The world's oceans have always both challenged and helped humanity, providing food for our table, linking settlements around the globe and driving the weather systems that influence our daily lives. Now we are finding mineral and energy resources on the ocean floor that will be as important to mankind as the resources we presently exploit on land. The oil industry has already moved offshore. However, the methods and capital required to exploit offshore oil and gas are not appropriate to find and develop seafloor mineral and gas hydrate deposits. To find and exploit them, exploration methods used on land have been re-invented for the sea.

Exploration activities must be economical and the scale of operations must be appropriate. In the past, humans have gone directly down to the seafloor to explore and map it, or have used crude machines to retrieve samples. This is expensive, high risk to human life, and not always successful in deep water. Today, robotic devices have replaced using people on the seafloor, increasing safety and increasing the periods of active operations near or at sea floor. Using robots and remotely operated sensors, we can map, sample, and mine the seafloor. Robotic systems provide economies independent of scale. The size of individual operations can be adjusted to provide a profit without building and operating gargantuan projects.

Remotely operated and autonomous underwater vehicles (ROVs/AUVs) are central to this process. Ship borne sonar and multibeam systems map the seafloor at scales of about 1:50,000 or smaller. Sonar, and particularly synthetic aperture sonar, can map the seafloor at scales of 1:100 using AUVs/ROVs. Water chemistry sensors, magnetometers and cameras can be operated on vehicles tasked for other purposes. Sampling can be done using ROVs, and drilling done using robotic seafloor drills. 3D seismic cubes can be acquired using small hydrophone arrays easily deployed from small vessels. Electromagnetic systems and interpretation algorithms exist to map both shallowly buried and seafloor massive sulfide deposits and gas hydrate deposits. Positioning of subsea vehicles and installations is not simple, but off the shelf transponder systems are available, and subsea sonar based navigation systems allow multiple assets to be located within a transducer array. These systems are becoming smaller, less expensive, and deployable from general purpose vessels rather than specialized purpose built ships.

The principal economic targets today are seafloor deposits of gas hydrates, submarine massive sulfides, and polymetallic nodules. The geologic signature of these deposits is understood. Best practices to find and exploit them are well known or are being developed. The impact of robotics is that "bigger is not necessarily better" and that exploration can be done cost effectively and safely using smaller, reliable, more capable, and less expensive equipment. Mining at sea, long delayed, is about to become an established industry.

MAJOR ECONOMIC TARGETS
The major economic targets for seafloor exploration today are submarine massive sulfides (SMS), manganese nodules and manganese crusts, and gas hydrates (Figure 1). Also, significant potential exists for phosphate exploitation and diamond mining is ongoing off the west coast of Africa.

The drivers for mineral exploration are twofold: the potential for highly profitable future mining operations as the technology develops to exploit known seafloor deposits, and a strategic desire by a number of nations to establish secure and stable supplies of energy and metals to support their national industrial base. Japan, in particular, has stated that it is a national priority to develop the technology to exploit the seafloor resources within their Exclusive Economic Zone (EEZ) (Figure 2). The country has a strong industrial base, but presently imports raw materials and oil and gas. Their objectives are to enable trial mining of SMS deposits in the Japanese EEZ this year, to enable commercial exploitation of gas hydrate deposits in 2018, and to initiate exploration and build the technology for the exploitation of manganese nodules and crusts to supply manganese, cobalt, nickel, and rare earths to Japanese industry with a target date of 2025.

DEPOSIT TYPES AND EXPLORATION TECHNOLOGY

Submarine Massive Sulfides
There is considerable crossover between methods applied for different deposit types. There is generally an association between methods and type of target, but usually the methodology is applicable across the full range of deposit types.
SMS are a new deposit type first found on the East Pacific Rise in 1979 (Speiss et al. 1980). Since then they have been found around the world, with new deposits being discovered on a regular basis. They are attractive economic targets as they have high grades, with higher gold and copper grades located in deposits along the trend of the famous ring of fire of the Western Pacific, extending from Japan to New Zealand. The economics of mining these deposits will be quite different from that of a deposit on land. The capital cost, and risk profile of a mining investment is very different. The mining system, once built, can move and hence amortized over many deposits. The sequence of mining is highly flexible. Grades are high, and there is no stripping required. The infrastructure is modular and is built in a shipyard, and the mining operation is robotic and thus amenable to a staged implementation using standard mining modules rather than requiring an upfront commitment to achieve economies of scale.

Exploration for SMS deposits has been ongoing seriously since 2006. Ocean Floor Geophysics (OFG) has participated on more than 20 mineral exploration cruises of up to 3 months duration since 2007. Other ships and exploration teams have been at sea every year. They have been funded privately, by governments, and by parastatal organizations. This continuing work is motivated by a desire to start mining. It is not academically motivated. Figure 3 illustrates the distribution of known vent fields documented in the InterRidge Vents Database (Beaulieu, 2015). The highest grades of copper and gold presently have...
been found in vent fields within the back arc environment of the Western Pacific. Most of these deposits lie within the EEZ of coastal nations. Hence the legal environment relating to tenements is more favourable for private companies, and most privately funded exploration has occurred in this area. Deposits in the central Indian Ocean, and along the Mid Atlantic Ridge are administered by the United Nations International Seabed Authority (ISA) and are being explored by national entities, for example, the EU, Russia, China, India and Japan within tenements issued by the ISA.

Regional exploration for new vent fields is done using ship borne bathymetry, looking for favourable seafloor morphology, i.e. spreading arc centers, calderas, and seafloor volcanic features. This is followed by transects using towed sonars, and water chemistry and water sampling systems such as the tow-yo water sampling system (Figure 4). In a tow-yo cast, continuous pH, Oxidation-Reduction Potential (ORP), turbidity and a discrete series of water sample measurements are made towing an instrument sled and simultaneously winching it up and down to search for hydrothermal plumes in the water column. Anomalous values provide a spatial indication of nearby hydrothermal venting. Turbidity and ORP anomalies are highly correlated with active hydrothermal venting (de Ronde, 2001), but are not necessarily indicators of economic mineralization. Also, detection of regional magnetic anomalies that disrupt the normal linear patterns of magnetization may indicate favourable areas that localize hydrothermal activity. This can be done using towed ship-based magnetometers (Barkhausen et al. 2016).

Figure 3: InterRidge Vents Database - location of hydrothermal vents and vent fields. The back arc spreading centre deposits of the Western Pacific are generally associated with high grades of copper and gold. Map after Stace Beaulieu, Woods Hole Oceanographic Institution.

Figure 4: (Left) Typical water chemistry anomaly passing through a hydrothermal plume. Note that methane and manganese measured in water samples are enhanced in the plume, while optical transmissivity falls. The optical transmissivity is a continuous measurement. (Right) Tow-yo image of turbidity combined with multibeam sonar backscatter in 3D visualization (picture courtesy Nautilus Minerals, rights reserved).
Seafloor morphology indicated by sonar is used to localize SMS deposits once a target region has been identified using regional methods. Many different sonar systems have been deployed. Side-scan sonar has a longer range than multibeam, but multibeam provides bathymetric information while side-scan sonar generally provides backscatter only. Often a multibeam sonar will be used to map the bathymetry below the ROV or AUV, while side-scan will be deployed concurrently to map a swath on either side of the vehicle. Interferometric side-scan systems provide additional information as they can provide bathymetric information as well as backscatter in the image swath, widening the effective width of investigation. The gold standard is High Resolution Synthetic Aperture Sonar (HISAS), which uses synthetic aperture processing that combines multiple pings along the vehicle track into a synthetic ping with a very narrow beam width, to produce very high resolution sidescan imagery (Table 1) with constant resolution across the full swath width. In the Hugin AUV implementation (Figure 5), two receiver arrays on each side of the vehicle also produce very high resolution interferometric bathymetry data (Hansen, 2011).

Figure 6 illustrates a SAS image collected using HISAS on a Hugin AUV. The mosaic was made by combining imagery from several AUV passes. It is suitable for geological interpretation and can be viewed in 3D when combined with high resolution bathymetric data collected concurrently. Denny et al. (2015) describes many typical morphological anomalies that can be used to aid the recognition of hydrothermal mineralization using high resolution AUV backscatter and bathymetric imagery.

Figure 7 shows sonar imagery from the Gondou SMS field discovered by the Japanese Coast Guard in June 2015. This may be the largest SMS field discovered to date in the Japanese EEZ. The field was mapped in two days during two dives by the Japan Coast Guard AUV Gondou (Minami, 2015). The single chimney highlighted has a height of 23 m above the seafloor, a diameter of about 8 m, and a mound at the seafloor about 20 m in diameter. A very rough tonnage estimate for this chimney is about 7500 tonnes, which would provide a week's feed for a 1000 tonne/day mining and processing system.
Table 1: Hugin HISAS sonar specifications.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Synthetic Aperture Sonar</th>
<th>Interferometric Bathymetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>100 khz</td>
<td>Cross track resolution</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.5 cm</td>
<td>Along track resolution</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>30 kHz</td>
<td>Relative bathymetric resolution</td>
</tr>
<tr>
<td>Total frequency range</td>
<td>50-120 kHz</td>
<td></td>
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<tr>
<td>Along track resolution</td>
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<td></td>
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<tr>
<td>Cross track resolution</td>
<td>2 cm</td>
<td></td>
</tr>
<tr>
<td>Maximum Range @ 2m/sec</td>
<td>200 m</td>
<td></td>
</tr>
<tr>
<td>Area coverage rate</td>
<td>2 km²/hr</td>
<td></td>
</tr>
</tbody>
</table>

Magnetometry

Magnetometry is a useful method of mapping geology in the SMS environment (Figure 8), as it is on land. However, there are challenges not faced on land. Doing a dedicated magnetic survey is not cost effective; data acquisition is efficiently done during dives purposed to multiple objectives. ROVs and AUVs are not good magnetometer platforms, being constantly modified and having significant and varying self magnetizations that interfere with the measurement of the ambient field. There is no place to put a base station on a ship – it is a large magnetic object. Also, the benefit of doing magnetic tie lines is generally deemed not worthwhile as the time taken to do this can be used to acquire other data. The cost of putting a geophysicist on a ship to manage the magnetic data acquisition is seen to be significant. Finally, the mounting of a magnetometer will generally be done by technicians and equipment mechanics not experienced in the art of magnetic data acquisition. Even so, it is possible to acquire very useful magnetic data that can provide geologic information of considerable value. Magnetic anomalies in the SMS environment are often large enough that compensated data acquired without diurnal corrections and tie lines can be used effectively. Interpretation methods taken from land based and airborne magnetic surveying in the mineral industry can be applied in the marine environment, particularly magnetic inversion methods. This takes the use of magnetic maps well beyond the stage of looking at images to a quantitative analysis method that maps geological contacts, faults, magnetite rich zones and alteration envelopes associated with SMS mineralization.

Initial compensation methods for ROV and AUV deployment were practical but crude, depending upon the ROV or AUV maintaining fixed headings and then building a table of adjustments to correct data combined to a common datum. Automatic magnetic compensation methods have now been developed that allow magnetometers to be mounted onto an ROV or an AUV of opportunity, and to collect useful data (Bloomer et al. 2014). Figure 9 shows uncompensated and compensated data collected using an AUV over an SMS prospect. The AUV was tasked with mapping the prospect with multibeam and sidescan sonar, and collected water chemistry measurements and magnetic measurements concurrently. The ability to collect compensated magnetic readings simply without impacting the crew size supporting a ROV or an AUV, or requiring specialized staff on the ship makes the routine collection of good magnetic data practical, and adds considerable value to an ROV or AUV dive purposed to other tasks. Some care still needs to be taken when mounting a magnetometer; this is a matter of good practice.

Figure 8: (Left) Two fluxgate magnetometers mounted on a work class ROV during a 2008 SMS survey deployment. The ROV was tasked with doing EM, video acquisition, and sampling. The fluxgates were 3-component +/- 2.0nT instruments. (Right) A magnetic map acquired this system.
Electrical and Electromagnetic Methods

SMS deposits are conductive and present good targets for electromagnetic (EM) prospecting (Figure 11). The principal issues for the use of EM are the practical issues of deploying an EM prospecting system close to the sea bottom in the deep ocean, surrounded by a conductive medium. The volcanic terrain is typically quite rugged, the seafloor is a jagged and sharp so not easy to lay equipment on or to drag equipment across. As well, the mounting of an EM system on various ROV or AUV platforms requires a purpose-built system for each platform which is typically different for each mineral exploration campaign. Free swimming AUVs do not have much power available, and the available system geometries for an AUV system are limited as the attachment of anything to the exterior an AUV can impede the control of the AUV and will slow it down. ROVs have power and good communications to the surface vessel, generally through fibre. However, operating ROVs close to the seafloor in a survey geometry is challenging, and the ROV itself generates significant amounts of EM noise.

These problems have been overcome by some systems that have been successfully deployed and show considerable promise. The first system to be successfully deployed is the Ocean Floor Geophysics (OFG) EM system (Kowalczky, 2008). It was used at the Solwara 1 deposit of Nautilus minerals and mapped out the limits of the conductive mineralization. The bounds of the deposit mapped by EM were used in the NR43-101 securities report describing the deposit (Lipton, 2012). To the author’s knowledge, this is the first and perhaps the only case where EM has been used as an integral part of defining an ore reserve. Towed time domain systems have since been developed such as the Waseda University system (Nakayama and Saito, 2016) (Figure 12) and the Golden Eye system (Müller et al. 2016) which can operate both in frequency domain and time domain. These systems are coincident loop systems that can either be towed by an ROV just above the seafloor, or can be landed on the seafloor to do EM soundings. The Waseda University system has been deployed during several campaigns mapping SMS mineralization in the Japanese EEZ and has successfully
detected known mineralization buried at a depth of 30 m (Figure 13).

![Figure 12: Waseda University TEM system. This system can be landed on the seafloor, or towed about 1.5 m above the seafloor (photo Professor A. Saito, Waseda University).](image)

Controlled source electromagnetic (CSEM) using a towed EM electric dipole source and E-field receivers has recently been shown to be an excellent method to detect SMS mineralization. The method was developed for gas hydrate exploration, but is applicable to SMS exploration. Using a deep tow CSEM array very clear anomalies have been measured (Murton, 2017) over known mineralization at the TAG field on the mid-Atlantic ridge. The disadvantage of a deep tow method is that it is difficult to navigate the array at the end of a long tow cable, it is difficult to maintain a low altitude over the rugged topography, the array can only be towed at slow speeds, and much of the survey time is spent in turns if multiple closely spaced lines are flown over a deposit to define its geometry.

The use of fixed seafloor transmitters and a roving E-field sensor mounted on an AUV overcomes these problems. Ocean Floor Geophysics, working with Steven Constable at Scripps and Fukada Salvage and Marine Works has completed a CSEM-AUV survey over the Iheya deposit in the Japan EEZ (Figure 14 to Figure 16). Strong and interpretable EM anomalies were detected over the mineralized zones. Interestingly, mounting the E-field sensors on the AUV allows a highly sensitive self potential measurement to be made, something that is difficult to do using an ROV. Use of an AUV allows very accurate navigation, good altitude control, and tightly spaced traverse lines to be achieved efficiently. It is also possible to use all the other sensors on the AUV concurrently: sidescan and multibeam sonars, sub-bottom profiler, and water chemistry sensors. The result is a very cost effective survey. This system uses robust well tested equipment and provides significant cost savings over other EM systems designed for SMS exploration.

![Figure 13: TEM anomaly over the Izena SMS deposit, Okinawa trough, Japan, measured with the Waseda TEM system. Blue are early time windows, purple late time. The anomaly is clearly visible in the early and mid time windows. The left-hand portion of the anomaly is the response traversing over buried mineralization of up to 30 m depth, the right-hand portion is the response crossing the sulfide mound. Data is raw, unstacked data (A. Saito, pers. comm.).](image)

![Figure 14: AUV CSEM survey, Sea of Japan Nov 2016. (Left) AUV with electric dipole mounts on AUV. (Right) Scripps DUESI seafloor transmitter being deployed.](image)
Targeting 1: Deep or Under Cover

Figure 15: Bathymetry and apparent resistivity collected during an AUV-CSEM survey. Grid lines are every 500 m. Water depth is about 1500 m. Note the strong conductivity anomalies associated with the general zone of mineralized mounds. The multi-transmitter, multi-frequency EM survey is amenable to 3D inversion to locate the burial depth and limits of the conductive zones.

Figure 16: Self Potential (SP) anomalies detected over the hydrothermal system shown in Figure 15 (Constable, 2017). Multiple passes of the AUV are plotted. As the SP voltage was collected using 3 components it is possible to draw quiver plots showing the direction of the SP currents. Note the well organized and repeatable directions of the voltage gradients pointing away from an SP source. Hydrothermal flow is hypothesised as the source of this anomaly.

Gravity

Gravity responds to density changes, so is suited to mapping SMS deposits. Like EM, the difficulty has been the practical problems of making a gravity measurement on the seafloor. Evans (1996) made a gravity traverse across the TAG SMS mound that unambiguously indicated a gravity anomaly due to the massive sulfides, and for which it was possible to compute an excess mass (Figure 17) on the seafloor. The gravity meter was in the submersible with the operator. This proved the utility of the gravity measurements, but is not a practical method for routine surveys. There has been work done using ROV deployed gravimeters (Sasagawa et al. 2003) and attempts to measure gravity using free swimming AUVs. ROV deployed gravimeters have excellent sensitivity, but low productivity and hence high costs for a seafloor minerals exploration application. Figure 18 shows a recent advancement, a self levelling ocean bottom gravimeter has been mated to a small "hopping" AUV that allows seafloor gravity to be collected from a ship primarily tasked to other purposes (A. Oshida, pers. comm.). The accuracy and ease of use of this system allows gravity surveys to be done readily to assist resource tonnage estimation during the assessment of an SMS deposit prospect.
**Figure 17:** (Left) Gravity traverse over the TAG SMS mound (Evans, 1996). (Right) The anomaly due to the massive sulfides is easily recognizable.

**Figure 18:** Seabed landing AUV with self-leveling ocean bottom gravimeter (OBG). Photo A. Oshida/ KGE.

**Seismic**

Seismic methods have high resolution and are the only method that can reliably map the top and bottom of an SMS deposit. However, it is difficult to acquire useful seismic data over an SMS deposit using normal high resolution marine seismic methods. The problem is the large size of the Fresnel zone, the small size of a deposit and the strong diffraction effects caused by the rough seafloor and often dipping and faulted volcanic stratigraphy. Also, the mobilization costs of bringing a seismic ship to survey a small area at high resolution is relatively high. These issues have been overcome by the Vertical Cable Seismic method (VCS) (Asakawa, 2015). This method uses vertical receiver arrays anchored on the seafloor over the survey area, and a traversing source over a grid pattern on the surface. The receivers are close to the seafloor so a 3D data cube can be developed with high resolution. The system is not large, is readily shipped and can be deployed from a ship of opportunity. Again, like gravity, the method reduces the amount of drilling required to establish an ore reserve and provides detailed information about the limits and thickness of both seabed and shallowly buried deposits (Figure 19).
Targeting 1: Deep or Under Cover

Figure 19: 3D seismic section through the Izena Deposit, Japan. The data was acquired using a vertical cable seismic array and a surface source. The left hand edge of the section starts at the edge of a seafloor mound, the buried mineralization between VC2 and VC3 has been confirmed by drilling (Asakawa, 2015).

Figure 20: (Left) Multiscale imagery from the Iheya North field, Japan (Thornton et al. 2016). Note that imagery can be retrieved to show the entire prospect, or zoomed in to display a 40 cm image area with a crab in it. The yellow arrows indicate nested images at different scales. (Right) Mosaiced seafloor image built after automatic position adjustment of AUV track lines using image correlation (Woolsey and Woolsey, 2016).

Video Imagery

Multiple video imagery streams are routinely acquired during ROV operation to aid piloting, and an AUV operating near the seafloor can also acquire seafloor imagery. Considerable long term value can be created from this data if it is indexed in a project database that allows interactive image review at different scales. It becomes more valuable as more data is acquired and can be used to plan subsequent work, to do environmental baseline work, and for change detection (Figure 20). The principal issue is the use of appropriate software to allow rapid access at different scales and that will remain scalable over time as the image database becomes very large. It is critical to be able to reference images by both time and position, and at multiple scales. Also, notes attached to the images during acquisition need to be retained and accessible, for example noting the identification of fauna or flora that are of import to an environmental assessment.

Manganese nodules

Manganese nodules occur widely throughout the world on the ocean abyssal plains. As well, widespread occurrences of manganese crusts occur on the flanks of seamounts and other occurrences of volcanic rock such as ridges and plateaus (ISA, 2017). Nodules particularly are of economic interest both because of their large tonnages, and because they contain...
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significant credits of Ni, Co, and rare earths. At present, most exploration attention is being directed to the Clarion-Clipperton Fracture zone in the Eastern Pacific where numerous mineral tenements have been established under the authority of the United Nations ISA (Figure 21) to the present exploration, as well as the value of the contained Ni and Co, which may be greater than the manganese values. Rare earths are a strategic resource and the world supply is presently controlled by China. Outside China, the establishment of a seafloor mining capability may contribute to world security of supply.

In the 1970s, three United States based consortia conducted mining tests in the Pacific using hydraulic mining systems. These efforts stopped when commodity prices fell, but they demonstrated that the nodules could be lifted to surface using hydraulic risers and that the nodules constituted a potential economic resource.

Present exploration has advanced to the stage of doing engineering feasibility tests. Many national entities and at least one private company are actively doing nodule exploration. The principal objective of these programs is to establish the concentration of nodules across large areas prior to starting mining operations. Ship borne MBES and backscatter imagery is being used regionally to identify areas of interest. Sonar is useful mapping nodule concentration, but in detail it is difficult to link grades from the physical samples collected with boxcores to sea-floor photography, and then to sonar responses across large areas. AUV seafloor photography and high resolution MBES bathymetry are the principal tools used at the seafloor to extend estimates of ore tenor away from the locations of physical samples. Detailed bathymetry is being acquired using AUV systems to map out areas suitable for the operation of seafloor collector systems, which need to be designed to traverse across the expected topography. In deep water, navigation and linking of seafloor sampling and AUV photography and sonar imagery generally requires the installation of seafloor transponders to provide accurate positioning.

Gas Hydrates

It is perhaps debateable whether gas hydrates should be considered a mineral. They are a hydrocarbon resource, but are quite different from conventional oil and gas and different methods used to explore for them that have more in common with mineral exploration than traditional oil and gas exploration. Deposits of gas hydrate comprise frozen methane in the interstitial pore space of sea floor sediments. They occur worldwide. Their stability zone extends from the seafloor to some 200–300 m below the seafloor. In the arctic, they can be found close to surface, throughout the world they generally occur below at water depths below 300 m. They are important because there are huge amounts of methane existing as gas hydrates. Present estimates are that there are undiscovered conventional natural gas resources on the order of $10^4$ Trillion Cubic Feet (TCF). The global gas hydrate resource is estimated at $10^7$ to $10^8$ TCF, that is 10 to 10,000 times greater (Ruppel 2011). Only a small portion of this will be recoverable but clearly it is an important resource, particularly for nations like Korea and Japan, and for emerging economies such as India that do not have substantial developed conventional resources.

![Figure 21](image-url)  

Figure 21: Map of mineral tenements 2014 from the ISA. Green blocks surrounding the tenements are ecological reserves established around potential mining areas.
Historically, economic gas hydrate targets have been targeted at the base of the gas hydrate stability field (Figure 22 – left image). These would be exploited by drilling, and warming of the gas hydrate in situ or by CO₂ replacement. Japan has demonstrated production from this type of occurrence in the Nankai Trough using the drill ship Chikyu. Recently it has been shown that seafloor gas hydrate mounds (Figure 22 – right image) can be a part of larger bodies that contain large concentrations of gas hydrates immediately below the seafloor. These have been mapped effectively using the Scripps towed VULCAN CSEM method (Constable et al. 2016). Exploration for these seafloor deposits comprises regional exploration for mounds, seafloor pockmarks, and methane venting and bubble streams using full water-depth multibeam imaging. A detailed seafloor investigation follows using AUV bathymetry mapping and the acquisition of sub-bottom profiler data. Favourable areas can then be mapped using the Vulcan CSEM. Resistive anomalies have been interpreted using the MARE2D EM code (Key, 2012) (Figure 23), or in 3D using the E3D code (Oldenburg et al. 2005). The successful use of these methods has been emphasized by a press release from METI, the Japanese ministry funding gas hydrate exploration technology research, stating that resistivity was the best method after drilling to estimate near sea bottom gas hydrate resources (METI, 2016).

**SUMMARY**

Geophysical methods have become key to the cost-effective exploration for minerals on the seafloor. Best practices and robust methods have been tested and are now being applied routinely. Geophysical systems can be deployed on AUV and ROV platforms. AUVs are becoming the main vehicle for geophysical surveys as they are more cost effective to deploy than ROVs, and can survey using multiple systems at the same time. They can be deployed from smaller ships than ROVs. However, for sampling in SMS terrains, and for the support of seafloor drills, ROVs remain critical. For some applications, towed systems are still effective and regularly used, e.g. tow-yo, towed sonar, and CSEM systems. However, these require larger surveys to be cost effective as lines cannot be turned around quickly, and significant support equipment and crew are required on the ship.
AUVs can navigate accurately in deep water and with closely spaced lines. Synthetic aperture sonar, multibeam sonar, and interferometric bathymetry provide excellent images. AUVs can also collect magnetic, CSEM, water chemistry, seafloor imagery, and sub-bottom profiler data concurrently with the operation of high resolution sonar systems.

For manganese nodules, AUVs can be deployed to map nodule distribution on the sea bed. An advantage of AUV operations is that physical sampling such as box coring can be done from the AUV mother ship while the AUV survey is in progress. ROVs can be utilized to acquire video, EM and magnetic data, and do seafloor sampling.

These systems are now robust, tested systems than can be effectively incorporated into a mineral exploration program. Magnetic and EM methods can explore around known deposits for shallow buried extensions or sister deposits. Localized, low logistics gravity and seismic methods can delineate the tonnages and dimensions of deposits once located. These systems combine with new technologies in seafloor drilling to reduce the amount of drilling required to establish the grade and tonnages of deposits, and will allow a mining operator to rank their prospects and to plan their exploitation cost effectively.

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