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# EXPLORATION TECHNIQUES FOR LOCATING OFFSHORE GOETHERMAL ENERGY NEAR ICELAND

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## ABSTRACT

The world's oceans hold an abundance of geothermal resources, none of which are being utilized today. The majority of these high temperature resources lie along mid-ocean ridges. Since Iceland is uniquely situated on the Mid-Atlantic Ridge, which runs right through the center of Iceland, it is likely that there are high temperature geothermal resources offshore Iceland. We describe exploration techniques that can be used for locating hydrothermal vents such as towing a variety of temperature, chemical, and optical sensors from a ship and the use of various underwater vehicles. Then geophysical methods such as resistivity, magnetic, seismic, and gravity surveys for defining reservoir characteristics were looked at. Many of the established geothermal exploration methods used on land may not work in the same way at sea, so new approaches for these methods need to be developed. We looked into various marine geophysical methods used today and determined how and if they can be used and/or modified for offshore geothermal applications. In order to find suitable locations for future offshore geothermal utilization this research investigated what is already known about the ocean floor around Iceland, both near shore and out in the open ocean. All of the oceans around Iceland were considered in this research; however, the main region of focus was along the Reykjanes Ridge. High temperature hydrothermal vent sites around Iceland such as Steinahóll and Grímsey were addressed, as well as other known and inferred vent sites around Iceland.

## INTRODUCTION

Geothermal energy is quickly growing for heat and electricity production around the world, especially in Iceland. Five major geothermal fields are currently being utilized in Iceland, all on land. High temperature geothermal resources exist offshore near Iceland and it has been proposed that in the future Iceland might benefit from these energy sources. In this paper we look into potential offshore geothermal areas around Iceland and the exploration techniques that may be used for locating and evaluating these resources. Although not easily justifiable today, offshore geothermal production may in the near future become economical and will help the geothermal industry to grow. Preparing for an expansion of geothermal energy production into the sea will be beneficial to Iceland, as well as other areas, as it will open up more options for clean renewable energy production. Part of this preparation is to start exploring these offshore resources. If ocean resources become feasible and economically attractive, it could open up possibilities for a lot of new geothermal sites around the world.

There are both advantages and disadvantages to offshore geothermal utilization compared to on land. Advantages of locating a geothermal power plant at sea would be the virtually infinite recharge of water into the geothermal reservoir and unlimited cold seawater in order to operate condensers without the need for cooling towers. Another possible advantage is that the use of thermoelectric generation might be a justifiable method due to the unlimited cold seawater and ample hot geothermal fluid. Disadvantages of offshore geothermal utilization include much higher costs for exploration, plant construction, and operation compared to on land. Furthermore, as the distance from land increases the power plant will be more difficult to access, putting it at higher risk in operation. To sum up, there will be many challenges involved with an offshore geothermal utilization, because so much is still unknown, but as with the offshore oil industry it may at some time be realized that going offshore will be beneficial for geothermal energy production.

Until recently, little research has been done on utilizing offshore geothermal energy, but Italy is leading in this field of study. Italy has future aspirations of constructing the world's first offshore geothermal power plant on the Marsili Seamount by the year 2015 (Eurobuilding SpA 2012). Italy may well pave the way to offshore geothermal energy, but Iceland might potentially follow suit. This paper explores if offshore geothermal resources are available at reasonable distances from land and at reasonable depths, and how to explore them in this unconventional marine environment.

## METHODS FOR EXPLORATION

Right now there are no offshore geothermal power plants in the world so this field of research is in its youth. The strategy of this paper is to investigate how geothermal exploration is currently done and determine which exploration methods will be the most applicable offshore. Some methods are found to be potentially useful but others need to be modified or are not applicable. Geophysical techniques that are relevant to geothermal exploration, hydrothermal vent exploration, and general marine geophysical exploration as well as methods that the offshore oil and gas industry uses are discussed and evaluated.

### Methods for Locating Hydrothermal Vents

Locating a geothermal area on land normally begins with finding areas which have surface features such as fumaroles and boiling pools. Similarly, the most obvious evidence for a geothermal heat source on the ocean floor is hydrothermal venting. On land, these features are easily found with simple geologic reconnaissance and direct observations, but ocean exploration is a different story and direct observations of vents require submersibles or towed cameras, and getting to vent sites usually requires a large ocean worthy ship. The following sections discuss the various methods and technology being used for finding hydrothermal vents.

#### *Sound navigation and ranging (sonar)*

The most commonly used type of sonar is for mapping the ocean floor, called multibeam swath bathymetry or echo sounding. Swath bathymetry can be useful for locating hydrothermal vents if the rising fluid is rich with gas bubbles, causing acoustic scattering (Figure 1) (Hannington et al. 2001).

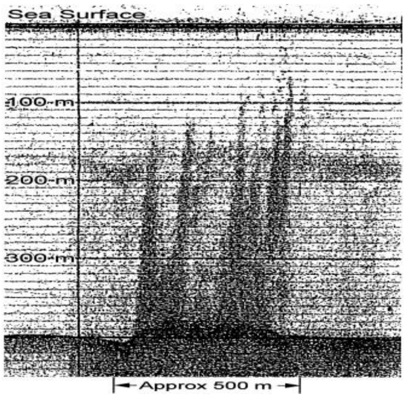

*Figure 1) An exceptional profile from an 18 kHz echo sounder on a the ship travelling across the Grímsey vent field showing obvious acoustic scattering from the bubble rich plumes that rise from the vents (Hannington et al. 2001).*

Another sonar technique called side scan sonar uses the backscattering strength of multibeam data to provide information on rock types and structures on the ocean floor. Different backscatter intensity can help to identify and distinguish different lava flow events from each other; landslides and faults can also be visible in side scan sonar data (Höskuldsson et al. 2007). This technique helps in identifying the material and texture of the ocean floor, thus helping in locating potential hydrothermal sources.

Passive sonar has not been used for finding hydrothermal vents, as far as we know, but it may prove useful. Towed arrays of hydrophones are mainly used on navy ships to detect submarines from long-range, but they may possibly be used to detect sound of particular frequencies, characteristic of hydrothermal vents. The array of hydrophones can detect, isolate, and display a wide range of acoustic frequencies in the water. If a particular frequency could be recognized as coming from hydrothermal vents, then frequency shifts caused by the Doppler Effect could be used to locate the vents. This idea has not been tested for the purposes of locating hydrothermal venting, and it is of interest to know if venting would produce clear and strong enough sound waves to be detected by an array of this type. Also, it could be a difficult technique to use if there is other shipping traffic in the area causing too much noise in the water to isolate the frequencies from a vent.

#### *Chemical Analysis*

Hydrothermal vents produce many chemicals and dissolved gasses at elevated levels compared to ordinary sea water, so chemical analysis of the water column is an important and useful method for locating plumes from active hydrothermal vents.

Chemical methods that can be used to detect hydrothermal venting include analyzing isotope ratios, dissolved gasses, and reduced chemical compounds. High ratios of $^3$He/ $^4$He isotopes in the water column is a useful indicator of hydrothermal activity (Riedel et al. 2001). High levels of dissolved substances such as $CH_4$, $CO_2$, Si, $H_2$, $H_2S$, Fe, and Mn in the water column are also potential indicators of hydrothermal activity (German 1993). Several different instruments are available for real-time chemical measurements in the water column, including electrochemical redox (eH), methane, and pH sensors.

### *Optical Sensors*

Light Backscattering Sensors (LBSS), also known as optical backscattering sensors, are simple yet highly sensitive instruments for locating hydrothermal vents. Visible clouds of precipitating minerals form at many vents, and an LBSS can detect these suspended particles. LBSS are relied on heavily when searching for hydrothermal vents because they are reliable, inexpensive, easy to use, and can be used in conjunction with many other instruments (Resing 2005).

### *Cameras*

The first method for obtaining visual confirmation of hydrothermal vents is often the towed camera. Cameras can also be mounted to submarines Remotely Operated Vehicles (ROVs), and Autonomous Underwater Vehicles (AUVs). They are vital to navigation and important for studying hydrothermal vents up close. Getting visuals of a hydrothermal vent site helps to determine the size of the area and can give clues to the chemistry and temperature. Capturing a vent field on camera is the most direct and satisfying way to confirm its existence.

### *Dredging*

Rock samples from dredging can provide evidence of hydrothermal venting because rocks near vents can be affected by hydrothermal activity. The presence of sulfide minerals in the rocks is a common indicator of possible hydrothermal activity nearby (Riedel et al. 2001).

### *Magnetic survey*

Magnetic surveys can be used for many purposes: to find structural/tectonic trends, age relationships between crustal areas, estimate sizes and thicknesses of rock formations, and to find unusual magnetic properties which can then be linked to other geologic features (Jónsson et al. 1991). Magnetic surveys can also be a useful tool for locating hydrothermal areas and delineating hydrothermal vent systems because the magnetic properties of the rocks can be severely affected by the hydrothermal fluids (Tivey and Dyment 2010). A localized reduction in crustal magnetization is often found at hydrothermal upwelling zones and the localized low magnetic anomalies might be approximately a few hundred meters across (Tivey and Dyment 2010), therefore detection of hydrothermal vent systems may need detailed magnetic surveys, preferably near bottom surveys.

Fresh, rapidly cooled basalts are normally strongly magnetic due to significant amount of magnetic titanomagnetites and small grain size. For these reasons most young mid-ocean ridge basalts are highly magnetized, but studies have shown that magnetic minerals in oceanic crust are highly susceptible to alteration from hydrothermal fluids (Tivey et al. 1993). Hydrothermal fluid circulation can drastically decreases the magnetization of the rocks by changing the original minerals into less magnetic minerals such as rutile (Rona 1978) and pyrite (Tontini et al. 2012). Hydrothermal fluids can also cause leeching out of the iron content in the rocks, thus causing demagnetization (Levi and Riddihough 1986). In addition, elevated temperature also reduces the magnetization of the rock, especially as the temperature approaches the Curie temperature of the magnetic minerals (Audunsson and Levi 1992). The net magnetic signature left behind is a magnetic low anomaly due to the hydrothermal activity, which can be detected in magnetic surveys (Tivey and Dyment 2010), (Tontini et al. 2012). It should be noted, that not all hydrothermal activity will result in reduced crustal magnetization (Tivey and Dyment 2010).

### *Conductivity, Temperature, Depth (CTD) Sensors*

CTD sensors are the most routine instrument used when searching for hydrothermal vents (NOAA/PMEL 2012). A CTD measures the conductivity, temperature and pressure. This instrument package is usually lowered or towed from a ship via a cable so the data collected can be observed in real-time. CTDs in use today are small and may also be attached to underwater vehicles. The instrument package can also be fitted with many other auxiliary instruments such as optical sensors, cameras, ph sensors, various chemical detectors, and sampling bottles (NOAA/PMEL 2012).

### *Miniature Autonomous Plume Recorder (MAPR)*

MAPR is a small inexpensive instrument package similar to a CTD. The MAPR was designed to be a simple universal instrument that can be integrated with any shipboard tow cable and operated by someone with very little specialized training. The instrument package has an optical backscattering sensor, an eH sensor, a temperature sensor, and a pressure sensor (NOAA/PMEL 2012).

## Methods for Reservoir Assessment

Once the resource locations are known the next step is to estimate the energy potential and collect geophysical data to constrain a reservoir model. Of course as many different geophysical studies should be conducted as economically and practically possible in order to help build a realistic reservoir model, and locate the best sites for boreholes.

### *Resistivity*

Resistivity models of geothermal areas on land provide essential information when estimating the size, location, geometry of a reservoir, and deciding on a drilling location (Georgsson 2009). Geothermal areas on land normally have a reasonably well documented resistivity structure (Georgsson 2009), but how well this structure represents marine geothermal areas is not at all obvious. The main problem with using electrical and electromagnetic (EM) methods to explore the ocean floor is the fact that the seawater is so much more conductive than the crust. Therefore, different, or at least modified, methods are needed in ocean environments compared to what is done on land. To perform simple dipole-dipole resistivity exploration on the seafloor similar to on land would require tremendous distances rendering the method impractical. Also, typical magnetotelluric (MT) methods for shallow crustal depth penetration are not easily applicable due to the screening of the conductive seawater, although lower frequency signals may give information on the large scale structures. When MT is performed the sensors are left on the seafloor for a few days (Constable 2006). Therefore, due to the limited energy transmitted through the ocean for MT, controlled source EM (CSEM) appears to be a promising method for geothermal exploration in the oceanic crust. There is recent interest in the application of EM stimulated by offshore exploration for hydrocarbon reservoirs (Constable and Srnka 2007), (Edwards 2005). Besides the MT-method discussed earlier, there are three very similar types of CSEM marine resistivity techniques that we believe would be best for offshore geothermal exploration. Those methods are Controlled Source Electromagnetic (CSEM) (Figure 2), Multi Transient Electromagnetic (MTEM), and Magnetometric Resistivity (MMR) (Figure 3). All three methods utilize ocean bottom electromagnetic detectors (OBEM). The CSEM and MTEM methods are basically the same except in MTEM two vessels are used and the ocean bottom electromagnetic sensors are lowered via tow cable from one of the vessels.

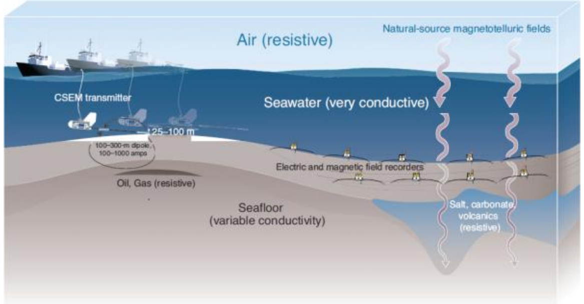

*Figure 2) A CSEM survey applying the horizontal electric dipole-dipole method. It begins by deploying OBEMs over the area of interest, and then a ship towing an electrical dipole-dipole transmitter along the seafloor makes passes by the OBEMs (Constable 2010).*

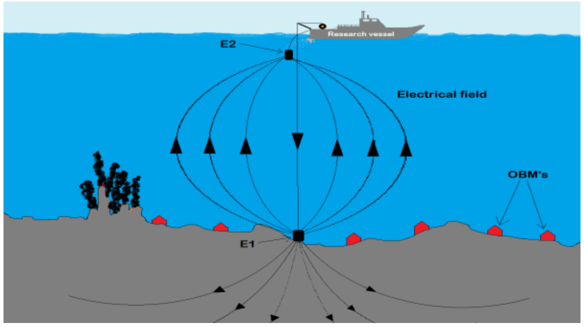

*Figure 3) The MMR method uses OBEM's deployed on the ocean floor and a vertical bipolar source for the electric current. Figure based on (Edwards 2005).*

The MMR method would be the most ideal for depths less than 1000 m because CSEM has trouble in shallower depths (Constable 2006). MMR would also be the best method in rugged terrain because it utilizes a vertical bipolar source (Edwards 2005). The vertical source cable can be lowered and raised easier than a horizontal source array. The downfall of MMR compared to CSEM and MTEM is that it takes more time to cover a large area due to the vertical array. CSEM, MTEM, and MMR methods have the advantage of being capable of collecting passive MT data for analysis as well. The best technique to use will depend on the topography revealed from a detailed bathymetry survey, time and budget constraints, depth, detail sought after, and the size of the survey area.

### *Magnetic methods*

Obtaining a detailed magnetic model of a geothermal area is very useful before utilization (Georgsson 2009). Detailed magnetic surveys can help to estimate the surface area of the reservoir and potentially delineate the region of the vent field with the most intense hydrothermal alterations, which can indicate where the most subsurface hydrothermal flow is located. Magnetic surveys may also be useful to reveal the depth to the Curie isotherm (580°C) (Bouligand et al. 2009). The most ideal methods for high resolution magnetic surveys are utilization of submarines or ROVs, because to obtain high resolution magnetic data the sensor must be close to the ocean bottom. An ROV would probably be the top choice because it would be less expensive than a manned submersible, it can stay down long enough to thoroughly cover a large area, and it will provide high resolution data. Utilizing an AUV would also be very effective because AUVs can survey a larger area while staying close to the sea bottom. In shallow waters, near shore, magnetic measurements can be conducted from surface boats relatively easily and inexpensively.

### *Seismic*

Detailed seismic monitoring and analysis using Ocean Bottom Seismometers (OBSs) placed around the hydrothermal vent fields for days to months can provide information on the tectonic structures and possibly hydrothermal flow and the depth of the active system. Hydrothermal vents are commonly linked with nearby tectonic structures and subsurface faults, which often provide the easiest pathways for the flow of hydrothermal fluids (Tivey and Johnson 2002). OBSs can also help to show where the most micro-seismic activity is occurring, which can be an indicator of where the highest concentration of hydrothermal fluid flow is located (Silas 2009).

### *Fluid chemistry*

Detailed analysis of fluid samples provides information on pH, dissolved minerals, and gasses, and may be used to estimate the reservoir temperature. Fluid chemistry needs to be known before utilization can take place because the power plant and component design will be highly affected by the chemistry. The best way to analyze reservoir fluids is to collect samples directly from the vents using a submarine or ROV.

## POTENTIAL SITES

Knowledge about offshore geothermal resources around Iceland is still sparse because only a small percentage of the ocean floor has been thoroughly explored. Currently, several offshore geothermal resources are recognized and a number of potential resources are suspected (Figure 4). There are also many hot springs around Iceland that have been found in the tidal zones (Figure 5). Some of these hot springs may be linked to larger onshore or offshore resources, but further exploration needs to be done to support that theory.

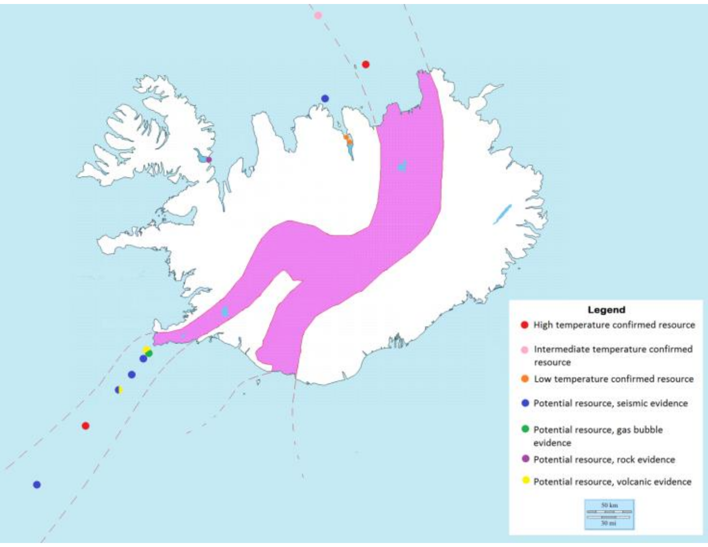

*Figure 4) Map of confirmed and potential offshore geothermal resources around Iceland. The purple area is the active rift zone that runs through Iceland, based on (Fridleifsson and Albertsson 2000). The dotted lines extending from the active rift zones are the inferred high temperature zones in the ocean. The potential resources from seismic evidence (blue dots) are either from earthquake swarms (Icelandic Meteorological Office 2012) or micro-seismic data collected over many years (Höskuldsson et al. 2007). The potential resource from gas bubble evidence (green dot) is from scattering in sonar profiles, which is thought to be caused by gas bubbles (Benjamínsson 1988). The potential resource from rock evidence (purple dot) is referring to a hydrothermally altered rock found in Steingrímsfjörður ("Unique Stalagmites in North Iceland Damaged" 2012). The potential resources from volcanic evidence (yellow dots) are referring to possible volcanic activity that has occurred along the Reykjanes Ridge in the last 100 years (Höskuldsson et al. 2007).*

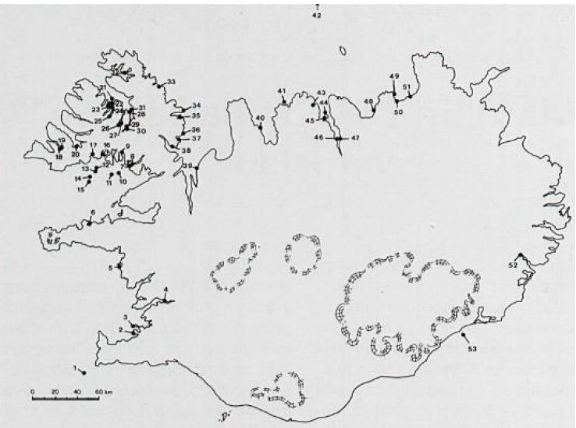

*Figure 5) Locations of tidal zone hot springs documented around Iceland (Benjamínsson 1988).*

## Confirmed Resources

There are five confirmed offshore resources near Iceland (Table 1) and all have hydrothermal venting. These locations require plenty of exploration before reservoir models and energy potential estimates can begin.

*Table 1) Summary of confirmed resources in order of highest interest in terms of utilization*

| Site | Location | Distance to land | Depth (m) | Vent temp. (°C) |
|---|---|---|---|---|
| **Grímsey** | North of Iceland | 16 km from the small island Grímsey and 50 km from Iceland | 400 | 250 (measured) |
| **Steinahóll** | Reykjanes Ridge | 120 km | 250-350 | 220 (inferred) |
| **Kolbeinsey** | North of Iceland | 65 km from Grímsey and 100 km from Iceland | 100 | 131 (measured)<br>180 (inferred) |
| **Arnarnes-strytur** | In Eyjafjörður | 1 km | 18-46 | 80 (measured) |
| **Strytan** | In Eyjafjörður | 3 km | 15-65 | 75 (measured) |

### *Grímsey*

The Grímsey resource is the most compelling site for an offshore geothermal power plant based on current knowledge. Although it has by far been the most extensively surveyed offshore resource around Iceland, only very limited information is available on reservoirs temperature, size, and energy content. The vent field is similar in size to many of the largest geothermal areas on land in Iceland and the measured vent temperatures are close to the reservoir temperatures in the Krafla geothermal area (Hannington et al. 2001). Furthermore, due to the close proximity to land (16 km from the island of Grímsey and 50 km from Iceland) and depth (400 m) (Hannington et al. 2001), the Grímsey hydrothermal vent field is the most feasible location, out of the known resources, for an offshore geothermal power plant. In addition, there appears to be little biologic activity at Grímsey; thus environmental impact would be less significant. The Grímsey vent field could offer a renewable source of energy for the island of Grímsey which has been a pressing issue for many years.

### *Steinahóll*

The only confirmed geothermal resource along the Reykjanes Ridge is Steinahóll, but it may not be the most ideal location for a geothermal power plant at this point in time. Due to the distance from land (120 km) and depth (250-350 m) (German et al. 1994), building a geothermal power plant at Steinahóll would be a technical and economical challenge. In addition, little is known about Steinahóll; the vent field has not been mapped, the size of the hydrothermally active zone is unknown, the temperatures have not been directly measured, and the vent fluid has not been sampled. The temperature is inferred based on the boiling temperature of seawater at its depth (Hannington et al. 2001).

### *Kolbeinsey*

The Kolbeinsey vent field is not a good candidate for utilization because it is largely outcompeted by the Grímsey vent field, both in terms of distance from land and temperature. The Kolbeinsey field is at 100 m depth and the hydrothermal fluids have been measured to be up to 131°C (National Oceanography Center 2012). Temperatures may be higher because the submersible could not reach some areas, but gas bubbles, possibly from boiling, could be seen rising from some craters (Fricke et al. 1989).

### *Eyjafjörður*

The two vent sites in Eyjafjörður, Arnarnesstrytur and Strytan, although very close to land and sheltered in the fiord, are not good sites for a geothermal power plant because they are very unique, environmentally protected areas. Also the temperatures at these sites are low, less than 80°C (Bogason 2012). All the confirmed vent sites can be seen in (Figure 6).

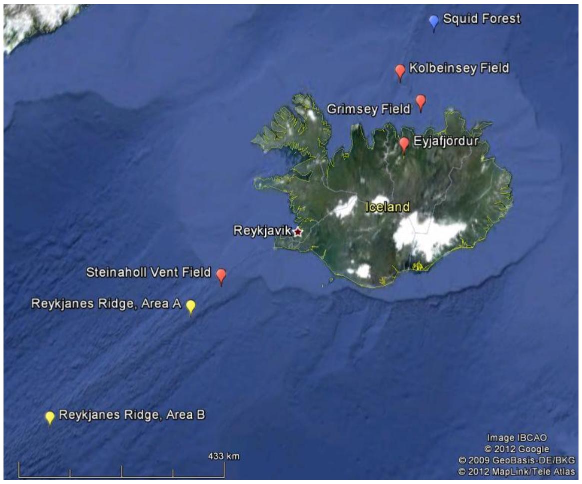

*Figure 6) Google earth map of all the documented hydrothermal vent fields near Iceland (National Oceanography Center 2012). Red markers indicate confirmed vent fields, yellow markers indicate inferred vent fields, and the blue marker indicates an extinct vent field. The Eyjafjörður marker includes Strytan and Arnarnesstrytur.*

## Potential Resources

Potential resources are areas that are only suspected of having a geothermal heat source and need to be explored further. Potential sites are listed in (Table 2).

*Table 2) Summary of potential resources in order of highest interest of further geophysical exploration*

| Site | Distance from land (km) | Depth range in the area (m) | Type of evidence found |
|---|---|---|---|
| **Around the island of Eldey** | 14 | 25-150 | Gas bubbles and volcanic activity |
| **Fuglasker Seamount** | 25 | 40-180 | High frequency of micro-seismic events |
| **Eldeyjarboði** | 65 | 60-180 | Earthquake swarm and possible volcanic activity |
| **September 16th 2012 earthquake swarm** | 40-50 | 100-260 | Earthquake swarm |
| **Steingríms-fjörður** | 0-3 | 1-100 | Rock found with hydrothermal alterations |
| **Tjörnes fracture zone earthquake swarm** | 10-15 | 100-300 | Large ongoing earthquake swarm |

### *Eldey*

Near the Island of Eldey (Figure 7), fishermen noticed anomalous scattering in their sonar scans, thought to be caused by rising bubbles from speculated hydrothermal venting; however no other evidence of hydrothermal venting has been identified (Benjamínsson 1988). In addition, volcanic activity occurred near the island of Eldey in 1926 (Höskuldsson et al. 2007), further supporting the idea that there could be a geothermal heat source somewhere near the island.

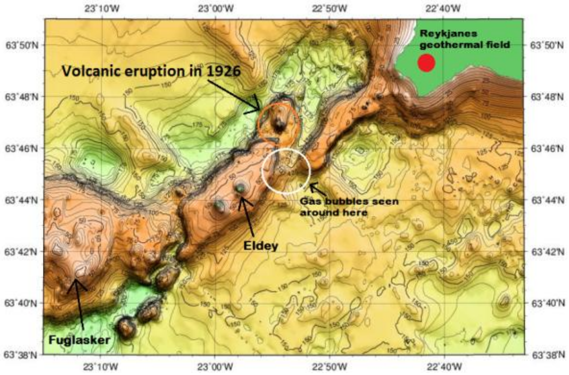

*Figure 7) Locations of three potential resource areas, the Fuglasker Seamount and two areas near Eldey, where further exploration would be beneficial. Map modified from (Höskuldsson and Kjartansson 2005), gas bubble evidence is from (Benjamínsson 1988), and volcanic eruption date is from (Höskuldsson et al. 2007).*

### *Fuglasker*

The Fuglasker Seamount (Figure 7) has shown high numbers of micro-seismic events over the course of many years (Höskuldsson et al. 2007), which is a common characteristic for geothermal fields in Iceland (Hjaltadóttir 2009), and may indicate hydrothermal circulation in the ground. The seamount is at relatively shallow depths; the base is approximately 180 mbsl and the summit is approximately 40 mbsl (Höskuldsson et al. 2007).

### *Eldeyjarboði*

The Eldeyjarboði seamount is of interest because it may have erupted in 1970 (Höskuldsson et al. 2007); however that has not been confirmed. Additionally, a small earthquake swarm occurred at Eldeyjarboði on February 8th 2012 (Figure 8) (Icelandic Meteorological Office 2012), indicating that some interesting activity may be occurring in the area.

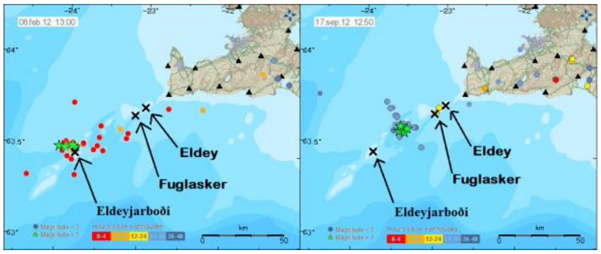

*Figure 8) Comparison of two small earthquake swarms that occurred on the Reykjanes Ridge in 2012. Maps modified from (Icelandic Meteorological Office 2012).*

### *Reykjanes earthquake swarms*

Small earthquake swarms occurred at two locations along the Reykjanes Ridge in the last year (Figure 8). The first occurred at the Eldeyjarboði Seamount and the another about halfway between Eldeyjarboði and Fuglasker (Icelandic Meteorological Office 2012). Large earthquake swarms have proven successful in the past directing researchers to potential vent field, as happened when the Steinahóll vent field was discovered. Continued record keeping of earthquake swarms may someday help to identify other locations with potential heat sources, and long term deployment of OBSs might provide interesting data.

### *Tjörnes Earthquake Swarms*

An earthquake swarm in the Tjörnes fracture zone has been active for the latter part of 2012 (northern Iceland) (Figure 4) (Icelandic Meteorological Office 2012). The Tjörnes fracture zone consists of transform faulting so earthquake swarms can often be caused strictly from plate movements and not have any geothermal heat source related to them (Jakobsdottir 2012). Nevertheless, this location is worthy of further exploration, and if a geothermal resource is found it would be in a very nice location because the majority of seismic events are only about 10-15 km from land.

### *Steingrímsfjörður*

A rock affected by hydrothermal activity, found in Steingrímsfjörður (northwest Iceland, purple dot in Figure 4), indicates potential vents in the fiord ("Unique Stalagmites in North Iceland Damaged" 2012). If there are hydrothermal vents they are in a very good location for utilization because it is very close to land and protected inside the fiord. In all likelihood, if venting is occurring at Steingrímsfjörður it would be similar to the vents in Eyjafjörður and would not be a high energy resource. Nevertheless, this area would be interesting to explore further because perhaps another active vent at less than 30 m depth, shallow enough for recreational scuba diving, will be discovered.

## RESULTS

### Exploration Strategies for the Confirmed Resources

The confirmed resources of most interest are Grímsey and Steinahóll. The next step in exploration is to estimate the energy potential and construct a reservoir model. If either one of these areas are chosen for further studies toward utilization the next recommended surveys are magnetic, seismic monitoring with OBS, and resistivity. The recommended resistivity methods are CSEM, MTEM and MMR, but which one specifically will depend on a detailed bathymetric analysis of the area. The resistivity methods also need further development for marine hydrothermal exploration.

### Strategies for the Potential Resources

The potential resources of most interest are the ones closest to land along the Reykjanes Ridge, Eldey and Fuglasker. The most effective way to search these regions for hydrothermal vents would be to utilize an AUV that can cover wide areas in detail. The AUV should be equipped with active sonar, a CTD sensor, an optical backscatter sensor, an eH sensor, and a magnetometer. While the AUV is operating the surface vessel can also conduct profiles with towed sensors. The ship surveys should include detailed bathymetry and a towed array equipped with cameras, side scan sonar, a CTD with rosette, a methane sensor, a pH sensor, and multiple MAPRs; if possible. Once the detailed surveys are conducted in target areas, any promising anomalies found can be further investigated. If an ROV is available it should be used to confirm any suspected vents; otherwise a towed camera can be used. Also, it would be beneficial to collect rock samples at any sites of interest either by dredging, ROV, or submarine.

All the methods listed above are mainly used for locating hydrothermal venting; however in some cases, a geothermal heat source might exist but hydrothermal venting may be very diffuse and difficult to detect, a sort of "blind system" (Young et al. 2012). Other methods that might be useful are micro-seismic monitoring with OBSs.

### Strategies for Discovering New Resources

The exploration strategy for regions of hydrothermal activity not yet explored should use the same instruments as for the potential resources; except surveys should be designed to scan very large expanses of the ocean. Regions near shore on the Reykjanes Ridge should definitely be surveyed more. The area near Vestmannaeyjar and Surtsey might be a good location to find resources since the volcanic activity in that region is relatively young. It would be beneficial to explore further areas where tidal hot springs have been found, especially those within the high temperature rift zones such as numbers 48-51 in Figure 5, which are in Skjálfandi and Öxarfjörður, northeast Iceland. It is possible that these tidal hot springs are connected to larger high temperature offshore reservoirs. Exploration techniques that can be done from a small ship, such as echo sounding, CTD measurements, optical backscatter, chemical analysis, magnetic, and dredging would be relatively simple, inexpensive and effective near tidal hot spring zones.

## CONCLUSIONS

(1) The most practical methods for exploring the potential resources involve searching for evidence of hydrothermal venting. Magnetic techniques and monitoring of seismic activity with OBS are useful techniques for detecting possible hydrothermal activity. The most important techniques and sensors to use for locating new hydrothermal vent areas are: CTD sensor, MAPR sensor, chemical analysis, light scattering sensor, sonar, cameras, magnetic, seismic monitoring, and dredging.

(2) To estimate the size of confirmed resources and to help in constraining reservoir models these geophysical methods are applicable for offshore exploration: magnetic, seismic monitoring with OBS, resistivity and chemical analyses.

(3) Magnetic and seismic monitoring are at the top of this list because they are helpful for geothermal exploration and known to be effective in a marine environment. These techniques are unaffected by the deep saltwater environment and have been successfully used in offshore geothermal environments such as the Marsili Project.

(4) Resistivity techniques are highly valuable in geothermal exploration and can be used in marine environments as well. However, the methods are still under development and have not been used specifically for offshore geothermal exploration.

(5) Chemical analysis will help to construct a more complete reservoir model because it is useful for inferring reservoir temperatures.

(6) The most feasible location for offshore geothermal power production in Iceland is at the Grímsey hydrothermal vent field. Grímsey is a high temperature reservoir and appears to be a large geothermal source, comparable to other high temperature resources on land in Iceland (Hannington et al. 2001). Grímsey is also the closest known offshore resource to Iceland.

(7) Along the Reykjanes Ridge, the only confirmed resource is the Steinahóll hydrothermal vent field. The reservoir size is unknown, the temperatures and fluids have not been directly measured and the vent field lies at 120 km from land.

(8) Many potential resources are suspected around Iceland due to evidence from earthquakes, volcanic activity, gas bubbles, dredge samples, and tidal zone hot springs.

(9) Offshore geothermal energy production off the shores of Iceland may at some time in the future be feasible. By comparison with the Marsili project, Grímsey, and possibly Steinahóll, might be technologically feasible for utilization based on the resources locations, temperatures, and depths.

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