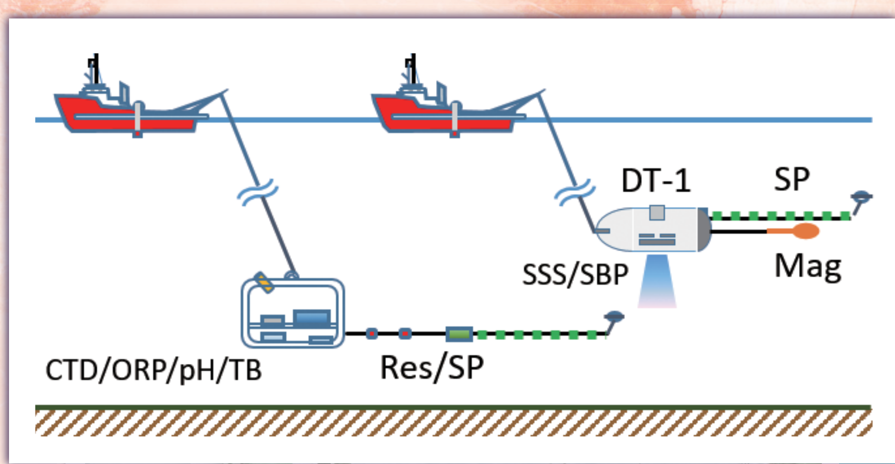
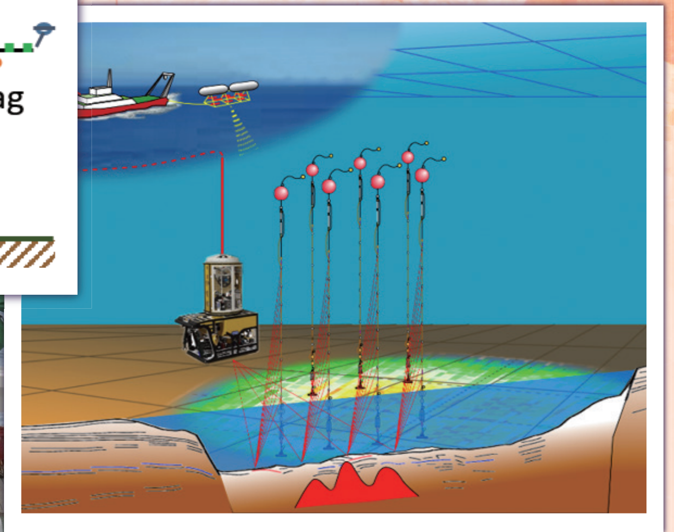
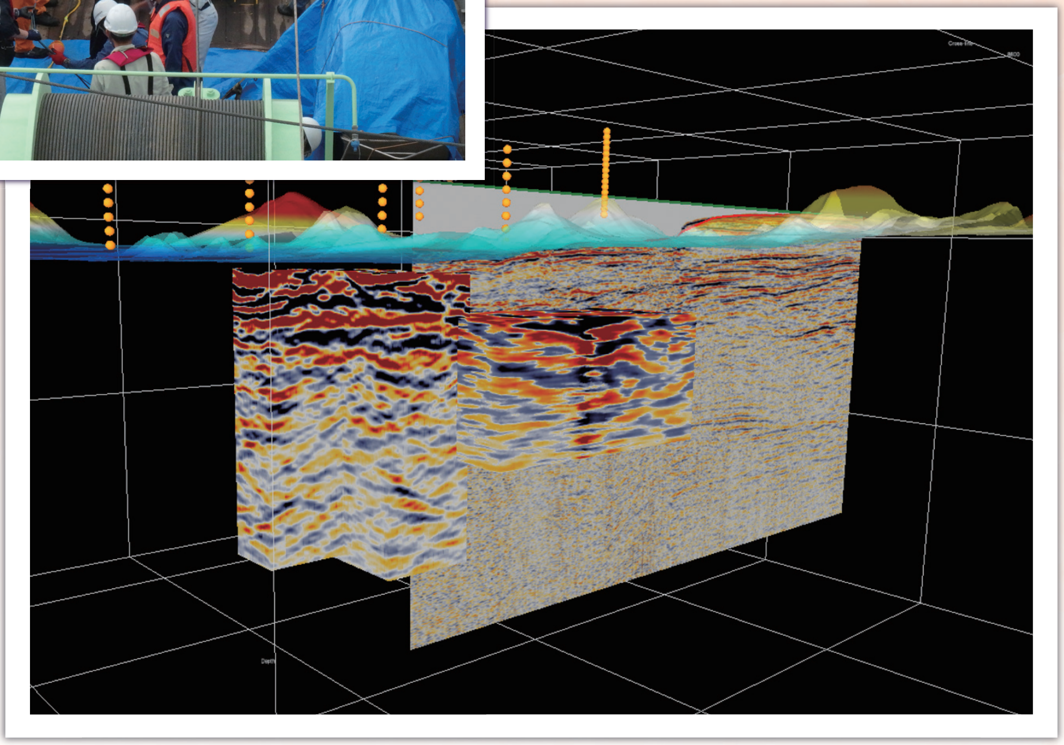
SIP 戦略的イノベーションプログラム
Cross-ministerial Strategic Innovation Promotion Program
Next-Generation Technology for Ocean Resources Exploration
"Zipangu-in-the-Ocean"

Survey Protocol for Seafloor Massive Sulfide Deposits

Revised edition







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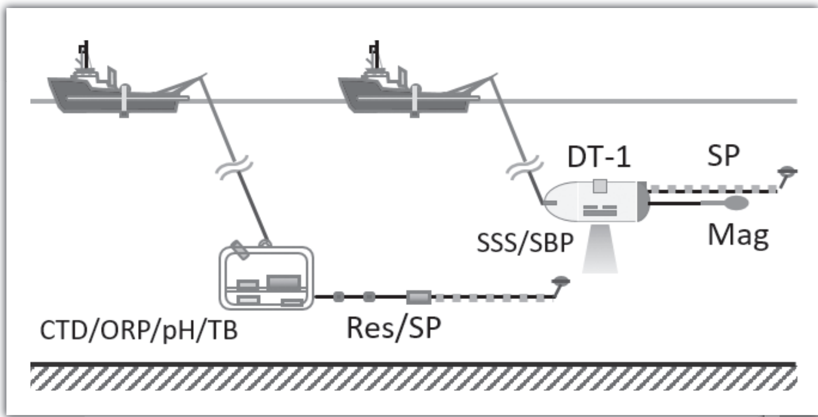

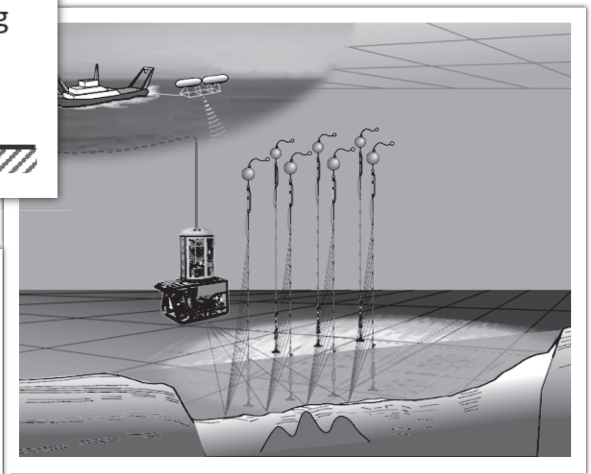

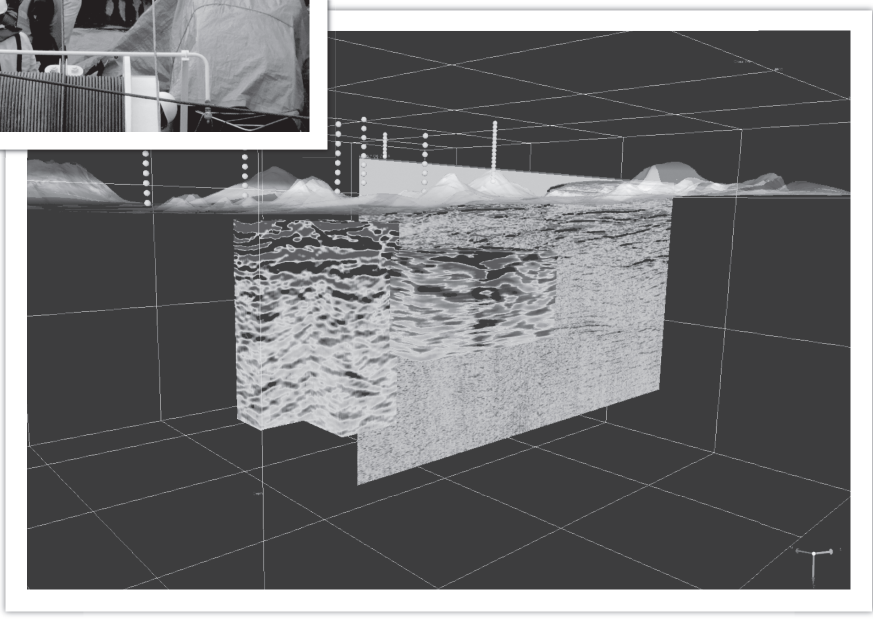

FOREWORD

Tetsuro Urabe Ph. D.
Program Director, SIP “Next-Generation Technology for Ocean Resources Exploration”
(*Zipangu-in-the-Ocean Project*)

The innovation is dependent on a range of technologies, which, in turn, depend on a multitude of materials. Serious disruptions of any of these materials could limit the ability of the industries to innovate. It is, therefore, increasingly essential for an industrialized nation such as Japan to have secure access to raw materials, because new technologies, green energy, and responsible industries require more than ever of these rare/critical metals.

The "Next-Generation Technology for Ocean Resources Exploration (*Zipangu-in-the-Ocean Project*)" has been executed since 2014 as a part of the Strategic Innovation Promotion Program (SIP) of the Cabinet Office of Japan to develop world's first deep-sea mineral resource survey technology system. The project selected two private company groups; Research and Development Partnership for Next Generation Technology of Marine Resources Survey (J-MARES) and Japan Marine Surveys Association (JAMSA), for the fulfilment of exit strategy of SIP, industrialization of the technology.

Fortunately, the development of individual elemental technologies had been completed one year ahead of schedule and we started the actual sea trial in 2016 against a “known” Seafloor Massive Sulfide (SMS) deposit in Okinawa Trough, southwestern Japan, under the cooperation of Japan Oil, Gas and Metals National Corporation (JOGMEC). The results indicate that the concealed SMS ore body can be detected at sub-bottom depth of >30 meters by geophysical techniques and match the results of numerous drillings done at the site by JOGMEC. Encouraged by the results, we applied the improved survey protocol in 2017 in the western part of Okinawa Trough, off-Kumejima island, where some seafloor drillings were carried out by JOGMEC.

The “Integrated Ocean Resource Surveying System” which is the systematic, step-by-step protocol for the survey aiming to narrow down the target areas from regional to detailed sizes, is now proven to be successful to identify both concealed and exposed SMS deposits at the water depth of 2,000 meters. In addition, in the final year of 2018, these private groups have been conducting actual resource survey in an "uninvestigated" area to demonstrate the applicability of the protocol at a cost comparable to land-based explorations.

The purpose of this booklet is to briefly introduce the survey protocol together with the results of technical verification. Please note that this booklet is a simplified version for the general public, but we are proud that the information given here is the world's first information of this kind. We sincerely hope that the technology will provide some solutions to one of the major risks of seabed mining, that is, the lack in significant ore reserves, in near future.

Finally, I would like to stress that one of the main research targets of this SIP project is the development of environmental impact assessment (EIA) technologies. These results are not covered in this booklet but are downloadable at "Ocean Data Standards and Ocean Best Practices" site of the IOC/UNESCO (http://www.oceanbestpractices.net/handle/11329/326, http://www.oceanbestpractices.net/handle/11329/325) and at JAMSTEC SIP Protocol series site. The results of an environmental workshop, "EcoDeep-SIP Workshop II in 2017 in Tokyo" have been published as ISA Technical Study: No. 18 by International Seabed Authority (ISA) and is also downloadable from ISA Homepage (https://www.isa.org.jm/documents-resources/publications).

We strongly recommend performing environmental baseline survey in parallel from the initial stage of all resource-related surveys. The reason for this is that it is essential to carry out environmental impact assessment (EIA) well ahead of planning for any mining operation to satisfy environmental standards, e.g. the World Bank's 'The Equator Principles' that emphasizes the protection of marine environment.

Planning and editing of this protocol was done by JAMSTEC Team under the theme leader Eiichi Kikawa. We are also indebted to the advice given by JOGMEC personnel and other researchers for the improvements. I strongly hope that this booklet may contribute to the realization of the seabed resources development not only in the EEZ of Japan but also that of many Island States in the world.

浦辺徹郎

Tetsuro Urabe Ph. D.

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1. Outline and Purpose of the Survey Protocol

The Current Status of Seafloor Mineral Resources

A metal resource exploration budget exceeding US$10 billion per year

In the 21st century, the extraction of metal resources has increased at a rate that exceeds that of energy resources, while the market capitalization of the metal mining industry (based on 2011 figures) has exceeded US$2.3 trillion, and metal mining has become one of the largest sectors of the world economy[1]. Although total investment in the exploration of nonferrous metals has continued to decline from its peak of approximately US$22 billion in 2012, even when metal prices bottomed out in 2015, investments still reached approximately US$10 billion.

Opinions are divided on when, and to what degree, this large-scale exploration of nonferrous metals on land will expand into the marine realm. For example, given the critical importance of a stable resource supply to global economic development, the OECD (2015)[2] forecasts that the development of seafloor resources will become a €10 billion industry by the year 2030. Despite the extremely limited market for the exploration and surveying of seafloor resources today, there is a potential for rapid growth once the industry begins to expand. Therefore, Japan must build a foundation from which it can become a world leader in the seafloor resource survey industry.

A metal deposit is a geological feature in which useful metals have been concentrated to the point of being economically viable for recovery. In other words, in order for a body of rock to be considered a deposit, it must not only meet certain geological criteria, such as metal concentration, but must also meet economic criteria set by the profitability of the production process. In the absence of detailed economic analysis, seafloor minerals cannot meet the strict definition of a deposit. However, due to the general expectation of profitability, these resources are often referred to as "ore deposits." In this protocol, we will use the term seafloor massive sulfide deposit (SMS deposit) in a similar manner.

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1 SNL Metals & Mining (http://pages.marketintelligence.spglobal.com/state-of-the-market-mining-q4-update-download-emc.html?aliId=18849384)

2 Coulomb, R. et al. (2015), “Critical Minerals Today and in 2030: An Analysis for OECD Countries”, OECD Environment Working Papers, No. 91, OECD Publishing, Paris. http://dx.doi.org/10.1787/5jrtknwm5hr5-en and OECD (2014) “Future of Ocean Economy”

Which seafloor resource is closest to commercialization?

The EU, OECD, and others expect SMS deposits to become the first of the seafloor mineral resources to be extracted commercially[3]. This is because SMS deposits are more valuable per ton of ore than other resources, are typically located close to land and within the exclusive economic zones (EEZs) of coastal nations, are concentrated in discrete areas at relatively shallow depths, and because extraction activities would impose a small ecological footprint[4], among other considerations.

First-in-the-world survey technologies for seafloor resources

A precondition for achieving the commercial extraction of SMS deposits is the establishment of a systematic exploration methodology. In this Cross-Ministerial Strategic Innovation Promotion Program (SIP), we worked toward the development of the world's first such methodology and achieved significant success in reaching this goal. The system we created is likely to receive some portion of the investment in land-based resources and should be further developed toward commercialization. Moreover, it is important to note that many of the technologies and systems developed through this program can also be applied to the exploration of other resources such as cobalt-rich crusts.

Goals for the Survey and Exploration of SMS Deposits

Toward a seabed exploration methodology that is comparable to land-based exploration

Land-based metal resource exploration encompasses a diversity of methodologies, ranging from those practiced by small, specialist exploration companies known as junior mining companies, to those practiced by major resource extractors like Rio Tinto and BHP. As neither type of company exists in Japan, JOGMEC currently conducts overseas exploration on behalf of Japanese mining companies. Although the budgets for JOGMEC's projects vary substantially, many average about JP¥500 million per year.

In order for private sector-led seafloor exploration to be competitive with land-based equivalents, the operating budget must fall within a similar range. Therefore, by working to reduce costs, we created a survey package that could be implemented for JP¥500 million (US$4.6 million). The biggest obstacle to achieving this goal was the high cost of ship time. Although the precise cost depends on a ship's tonnage and performance, mining companies would have to pay roughly JP¥2 million to JP¥5 million (US$19,000 to US$46,000) per day to hire a private vessel to conduct surveys or explorations. Therefore, the most important tasks were to boost the efficiency of our surveys and reduce the number of ship days as much as possible.

[3] e.g., ECORYS (2013) Study to investigate the state of knowledge of deep-sea mining, Final Report under FWC MARE/2012/06 - SC E1/2013/04

[4] S. Petersen et al. (2016) News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources, Marine Policy, 70, 175–187

Multiple AUV operations offer significant advantages

One of the core technologies of this SIP is the operation of multiple autonomous underwater vehicles (AUVs). Our proposal to use up to four AUVs equipped with sensors for resource exploration, all controlled by an autonomous surface vehicle (ASV), constitutes the world's first use of this technology in a commercial context. By having ASV-controlled AUVs use their numerous sensors while the mother ship is engaged in tasks that require human involvement, we were able to realize a five-fold boost in efficiency.

Additionally, the use of multiple AUVs provides a further advantage: although safety considerations require that marine surveys be halted during inclement weather, with our method, we can make full use of favorable weather windows, even in environments where such opportunities are scarce.

Cost calculations based on field data

In order to establish an ocean resource survey industry that is in no way inferior to its land-based counterpart, it is important to estimate costs based on actual surveys conducted in the field. For this SIP, we examined survey cruises conducted in 2016–2018, mainly by two groups of private businesses, to obtain empirical cost data. Currently, we are in the process of evaluating different cost-calculation procedures to determine the most accurate method.

1–1. Outline and Purpose of the Survey Protocol

Summary of the Survey Protocol

The importance of ore genesis models in narrowing down the search area

With land-based exploration, it is common to narrow down the search area through the use of remote sensing data from aircraft- or satellite-based sensors. However, since seawater absorbs light and other electromagnetic waves, there is currently no method for exploring a wide area of the ocean.

Therefore, in order to narrow the search area from the wide expanse of the ocean to just the locations with high resource potential, it is critical to establish candidate sites through the use of science-based ore deposit ore genesis models.

As a result, after reviewing the necessary topics, we set the following three goals for this SIP *Zipangu-in-the-Ocean* project: (1) develop a method for constraining search areas based on scientific research into the formation processes of ocean resources, (2) develop ocean resource survey technologies, and (3) establish an environmental impact assessment protocol based on ecological research and the development of long-term monitoring technologies. These goals were then combined into the **SIP Integrated Ocean Resource Surveying System**, as described above.

Phased implementation of research cruises

One characteristic of our system is that we examine the candidate sites selected by using our ore genesis models through a phased process that consists of regional, semi-detailed, and detailed surveys. In other words, we implement a transition from a "rapid" survey method that is capable of covering large areas to fine-grained methods that provide more precise data but can only examine a limited area per unit time. Specifically, we start with research vessel-based techniques, followed by AUVs and finally by remotely operated vehicles (ROVs), to progressively and efficiently narrow down the location of greatest resource potential. This protocol describes the procedures we have developed to accomplish this.

Advantages and disadvantages of seafloor boring

Once the detailed surveys are complete and a given candidate location has been narrowed down to within a few km^2, it is time for resource development companies to conduct feasibility studies (FS). The most effective exploration method for FS is high-density boring, in which, for example, boreholes are drilled in a 50-m grid to determine the proven ore reserves and the distribution of ore quality. Whether for resource development on land or in the ocean, this is a crucial preparatory step.

However, as determined by this SIP's Strategy Formulation Task Force, the per-meter cost of seafloor boring is JP¥1 million to JP¥2 million (US$8,500 to US$19,000), or roughly 100 times higher than the cost on land. Consequently, it is imperative from an efficiency and cost standpoint to minimize the number of boreholes that need to be drilled prior to the detailed survey phase, and to instead determine the outer boundary of the deposit by means of geophysical exploration techniques. While our system makes this possible, conversely, we have not considered an exploration process that involves numerous boreholes.

Aims of our Survey Protocol

Technological goals

We cite the following as specific objectives: (1) develop techniques and technologies to narrow ocean areas for exploration to one-ten-thousandth of the ocean area, (2) develop instruments capable of conducting low-cost, high-efficiency surveys up to a depth of 2,000 m, and (3) create survey methods for discovering buried ore deposits up to 30 m below the seafloor.

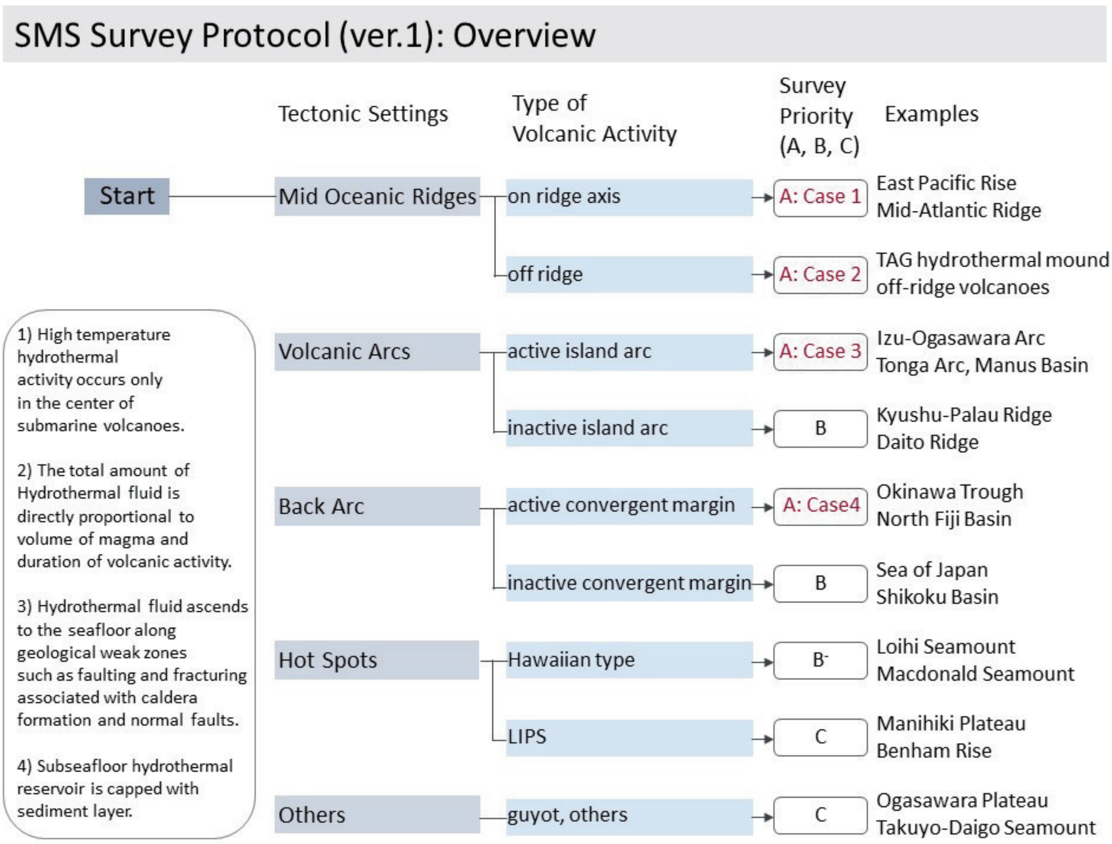
Industry-related goals

Create an ocean resources survey industry that can compete on the world stage by late 2018 by transferring the novel survey technologies and methodologies developed by our program to a wide range of private sector enterprises including resource exploration, equipment manufacturing, and marine engineering companies.

Furthermore, we aim to expand our survey system not only domestically but also overseas with the goal of generating demand for resource surveys. Specifically, it is imperative that we consider expanding this industry to other Pacific island nations where similar SMS deposits are expected to be available. Of course, because small island developing states (SIDS) largely lack the resources or companies necessary to implement our protocol, this will require the provision of official development assistance (ODA) from the Japanese government.

Initiatives targeting other seafloor resources

For this SIP, our efforts have focused on the development of survey systems for SMS deposits as a matter of urgency. Yet at the same time, we are also considering ways to develop the world's first technologies to achieve low-cost, high-efficiency surveys of other ocean resources such as cobalt-rich crusts and rare-earth containing sediments (REY-rich muds). Similar protocols with their basis in specific ore genesis models are currently being drawn up for these resources as well.



Details of the Survey Protocol

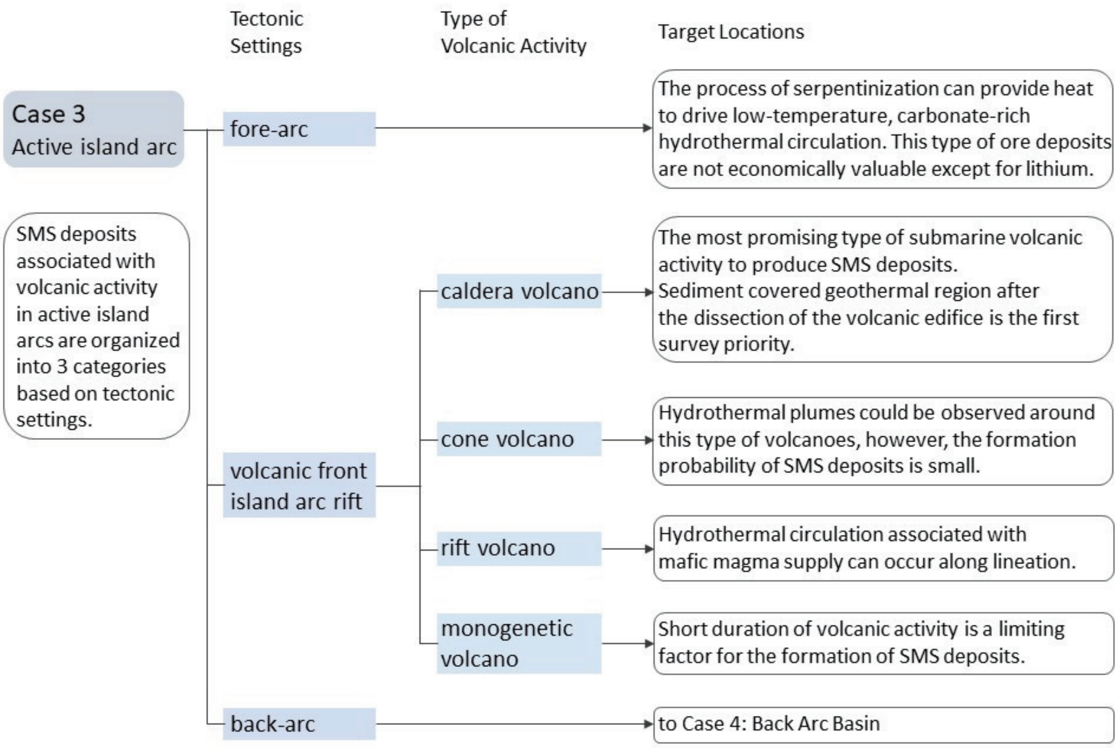
Ore genesis model-based methods for narrowing down the search area

The oceans as a whole cover an area of approximately 361.06 million km^2. From this large domain, it is necessary to narrow down the focus to individual tectonic zones of several hundreds of thousands of km^2, which is the scale of most large-scale maps, for review (see examples above). Whereas the available literature[2] contains ample discussion of the resource potential of mid-ocean ridges, barring a few exceptions, there is almost no information on island arcs. The Strategy Formulation Task Force for this SIP gathered all of the limited information available and concluded that the exploration of the A-ranked regions, described above, was most urgent. In other words, even though there is reason to consider investigating the regions ranked B or C in the future, the first priority should be to investigate the A-ranked regions.

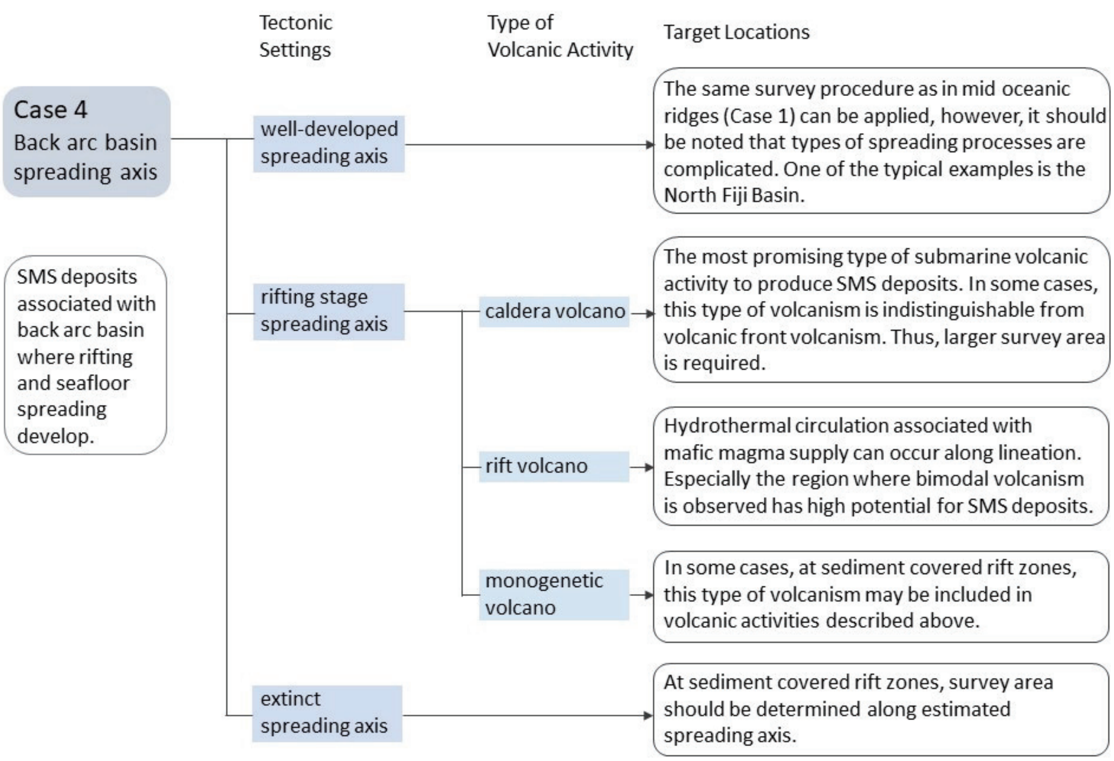
Furthermore, among the regions ranked A according to our ore genesis models, we further narrowed our focus to Cases 3 and 4 (described above) for this SIP by choosing regions that merited on-site surveys (see the example below). (The current protocol is based on these cases, and slight modifications would be required for application to Cases 1 or 2.) At this stage, the target locations for regional surveys can be narrowed down to areas in the range of several tens of thousands of km^2 in size. It should be noted that refinements to the search area based on a scientific understanding of the formation processes of resource deposits are not exclusive to this stage, but remain factors in decisions undertaken later in the resource survey such as whether to proceed to the next phase or give up and move to a different region. For further details, please refer to Chapter 2.

[2] See for example:
Hannington, M. et al. (2011) The abundance of seafloor massive sulfide deposits, Geology, v. 39; no. 12; p. 1155–1158; doi: 10.1130/G32468.1
Singer, D.A. (2014) Base and precious metal resources in seafloor massive sulfide deposits, Ore Geology Reviews 59, 66–72

SMS Survey Protocol: Active Island Arc



SMS Survey Protocol: Back Arc Basin Spreading Axis



Exploration technology-based methods for narrowing down the search area

Once the search area has been refined to a regional survey target area of several tens of thousands of km^2, exploration technology-based methods are applied to gradually winnow it down to a region that is several tens of km^2 in scale. The regional survey phase involves ships, ship-towed equipment, and AUVs. The upper limit of reliance on this regional mode of resource exploration is determined by the level of investment, and some nation-led survey proposals are likely to implement it across a wide area. Further details on the methods used in this phase are contained in Chapter 4 and in subsequent chapters.

Chapter contents

In Chapter 2, we will explain the process for narrowing down the target search area based on ore genesis models. Here, the objective is to select an area that is tens of thousands of km^2 in size, which is the feasible area of coverage for a regional survey conducted by ship. The process for doing so is based on a formation process model for SMS deposits created through this SIP, in which we maximized our use of the knowledge gained from research into the formation processes of ocean resources. The ore genesis model will be updated as new research results become available. Because such updates have the potential to enable an even more efficient winnowing down of the search area, model updates should be implemented on an ongoing basis.

In Chapter 3, we discuss our concept for the survey package that will actually be implemented. In the subsequent chapters, we discuss each element of the survey technology. Chapter 4 discusses the technologies involved in acoustic exploration, Chapter 5 electrical and electromagnetic exploration, Chapter 6 gravitational and magnetic exploration, and Chapter 7 discusses the other exploration methods that can operate in parallel with geophysical exploration. The technologies covered in Chapters 4–6 are generally established and widely utilized already, and are currently undergoing further refinement to reduce costs and boost resolution. In Chapter 7, we discuss supplementary exploration technologies along with chemical methods.

The tools covered in Chapters 4–7, including acoustic bathymetric systems carried by ships and AUVs, are used in regional surveys. For semi-detailed surveys, seismic surveys are effective for detecting horizontal anomalies, and self-potential measurements can detect hydrothermal fields or mineralization bands under the seafloor. Once an interesting feature is discovered during a semi-detailed survey, detailed surveys can be used to examine its vertical structure. Here, high-precision seismic surveys can be effective.

The wide variety of data obtained from regional, semi-detailed, and detailed surveys are then collated into a form that can be stored in databases. However, if each data type is simply examined individually (for example, by plotting it with GIS software), we run the risk of missing the physical and chemical indicators that provide clues to the location and extent of an ore deposit, which is ultimately what we want to discover. Ideally, multiple data types would be integrated into a single visualization to allow even non-experts to gain a clear view of the structure of the deposit. For example, by integrating borehole-logging data obtained via excavation with data on the seismic reflection structure, we could show the seismic velocity structure along with the extent of the mineralized zone[3].

1–2. Using the Protocol

Organization of the Survey Protocol, and Directions for Use

<u>Usage notes</u>

This survey protocol is intended to serve as a manual summarizing the resource survey techniques used in, or developed by, this project. It is not intended as a guide to evaluating or extracting mineral resources.

<u>The importance of simultaneously implementing environmental baseline surveys</u>

Under the United Nations Convention on the Law of the Sea, when conducting activities under government jurisdiction such as the development of seafloor resources, laws and ordinances must be applied to prevent, minimize, and regulate the contamination of the marine environment in accordance with international rules and standards. For details, please refer to the social science reference book *Towards an Ocean Resource Development Industry that Prioritizes Marine Conservation*, which will be prepared separately by this SIP.

We believe that implementing baseline ecosystem surveys during the exploration phase and prior to any resource extraction can in fact reduce costs and speed up the FS, which will in turn lead to more rapid resource development. Therefore, while implementing research cruises for the **SIP Integrated Ocean Resource Surveying System** described above, we have also conducted environmental impact assessment (EIA) studies. Future endeavors should maintain this same approach to conducting ocean resource surveys.

The United Nations and other international organizations have demonstrated a heretofore-unprecedented awareness of marine conservation issues. Regardless of whether the resource extraction occurs within Japan's exclusive economic zone (EEZ), to do so absent an EIA would be unthinkable. This SIP is also developing technologies to minimize the cost and maximize the efficiency of EIA, and has separately created an EIA protocol. The EIA protocol is a companion document to this survey protocol. It is crucial that both protocols be used when carrying out resource exploration and development.

[3] Tsuji, T. (2016) 次世代海洋資源調査技術研究開発成果資料集 海底熱水鉱床の成り立ち―調査手法の確立に向けて― [Next-generation ocean resource survey technology R&D results: The origin of seafloor massive sulfide deposits –Toward the establishment of a survey method], Ch. 3, Section 2

2. Identification of Promising Ocean Areas for Investigation Based on Ore Genetic Study Results

2–1. Distribution, Tectonics, and Geology of SMS Deposits

SMS deposits are mineral deposits formed through seafloor hydrotheralism lasting several years (short-term) to a hundred thousand years (long-term). Hydrothermal fluids leach metallic elements from the sediment, crust, and magma, and carry them to the seafloor to form concentrated precipitates. Submarine hydrothermalism is ubiquitous at mid-ocean ridges, island arc volcanoes, and back-arc basins. There are estimated to be around a thousand hydrothermally active sites in and around these geologic features on the seafloor across the world's oceans. Additionally, igneous areas known as hot spots are thought to be involved in the formation of some oceanic islands. However, high temperature fluids are rarely discharged from seafloor hydrothermal vents around such islands. Consequently, these areas have low resource potential.

Among the regions of seafloor hydrothermalism mentioned above, mid-ocean ridges and back-arc basin spreading centers produce igneous basement rocks consisting of lava and plutonic rocks arising from mafic volcanism, as well as ultramafic rocks derived from the mantle. By contrast, island arc volcanoes range from mafic to felsic, and their igneous basement rocks can include pyroclastic rock, lava, intrusive rock, plutonic rock, and older continental crust. In some regions, the bedrock of island arc volcanoes lies exposed on the surface of the seabed, whereas in other regions such as at the continental margins, the bedrock is covered by a thick layer of terrigenous sediment. The latter type is said to be "sedimented" or "sediment-covered," and is known to occur on mid-ocean ridges, back-arc basins, and island arcs. Of these geologic features, back-arc basins commonly occur on the western margins of the Pacific Ocean. The fringe of such basins extends from the Bering Sea, through the Sea of Japan and the Okinawa Trough, and continues into the Fiji and Lau Basins (Figure 2–1).

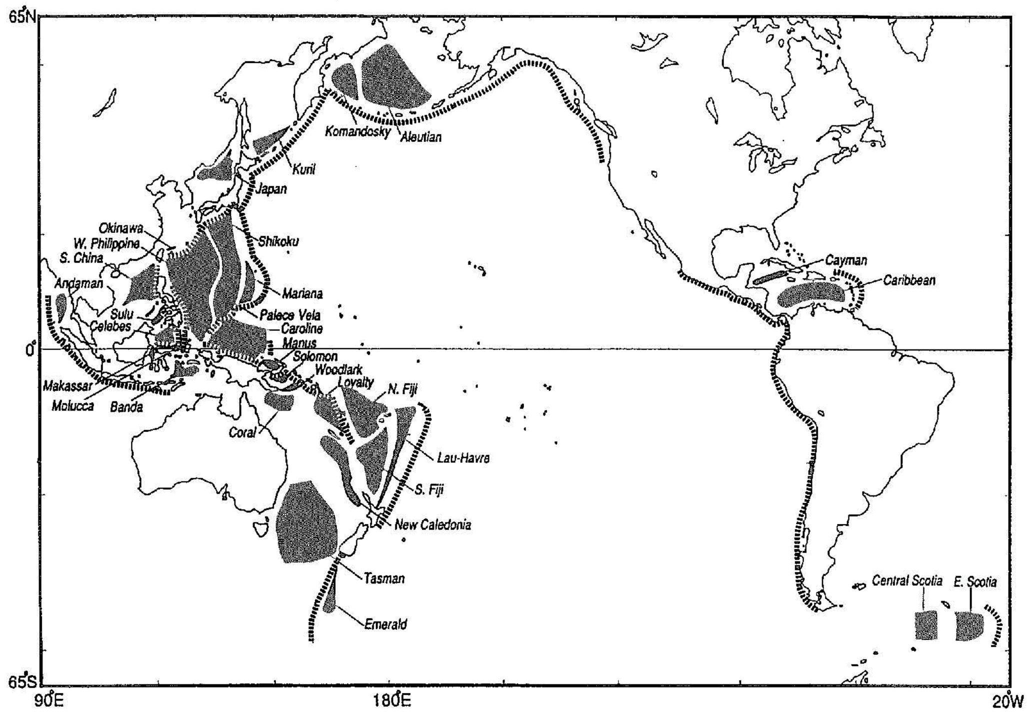


Figure 2–1 Distribution of back-arc basins (Tanahashi, 1994). The shaded areas represent the back arc basins.

2–2. Outline of the Ore Genesis Model

Although hydrothermal sediments, which are sediments associated with hydrothermalism, are present in most hydrothermal areas, they differ substantially in their extent and chemical composition. For example, low-temperature hydrothermal vent fluids are known to produce hydrothermal iron-manganese oxides, silica-rich strata, sulfur, and sulfate minerals such as baryte. Only high-temperature vent fluids, however, are capable of producing economically valuable deposits. This is because minerals such as copper, zinc, and lead sulfides only precipitate at temperatures above 250 °C. As shown in Figure 2–2, the solubility of base and precious metals is highly temperature-dependent, and is highest at high water temperatures. For example, based on the data shown in Figure 2–2, the saturation point of copper in 350 °C seawater is a few dozen ppm. Once this high-temperate water cools upon contact with the seabed, copper precipitates will form at a rate of a few dozen grams per ton of water. By contrast, only 1 g of copper precipitate would form from water at 250 °C, illustrating the importance of temperature in this process. In turn, the temperature of hydrothermal vent fluid is strongly constrained by the pressure-boiling point relationship of seawater. Using this relationship, we can calculate that only vents located at greater than 1,000 m depth can reach temperatures that favor deposit formation. Because shallower vents are enriched in minerals such as arsenic (As) and antimony (Sb) sulfides, they are of limited economic value. Vents that are deeper than 1,500 m, on the other hand, can exceed 350 °C. Since the solubility of copper increases rapidly around this temperature, vents at these depths have the potential to be highly valuable.

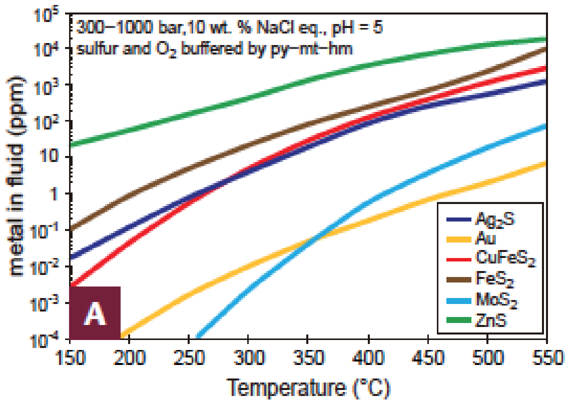


Figure 2–2 Solubility curve for base and precious metals under typical formation conditions for hydrothermal deposits (Figure 3, Fontboté et al., 2017. Reprinted with permission from the Mineralogical Society of America).

As illustrated by the above examples, depth (i.e., water temperature) is the most important condition for the formation of highly valuable deposits. However, other conditions must be met for such deposits to occur at large scales. A drop in temperature is one such prerequisite for efficient mineral precipitation. Based on the extremely fine-grained nature of SMS deposits, these deposits appear to have undergone rapid cooling by mixing with low-temperature seawater at or just beneath the seafloor. When mixing occurs at the seafloor, sulfide minerals in the hydrothermal fluid undergo rapid nucleation to form black smokers. This process releases nearly all of the ore minerals into the seawater. When mixing or cooling occurs beneath the seafloor, the precipitation of anhydrite at the reaction site inhibits the mixing of seawater and high-temperature hydrothermal fluids in a process known as "self-sealing." This prevents the dissipation of ore minerals but lowers precipitation efficiency.

Once an ore deposit has been produced, certain conditions favor its preservation. In particular, since sulfides are thought to undergo relatively rapid decomposition in oxidative seawater, it is commonly believed that reductive water masses or subsurface environments are preferable for deposit formation (e.g., Tornos et al., 2015). According to this viewpoint, deposit minerals can exist as (1) chimney formations on the seafloor, (2) mounds created by chimney collapse, and (3) sub-seafloor strata formed by precipitation or replacement. However, none of the models proposed to date can account for the entirety of the observed data.

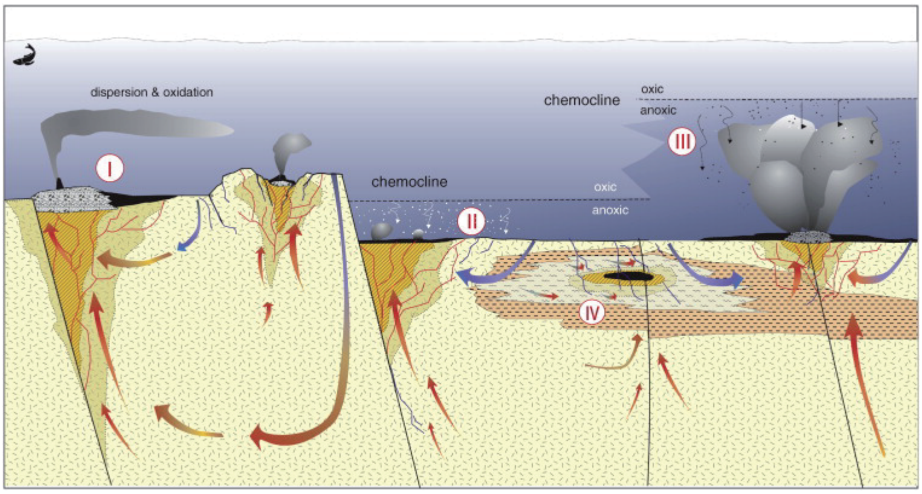


Figure 2–3 Schematic diagrams showing several examples of seafloor massive sulfide deposit formation (Figure 8, Tornos et al., 2015. Reprinted with permission from Elsevier).

Therefore, in our research for the *Zipangu-in-the-Ocean* Program, we have focused specifically on identifying and studying the sites where large-scale ore deposits are likely to form. Our results are summarized in the handbook *Seafloor Massive Sulfide Deposit Formation Research Materials Collection* published in 2016. Based on this work, the following conditions were found to be suitable for the formation of large-scale ore deposits:

- The site is located in a depression (however, some exceptions have been found in the Okinawa Trough)
- The sediment layer is of a certain thickness (around 100 m) and, in particular, includes a highly permeable pumice layer (one hypothesis holds that subsurface deposits form by displacing this pumice layer)
- The site has experienced long-term hydrothermal circulation

This hydrothermal circulation, in which seawater permeates under the seabed including through the sediment layer described above, before being driven upward by buoyancy, primarily functions to elute and transport metal elements directly above the heat source of the magma chamber. Observations of the Oman Ophiolite and others have indicated that the reaction zone (a 350–400 °C region that forms chlorite and epidote minerals) located directly above the magma chamber contributes greatly to deposit formation. Yet fluid dynamic calculations suggest that hydrothermal fluids rise adiabatically from the reaction zone to the seafloor within only a few minutes, meaning that the scope for chemical reactions in this zone is extremely limited. The scale of hydrothermal circulation depends on the size of the heat source and the sub-seafloor structure at the site, and the duration of the circulation is roughly determined by the lifetime of the heat source. Currently, it is difficult to estimate the size of a particular heat source. On a global scale, however, mid-ocean ridges are the site of the overwhelming majority of volcanic activity, accounting for over 80% of total magma production on Earth. Yet even at fast-spreading ridge systems that should have the highest rates of magma production and supply, individual zones of hydrothermalism appear to be quite small (i.e., they occur over relatively short periods). This discrepancy has long puzzled researchers, but is likely related to the small scale of the narrow magma chambers that form under spreading centers at relatively shallow depths (1–1.5 km below the seafloor), which tend to be less than 50 m in thickness and 1 km in width. Consequently, these magma chambers only contain enough heat to sustain several black smokers for around a single year. Moreover, due their proximity to a spreading center, the magma supply from these chambers is frequent yet limited in volume, and the widespread occurrence of seawater penetration through cracks in the bedrock leads to rapid cooling (see, e.g., Umino, 2009). By contrast, the Mid-Atlantic Ridge, which is characterized by a low spreading rate, is associated with the largest hydrothermal mound in the entire ridge system (the TAG hydrothermal mound). The deeper location of the magma chamber underlying this hydrothermal mound is thought to provide a more stable heat source for hydrothermalism. Similar conditions can also be found in mature back-arc basins with well-developed spreading centers.

When situated in spreading centers, individual magma chambers within island arc volcanoes can be quite large, and include caldera-forming chambers on the order of 10 km^3. Those situated in areas of compression (including the present-day Japanese archipelago), however, are generally likely to be small. This fact accounts for the small scale typical of major eruptions (e.g., 0.1–0.01 km^3) by island arc volcanoes situated in areas of compression. Accordingly, the Tohoku Arc, which formed Japan's large Kuroko deposits 15 Ma, is thought to have been located near a spreading center or under an extensional stress field. In fact, the volume of pyroclastic rock produced at the Tohoku Arc at this time was quite large, and is even comparable to the volume of ash-flow tuff associated with the Yellowstone Batholith in western North America. The Okinawa trough is also currently located in a spreading center, and although the scale of magma chambers in this region remains unknown, it may be fairly large. Interestingly, when compared against other magma chambers of the same scale, felsic magma chambers in island arc volcanoes are characterized by an overwhelmingly long lifespan (see, e.g., Koyaguchi and Kaneko, 1996). This is because of a difference in the timescale of cooling, with mafic magmas tending to undergo rapid heat loss due to extensive convective flow, whereas the high viscosity of felsic magmas leads to more gradual conductive heat loss. Although this tradeoff between size and longevity in felsic vs. mafic magma chambers is complex, it may be circumvented by the unique dynamics of the magma supply system in some island arc volcanoes, in which shallow felsic magma chambers are intermittently supplied with mafic magma.

The presence of bottom sediments is highly advantageous to large-scale deposit formation, including by (1) maintaining a highly permeable aquifer that can serve as a site for ore deposition, (2) shielding the ore deposit from oxidation, and (3) promoting the leaching of metallic elements via water flow through the sediment layer. In fact, in a site known as Izena Hole in the Okinawa Trough, concealed ore bodies were found to be larger than those that lay exposed atop the bottom sediments. Previously, there were no methods available to detect concealed ore bodies effectively. However, through the *Zipangu-in-the-Ocean* Program, we have succeeded in developing and implementing a powerful new technique for this purpose.

2–3. Identification of Promising Areas According to Ore Genesis Study

From the above discussion, it is clear that the methods used to narrow down a search area during the exploration of mineral resources must also apply to ore bodies concealed within the sediment layer (i.e., concealed ore deposits).

So far, we have established the following key characteristics of SMS deposits:

- Concealed sulfide ore bodies behave in a battery-like manner. Therefore, they have a negative self-potential signature and can be detected via passive electrical survey techniques (Kawada and Kasaya, 2017)
- Ore bodies are electrically conductive, and can be mapped using active electrical survey techniques
- The horizontal extent of concealed ore bodies is unknown, however, some ore bodies are known to reach approx. 300 m in size
- Disseminated ore may be distributed at depths of 20–40 m or more below the seafloor

Based on the above, it is clear that we need to employ a combination of technologies and techniques capable of sensing and resolving these characteristics. Moreover, our efforts should target depths of 20–40 m below the seafloor, which is in line with the capabilities of the mining technologies available at present. To do so using either acoustic (Chapter 4) or electrical/electromagnetic techniques (Chapter 5) will require that the appropriate sensors be placed in close proximity to the seafloor via AUVs, ROVs, or deep-towed platforms in order to achieve the required sensitivity and resolution. In principle, both passive exploration methods, which rely on the observation of naturally occurring fields, and active exploration methods, which use an artificial source, could be employed. The depth penetration of active methods is highly dependent on the power of the source signal. Consequently, it is difficult to make observations at substantial depths below the seafloor. The resolution of these methods, however, can be fairly easily increased by achieving a greater proximity to the seafloor, and by optimizing the geometry of signal transmission and reception. Similarly, passive methods are also amenable to achieving higher resolution by optimizing the arrangement of signal receivers. Moreover, the comparatively simple construction of passive observational instruments compared to active ones allows us to more easily conduct surveys that cover a wide area or to collect more data at depth.

Therefore, a survey technology package used to narrow down the search area once a few tectonic regions have been selected as locations of interest would, in accordance with the points raised in this chapter, most likely take the following form:

Identify features of interest in the terrain and subsurface structure by using acoustic exploration methods (i.e., regional survey)

→Detect negative electrical potentials using passive methods (self-potential survey), and use these data to rank potential survey sites from highest to lowest priority (i.e., semi-detailed survey)

→Use active electrical methods to detect the horizontal extent of high-conductivity zones while using high-resolution seismic surveys to collect data on the vertical plane (i.e., detailed survey).

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3. Survey Protocol Package

3–1. Basic Concepts Behind the Survey Protocol Package

1) Overview of regional, semi-detailed, and detailed surveys

The basic workflow starts with search areas selected using the ore genesis model (informed by data on tectonic and geological context), as described in Chapter 2. These relatively large regions are then refined into smaller areas through a series of increasingly fine-scale surveys. Surveys are classified into three phases (regional, semi-detailed, and detailed), and are differentiated by their scale (survey area) and by the resolution of the collected data. Table 3–1 lists the survey components corresponding to the exploration techniques used in each phase.

Regional surveys largely rely on ship-based techniques to achieve high spatial coverage and winnow down the search area. These techniques include the use of multibeam echo sounders (MBES), which can determine bathymetry as well the location and extent of hydrothermal plumes. Additionally, other ship-based techniques may be used to ascertain tectonic and geological context across a large area. These include gravity and magnetic exploration to easily infer subseafloor structure, reflective or refractive seismic surveys using air guns and other source signals, and magnetotelluric (MT) / controlled source electromagnetic (CSEM) methods, which can also help determine subseafloor structure.

Data obtained through regional surveys, including bathymetry and subseafloor structure, are used to infer the presence of seafloor formations such as calderas and faults, which in turn are carefully examined to identify features of interest. These features are more closely examined during the semi-detailed phase. The principle aim of semi-detailed surveys is to identify horizontal anomalies (i.e., features on the horizontal plane). These surveys require deep-towed and AUV-based methods that can operate in close proximity to the seafloor to achieve a high resolution. The techniques employed in semi-detailed surveys include detailed bathymetric surveys (including hydrothermal plume mapping), self-potential anomaly, electrical and electromagnetic surveys, and seismic reflection surveys using Autonomous Cable Seismic (ACS), a seismic method that uses towed instruments. In addition, AUV-based and deep-towed surveys of gravity and magnetic field strength can also be used to infer subseafloor structure and are a useful complement to the data types described above.

Any anomalous features identified during semi-detailed surveys are then further examined through

Table 3–1 Survey components for regional, semi-detailed, and detailed surveys.

<table>
<tr><th></th><th>Exploration technique</th><th>Survey component</th><th>Platform</th></tr>
<tr><td rowspan="3">Regional survey</td><td>Acoustic</td><td>Ship-based bathymetric survey (by MBES)
Ship-based hydrothermal plume mapping (by MBES)
Ship-based survey of subseafloor structure</td><td rowspan="3">Ship
(Includes devices fixed to the hull, towed devices, and free-fall, pop-up instruments.)</td></tr>
<tr><td>Electrical/electromagnetic</td><td>Electromagnetic exploration, including by MT methods</td></tr>
<tr><td>Gravity and magnetic</td><td>Ship-based survey</td></tr>
<tr><td rowspan="3">Semi-detailed survey</td><td>Acoustic/seismic</td><td>AUV-based bathymetric survey (by MBES, SSS, etc.)
AUV-based hydrothermal plume mapping (by MBES, SSS, etc.)
Seismic reflection survey by ACS</td><td rowspan="3">Deep-tow
AUV</td></tr>
<tr><td>Electrical/electromagnetic</td><td>AUV-based or deep-towed self-potential survey
AUV-based or deep-towed electrical/electromagnetic exploration</td></tr>
<tr><td>Gravity and magnetic</td><td>AUV-based or deep-towed survey</td></tr>
<tr><td rowspan="3">Detailed survey</td><td>Seismic</td><td>Seismic reflection survey by VCS</td><td rowspan="3">ROV</td></tr>
<tr><td>Electrical/electromagnetic</td><td>ROV-based electromagnetic exploration</td></tr>
<tr><td>Gravity and magnetic</td><td>ROV-based survey</td></tr>
</table>

detailed surveys. Because detailed surveys principally focus on the vertical structure of the seafloor, they rely on ROV-based methods to achieve the required resolution. The main techniques used in these surveys include three-dimensional seismic reflection surveys using Vertical Cable Seismic (VCS), which is a moored acoustic exploration method, as well as ROV-based electromagnetic surveys. ROV-based seafloor gravity surveys, which have been shown to be effective for estimating the density structure of small-scale features, may also be employed.

Details on the geophysical exploration methods described above can be found in Chapters 4–6, where we discuss each survey component by exploration technique for regional, detailed, and semi-detailed surveys, respectively. Although we have outlined a workflow for using regional, detailed, and semi-detailed surveys to narrow down search areas and identify the distribution of SMS deposits through the accumulation of progressively higher-resolution data, it is also important to be flexible in selecting a varying mix of data collection categories during each survey phase in order to minimize costs and maximize efficiency. Moreover, the geochemical investigation methods discussed in Chapter 7 can also be employed during each survey phase and carried out concurrently with the geophysical methods described above. In particular, small geophysical/geochemical sensors can easily be installed on AUVs or deep-towed systems, and are especially useful for observing active hydrothermal fields.

2) Package overview

A flowchart for the main survey components included in the survey protocol package is provided in Figure 3–1. In unexplored waters, the workflow begins with regional surveys to collect bathymetric data. In areas close to known deposits, however, because we assume that bathymetric data has already been collected, the workflow generally begins with semi-detailed surveys.

As discussed in Section 2–3: Identification of Promising Areas According to Ore Genesis Study, bathymetric data are foundational to the survey protocol. Therefore, in cases where no preexisting bathymetry dataset is available, it must be collected from scratch. Bathymetric data makes it possible to identify bathymetric and structural features of interest on calderas, faults, and other seafloor structures.

Even where preexisting bathymetric data are available, it may be useful to collect new data if the resolution of the existing dataset is too low. In this case, if the existing dataset is sufficient to identify bathymetric and structural features of interest to a certain extent, it could be acceptable to conduct semi-detailed surveys in the vicinity of these features. In other words, by narrowing the swath of a shipboard MBES system and collecting data at low speeds (around 5 knots), a survey team could obtain high-resolution bathymetric data and determine the distribution of any hydrothermal plumes.

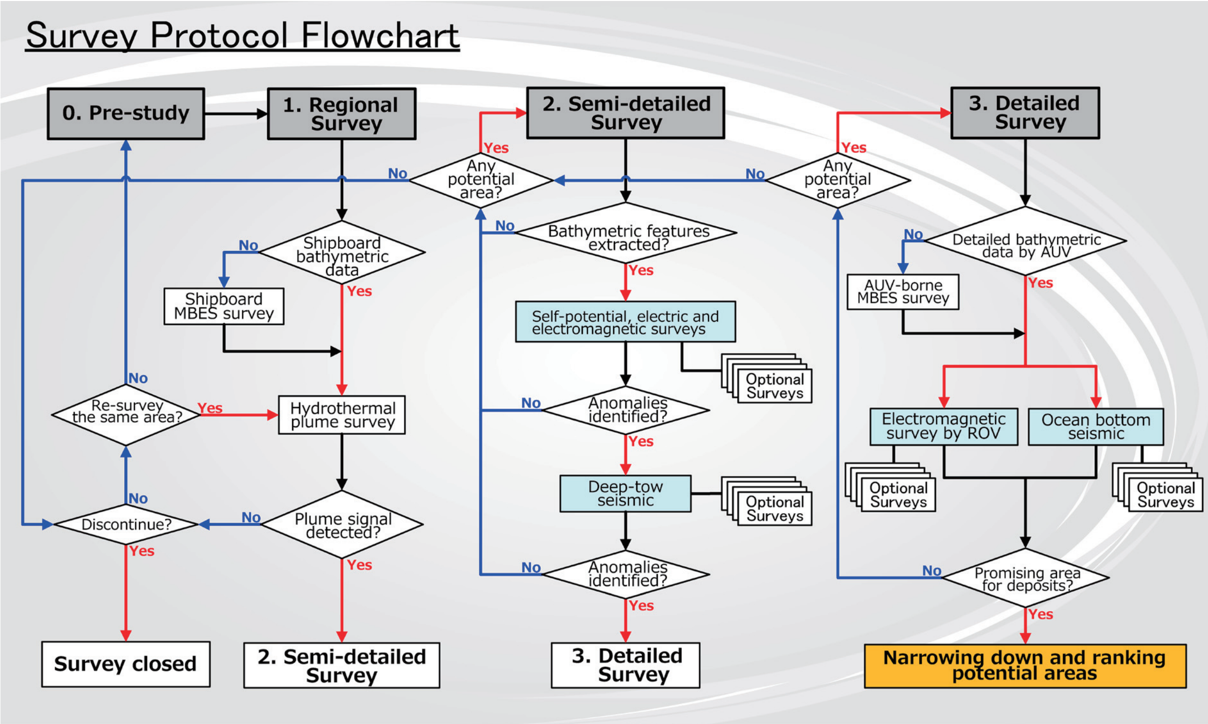


Figure 3-1 Flowchart for the survey protocol package.

In the next phase, semi-detailed surveys, self-potential anomalies are surveyed in the vicinity of features of interest identified in the bathymetric data or geological structure. For these geophysical surveys, AUVs or deep-towed systems are used to continuously measure the potential difference between two electrodes. This is a simple but effective method of detecting and winnowing down the probable distribution of any deposits. An additional advantage is that these measurements can be conducted alongside measurements of electrical conductivity. Deep-towed systems, which can tow several-hundred-meter-long cables, can sense electrical properties at greater depths below the seafloor compared to AUV-based methods.

However, AUVs have the advantage of being able to carry and operate a variety of other instruments (e.g., MBES or side-scan sonar (SSS)) and small geophysical/geochemical sensors (e.g., magnetometers, turbidity meters, ORP sensors, or pH meters) at the same time. These additional instruments make it possible to simultaneously collect data on environmental parameters, as well as to obtain the high-resolution bathymetry data necessary for detailed surveys. Of course, these types of simultaneous observations can also be implemented with deep-towed surveys of self-potential anomalies.

Once a self-potential anomaly has been detected and mapped, ACS is used to conduct a seismic reflection survey in the vicinity of the anomaly with the aim of understanding the distribution of volcanic rocks (including ore bodies) and sediments. By doing so, it is possible to map horizontal patterns in geological characteristics in the region of the anomaly. It is important to note that although the simultaneous implementation of electrical exploration or self-potential anomaly surveys with ACS-based seismic reflection surveys is an option for known ore deposits, in unexplored waters, it is more advantageous from a cost standpoint to use electrical exploration or self-potential anomaly surveys to winnow down the search area for potential deposits before carrying out further observations.

Once both electrical exploration or self-potential anomaly surveys and ACS-based seismic reflection surveys have been utilized to winnow down the search area, the search moves into its next phase, the detailed survey. The detailed survey phase is predicated on the availability of high-resolution bathymetric data. If such data were not collected during the semi-detailed survey phase, they must be collected in this one. Therefore, the simultaneous collection of self-potential anomaly or electrical data and high-resolution bathymetry during the semi-detailed survey phase will help reduce the total duration of the survey (i.e., reduce overall costs).

Detailed surveys involve ROV-based electromagnetic exploration and moored seismic reflection devices (i.e., VCS seismic reflection surveys).

By using ROVs to conduct towed electromagnetic surveys in close proximity to the seafloor, it is possible to map the conductivity and chargeability of the search area, including by measuring the Induced Polarization (IP) effect of rocks containing metal sulfides. Because this phase of the survey relies on ROVs, it is also possible to observe the seafloor and collect geological samples while carrying out electromagnetic exploration. Moreover, additional simultaneous modes of data collection could include the operation of geophysical/geochemical sensors, as well as the recording of video footage and other environmental survey data.

VCS seismic reflection imaging conducted during a detailed survey can determine three-dimensional subseafloor structure (including velocity structure) even in rough terrain, which is often encountered in the vicinity of SMS deposits. After consolidating the results of the electrical and electromagnetic exploration described above, the next step is to finalize the estimated extent of the SMS deposit and begin preliminary steps toward excavation and development.

Once again, it is crucial to point out the necessity of processing, analyzing, and visualizing the various data types described above, as well as of simultaneously visualizing multiple data types for the purposes of comparison or further analysis. This work should be conducted during each of the survey phases (regional, semi-detailed, and detailed) and upon completion of the detailed survey. In the future, there is a critical need to develop further techniques for integrated data analysis and evaluation.

4. Acoustic Method

Acoustic waves have higher transparency in seawater and sub-seafloor than light and electromagnetic waves, and it has physical quantities such as amplitude and frequency. The acoustic survey is to observe water column, seafloor, and sub-seafloor, using physical phenomena, such as reflection, refraction, backscattering. In this chapter, acoustic survey methods for seafloor / sub-seafloor hydrothermal activities investigation are organized into three steps, from a regional survey to a semi-detailed survey and then to a detailed survey. Regional survey methods (Section 4-1), as a broad area ship-borne survey, include seafloor mapping and acoustic anomalies survey using Multi-Beam Echo Sounder (MBES), and imaging sub-seafloor structures using seismic reflection instruments or Sub-Bottom Profiler (SBP). Subsequently, semi-detailed survey methods (Section 4-2), as the narrow area AUV-borne and deep towed system survey, include seafloor detailed mapping, hydrothermal plume survey and seafloor classification using high-frequency multi-beam echo sounder and side scan sonar, as well as imaging of sub-seafloor structure using Autonomous Cable Seismic system (ACS). A detailed survey method (Section 4-3) is imaging of sub-seafloor 3D structures using the Vertical Cable Seismic system (VCS) and Zero-offset VCS (ZVCS).

4. Acoustic Method	4-1. Regional	4-1-1. Ship-borne MBES Bathymetry Mapping
Survey Method	**Ship-borne MBES Bathymetry Mapping**	

Summary

Principles:
1) The MBES transducer, oriented bow-to-stern and directed towards the seafloor, emits acoustic beams arranged in a row, and the position and angle (lateral direction) of the returned beams are received by a hydrophone and interferometrically interpolated to form a multibeam image, a fan-shaped arrange of several sounding points perpendicular to the ship's heading.
2) Backscatter strength: The position and angle of each single beam emitted by the MBES are recorded individually and used to create a side scan image.
Features:
1) Multibeam echosounders can be used to map the bathymetry of uncharted areas relatively quickly.
2) The impact of sea conditions is relatively low, and surveys can be mostly carried as planned.
3) Changing the transect data density, ship speed, and beam width, allows to obtain bathymetric data at different point densities.
Objectives: To create bathymetric contour maps, 3D color maps, and stereoscopic seafloor topography maps, extracting the areas likely to contain hydrothermal sites, using the collected seafloor X, Y, and depth data.

Examples

Practice: Bathymetric survey conducted in 2015 by the Japan Marine Surveys Association (JAMSA) near the Iheya Minor Ridge, in the Okinawa Trough. Used MBES: EM302
Results: Fig.1 shows the seafloor bathymetry obtained with the MBES, Fig.2 displays the backscatter strength map (only west-side of North-South transect lines used, depth contours overlaid). Fig.3 presents the seafloor topography with interpreted results.

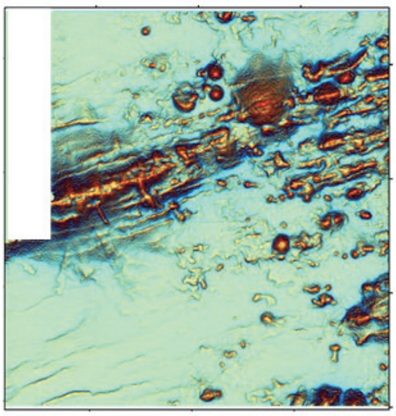


Fig.1. Bathymetric map

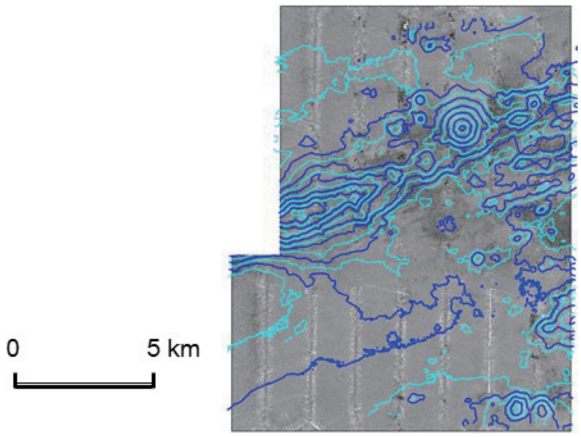
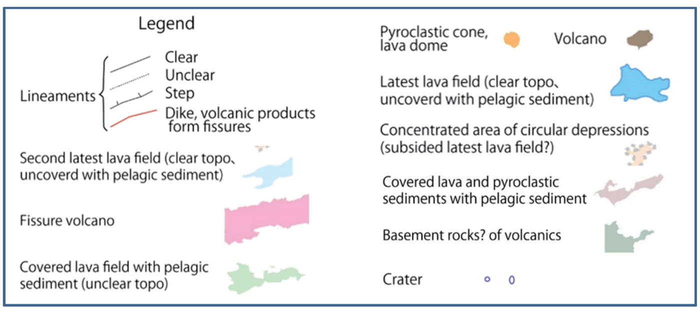


Fig.2. Backscatter strength with bathymetric contours



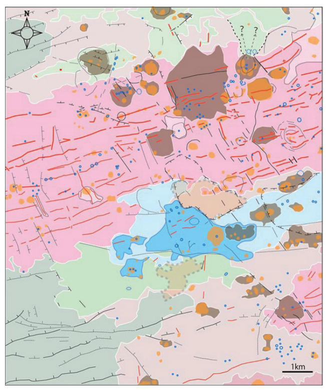


Fig.3. Data interpretation of seafloor topography

Specifications:
Combined with magnetic survey.
Conditions: 1,300-1,600 m depth, 7-knot speed, 90-km transect length, 149 km^2 area, ~12 h survey, North-South transects, equidistant measurements (set at 1,500 m in one transect side), 75° swath angle, point density of 3.5 m in swath direction and 3.6 m in forward direction.

Advantages

1) Rapid method to survey and collect seafloor topography data of large regional areas.
2) Initial data processing can be done onboard for preliminary identification of sites with hydrothermal activity.

4. Acoustic Method	4-1. Regional	4-1-2. Ship-borne MBES Water Column Imaging
Survey Method	**Ship-borne MBES Water Column Imaging**	

Summary

Principles: The detection of acoustic anomalies near the seafloor can be used to identify active hydrothermal sites from vast survey areas.
Features: The hydrothermal plumes observed with low frequency MBES are likely composed by carbon dioxide or methane bubbles. However, since the detection limit of the hydrothermal plume varies with the acoustic frequency used, small emissions can only be detected using AUV-mounted side scan sonars or ROV-mounted high frequency MBES.
Objectives: To detect hydrothermal plumes and their amplitude changes in the water column with the acoustic scatter caused by the different acoustic impedance of seawater and hot-springs or gas emissions.

Examples

Practice: Hydrothermal plume survey conducted in 2015 by the Japan Marine Surveys Association (JAMSA) near the Iheya Minor Ridge, in the Okinawa Trough. Used MBES: EM302
Results: Fig.1 shows the hydrothermal plume captured with the MBES (SoundingDiver software). Fig.2 presents hydrothermal plumes detected by the same software. Fig.3 displays a 3D view of the seafloor bathymetry overlaid with the hydrothermal plumes drawn by ArcGIS.

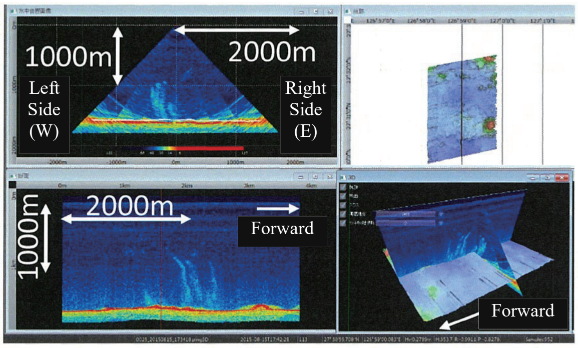


Fig.1. Acoustic Image with MBES

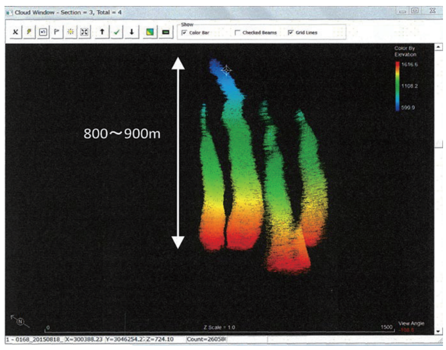


Fig.2. Extracted hydrothermal plume

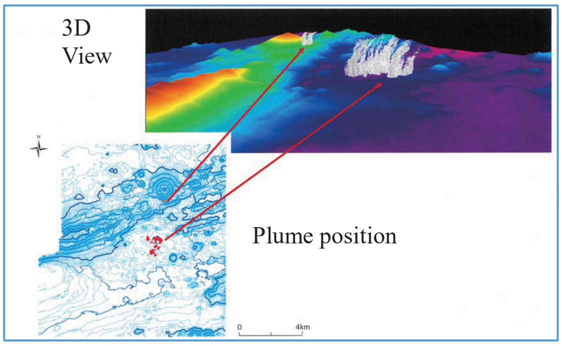


Fig.3. 3D view of the hydrothermal plume

Specifications:
Combined with magnetic survey.
Conditions: 1,300-1,600 m depth, 7-knot speed, 90-km transect length, 149 km^2 area, ~12 h survey, North-South transects, equidistant measurements (set at 1,500 m in one transect side), 75° swath angle.

Advantages

1) Rapid method to investigate acoustic anomalies in large regional areas.
2) Can be easily combined with other surveys.
3) Initial data processing can be done onboard for preliminary identification of sites with hydrothermal activity.

4. Acoustic Method	4-1. Regional	4-1-3. Ship-borne Acoustic Subsurface Imaging
Survey Method	**Sub-Bottom Profiler (SBP)**	

Summary

Principles: The thickness of the sedimentary layer is measured from the 2-way travel time of acoustic wave reflected from the geological boundary below the seafloor.
Features: The amplitude of the reflected wave from the boundary surface depends on the acoustic impedance ratio between two layers.
Objectives: To estimate surface geology and sedimentary environment.

Examples

Practice: The SBP survey at off west Kumejima in the mid-Okinawa Trough (YK16-10)
Results: Fig.1 shows a recorded section at the slopes of the volcanic terrain. Diffracted waves appear at the place where the topography is changing drastically (left side of the record), indicating that the topography is not sufficiently expressed. Also, near the shallowest part on the right side, diffracted waves from the surrounding neighboring terrain appear. At the central part of the record, a stratum boundary of about 100 m under the seafloor is recognized.

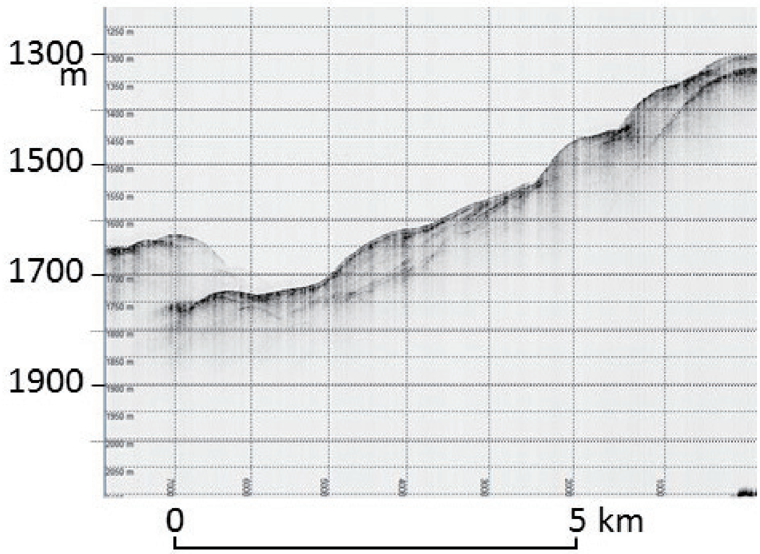


Fig.1 An example of SBP's record section observed in YK16-10

Specifications:
Combined with bathymetric survey.
Survey area ~2,300 km^2 (20 nmi x 33 nmi) per day.

Advantages

1) Rapid and easy method to investigate the situation of sub-surface sediments.
2) Can be combined with bathymetric survey at ease.
3) Results can be seen on board in real time.

4. Acoustic Method	4-1. Regional	4-1-3. Ship-borne Acoustic Subsurface Imaging
Survey Method	**Seismic Reflection Survey**	

Summary

Principles: The continuous geological structure under the seafloor is investigated by the 2-way travel times of seismic waves reflected from the geological boundaries.

Features:

1) The amplitude of the reflected wave from the boundary surface depends on the acoustic impedance ratio between two layers.

2) Reflection survey in a wide area is useful for understanding the geological background of generating seafloor hydrothermal deposits.

Objectives: To estimate geological structure within the crust.

Examples

Practice: Reflection seismic surveys by using controlled seismic sources (air gun) was carried out around the Iheya North Knoll in the mid-Okinawa Trough (Tsuji et al., 2012).

Results: (a) the white lines indicate survey lines, the red lines show seismic sections of the lines (b) and (d), respectively. In the seismic section (c), a characteristic layer structure can be confirmed around the hydrothermal vent. In the section (d), the pumice mountain (low amplitude) is observed. Such pumiceous deposits are ubiquitously found around the Iheya North Knoll.

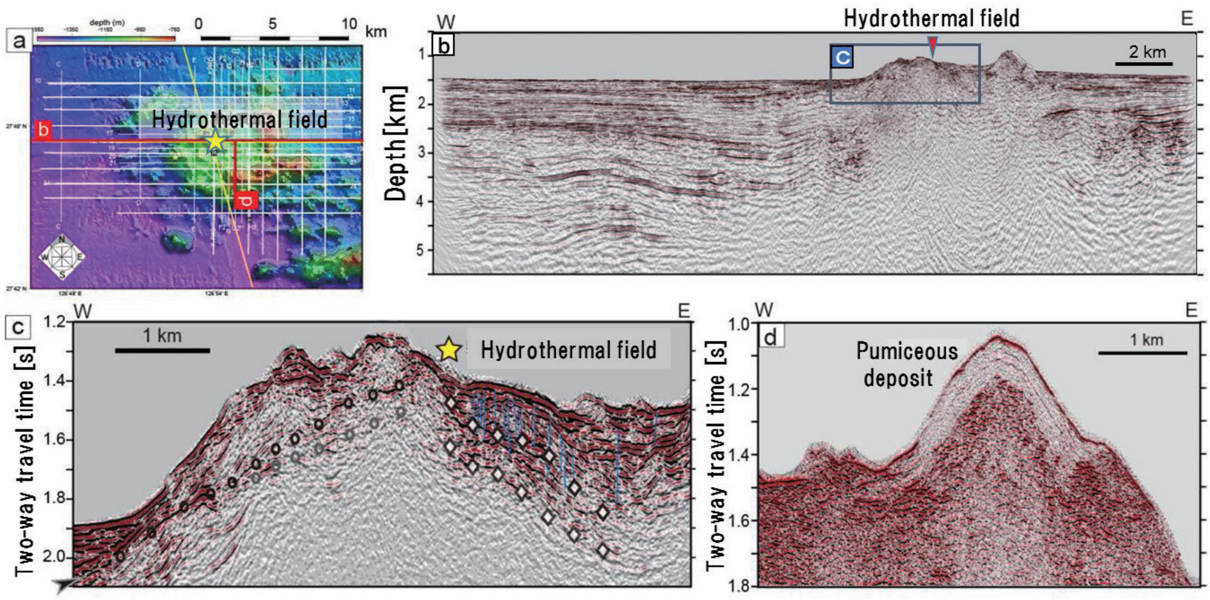


Fig.1 Results of the seismic reflection survey around the Iheya North Knoll hydrothermal field.

Specifications:

The survey area in Fig.1 (a) is about 12 nmi x 9 nmi, and the total number of survey lines is 54 including both long and short lines.

Advantages

1) Allows continuous investigation of the underground structure in regional area with high resolution.

2) The P wave velocity structure can be estimated from the stacking velocity during the processing of reflection seismic data.

4. Acoustic Method	4-1. Regional	4-1-3. Ship-borne Acoustic Subsurface Imaging
Survey Method	**Seismic Refraction Survey**	

Summary

Principles: In the condition that the seismic wave velocity of the lower layer is higher than that of the upper layer, a seismic wave incident from the upper layer generates a refracted wave transmitted along the layer boundary with the lower layer seismic velocity. The change of seismic velocity structure of the earth is investigated from the travel time curve of this refracted wave.

Features:

1) Since the refracted wave reaches relatively far, it is suitable for the survey of the deep structure in a regional area.

2) Refraction survey in a wide area is useful for understanding the geological background of generating seafloor hydrothermal deposits.

Objectives: To estimate seismic velocity structure within the crust and uppermost mantle.

Examples

Practice: Refraction seismic surveys by using controlled seismic sources (air gun) and ocean bottom seismographs (OBS) were carried out on the Ryukyu Trench, the mid-Okinawa Trough (Nishizawa et al., 2017).

Results: The Philippine Sea plate that subducts from the south east under the island arc and the crust is thinning under the Okinawa Trough are understood (Fig.1). The numerical value represents Vp (km/s), and the oval indicated by the wavy lines show the fracture zones.

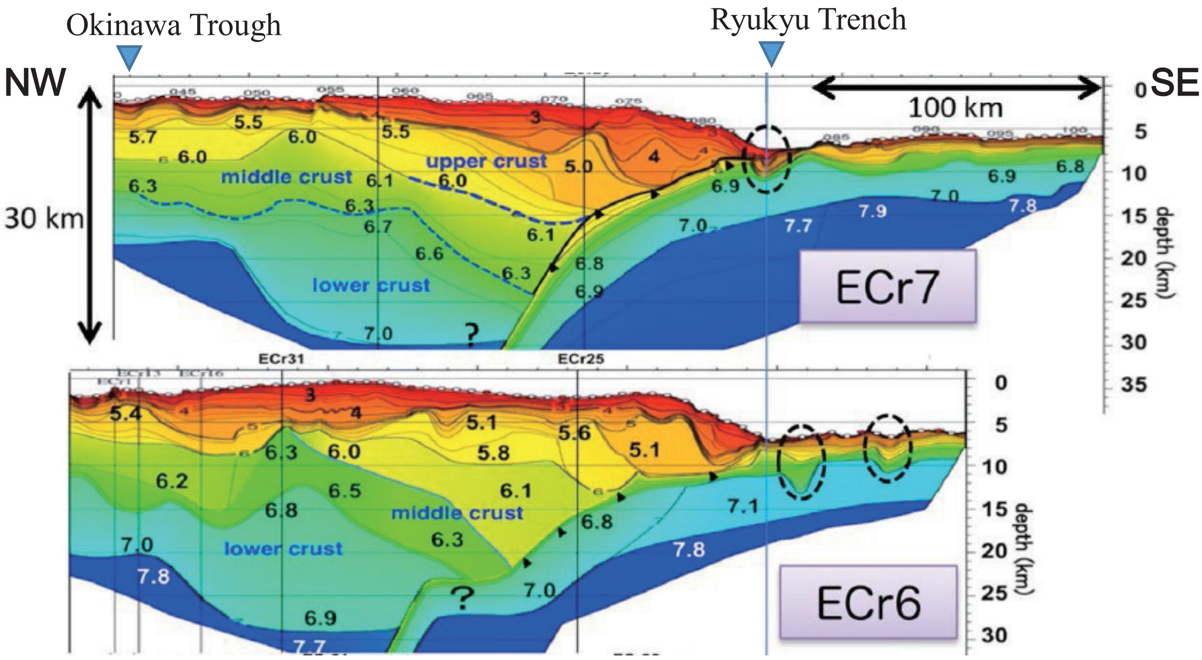


Fig.1 P-wave velocity models in and around the Ryukyu Trench.

Specifications:

Conditions: Ocean bottom seismographs are installed at about 5 km intervals, and the interval between the seismic sources is 200 m. Performed in conjunction with reflection seismic survey.

These analyses were mainly based on the forward modeling.

Advantages

Allows to estimate detailed seismic velocity structure within the crust and uppermost mantle.

4. Acoustic Method	4-2. Semi-detailed	4-2-1. AUV-borne MBES/SSS Bathymetry Mapping
Survey Method	**MBES/SSS Bathymetry Mapping**	

Summary

Principles:

1) MBES: The acoustic pulse transmitted from the transducers arrayed in the bow-stern direction toward the seafloor is received by the hydrophones arrayed orthogonally to the transducers, and multi-beams are formed by the interferometric method. Then obtain a lot of sounding points distributed in a fan shape, which orthogonally crosses the bow.

2) SSS: The acoustic pulse transmitted from the transducers on both sides of a AUV toward the seafloor is received by same transducers as the returned backscatter signals from the seafloor in time series.

Features:

1) MBES can be used to map the bathymetry of uncharted areas relatively quickly.

2) SSS can quickly investigate seafloor surface conditions such as fine topography changes and sediment conditions.

Objectives:

1) MBES: To create detailed bathymetric contour maps with grid intervals of 1-2 meters.

2) SSS: To estimate the seafloor geology.

Examples

Practice: Bathymetric survey conducted off west Kumejima by "URASHIMA". AUV speed to ground was 3 knots, altitude was 70 m above the seafloor, systematic survey lines were designed to be west-east and southwest-northeast directions with 100 m line interval.

Results: Fig.1 shows the detailed bathymetry obtained with the MBES, and Fig.2 shows the mosaic diagram by the SSS. Chimneys can be found clustered on the eastern side of the survey area.

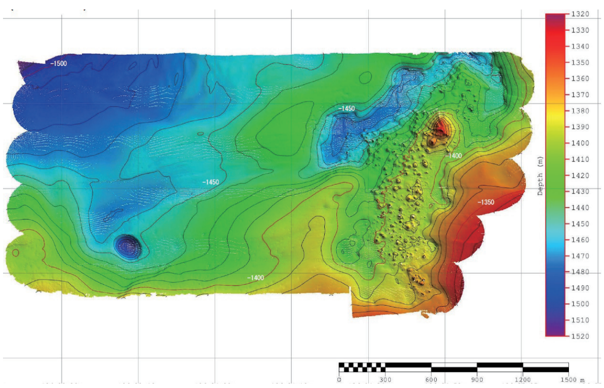


Fig.1 Detailed bathymetry

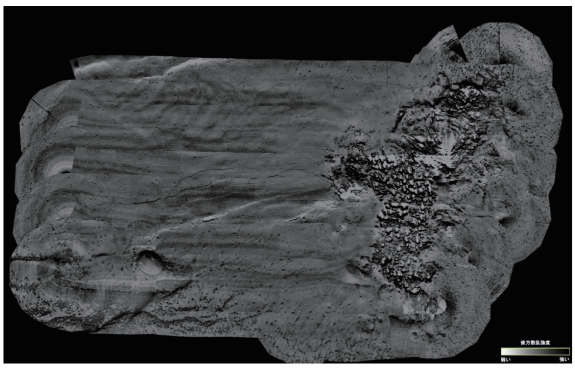


Fig.2 Mosaic diagram by the SSS

Specifications:

Combined with SBP survey

Conditions: 1,500-1,600 m depths, Total distance of survey line was about 18 nmi, swath angle 128°. The grid interval is 2 m.

Advantages

1) Rapid method to survey and collect seafloor topography data of the semi-detailed survey areas.

2) Can be combined with other investigations, such as geochemistry and geomagnetic survey.

3) Allows to identify the promising area for investigation of hydrothermal activity through initial data processing on-board.

4. Acoustic Method	4-2. Semi-detailed	4-2-2. AUV-borne MBES/SSS Water Column Imaging
Survey Method	**MBES/SSS Water Column Imaging**	

Summary

Principles:

1) Detect hydrothermal plumes and their amplitude changes in the water column with the acoustic scatter caused by the different acoustic impedance of seawater.

2) MBES: Detect amplitude fluctuations caused by acoustic impedance variations in the water column part above the seafloor among a large number of fan-shaped acoustic beams are captured.

3) SSS: Detect amplitude fluctuations caused by acoustic impedance variations in the water column above the seafloor of the signals transmitted from both sides are captured.

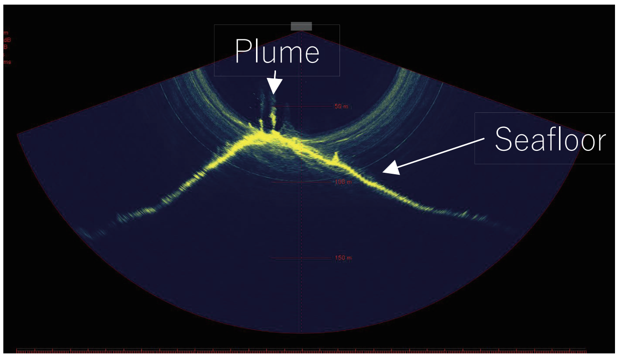
Features: The water column imagery can be obtained secondarily through seafloor bathymetry survey.

Objectives: To estimate the distribution of the hydrothermal plume.

Examples

Practice: Surveys in the mid-Okinawa Trough. Case-1: Water Column Image (WCI) by the MBES off west Kumejima, Case-2: WCI by the SSS in the Iheya North Knoll.

Results: Figs.1 and 2 show the results of Case-1 and Case-2 respectively. Both were observed by AUV “URASHIMA”.



(a)
(b)
(c)
(d)

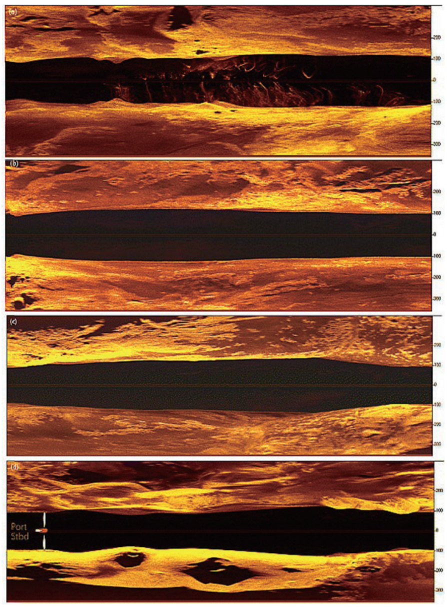


Fig.1 An example of WCI by the MBES (upper)

Fig.2 Examples of WCI by SSS (upper right) (Kumagai et al., 2010)

(a) Type A filament shape,
(b) Type B fog,
(c) Type C weak signals,
(d) No signal.

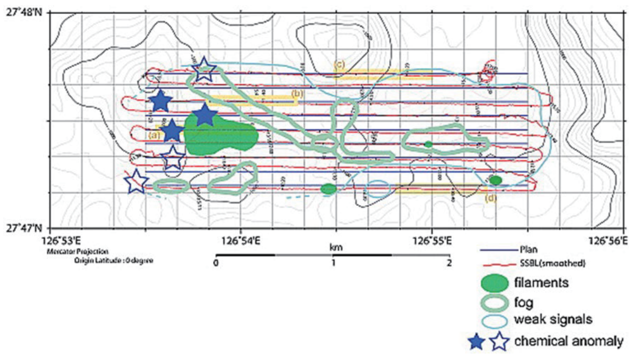


Fig.3 Distributions of the types A-C (lower right)

Specifications:

Case-1, 1,000-1,500 m depth, Total distance of survey line was about 17 nmi, swath angle 128°.

Case-2, 1,000-1,200 m depth, Total distance of survey line was about 18 nmi. Maximum slant range of the SSS is 300 m.

Advantage

1) Allows rapid exploration of hydrothermal plumes in semi-detailed survey areas.

2) Allows to identify hydrothermal plumes on-board for preliminary interpretation.

4. Acoustic Methods	4-2. Semi-detailed	4-2-3. Autonomous Cable Seismic (ACS) Reflection Imaging
Survey method	**Reflection Seismic Survey**	

Summary

Principles: To investigate sub-seafloor structures using the travel time and the amplitude of reflected seismic waves from boundary of physical property.

Features:

1) Two dimensional cross sections of sub-seafloor structures with velocity information are obtained.
2) Hydrothermally altered sub-seafloor areas are delineated by interpreting seismic facies.
3) Dual seismic sources (frequency ranges of 20-400 Hz and 500-2,200 Hz) are available to obtain shallow and deep structures.
4) Deep-towed surveying system near the seafloor can provide subsurface structures with higher lateral resolution compared to ocean surface seismic surveying system.

Objectives: To obtain sub-seafloor structures within the area about tens of square kilometers.

Examples

Practice: The ACS reflection survey (Fig. 1) was carried out in hydrothermal areas in the Okinawa Trough.

Results:

1) The sub-seafloor structures below the white line at Fig. 2 (a) were obtained as shown in Fig. 2 (b).
2) Structural differences between the depressed zone and outside zone were recognized.
3) Seismic facies such as amplitudes and continuity suggested that sedimentary structures were collapsed with a volcanic depression.

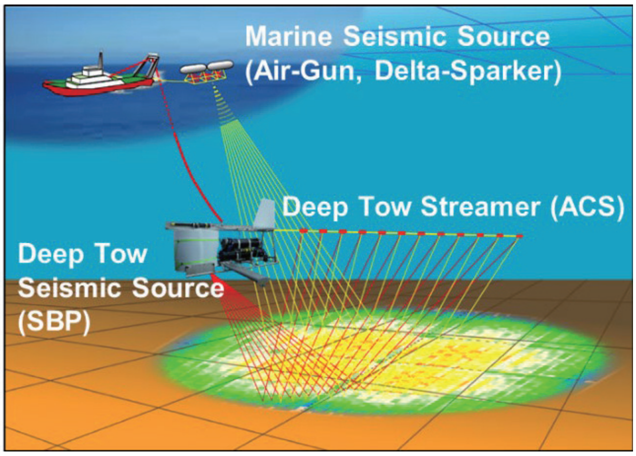


Fig. 1 Schematic of ACS survey.

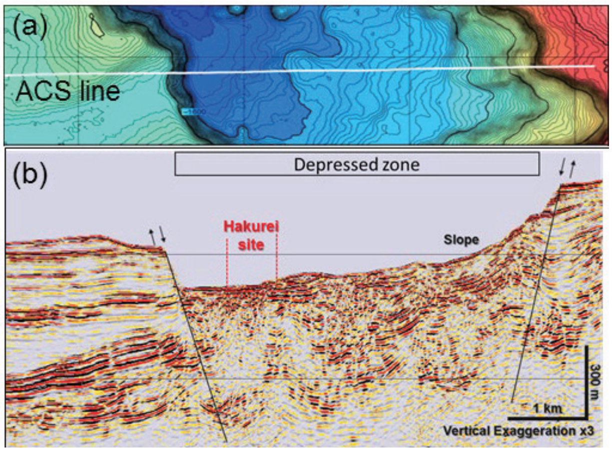


Fig. 2 Bathymetry map (a) and cross section (b) of ACS survey along the white line.

Specifications:

Conditions:

Depth of survey area: ~2,000 m

Minimum operating elevation of ACS: 100 m

Shooting interval: 5 m (surface source), 3 m (deep towed source)

Line length per half day: ~25 km with the vessel speed of 2 knots, including time of preparation and turnaround.

Advantages

1) High lateral and vertical resolution.
2) High S/N ratio and low ambient noises.
3) Multi seismic sources (surface and deep towed).
4) Data QC for a planning of the next day and preliminary interpretation can be done on-board.

4. Acoustic Methods	4-3. Detailed	4-3-1. VCS / ZVCS Reflection Imaging
Survey method	**Reflection Seismic Survey**	

Summary

Principles: To investigate sub-seafloor structures using the travel time and the amplitude of reflected seismic waves from boundary of physical property.

Features:

1) Three-dimensional sub-seafloor / velocity structures can be obtained by VCS (Vertical Cable Seismic system).
2) Detailed cross sections of sub-seafloor structures can be obtained by ZVCS (Zero-offset VCS).

Objectives: To obtain sub-seafloor structures at the area about a square kilometer.

Examples

Practice: The VCS / ZVCS reflection surveys (Fig. 1, Fig. 3) were carried out in hydrothermal areas in the Okinawa Trough.

Results:

1) Three-dimensional sub-seafloor structures around SMS area were obtained (Fig. 2).
2) Lower boundary of massive sulfide can be interpreted by detailed cross section of ZVCS (Fig. 4).

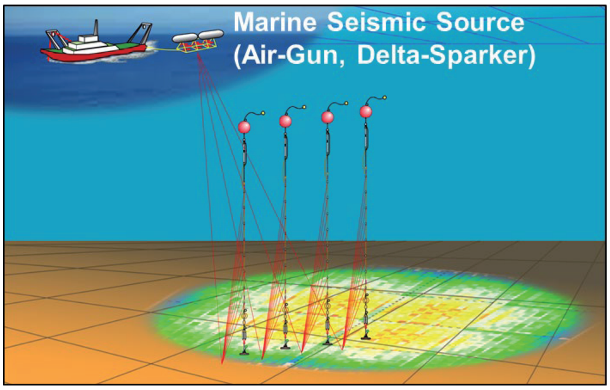


Fig. 1 Schematic of VCS survey.

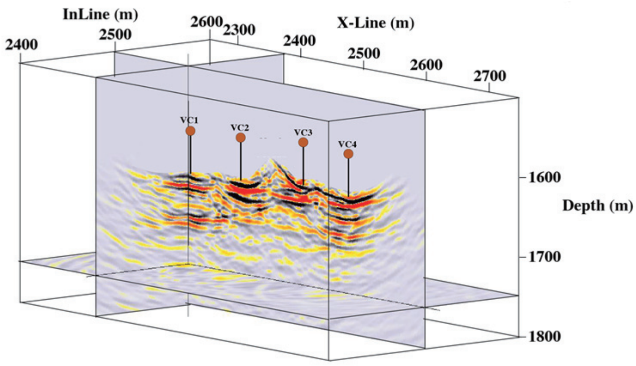


Fig. 2 Three dimensional sub-seafloor structure of VCS (source: GI gun).

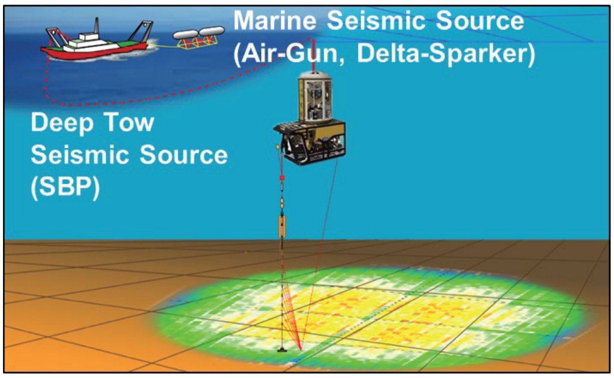


Fig. 3 Schematic of ZVCS survey.

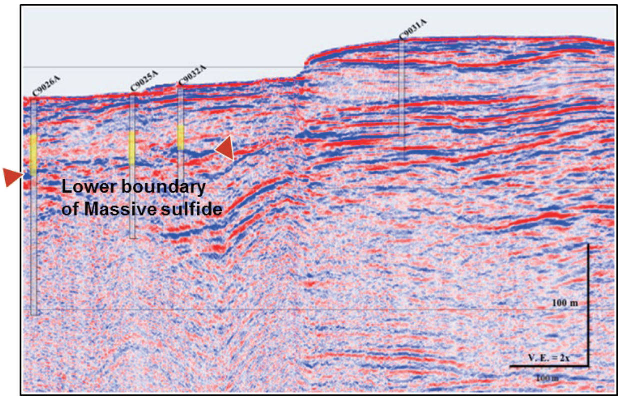


Fig. 4 Detailed cross section of ZVCS (source: Delta sparker). Drilling core information courtesy of JAMSTEC.

Specification:

Conditions: Depth of survey area: ~2,000 m
Minimum operating elevation: 10 m (ZVCS), 0 m (VCS, moored on the seafloor)
Coverage per day: 5-20 km (ZVCS), 300 m x 300 m (VCS, with 4 cables)

Advantages

1) High lateral and vertical resolution.
2) Noise attenuation of side reflections caused by chimneys and mounds.
3) Multi seismic sources (surface and deep towed).
4) Data QC for a planning of the next day and preliminary interpretation can be done on-board.
5) Velocity information by VCS.

5. Electrical and Electromagnetic Methods

Electromagnetic measurements are an important group of methods in terrestrial mineral exploration. They provide a map or profile, portraying the variation of physical properties (e.g. electrical resistivity, chargeability) of metal resources that extensively lie underground. However, in the sea area, the surrounding sea water make it difficult to predict the existence of resources below seafloor. Thus, the specialized survey technology and methodology had to be developed in order to detect the spread of minerals under the ocean floor.

In this chapter, electromagnetic survey methods for seafloor / sub-seafloor hydrothermal activities investigation are organized into three steps, from a regional survey to a semi-detailed survey and then to a detailed survey. Regional survey methods (Section 5-1), as a broad area ship-borne survey, include magnetotelluric (MT) method using natural earth currents (i.e. telluric currents) and controlled source magnetotellric (CSMT) method using an electrical dipole (an artificial source) with the aim of regional scale resistivity structural mapping. Semi-detailed survey methods (Section 5-2) include AUV-mounted / deep-towed self-potential and electromagnetic measurements in the seafloor areas deemed to have higher resource potential as a result of the phased narrowing-down process. Especially, self-potential survey can not only map out a broad structure over a large exploration area both quickly and effectively, but also be used in combination with other geophysical / geochemical sensors. A detailed survey method (Section 5-3) is ROV-borne electromagnetic measurement which can be used for closer investigation to better define and confirm any anomalies.

5. Electrical & Electromagnetic Methods	5-1. Regional	5-1-1. Magnetotelluric (MT) Measurement
Survey Method	**Marine MT Exploration and Marine CSEM Exploration**	

Summary

Principles: The resistivity or electrical conductivity structure under the seafloor are investigated by utilizing the difference in the resistivity of the rocks constituting the underground.

Features:

1) Metal deposits show lower resistivity than ordinary rocks, and oil/gas layers have high resistivity.

2) Since the short wave components of the natural-source electromagnetic phenomena is attenuated by seawater, marine MT method generally provides less information about subsurface structures at several km or shallower below the seafloor.

3) Marine MT method can investigate wide area and deep structure, and help understanding the structure of the entire submarine hydrothermal systems and the geological background of the entire trough axis.

4) Since the marine CSEM method uses an artificial current source, the resistivity structure within shallow to relatively deep layers (several tens of kilometers) can be obtained.

Objectives: To estimate resistivity structure beneath the ocean floor.

Examples

Practice: Case-1 (Marine MT Method): off Kii Peninsula (the 1944 Nankai Seismogenic Zone)
Case-2 (Marine CSEM Method): Oil gas layer survey on the continental shelf off western Australia

Results: Case-1 (Marine MT Method): The low resistivity within the accretionary prism suggests the possibility of the fluid supplied from the subducting plate (Goto et al.,2003).
Case-2 (Marine CSEM Method): The high resistivity area corresponds to the known gas layer.

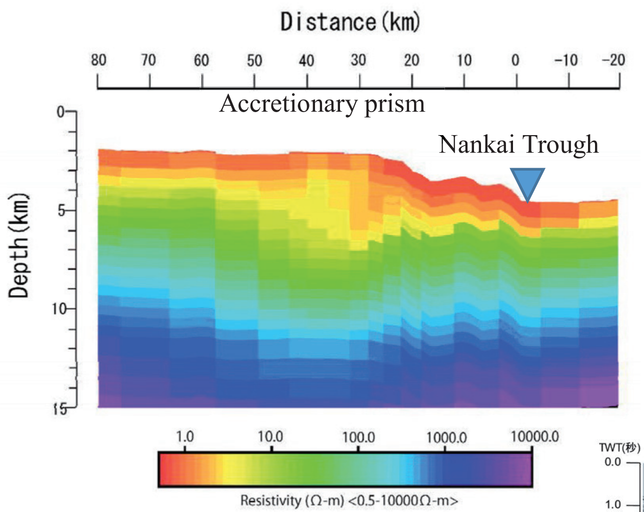
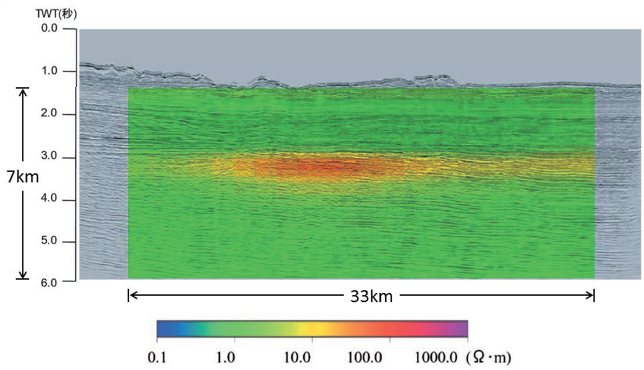


Fig.1 Case-1(Left): after Kimura et al. (2010)

Fig.2 Case-2(lower): after Yamane et al. (2009)



Specifications:

Case-1, Nine OBEMs were installed on a 100 km survey line and the measurement period was about 10 days.

Case-2, 23 OBEMs were installed on the 33 km Survey line. The transmitter was a dipole of 250 m, towed at altitude of 30 m above the seafloor. Towing speed was 2 knots.

Advantages

1) Although the shallow structure cannot be obtained by the marine MT method, it is possible to investigate the resistivity structure in the deep sub-seafloor region.

2) The marine CSEM method can obtain a resistivity structure from shallow to relatively deep portions.

5. Electrical & Electromagnetic Methods	5-2. Semi-detailed	5-2-1. AUV-borne / Deep-towed Self-Potential Measurement

Survey method	**AUV-based Electric Field Measurement**

Summary

Principles: To detect a negative self-potential anomaly related to the electrochemical reaction of sub-seafloor (Fig.1) using electric field measurement by an AUV.

Features:

1) Electrometer is mounted on an AUV.
2) Electrodes are towed with a towed FRP electrode rod or mounted on an AUV.
3) Measurement to the seafloor (altitude of measurement system: 50-100 m) with 2 knots.

Objectives:

1) Exploration for the sub-seafloor sulfides (SMSs).
2) Electric field data acquisition for the self-potential anomaly related to the sub-seafloor electrochemical reaction.

Examples

Practice:

1) Data acquisition using a middle-class cruising AUV observation with a towed FRP electrode loaded electrodes was conducted by JAMSTEC at the Myojin knoll caldera in the Izu-Ogasawara arc (Kawada and Kasaya, EPS, 2018).
2) Measurement was carried out on the 12 lines with 2.0 knots. Averaged measurement altitude was about 70 m.
3) Negative self-potential anomaly implies the existence of the hydrothermal deposit. However, we can only observe the electric field. Therefore, the horizontal and vertical electric field is observed as the inflexion point and extremum, respectively.

Results:

1) Very clear negative self-potential anomaly zone was detected. (Fig. 2).
2) The position of the detected anomaly area corresponds to the Sun-rise Hydrothermal Deposit Area.

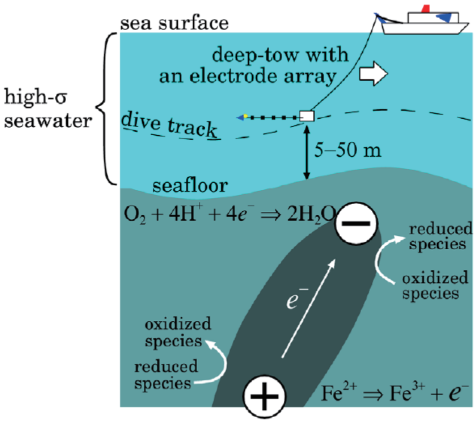


Fig.1 Schematic figure of the chemical reaction of sub-seafloor related to the self-potential anomaly.

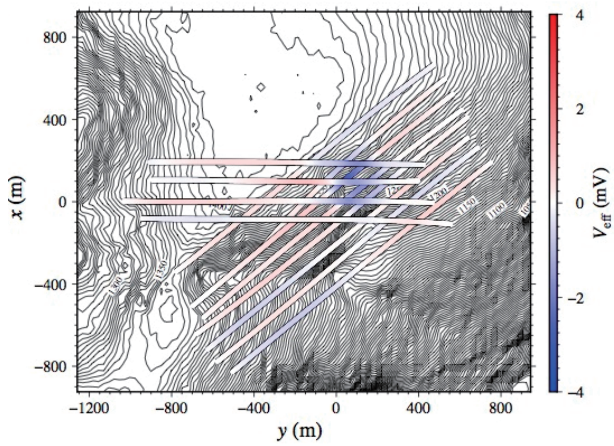


Fig. 2 effective self-potential along the dive track. The color scale is explained in the legend at the right of this figure (Kawada and Kasaya, EPS, 2018).

Specifications:

Maximum survey productivity for 4 hours is about 1,800 x 900 m (1 x 0.5 nmi) with survey line interval of about 100 m. Cruising speed of an AUV is about 2.0 knots at the averaged altitude of about 70 m.

Advantages

1) Easy data acquisition and identification of self-potential anomaly after the observation.
2) Detailed bathymetry and back scattering data of seafloor data can be obtained during data acquisition.
3) Geo-chemical sensors can also be loaded on an AUV during data acquisition.

5. Electrical & Electromagnetic Methods	5-2. Semi-detailed	5-2-1. AUV-borne / Deep-towed Self-Potential Measurement

Survey method Deep-towed Electric Field Measurement

Summary

Principles: To detect a negative self-potential anomaly related to the electrochemical reaction of sub-seafloor using electric field measurement by a deep-tow (Fig.1).

Features:

1) Electrometer is mounted on a deep-tow.
2) Electrodes are towed with a towed FRP electrode rod or mounted on a (Fig.1).
3) Measurement to the seafloor (altitude of measurement system: a few to 50 m) with 0.5-1.0 knot.

Objectives:

1) Exploration for the sub-seafloor sulfides (SMSs).
2) Electric field data acquisition for the self-potential anomaly related to the sub-seafloor electrochemical reaction.

Examples

Practice:

1) Data acquisition using a deep-tow observation with a towed FRP electrode loaded electrodes was conducted by JAMSTEC at the middle Okinawa Trough (Kawada and Kasaya, Sci. Rep., 2017).
2) Measurement was carried out on the 2 lines with 0.5-1.0 knot. Averaged measurement altitude was about a few to 50 m.
3) Negative self-potential anomaly implies the existence of the hydrothermal deposit. However, we can only observe the electric field. Therefore, the horizontal and vertical electric field is observed as the inflexion point and extremum, respectively. Obtained electric potential data shows at low latitude shows large anomaly and short wavelength variation.

Results:

1) Very clear negative self-potential anomaly zone was detected. (Fig. 2).
2) The position of the detected anomaly area corresponds to the sun rise hydrothermal deposit area.

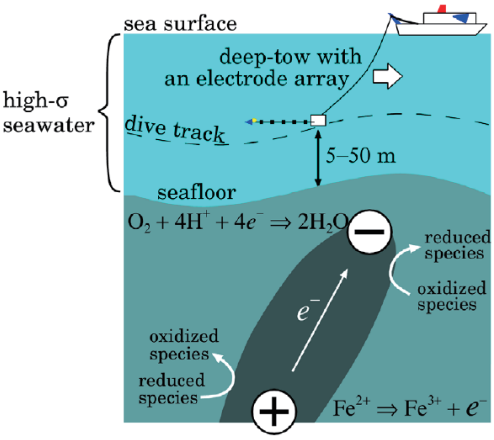


Fig. 1 Schematic figure of the chemical reaction of sub-seafloor related to the self-potential anomaly.

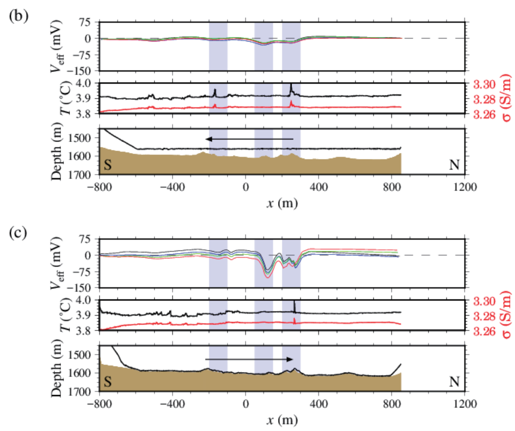


Fig. 2 Effective self-potential, temperature and electrical conductivity. (Kawada and Kasaya, Sci. Rep., 2017).

Specifications:

Maximum survey profile in 7 hours (only day time operation) with speed of 0.5-1 knot is about 5 nmi long.

Advantages

1) Easy data acquisition and identification of self-potential anomaly after the observation.
2) Geo-chemical sensors can be loaded on a deep-tow during data acquisition.

5. Electrical & Electromagnetic Methods	5-2. Semi-Detailed	5-2-2. AUV-borne / Deep-towed Electrical & Electromagnetic Measurement

Survey Method	Deep-towed Electrical (DC Resistivity) Method

Summary

Principles: The DC resistivity structure under the seafloor are investigated by utilizing the difference in the resistivity of the rocks constituting beneath the seafloor.

Features:

1) In the case where low resistivity materials such as metal deposits are distributed, a small voltage is observed for a constant current. Conversely, when there is a material with a high resistivity, a large voltage is observed.

2) By increasing the distance between the current electrode and the potential electrode, the depth of exploration increases.

3) The DC resistivity method conducted in the semi-detailed survey is useful for judging the existence of metal deposits.

Objectives: To narrow down a search area during the exploration of SMS deposits.

Examples

Practice: Electrical survey conducted off west Kumejima by using a deep-tow. Its speed to ground was 1.5 knots, altitude was about 50 m above the seafloor, systematic survey lines were designed to be west-east and southwest-northeast directions with 100 m line interval.

Results: Fig.1 shows the schematic deep-towed system. Fig.2 shows the apparent resistivity distribution for the current-potential electrode distance of 230 m. Low resistivity area are distributed along the southwest-northeast direction lines.

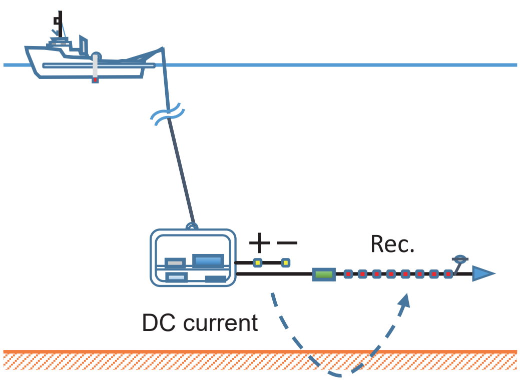


Fig.1 The schematic image of the deep-towed system

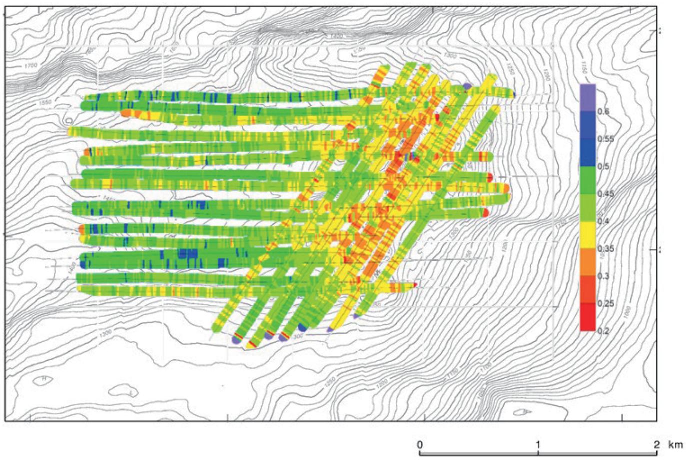


Fig.2 The apparent resistivity distribution

Specifications:

Combined with the geochemical survey.

Conditions: 1,400-1,600 m depth, altitude about 50 m above the seafloor, total length of survey lines was 92 km.

Advantages

1) Allows to investigate the resistivity distribution in a semi-detailed survey area both conveniently and quickly.

2) Can be combined with geochemical surveys at ease.

5. Electrical & Electromagnetic Methods	5-3. Detailed	5-3-1. ROV-borne Electromagnetic Measurement

Survey method	ROV-towed Electromagnetic Measurement

Summary

Principles: To investigate conductivity of sub-seafloor by measuring the secondary magnetic field caused by induced current occurred by artificially supplied magnetic field

Features:

1) Time domain Electromagnetic (TDEM) system towed by ROV
2) Measurement close to the seafloor (altitude of measurement system: 2~4 m)

Objectives:

1) Exploration for the seafloor massive sulfides (SMSs)
2) High resolution data acquisition for the secondary magnetic field under the seafloor

Examples

Practice:

1) ROV-towed TDEM survey was conducted by J-MARES at the Izena Hole, in the Okinawa Trough.
2) Measurement was conducted on the 5 lines (Altitude of TDEM system, 4 m; Distance from ROV to TDEM system, 6 m; ROV speed, 0.5 knot).

Results:

1) Complex conductivity of the sediment was estimated by 1D inversion based on 2 layer-model (Fig.1 & Fig.2).
2) Conductivity and chargeability near SMS mound were estimated by 3D inversion based on the GEMTIP model (Fig. 3).

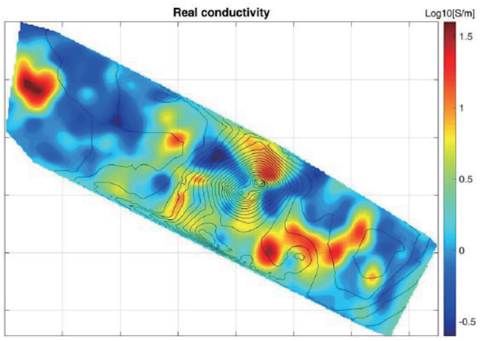


Fig. 1 The real part of complex conductivity of the sediment recovered from 1D inversion

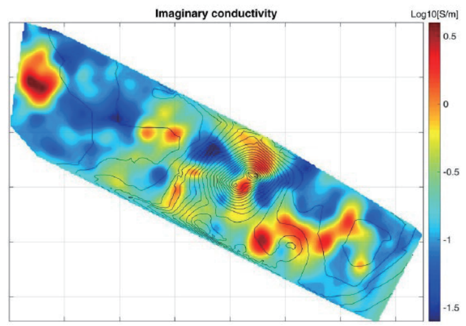


Fig. 2 The imaginary part of complex conductivity of the sediment recovered from 1D inversion

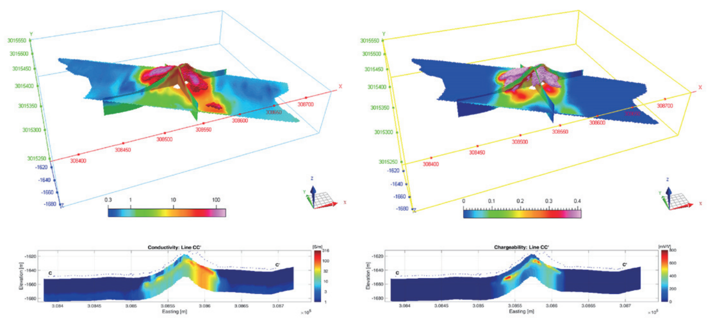


Fig. 3
Conductivity (left) and chargeability (right) of the sediment recovered from 3D inversion

Specifications:

Maximum survey productivity (including deployment and winching) for 1 day is about 300 m x 300 m as surface area. This survey conditions were water depth of less than 2,000 m, line interval of 25 m, and ROV speed of ~1.0 knot.

Advantages

1) Seafloor observation and rock sampling can be done simultaneously during data acquisition.
2) Deployment with other survey system such as magnetic field can be done simultaneously.
3) Real-time data transmission to the survey vessel.

6. Gravity and Magnetic Methods

Gravity and magnetic anomalies clearly reflect the density structure and magnetization intensity distributions beneath the seafloor. Surveys aimed at detecting these anomalies are therefore effective in estimating the three-dimensional distribution of hydrothermal ore deposits on and/or beneath the seafloor. In this chapter, gravity and magnetic survey methods for detecting hydrothermal ore deposits are introduced for each observation platform.

The accuracy of data obtained depends on the distance from the target which in turn depends on the observation platform, such as ship, AUV and ROV. Although ship-borne surveys (Section 6-1-1) are too low in resolution alone to detect the gravity and magnetic anomalies associated with hydrothermal ore deposits, it covers an extensive area in a relatively short time and can be combined with other methods at ease. This coverage is important for understanding tectonic processes and the geological background across an entire region. On the other hand, AUV-borne (Section 6-2-1) and ROV-borne (Section 6-3-1) surveys are carried out closer to the target and thus have higher resolutions and are able to detect anomalies directly associated with hydrothermal ore deposits. However, there are several disadvantages, such as the limited survey area and longer measurement time at each point. Consequently, for gravity and magnetic surveys, it is important to appropriately use and combine the respective observation platforms as suitable for surveys at varying scales, such as regional, semi-detailed, and detailed surveys.

6. Gravity & Magnetic Methods	6-1. Regional	6-1-1. Ship-borne Measurement
Survey method	**Surface Gravity Survey**	

Summary

Principles: To investigate sub-seafloor structures on the basis of anomalies in the gravity field, resulting from density anomalies of underlying rocks and/or density contrasts between underlying rocks.

Features:

1) High (positive) values of gravity anomaly indicate zones of relatively high density (e.g., ore deposits); whereas low (negative) values indicate zones of relatively low density (e.g., sediment layer).

2) The deeper the density structures, the longer the spatial wavelength of gravity anomalies.

3) Gravity surveys are able to cover an extensive area in relatively short time. This coverage is important for understanding the geological background of hydrothermal systems across an entire region.

Objectives: To estimate the sediment thickness (basement topography) and sub-seafloor density structures.

Examples

Practice: During the R/V Yokosuka cruises YK16-10 and YK16-12 carried out in 2016, detailed gravity surveys were conducted with a line spacing of 0.5 nmi at a ship speed of ~6 knots in hydrothermal areas of the mid-Okinawa Trough.

Results: Variations in free-air gravity anomaly (Fig.2) were correlated with topographic features on the seafloor (Fig.1). Knolls in the eastern area were dominated by negative bouguer anomalies (Fig.3), suggesting higher crustal thickness and/or domination by lower density materials.

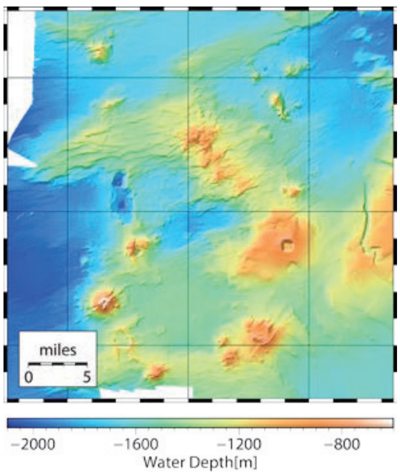


Fig.1 Bathymetric map

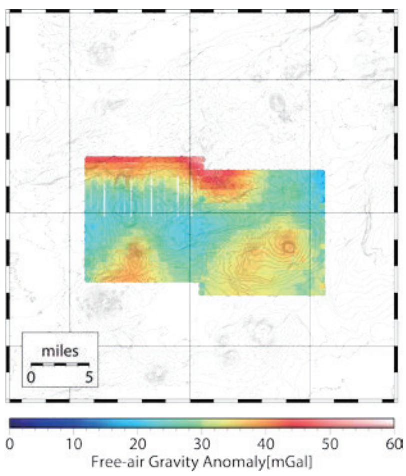


Fig.2 Map of free-air gravity anomaly

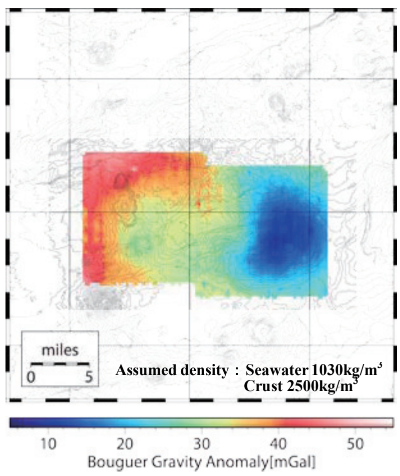


Fig.3 Map of Bouguer gravity anomaly

Note that the area and scale are identical in Figs.1, 2 and 3.

Specifications:

Case-1, combined with bathymetric survey using Multi-Beam Echo Sounder (MBES)

Conditions: 2,000 m depth, ship speed 10 knots, survey line length 20 nmi, swath angle 120° and 20% overlapped.

Expected grid interval of the bathymetric data: ~50 m

Maximum survey area per day: ~2,300 km^2 (20 nmi x ~33 nmi)

Case-2, combined with hydrothermal plume survey using MBES.

Conditions: 1,500 m depth, ship speed 5 knots, survey line length 10 nmi with a spacing of 0.5 nmi

Expected grid interval of the bathymetric data: ~20 m

Maximum survey area per day: ~190 km^2 (10 nmi x 5.5 nmi)

Advantages

1) Allows rapid exploration of regional subsurface structures.

2) Can be combined with other surveys at ease.

3) Initial data processing can be done on-board for preliminary interpretation.

6. Gravity & Magnetic Methods	6-1. Regional	6-1-1. Ship-borne Measurement
Survey method	**Surface Magnetic Survey**	

Summary

Principles: To investigate sub-seafloor structures on the basis of anomalies in the earth's magnetic field, resulting from magnetic properties of underlying rocks.

Features:

1) Hydrothermal sites in a volcanic field are typically associated with reduced magnetization, due to hydrothermal alteration and destruction of magnetic minerals. On the other hand, ultramafic-hosted hydrothermal sites exhibit enhanced magnetization, interpreted as results of high magnetic mineral contents (mostly magnetite and pyrrhotite).

2) Although surface magnetic surveys are low in resolution, they are able to cover an extensive area in relatively short time. This coverage is important for understanding tectonic processes and the geological background of the hydrothermal systems across an entire region.

Objectives: To estimate the distribution of magnetization intensity and magnetic properties.

Examples

Practice: During the R/V Yokosuka cruises YK16-10 and YK16-12, carried out in 2016, detailed magnetic surveys were conducted with a line spacing of 0.5 nmi at a ship speed of ~6 knots in hydrothermal areas of the mid-Okinawa Trough.

Results: Two distinctive distributions of magnetization were observed. One corresponded to magmatic activities of submarine volcanoes; a reduced magnetization zone associated with hydrothermal site was also seen. The other distribution was ENE-WSW trending, consistent with the trend of the bathymetric lineament. Together, these two features suggest that this area is affected by magmatism associated with both submarine volcanic activity and back-arc rifting.

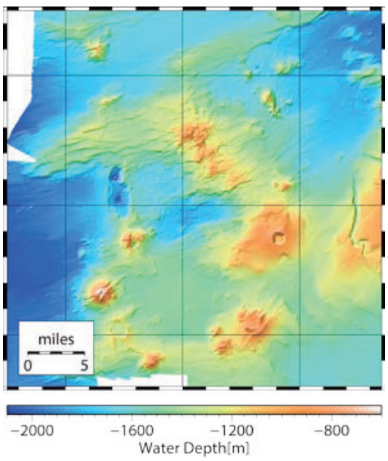


Fig.1 Bathymetric map

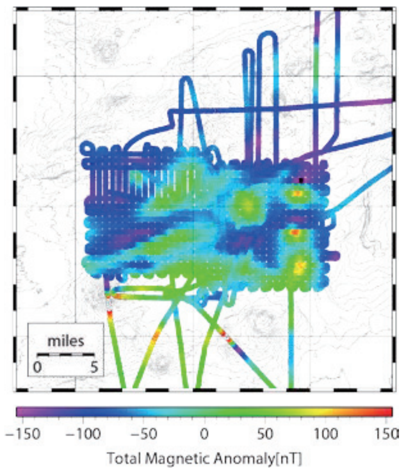


Fig.2 Magnetic total-field anomaly map with bathymetric contours

Note that both figures (Figs.1 and 2) show the same area on the same scale.

Specifications:

Case-1, combined with bathymetric survey using Multi-Beam Echo Sounder (MBES)

Conditions: 2,000 m depth, ship speed 10 knots, survey line length 20 nmi, swath angle 120° and 20% overlapped.

Expected grid interval of the bathymetric data: ~50 m

Maximum survey area per day: ~2,300 km^2 (20 nmi x ~33 nmi)

Case-2, combined with hydrothermal plume survey using MBES.

Conditions: 1,500 m depth, ship speed 5 knots, survey line length 10 nmi with a spacing of 0.5 nmi

Expected grid interval of the bathymetric data: ~20 m

Maximum survey area per day: ~190 km^2 (10 nmi x 5.5 nmi)

Advantages

1) Allows rapid exploration of regional subsurface structures.
2) Can be combined with other surveys at ease.
3) Initial data processing can be done on-board for preliminary interpretation.

6. Gravity & Magnetic Methods	6-2. Semi-detailed	6-2-1. AUV-borne / Deep-towed Measurement
Survey method	**Near-bottom Gravity Survey**	

Summary

Principles: To investigate sub-seafloor structures on the basis of anomalies in the gravity field, resulting from density anomalies of underlying rocks and/or density contrasts between underlying rocks.

Features:

1) High (positive) values of gravity anomaly indicate zones of relatively high density (e.g., ore deposits); whereas low (negative) values indicate zones of relatively low density (e.g., sediment layer).

2) By conducting gravity surveys in the vicinity of targets on or beneath the seafloor, the density structures can be estimated at a high spatial resolution.

3) AUV-borne gravity surveys allow measurements while moving at a relatively high speed.

4) High precision underwater gravity surveys can detect hydrothermal ore deposits effectively.

Objectives: To identify and estimate the size and extent of hydrothermal ore deposits on and/or beneath the seafloor.

Examples

Practice: During the R/V Yokosuka cruise YK14-14, underwater gravity surveys using AUV Urashima developed by JAMSTEC were conducted in a hydrothermal field of the mid-Okinawa Trough. The survey was conducted along 8 systematic survey lines at 2 knots at a constant height above the seafloor. The length of the latitudinal survey lines running north-south were 2 km in 100 m intervals (Fig.1).

Results: High free-water gravity anomalies were clearly detected and corresponded to small knolls in the survey area (Fig.1-2). Positive Bouguer gravity anomalies were detected in the southern part of the survey area (Fig.3), suggesting the existence of hydrothermal ore deposits.

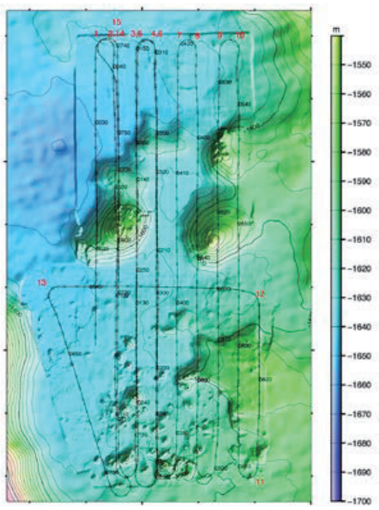


Fig.1 Bathymetric map

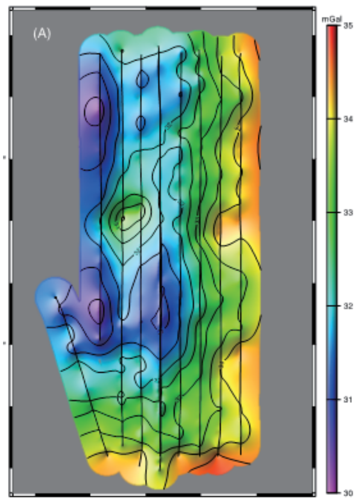


Fig.2 Map of free-water gravity anomaly

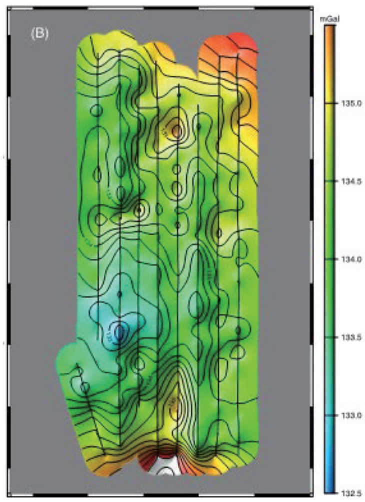


Fig.3 Map of Bouguer gravity anomaly

The survey area was ~2 km by 800 m. Fine bathymetry of the survey area was obtained by AUV and the crude bathymetry of the area is based on shipboard bathymetric survey conducted using Multi-Beam Echo Sounder (MBES). Observed free-water gravity anomalies (Fig.2) corresponds to free-air gravity anomalies detected by the ship survey, reflecting seafloor bathymetry (Fig.1). The crustal density of 2,500 kg/m^3 was used for calculating Bouguer gravity anomalies.

Specifications:

Conditions: 1,500 m depth, AUV speed of 2 knots at a constant height above the seafloor, survey line length 2 km with a spacing of 100 m and operation duration of 10 hrs.

Maximum survey area per day: ~4 km^2 (2 km x 2 km)

Advantages

1) Allows rapid exploration of a wider area compared to sea bottom gravity survey.

2) Able to conduct exploration aimed at identifying and estimating the size and extent of hydrothermal ore deposits on or beneath the seafloor, as AUV-borne gravity survey has a higher spatial resolution.

3) Able to detect seafloor hydrothermal ore deposits with a higher precision combined with gravity gradiometer surveys.

6. Gravity & Magnetic methods	6-2. Semi-detailed	6-2-1. AUV-borne / Deep-towed Measurement

Survey method	**Near-bottom Magnetic Measurement**

Summary

Principles: A geophysical method to investigate seafloor magnetization distribution by measurements of geomagnetic field near seafloor using AUV or Deep-tow system

Features: Inferring geological phenomena in and around SMS deposit areas as follows, the near seafloor geomagnetic survey is one of the valuable investigation methods.

1) Existence of low magnetization area related with fracture zone or hydrothermal alteration
2) Existence of high magnetization area due to high NRM minerals

The survey method enables to detect weak, and short-wavelength geomagnetic anomalies which is difficult to detect by ship-based geomagnetic measurements.

Objectives: To map seafloor magnetization especially caused by relatively small object such as clots of high NRM minerals or demagnetization area related with hydrothermal alteration or bedrock fracturing.

Examples

Practice: Near bottom magnetic survey by using a deep-tow in and around the Iheya Minor Ridge, in the mid-Okinawa Trough.

Results: Figs. 1 and 2 are showing magnetic total-field anomalies obtained at constant depths 600 m and 1,400 m below sea surface, respectively. Fig. 3 is the total-field anomaly of Fig. 2 reduced to the pole (RTP anomaly). Fig. 3 also shows locations of hydrothermal plumes (red circles). Figs. 1 and 2 indicate that amplitudes of total-field anomalies are large and anomalies with short wavelength become dominant in case of lower towing height (Fig. 2). Fig. 3 shows that an area of low magnetization inferred from the RTP and the distribution area of hydrothermal plumes are almost the same. This and other evidence such as geochemical measurement of sea water indicate that hydrothermal activity may cause the low magnetization of the crust. Furthermore, the area may be regarded as a possible SMS ore deposit area.

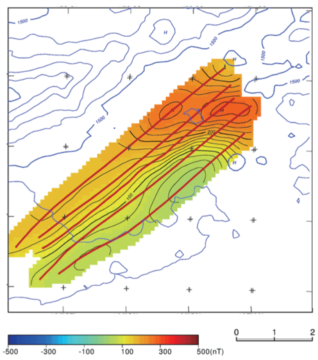


Fig. 1 Magnetic total-field anomaly (D=600 m)

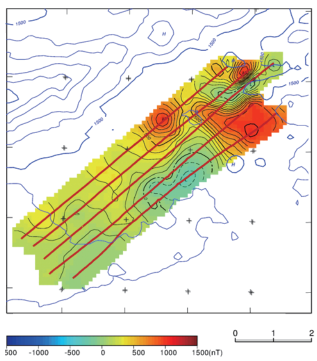


Fig. 2 Magnetic total-field anomaly (D=1,400 m)

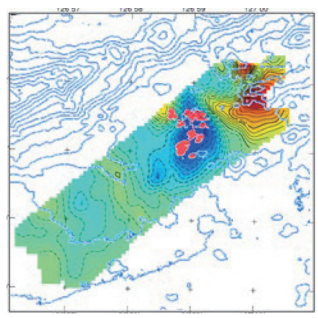


Fig. 3 Reduce-to-the Pole (RTP) anomaly of Fig.2 (D=1,400 m) and locations of hydrothermal plumes (red circles)

Specifications:

Instrumentation: Edge Tech 2000-DSS combined side scan sonar & sub-bottom profiler
Geometrics G880 marine cesium vapor magnetometer

Conditions: Water depth; ~1,600 m, Towing speed; 0.8-1.5 knots (ground spd.),
Towing depth; 600 m & 1,400 m, Survey line space; 500 m, Survey line length; 7,500 m
Actual survey time 44.5 hours for 5 lines (D= 600 m) and 5 lines (D=1,400 m).

Advantages

1) Suite for detection of low magnetization area concerned with fracture zone and hydrothermal alternation.
2) Suite for detection of clots of high NRM minerals.
3) Experiences about ship handling and winch operation will be required.
4) Extra time will be needed for winching when changing survey lines.

6. Gravity & Magnetic methods	6-3. Detailed	6-3-1. ROV-borne Measurement

Survey method	Seafloor Gravity Survey

Summary

Principles: Measuring gravity using the ocean bottom gravimeter (OBG) to estimate density structure below seafloor

Features: Positive gravity anomaly will be observed if the high-density material such as SMS exists. On the other hand, negative gravity anomaly will be observed if the low-density material such as soft sediment is accumulated over the base rock layer. Due to that the gravity is measured close to object compared with sea surface gravity measurement, gravity anomaly caused by the small object such as SMS ore deposits can be recognized. High precession gravity measurements relevant to those of land are possible. Survey efficiency is almost the same as gravimetry on land. This method is good for local precise survey.

Objectives: Investigation for small scale sub-bottom density structure such as SMS ore deposit.

Examples

Practice: Gravity survey at the Izena Hole in the mid-Okinawa Trough. The SMS ore deposits had been confirmed by several drilling core samples obtained by D/V Chikyu.

Results: Fig.1 shows the locations of the gravity measurement sites by ROV (red circles) and drilled sites by D/V Chikyu (yellow circles). Fig.2 shows topography (the bottom) and simple Bouguer gravity anomaly profiles which are variated density of the Bouguer plate. The Bouguer gravity anomaly profile adopted a density of 2.5 g/cm^3 shows no anomaly at the North Mound located 600 m of the survey line. This implies a bulk density of the mound is 2.5 g/cm^3. Also, there is a positive gravity anomaly without any correlation to topography between 700 m and 1,000 m of the line. This may imply the existence of high density material under the seafloor. Due to that the SMS ore deposits had been confirmed by several drilling core samples obtained by D/V Chikyu in the area, it is suggested that this positive gravity anomaly is related to the SMS ore deposits covered by sediments.

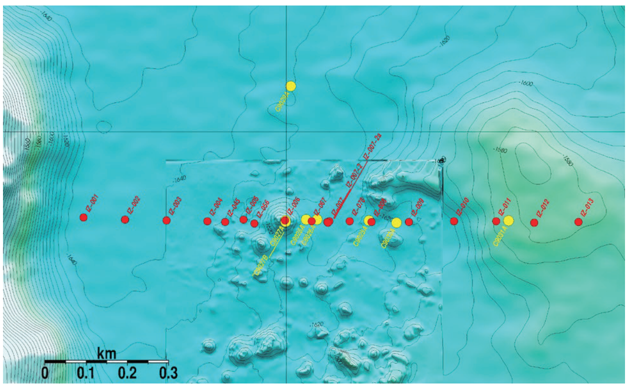


Fig. 1 locations of the gravity measurement sites (red circles) and drilled sites by D/V Chikyu (yellow circles)

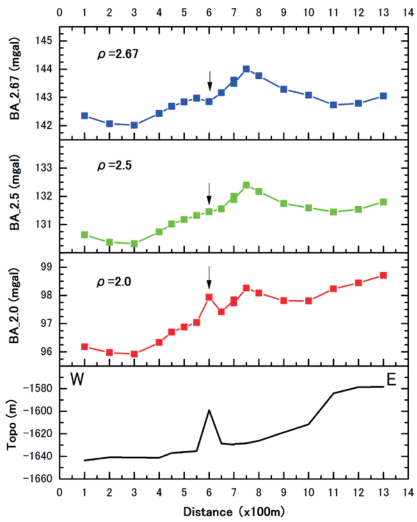


Fig. 2 Simple Bouguer gravity anomaly profiles of three different cases of Bouguer collection densities, and topography (the bottom)

Specifications:

Instrumentation: Hakuyo 3000 ROV and Ocean Bottom Gravimeter OBG-3

Conditions: Water depth; ~1,600 m, ROV speed; 1-2 knots,
Survey line length; 1,200 m, site distance; 100 m (partly 50 m)
Actual survey time 11 hours on sea bottom for 21 meas. (30 min./meas including transit time).

Advantages

1) Gravity measurement near objects enables detection of a weak anomaly caused by small scale object.
2) Ocean bottom gravimeter enables high precision gravity measurement comparable to those on land.
3) Suitable for local precise survey.

6. Gravity & Magnetic Methods	6-3. Detailed	6-3-1. ROV-borne Measurement

Survey method	ROV-towed Magnetic Survey

Summary

Principles:
To estimate magnetic anomalies in sub-seafloor by measuring the anomalies in earth's magnetic field affected by host rocks, massive sulfides and etc.

Features:
1) Measurement by the 3-Components Flux Gate Magnetometer
2) High resolution data acquisition by measurement close to the seafloor using ROV
3) High measurement efficiency and flexible adaptation for a changing of plan

Objectives:
1) Exploration for the seafloor massive sulfides (SMSs)
2) High resolution data acquisition for the magnetic anomalies under the seafloor

Examples

Practice:
1) ROV-towed magnetic survey (Fig. 1) was conducted by J-MARES at the Izena Hole, in the Okinawa Trough.
2) Magnetic inversion was conducted to estimate the crustal magnetization for exploration of Hydrothermal SMSs on and/or beneath the seafloor.

Results:
A buried SMSs were expected within the survey area from the magnetic survey results (Fig. 2), and it has been confirmed by the drilling survey later.

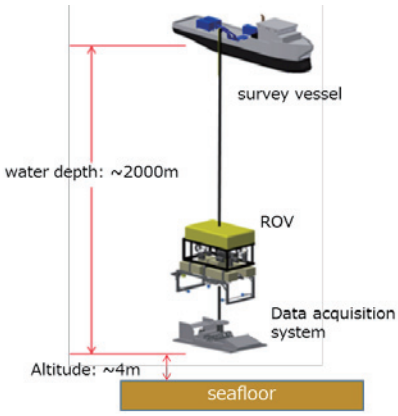


Fig. 1 Schematic diagram of the magnetic measurement system using ROV

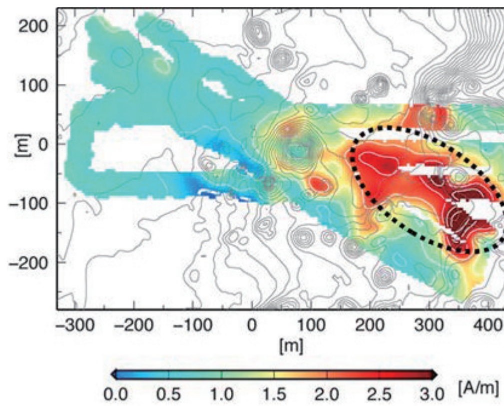


Fig. 2 Results of the magnetic inversion (J-MARES, 2017)

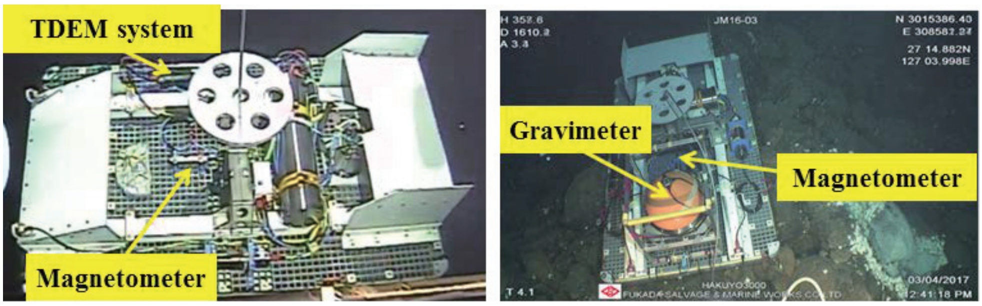


Photo 1 Appearance of the simultaneous survey using the towing system of J-MARES

Specifications:
Maximum survey productivity (including deployment and winching) for 1 day is about 500 m x 500 m as surface area. This survey conditions are water depth of less than 2,000 m, line interval of 25 m, and ROV speed of 0.5-1.5 knots.

Advantages

1) High resolution data acquisition compared with ship-borne (sea surface) or AUV-borne system (altitude of more than several tens meter), because could be close to the seafloor (altitude of several meters).
2) Able to conduct seafloor observation and rock sampling during data acquisition.
3) Deployment with other survey systems such as electromagnetic field or gravity surveys (Photo 1).
4) Real-time data transmission to the survey vessel.

7. Combination Survey Method

Previous chapters, from Chapter 4 through 6, described technological elements mainly categorized in geophysical techniques. Especially, the electric/electromagnetic method described in Chapter 5 is the newest method that has been developed to practical use during this SIP project, "*Zipangu-in-the-Ocean.*" Contrary to that, conventional oceanographic and marine-geological surveys are frequently performed following the bathymetric survey described in Section 4-1. Not only those method could share the ship-time with such geophysical method, but also they provides *Ground truth* represented by geological samples as the physical evidences. There is no doubt the importance of such *Ground truth*.

Thus, in this Chapter 7, conventional methods widely used in marine-geology and geophysics, and in oceanography will be described. Within those, seafloor heat flow measurement that could evaluate tectonic activities of the basin-wide or seamount-scale is included.

7. Combination Survey Method	7-1. Established Survey Method	7-1-1. Ship-borne Marine Geological Survey
Survey Method	**Geological Survey of the Seafloor**	

Summary

Principles: Specific minerals identified in geological samples collected from hydrothermal sites provide evidence for hydrothermal activity.

Features: Ore minerals such as sphalerite and pyrite, gaungue minerals such as anhydrite and barite are formed by precipitation from hydrothermal fluids. Clay minerals such as chlorite, illite and smectite, are formed by hydrothermal alteration.

Objectives: Geological survey provides important information for intensity, permeation, distribution of hydrothermal activity.

Examples

Practice: Jade site located at the northeast wall of the Izena Hole in the mid-Okinawa Trough was investigated during research cruise GH89-3 in 1989. Sediment samples were collected using a gravity corer which penetration ranged from 1 to 5 m (Marumo and Hattori, 1999).

Results: Occurrence of hydrothermal clay minerals were recognized in the sediment collected from the vicinity of fluid venting site (Fig. 1). Occurrence of illite (shown as open circles) was limited in the vicinity of high temperature fluid venting site. Occurrence of abundant chlorite (shown as closed squares) represented the outskirt part of the hydrothermal field. Occurrence of kaolinite (shown as closed circles) was often recognized in specific areas where low-temperature and gas-rich fluid venting.

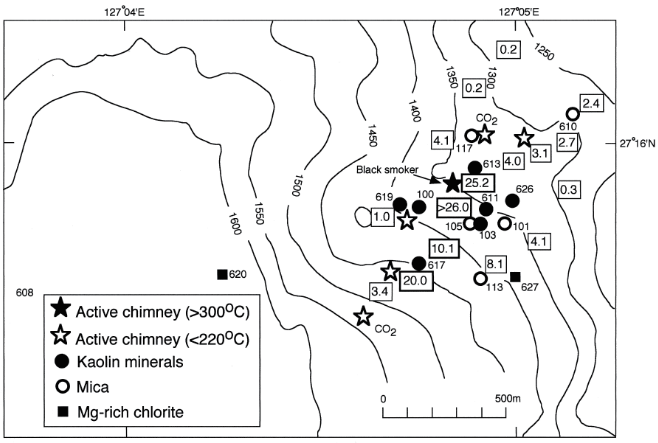


Fig. 1 Distribution of clay minerals in the sediment of Jade hydrothermal site at the Izena Hole, the mid-Okinawa Trough.
Numbers in squares show heat flow values in kmW/m^2 (Marumo & Hattori, 1999)

Specifications:

Case-1, Operation of ship-borne gravity coring or piston coring takes 1-3 hours for one site (depends on the water depth). Since this operation requires many deck men to handle heavy loads, it is usually assigned as a day-time work. Thus, operation at two to five stations would be maximum work for one day.

Case-2, By mounting thermocouples on the outside of the outer tube of the corer, heat flow measurement can be conducted simultaneously with the coring.

Advantages

The core analysis provides geological information to a few meters below the seafloor. Occurrence of specific minerals would be evidence not only for present but also previous hydrothermal activities.

7. Combination Survey Method	7-1. Established Survey Method	7-1-2. Oceanic Heat Flow Measurement
Survey Method	**Ocean Floor Heat Flow Measurement**	

Summary

Principles: A vertical profile of temperature below the seafloor obtained by precise temperature measurement provides temperature gradient, from which heat flow could be calculated at the measured point combined with thermal conductivity.

Features: Heat flow responds to fluid flow beneath the seafloor. For example, extremely high heat flow is observed above the aquifer.

Objectives: Variation of heat flow in/around an active hydrothermal site enables estimation of fluid flow pattern beneath the seafloor.

Examples

Practice: Ship-borne heat flow measurements were conducted around Jade site located at the northwest wall of the Izena Hole in the mid-Okinawa Trough during research cruises（SO56, KT88-17, SO71） using a long spear (3-5 m) (Fig. 1)（Kinoshita & Yamano, 1997）. Submersible or ROV-borne heat flow measurements were densely conducted around the Original site located at the Iheya North Knoll using SAHF (0.3-0.5 m length spear) (Fig. 2) (Masaki et al., 2011).

Results: Heat flow showed contours which center was located at the fluid venting site (Filled triangle in Fig. 1). Heat flow showed stepwise ranges according to distance from the fault where the venting sites aligned (Fig. 2). The low heat-flow zone was interpreted as an area where fluid recharges into the seafloor.

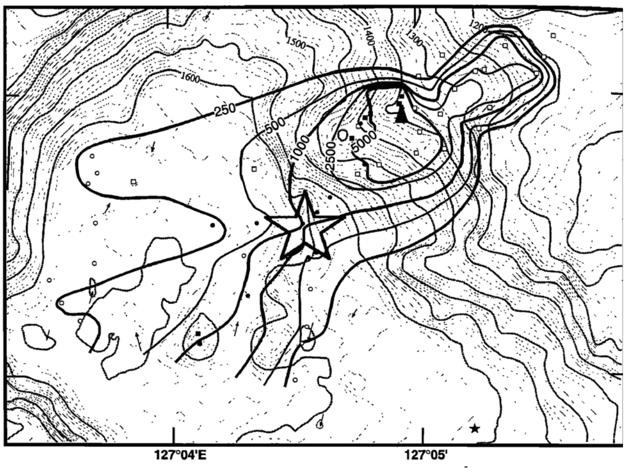


Fig. 1 Heat flow around Jade site at the Izena Hole. Numbers show heat flow values in mW/m^2.（Kinoshita & Yamano, 1997）

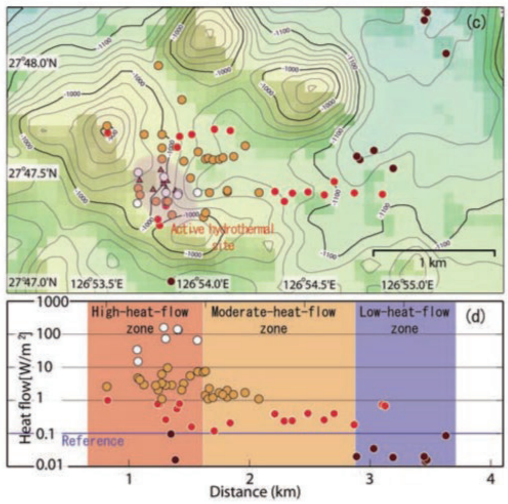


Fig. 2 Heat flow measurement around the Original site at the Iheya North Knoll.（Masaki et al., 2011）

Specifications:

Case-1, Operation of heat flow measurement takes 0.5-1.5 hours for one site (depends on the water depth). Stand-alone heat flow measurement operation can be conducted in night-time.

Case-2, By mounting thermocouples on the outside of the outer tube of the corer, heat flow measurement can be conducted simultaneously with the coring.

Advantages

Non-linear temperature profile suggests direct evidence for upward or downward fluid flow.

7. Combination Survey Method	7-1. Established Survey Method	7-1-3. Ship-borne CTD-CMS Measurement
Survey Method	**Exploration of hydrothermal plumes using CTD-CMS package**	

Summary

Principles: Hydrothermal plumes originated from vent fields are identified by mapping of physical and chemical anomalies in the water columns, using CTD and other sensors. Chemical analysis of the collected waters using CMS package provides information on geochemical features of the vent fluid (and associated ore deposits).
Features: Anomalies in physical properties such as temperature, turbidity, ox-red potential in the water column are good indicators of hydrothermal plume. Anomalies in specific chemical species such as methane, manganese in collected water samples reflect geochemical features (gas-rich vs metal-rich) of the vent fluid.
Objectives: To identify locality and distribution of presently active hydrothermal sites.

Examples

Practice: KS14-10 Cruise investigated hydrothermal plumes above Dai-ichi Amami Knoll in the north Okinawa Trough. Exploration was conducted at seven stations within the craters at the top of seamount, as shown in Fig. 1.

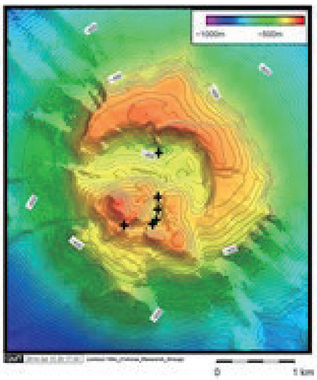


Fig.1 Topography of the target seamount, locality of stations

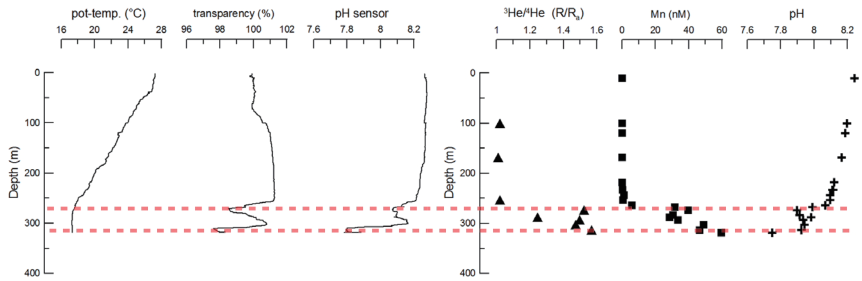


Fig.2 Profiles of temperature, transmission and pH detected by sensors (left) and $^3He/^4He$, Mn content and pH of collected waters (right).

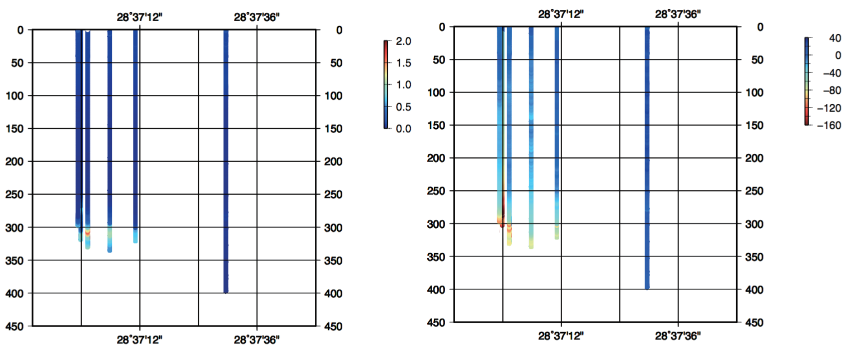


Fig. 3 Profiles of turbidity (left) and Ox-Red potential (right) composed from results of seven stations within the crater.

Results:

1) Physical anomalies were detected in profiles of physical properties during the operation. Chemical anomalies were recognized by analysis of collected waters at the same depth (shown as dashed lines) (Fig. 2)
2) Profiles of chemical properties indicated stronger anomalies in southern part of the crater (left side in Fig. 3), probably reflecting proximity of the activity center.
3) Chemical analysis of the plume waters showed high $\Delta CO_2/\Delta^3He$ and $\Delta Mn/\Delta^3He$, which suggest significant fluid-sediment interaction in the vent field (Wen et al., 2016)

Specifications:

Operation time depends on how deep the package are reached. It takes about 1 hour to deliver the package to the water depth around 1,000 m with the winch speed of 0.5-1.0 m/s. The whole operation requires another 10-20 minutes before the operation and 30-40 minutes after the operation. Without water sampling and their sub-sampling, we can conduct 8-10 times CTD vertical hydrocasts during 24 hours operation.

Advantages

1) Investigation of water column can be conducted without detailed seafloor topography information.
2) Exploration in wide region (e.g. half volcanoes in the Izu-Bonin Arc) can be conducted in one or two cruises.

7. Combination Survey Method	7-1. Established Survey Method	7-1-4. AUV-borne / Deep-towed Chemical & Physical Properties Measurement
Survey Method	**Exploration of Hydrothermal Plumes using AUV-borne / Deep-towed Sensors**	

Summary

Principles: Hydrothermal plumes originated from vent fields are identified by mapping of physical and chemical anomalies in the water columns, using various types of sensors.
Features: Anomalies in physical properties such as temperature, turbidity, ox-red potential in the water column are good indicators of hydrothermal plume. Exploration of the certain area at the constant depth or constant height from the seafloor is effective for precise mapping of hydrothermal activity.
Objectives: To identify locality and distribution of presently active hydrothermal sites.

Examples

Practice:
1) YK14-11 Cruise investigated hydrothermal plumes within Myojin Knoll caldera where the active site named Sun-rise deposit had been located at the southwest part of the caldera wall (marked as a red circle in Fig. 1) in 1997, which followed the CTD exploration during GH87-3 cruise in 1987 and the dive mission of SHINKAI 2000 in 1994.
2) Exploration of the water column at the constant height from the seafloor was conducted as a weigh point grid survey using AUV Urashima as the platform that mounted various type of sensors (turbidity, CTD, pH and Ox-Red Potential).
Results:
1) Significant pH anomaly (ΔpH =0.1-0.2) was recognized at 60-80 m above the Sun-rise deposit site (Fig. 2).
2) Certain pH anomaly together with anomalies in turbidity and Ox-Red potential was recognized also at northwest part of the caldera wall (Fig. 2).
3) Observed pH anomaly above the central cone was artificial, which reflected that the platform traveled at different height.

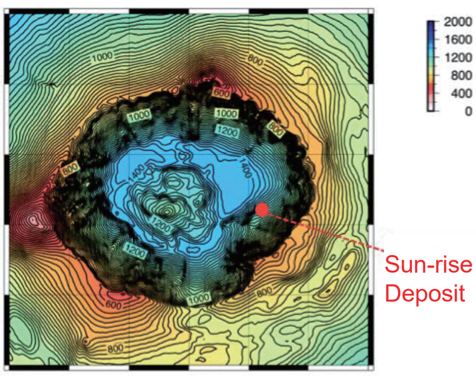


Fig.1 Topography of the target caldera, with locality of Sun-rise deposit site

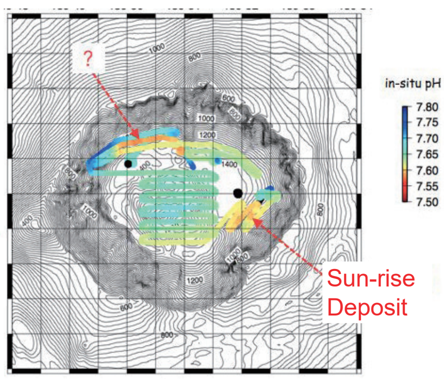


Fig.2 Detected pH anomalies in water column within the target caldera

Specifications:
Operation time of the exploration usually depends on operation time of the platform (AUV/deep-tow). In case of 1 km x 1 km size crater, it takes approx. 6 hours to conduct a horizontal 200 m grid survey by 2 knots AUV travel. The whole operation requires another 1 hour before the operation and 1 hour after the operation for sensor calibration, maintenance and data retrieval.
For continuous operation in long duration (> 24 h.), data sampling rate of sensors would be better to be decimated.

Advantages

1) Way point grid survey is effective for planar mapping of hydrothermal plumes at a certain depth, which is an efficient strategy for exploration of active sites in a caldera structure (AUV can travel as fast as 3 knots).
2) The ship-borne CTD measurement (Section 7-1-3) is effective for vertical survey and complementary to this method. Combination of these methods provide productive exploration of active hydrothermal sites.

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Survey Protocol for Seafloor Massive Sulfide Deposits

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Announcement and request for contents of this document

The content of this document is a summary of the results of the SIP “ Next-Generation Technology for Ocean Resources Exploration ”, “ Scientific Research on Formation Processes of Ocean Resources ” . The present research subjects are still in the process of research and development, and the results and contents contained in this document collection may be subject to change as future research and development progresses.

If you have any opinions, comments, and requests on the subjects of research and development issues covered in this document collection, the SIP “ Next-Generation Technology for Ocean Resources Exploration ”, and “ Scientific Research on Formation Processes of Ocean Resources ” , please let us know below. In order to be a more comprehensive survey protocol, we will make it a reference for research and development and we will strive to make efforts for practical application in the future.

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