ridge	SMS		Under application (as of 2014)
Neptune Minerals	Back-arc Basin, Commonwealth of the Northern Mariana Islands	SMS		Under application (as of 2014)