Exploration Techniques for Locating Offshore Geothermal Resources

By

Darren Atkins

Thesis
Master of Science in Sustainable Energy

January 2013

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Thesis submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment
of the requirements for the degree of
Master of Science in Sustainable Energy

January 2013

Supervisor:

Haraldur Audunsson – Assiciate Professor, Reykjavík University, Iceland

Examiner(s): Gylfi Páll Hersir, Iceland GeoSurvey

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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 (MAR), which runs right through the center of Iceland, it is likely that there are high temperature geothermal resources offshore Iceland. 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. We then 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 addition, a magnetic field study was conducted at the geothermal field Eldvörp, on the Reykjanes Peninsula, as a side project for this thesis. It was not possible to fund a research vessel and conduct a magnetic survey along the Reykjanes Ridge, so an on land survey was carried out. The purpose of this field work was to learn how a magnetic survey is done and how to interpret the data. The same principles can then be applied to a marine survey only the instrument would be towed behind a ship or mounted to an underwater vehicle rather than carried across the land.

Útdráttur

Í höfum heimsins er mikill fjöldi jarðhitasvæða sem ekki eru nýtt í dag. Mikill meirihluti þessara jarðhitasvæða er að finna á Miðhafshryggjum. Þar sem að Ísland er staðsett á Mið-Atlantshafshryggnum (MAR) verður að teljast líklegt að það finnist háhitasvæði neðansjávar við Ísland. Til þess að finna hentugt svæði til nýtingu jarðvarma við strendur Íslands fór þessi rannsókn fram. Farið var það sem er vitað nú þegar um sjávarbotninn í kringum Ísland, bæði grunnsævi og úthaf. Allt hafsvæðið í kringum Ísland var skoðað í þessari rannsókn. Megin áhersla er þó lögð á Reykjanes hrygginn. Háhitasvæði neðansjávar í kringum Ísland einsog Steinahóll og Grímsey voru skoðuð, sem og önnur þekkt svæði og svæði sem hafa ekki verið staðfest. Því næst er rannsóknaraðferðum sem gætu verið notaðar til þess að staðsetja jarðhitasvæði neðansjávar lýst. Þessar aðferðir eru meðal annars að draga úrval hitanema, efnanema og myndavéla á eftir rannsóknarskipi og notkun neðansjávarkafbáta. Jarðeðlisfræðilegum aðferðum eins og viðnámsmælingum og segulmælingum er beitt til þess að skilgreina eiginleika jarðhitasvæðanna. Margar af aðferðunum sem notaðar eru til jarðhitarannsókna á landi virka á sama hátt neðansjávar, sem kallar á nýjar nálganir við notkun þessara aðferða. Úrval aðferða sem notaðar eru í dag við jarðhitarannsóknir eru skoðaðar og fundið út hvort að hægt sé að nota þær eða aðlaga til rannsókna á jarðhitasvæðum neðansjávar.

Að auki er lýsing á segulmagnsmælingum sem fram fór við Eldvörp, á Reykjanesskaga, sem var aukaverkefni meðfram þessari rannsókn. Það reyndist ómögulegt að fjármagna leiðangur rannsóknarskips til segulmælinga á Reykjaneshrygg þannig að rannsóknin fór fram á landi. Tilgangur rannsóknarinnar var að læra hvernig segulmælingar fara fram og hvernig upplýsingarnar eru síðan túlkaðar. Mælingar neðansjávar fara fram á svipaðann hátt en þar eru mælarnir dregnir á eftir skipi eða festir á neðansjávarkafbát.

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List of Abbreviations

AGI………… Advanced Geosciences Inc.
AUV……….. Autonomous Underwater Vehicle
C-BASS……. Cable Burial Assessment Survey System
CSEM……… Controlled Source Electromagnetic
CTD………... Conductivity, Temperature, and Depth
DC…………. Direct Current
EGS……….. Enhanced Geothermal Systems
eH………….. electrochemical redox
EM…………. Electromagnetic
EMT……….. Electro-Magnetotelluric
GRS……….. Gamma Ray Spectrometry
IP………….. Induced Polarization
ISOR………. Iceland Geosurvey
LBSS………. Light Backscattering Sensors
LED………... Light-Emitting Diode
LiDAR……... Light Detection and Ranging
MAPR……... Miniature Autonomous Plume Recorder
MAR……….. Mid-Atlantic Ridge
MMR………. Magnetometric Resistivity
MT…………. Magneto-Telluric
MTEM…….. Multi Transient Electromagnetic
NFIP……….. Natural Field Induced Polarization
NTU………... Naphelometric Turbidity Units
OBC……….. Ocean Bottom Cable
OBEI………. SuperString Ocean Bottom Electrical Imaging System
OBEM……... Ocean Bottom Electro-Magnetometer
OBM……….. Ocean Bottom Magnetometer
OBS………... Ocean Bottom Seismometer
OBS/H……... Ocean Bottom Seismometer with Hydrophones
ORP………... Oxidation-Reduction Potential
RAMESSES.. Reykjanes Axial Melt Experiment: Structural Synthesis from Electromagnetics and Seismics
RISE……….. Reykjanes Iceland Seismic Experiment
ROV……….. Remotely Operated Vehicle
SIL…………. South Iceland Lowland
Sonar………. Sound navigation and ranging
SP………….. Self Potential
SUAVE…….. System Used to Assess Vented Emissions
SURTASS…. Surveillance Towed Array Sensor System
TACTASS…. Tactical Towed Array Surveillance System
TAG……….. Trans-Atlantic Geotraverse
TDEM……... Time Domain Electromagnetic
TEM……….. Transient Electromagnetic
XBT……….. Expendable Bathythermograph

1 Introduction

Geothermal energy is quickly growing as a means for heat and electricity production around the world, especially in Iceland. Five major geothermal fields are currently being utilized in Iceland, producing environmentally friendly electricity and hot water at an economically attractive rate [1]. It has been proposed that in the future Iceland might benefit from offshore geothermal energy. It is believed that high temperature geothermal resources exist in the oceans around Iceland. This research looks into potential offshore geothermal areas around Iceland and the exploration techniques that may be used for locating and evaluating these resources. The main region of in-depth geologic review is the Reykjanes Ridge (Figure 1); however all oceans surrounding Iceland are considered in this study.

The first main topic provides a background of what is already known about the Reykjanes Ridge. Then there is a review of the all known hydrothermal vents, and near shore hot springs around Iceland. Next, currently used and new potential methods for locating hydrothermal activity are discussed as that is the next logical step toward locating a suitable place for offshore geothermal energy production. After that, other geophysical methods are discussed because once hydrothermally active sites are found then further studies are needed to assess the characteristics of the reservoirs.

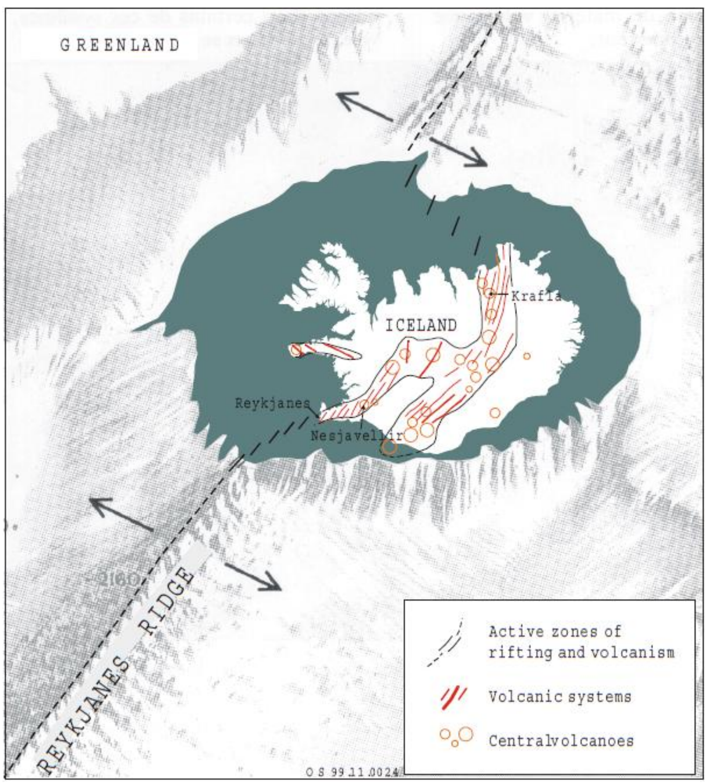

Figure 1) Reykjanes Ridge and active zones of rifting in Iceland [2]. It is not shown on this map, but volcanic systems are known to continue onto the Reykjanes Ridge.

1.1 Why Offshore?

To begin, harnessing offshore geothermal energy can offer environmental benefits. All of Iceland's geothermal power plants are located on land and there are still many geothermal fields which have not been developed, however as more of these resources are used, the feasible on-land resources become more limited and environmental concerns begin to arise. High energy reservoirs are often located in areas that are valued for tourism and nature preservation; therefore environmental effects that are unavoidable in the construction and operation of geothermal power plants are becoming increasingly important to take into consideration. One way to expand the use of clean geothermal energy while minimizing the negative environmental impact is to increase the amount of feasible resources. In other words, opening up the possibility of utilizing offshore resources will allow the industry to grow while preserving some of the beautiful geothermal areas on land. A geothermal power plant at sea will not use up any land space and most likely be out of site, so the physical presence would be minimal. By creating the option of utilizing offshore resources it will ultimately reduce the desire to disturb some of the pristine and touristic resources on land. There would however be an impact to ocean life and some environmental dangers from operating a power plant at sea, so the environmental assessment of this idea is certainly an important subject to consider, but that is the topic for another thesis.

In the future, offshore geothermal production may become economical and offshore options will help the geothermal industry to grow. When there are fewer resources available on land and all the best ones have been exploited, new geothermal fields will naturally be more expensive to develop. Eventually shifting to offshore resources might become economically as well as environmentally attractive, so it is important to know what resources are in the ocean. Overall, allowing and preparing for an expansion of geothermal energy production into the sea will be beneficial to Iceland and the world because it will open up many more options for clean renewable energy production. With the increasing prices and the inevitable exhaustion of fossil fuels, the demand for renewable energies will presumably grow. The earth's geothermal energy potential is enormous compared to the human energy consumption today [3], yet only a tiny percentage of this resource is tapped into because most of it is difficult to access. Almost all high temperature geothermal power plants are located in places which are on land, contain porous rocks, abundant water, and are along plate boundaries or near hot spots where relatively shallow geothermal heat exists [1]. Geothermal technology is advancing quickly though and the possibility of utilizing the earth's abundant heat from a more diverse range of environments is promising. For instance, in Australia a research pilot plant has been constructed in order to utilize heat from hot, dry, solid rock. This new type of geothermal power plant is called Enhanced Geothermal Systems (EGS) and involves creating man made fractures within the rocks at depth then pumping water down into the hot rock in order to produce steam [1]. This is one way that the geothermal energy industry is expanding because this technique creates artificial porosity and will eliminate the need to locate in a region with naturally porous rocks. Another way geothermal energy can expand is into the oceans. If ocean resources become feasible and economically attractive, it could open up thousands of possibilities for new geothermal sites around the world.

There are some advantages and disadvantages to offshore geothermal 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. Also, there is 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 sufficient method due to the unlimited cold seawater and hot geothermal source. Last, drilling at sea might make reaching supercritical fluids less challenging because drilling would begin at some depth below sea level. In other words, less rock to drill through to get to a certain depth and pressure might make reaching higher pressures less difficult. Disadvantages of offshore geothermal include higher costs for exploration, 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 case of any problems. The fact that the power plant would be located out in the open ocean holds inherent risks. To sum up, there will be many challenges involved with an offshore geothermal power plant, because so much is still unknown, but as with the offshore oil industry it may be found that going offshore is very beneficial for geothermal energy production as well.

Finally, opening up the possibility of producing electricity from geothermal power plants offshore would likely be very beneficial in the future. This technology could increase the available geothermal resource in the world drastically, which would be outstanding for the vision of a clean renewable future. It has been estimated that in the oceans tens of terawatts of geothermal energy is dissipated through hydrothermal vents alone [4], yet none of this energy is being utilized today. There has been little research done on utilizing offshore geothermal energy; however Italy is leading the world in this subject. Italy has future aspirations of constructing the world's first offshore geothermal power plant on the Marsili Seamount by the year 2015 [5]. Italy may well pave the way to offshore geothermal energy, but Iceland may not be too far behind them. Overall, the opportunity to go offshore will be a beneficial option for Iceland if resources ever become tight in the future. The question is, are offshore geothermal resources available at reasonable distances from land and reasonable depths? The following research will help to answer that question.

1.2 Exploration Strategy

The first step in finding a suitable location for on-land geothermal power plants begins with geologic reconnaissance. This involves collecting as much already available information and scientific data about an area. Geologists then explore and map all high temperature and low temperature geothermal fields. High temperature fields are defined as areas where the temperature is 200°C or higher within the top 1 km of crust. Low temperature fields are where the temperature is 150°C or lower within the top 1 km of crust [6]. Areas with temperatures between 150°C and 200°C are sometimes referred to as intermediate fields. High temperature fields are the most attractive sites for a power plant. The geophysical work also focuses on identifying the main geothermal reservoir and its characteristics including its size, temperature, permeability, water content, and energy potential. When exploring a geothermal reservoir a feasibility study is made. Once all the geothermal fields are located and the initial data are examined each area can be evaluated and ranked. The ranking must also take into account accessibility and environmental impacts. Once the best locations are identified, further geophysical research can be done to more accurately calculate reservoir characteristics and energy potential. After that, suitable locations can be chosen for exploratory drilling. Exploratory drilling will provide an even better understanding of the geothermal area, and then more geophysical studies can be conducted if necessary. Information from geophysical studies and exploratory drilling is collected until a firm understanding of the reservoir is established and productive well sites are determined.

That is the basic process for locating a geothermal power plant on land. Most high and low temperature geothermal fields in Iceland have already been thoroughly mapped (Figure 2). With all this in mind the first logical step toward locating a potential offshore geothermal power plant would be to gather all known information from the oceans around Iceland and locate all known hydrothermal vent sites and near shore hot springs. After that a similar map to Figure 2 can be made for the high and low temperature resources in the oceans. Hundreds of hydrothermal vents have been found around the world (Figure 3), but locating hydrothermally active sites in the sea is not as simple as locating geothermal sites on land. Hydrothermal vents are hidden beneath the sea surface and there is usually no indication of their existence on the surface, so it can be tricky to find them. Once they are found, it requires much more effort to obtain the basic information from them because often times a submersible needs to be sent down to the site, so the geologic reconnaissance step is much more expensive and difficult.

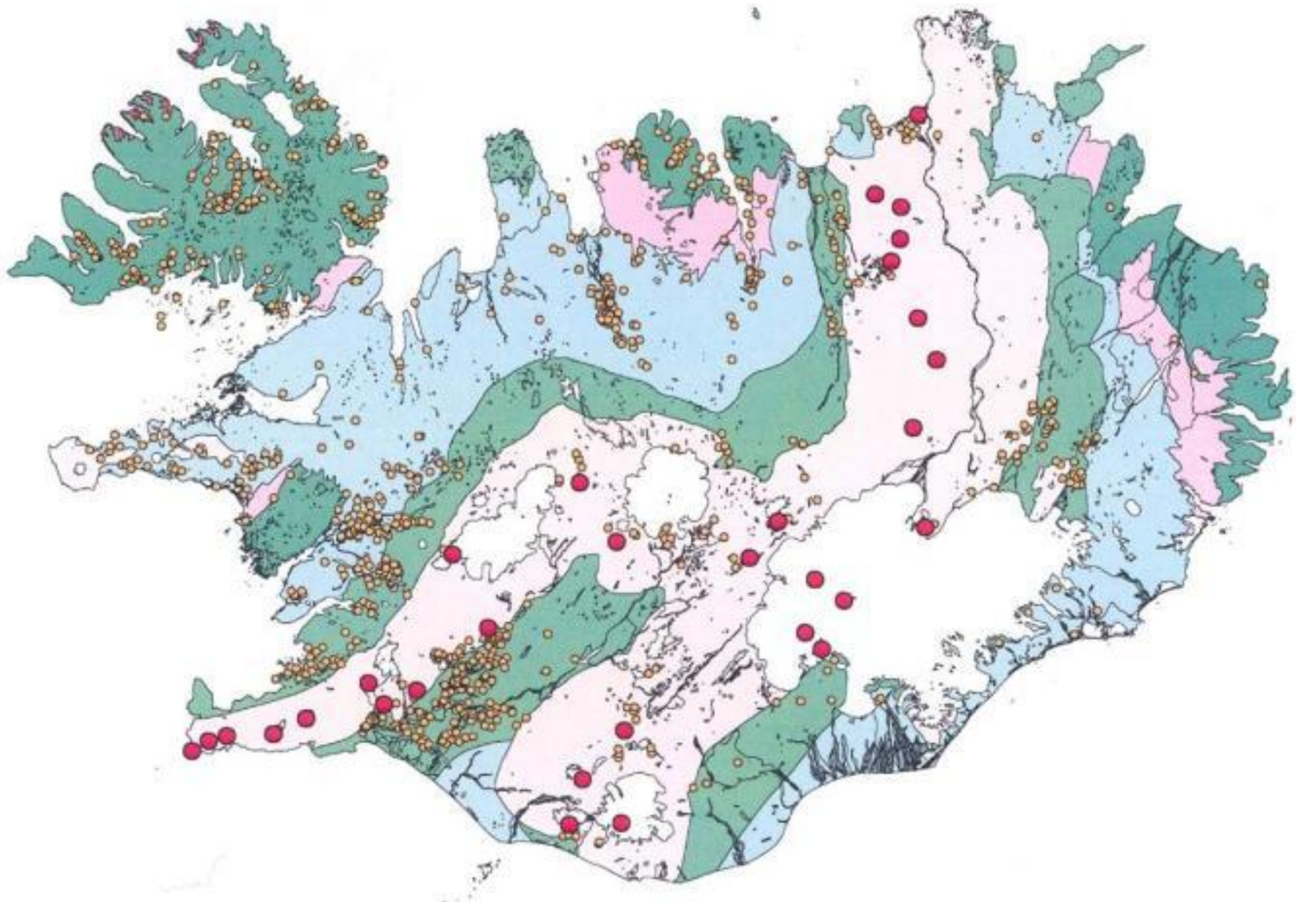

Figure 2) A Map of Iceland's high temperature (red dots) and low temperature (yellow dots) geothermal areas. The light pink area running through the center of Iceland is the active rifting zone [7].

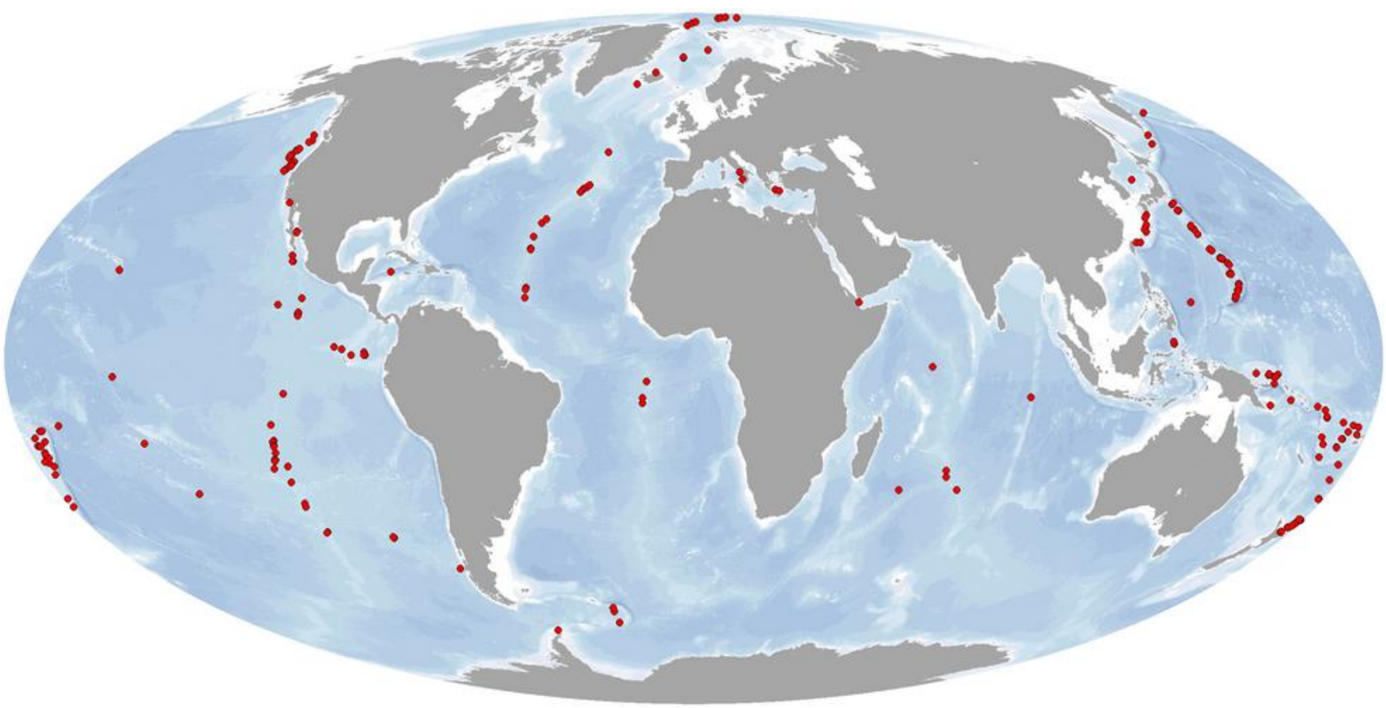

Figure 3) All confirmed high temperature hydrothermal vent sites around the world [8].

Right now there are no offshore geothermal power plants on earth so this research is very new. Not much has been done in this field of study, so one strategy of this research is to investigate how geothermal exploration is currently done and determine which exploration methods will be the most applicable for offshore exploration. Some methods are found to be useful, some need to be modified, and others cannot be used at sea. Methods that the offshore oil and gas industry uses and methods currently being used for locating hydrothermal vents are looked at. A summary for each method can be found in section 3. After that, a guideline is drawn up with a recommended approach for further offshore geothermal prospecting around Iceland. This will ultimately help any future companies who wish to pursue offshore geothermal energy.

The Reykjanes Ridge is the focus of this thesis because it is the part of the Mid-Atlantic Ridge that connects with southwestern Iceland as it may provide an optimal location for Iceland to have its first offshore geothermal power plant. The Reykjanes Ridge is part of the divergent plate boundary between the North American and European plate where geothermal activity is likely to exist (Figure 1). In this research, available information about the Reykjanes Ridge is sorted through so an assessment can be made about what is already known and what is still unknown. In the end, a recommendation, based on what is currently known, is made as to where the most suitable place for a geothermal power plant along the Reykjanes Ridge or other places around Iceland might be.

1.3 Magnetic Survey

One method commonly used to investigate geothermal areas is the magnetic method. As a side project to this a thesis a magnetic survey was conducted during the summer 2012. The survey was done in Eldvörp, which is a high temperature geothermal area on the Reykjanes Peninsula (Figure 4). The purpose of the field work was to learn about how a magnetic survey should be carried out and what the data can reveal about a geothermal area. The reason this field work was not done at sea is because funding did not allow for a research vessel to be rented for such a survey. This field work may have not been able to find anything related to offshore geothermal but the concepts are the same and the magnetic method might be very useful for future offshore exploration. The main difference between a land magnetic survey and a marine magnetic survey is that the magnetometer would be towed behind a ship or carried by a submersible rather than carried across the land. Other than that the data interpretation is similar and the types of anomalies that geophysicists would look for are similar.

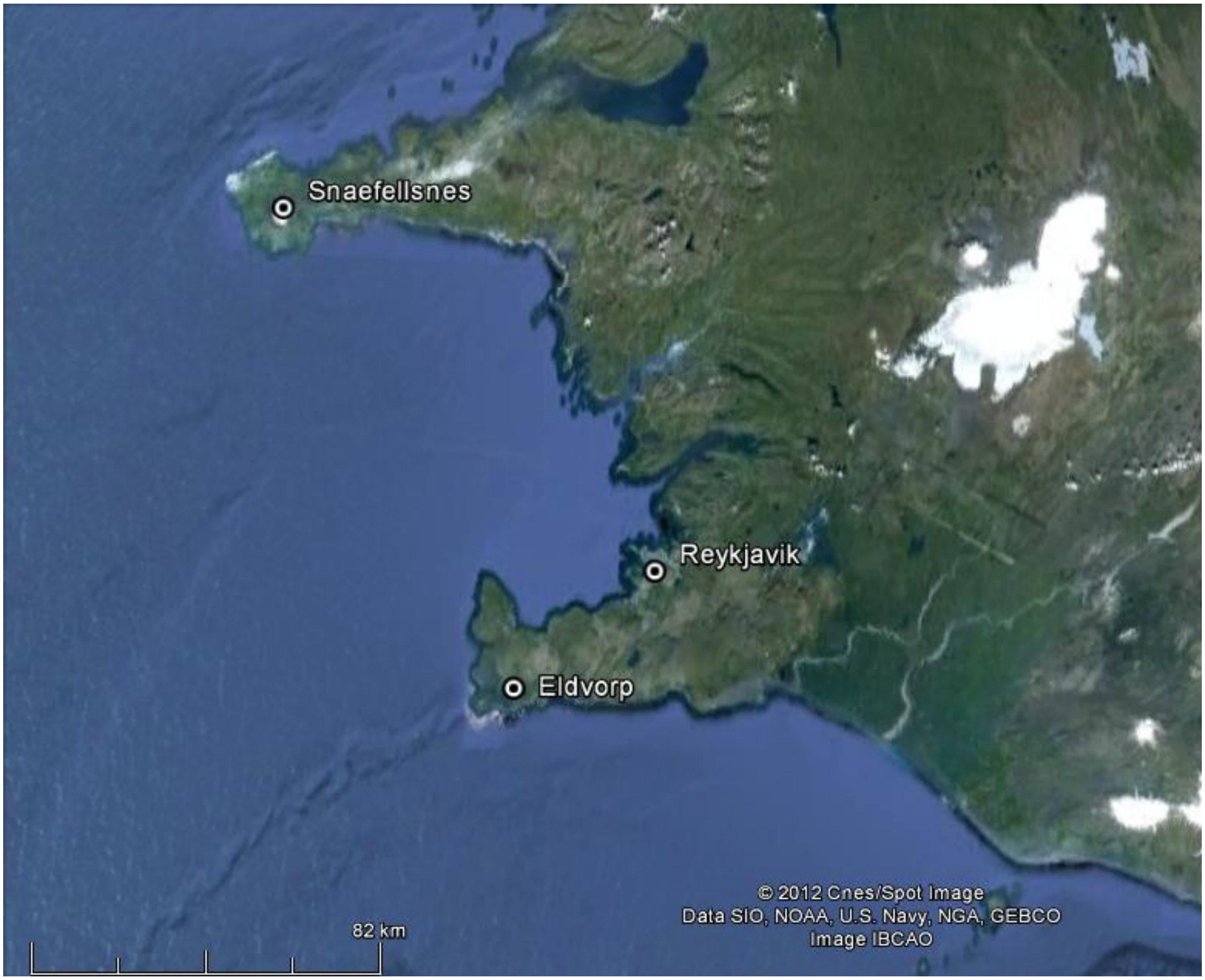

Figure 4) Google earth image of south western Iceland showing Eldvörp

2 Background and Literature Review

This section discusses what is currently known about the Reykjanes Ridge in relation to the geology and potential offshore geothermal resources. What is currently known about hydrothermal vents around Iceland is discussed. Then other offshore geothermal projects that are in progress around the world are mentioned.

2.1 Geology of Reykjanes Ridge

The most appealing area for an offshore geothermal power plant in Iceland is the Reykjanes Ridge, southwest of Iceland. It is believed that the Reykjanes Ridge holds a high potential for geothermal energy. One reason geothermal potential is expected is because several high temperature fields straddle the Reykjanes Peninsula connecting to the ridge with the Reykjanes geothermal field at the southwestern most tip of the

Peninsula (Figure 2). According the Iceland Geosurvey (ISOR) [9], the Reykjanes geothermal field is the highest temperature geothermal field in Iceland. The Reykjanes geothermal field has surface manifestations that cover an area of about 1 km^2. Resistivity surveys at Reykjanes indicate that the area of the geothermal reservoir is four times as large as what is indicated from the surface manifestations, and it extends well into the ocean to the southwest along the Reykjanes Ridge [9]. Another reason the Reykjanes Ridge is thought to have geothermal potential is because the ridge is a continuation of the active rifting zone that runs through the center of Iceland (Figure 1). Section 2.1 outlines the general geologic characteristics of the Reykjanes Ridge.

2.1.1 The Mid-Atlantic Ridge and Reykjanes Ridge

The Reykjanes Ridge extends south west from Iceland and is part of the Mid-Atlantic Ridge (MAR). The MAR spans across the globe nearly stretching from pole to pole. It separates the North American tectonic plate from the Eurasian plate and the South American plate from the African plate. The Reykjanes Ridge is only a small section of the MAR, stretching from the Bight fracture zone at about 57°N to the Reykjanes Peninsula at 63.8°N. The Reykjanes Ridge portion of the MAR is a slow spreading ridge with a half spreading rate of about 10 mm/year [10]. The southern end of the Reykjanes Ridge marks a point where the MAR topography changes from a median valley to an axial high, meaning the center of the ridge changes from a valley bottom to mountain tops in relation to the surrounding topography. This change in topography is suspected to be linked to the mantle plume beneath Iceland [10].

Hydrothermal activity on the ocean floor is one indicator of a potential heat source for an offshore geothermal power plant. The MAR is dotted with hydrothermal activity and on average hydrothermal vents are found roughly every 150-175 km along the MAR [11]. These hydrothermal vents expel fluids which can reach more than 360°C when located at great depths [11]. Considering how much thermal activity is found along the MAR and all the geothermal activity that is found on Iceland, it is a surprise that only one hydrothermal vent field has been confirmed along the 1000 km of the Reykjanes Ridge [11]. Based on the topography and geology of the Reykjanes Ridge and the characteristics of the rest of the MAR, it is highly likely that there are still undiscovered hydrothermal vents on the Reykjanes Ridge near Iceland.

2.1.2 Topography

The topography of Reykjanes Ridge just south of Iceland has been mapped using swath bathymetry (Figure 5). The ridge has many seamounts along its axis. The general trend is that the ridge gradually gets deeper as it extends southwest. Eldey is currently the only island that breaks the surface along the Reykjanes Ridge and it is about 14 km from Iceland. There are many seamounts lining the ridge and the topography appears to be very rugged near the ridge axis.

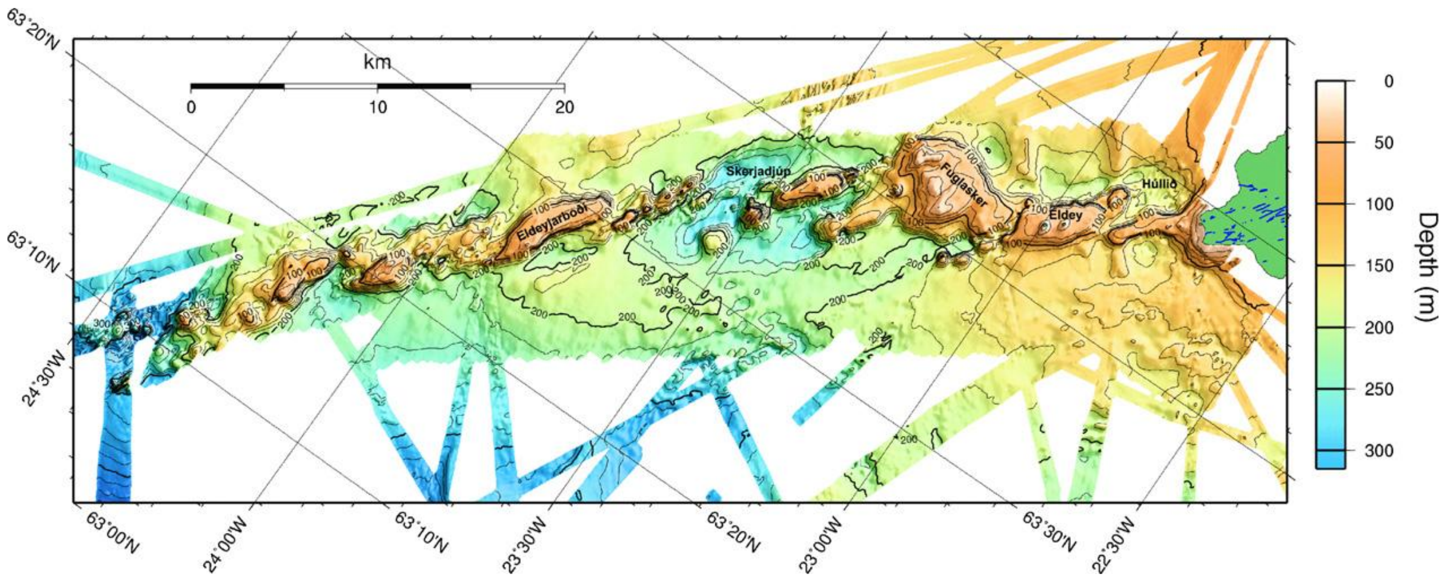

Figure 5) Bathymetry map of the northern Reykjanes Ridge [12].

2.1.3 Structure

The Reykjanes Ridge is a volcanic ridge consisting of many different pillow lavas. Hundreds of seamounts dot the ridge as it extends southwest. There is a pattern of en-echelon axial volcanic ridges along the Reykjanes Ridge. These axial volcanic ridges rise on average 200-400 meters above the seafloor [13]. There is also for the most part an en-echelon fault pattern on the ridge. Off the ridge axis, normal faulting that runs parallel with the ridge is found [13]. Right now not much detail is known about minor faults along the ridge.

One dispute still unanswered in the geologic community is whether or not the magma plume beneath Iceland extends along the Reykjanes Ridge [10]. The hydrothermal activity along the Reykjanes Ridge is not mapped well enough yet and a great deal is still unknown about the structures beneath the crust there, so the question arises: did the ridge form due to an extension of the magma plume or is it caused by passive seafloor spreading, comparable to the rest of the Mid Atlantic Ridge?

2.1.4 Petrology

The ridge consists of mainly pillow basalts and tuff with very little sediment cover. The quantity of sediment cover increases the greater the distance from the ridge axis [14]. This is expected because the rocks near the ridge axis are more recently erupted. Rocks collected from dredge samples are described as olivine tholeiites consisting of magnesium olivine, clinopyroxene (augite), and Plagioclase Feldspar (labradorite) [15]. The rocks are all fine-grained and vesicular except for a few samples where layered tuff has been recovered [15]. There are no reports of any unusual rock types found during dredging, so it can be assumed that the mineralogy of the basalts that form the Reykjanes Ridge are comparable to any other mid-ocean ridge.

2.1.5 Earthquake Activity

There is frequent earthquake activity along the Reykjanes Ridge mostly micro-seismic events, but occasionally larger earthquakes around 4 or 5 on the Richter scale occur [16]. Sometimes earthquake swarms occur along the ridge (Figure 6), where tens or even hundreds of seismic events occur very close to each other in a relatively short period of time [16]. These swarms could indicate volcanic events, plate movements, and/or hydrothermally related events. An earthquake swarm in 1990 is what lead scientists to the Steinahóll hydrothermal vent field [17], which is discussed in section 2.3.1.

In order to keep track of micro-seismic events in Iceland a network of seismometers has been put into place. This network is called the South Iceland Lowland (SIL) network and became fully operational in 1991 [18]. SIL is a network of seismometers placed around Iceland primarily to detect seismic events that occur on land. Its original purpose was as an earthquake prediction system. It measures and locates earthquake epicenters and micro-seismic events. Epicenters are automatically calculated by SIL, then manually checked and corrected for errors each day. The seismic station clocks have an accuracy of 1 ms, which allows for an accuracy of around 10 m for earthquakes within the network [18]. There are 58 seismometers in the network as of 2012, 7 of which are located on the Reykjanes Peninsula [19]. There are no seismometers located in the oceans around Iceland, which causes there to be higher error in locating earthquakes that occur out in the ocean.

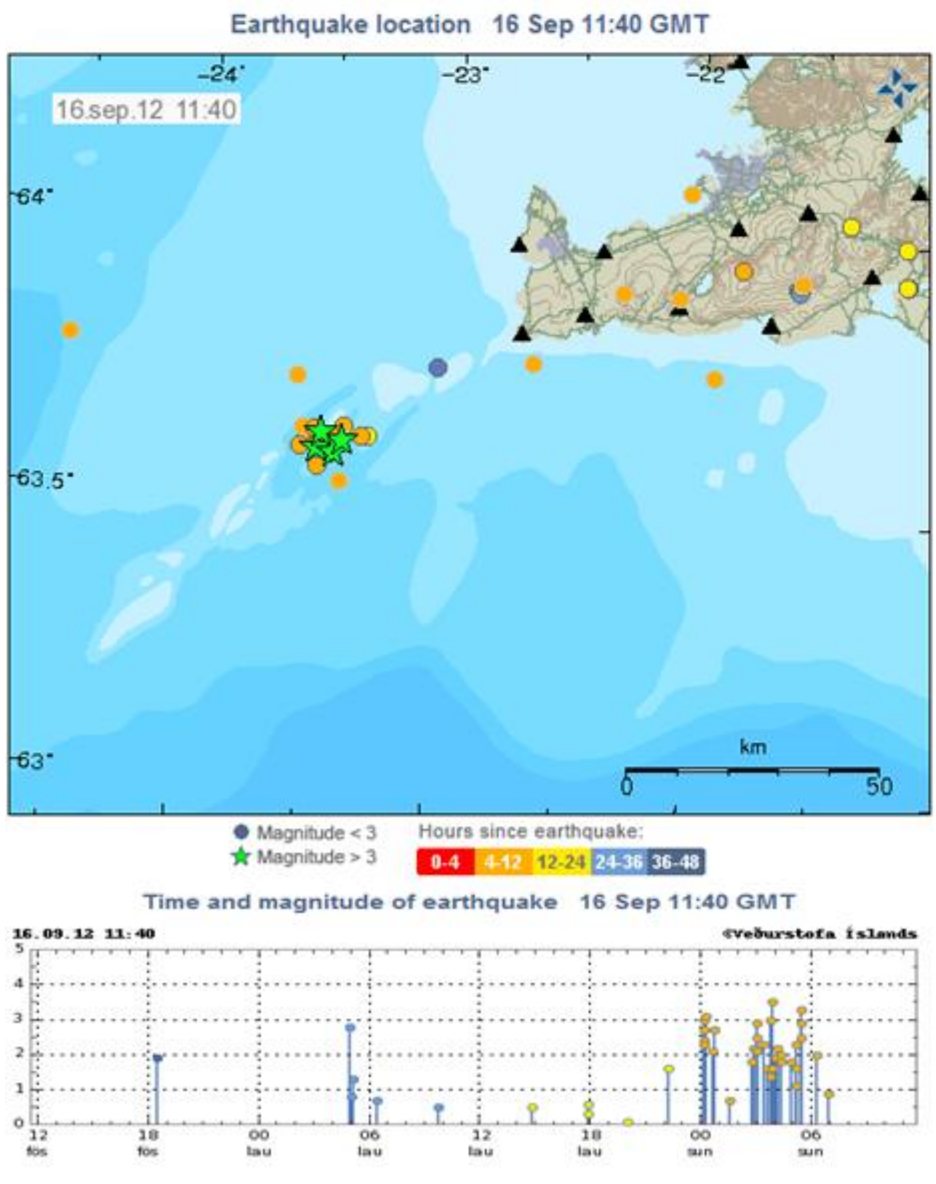

Figure 6) An example of a small earthquake swarm detected by the SIL network on September 16th 2012. The earthquake swarm is on the Reykjanes Ridge, roughly 45 km from land, between the Fuglasker and Eldeyjarboði seamounts. At this distance from the seismometers there is a narrow angle between the seismic activity and the instruments, so the location errors for each earthquake are less accurate compared to those within the network. The black triangles show the locations of the seismometers in the SIL network [19].

2.1.6 Volcanism

Throughout history there have been many submarine volcanic eruptions along the Reykjanes Ridge. The most recent confirmed eruption was in 1926 near the island of Eldey (Figure 7). Recent volcanic activity is a good indicator of an area below the crust with abundant heat. Figure 7 shows volcanic activity that has taken place on the Reykjanes Ridge since the 13th century. There have been eruptions on the ridge roughly every century.

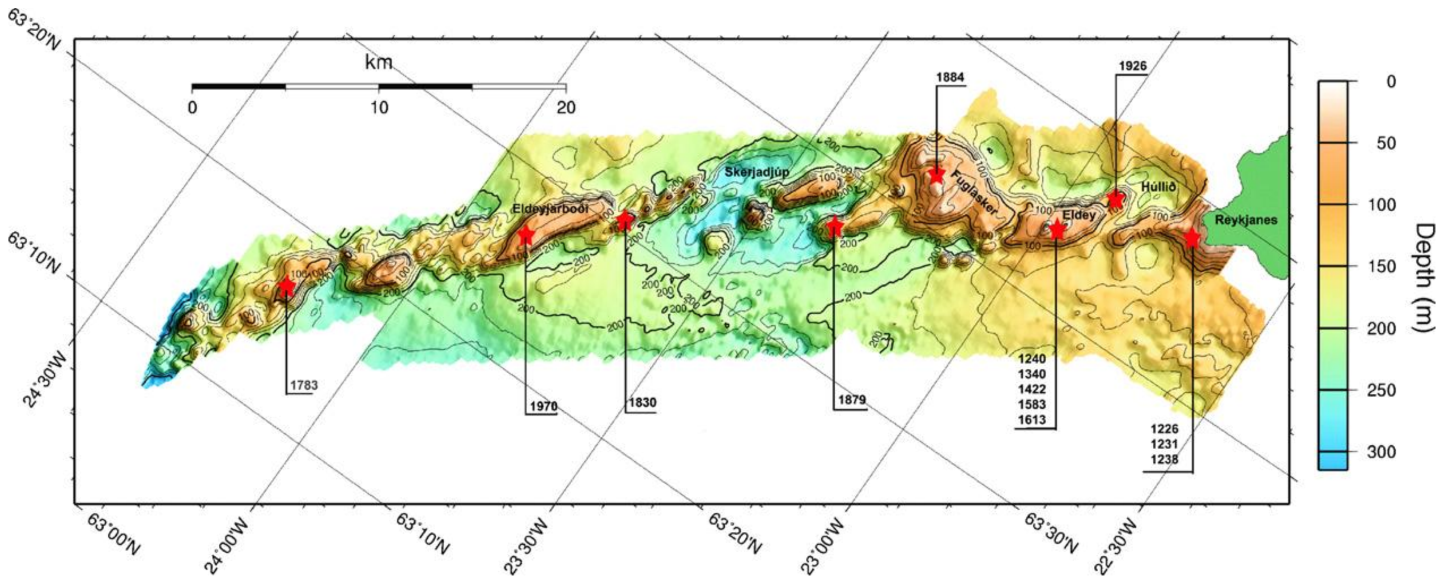

Figure 7) A Map of historical volcanic activity along the Reykjanes Ridge. The two most recent confirmed eruptions were near Eldey in 1926 and on the Fuglasker seamount in 1884. One eruption may have occurred in 1970 on the Eldeyjarboði seamount, but this has not been confirmed [12].

2.1.7 Ocean Currents

Before a geothermal power plant is constructed offshore, it is beneficial to have an idea about the ocean conditions. Figure 8 shows the general ocean currents around Iceland. The currents change seasonally and are very complex but overall they follow the patterns in Figure 8. Currents near shore on the Reykjanes Ridge mainly flow east to west [20]. Depending on the weather conditions the currents near shore can sometimes become very strong and make it difficult to work at sea [21]. Surface current components over the ridge crest average out to be close to zero [14] [22]. Northward currents, on the western side of the ridge average around 10-15 cm/s and southward flow, on the eastern side of the ridge are below 15 cm/s [23]. Bottom currents are relatively strong and flow southwest on the eastern side of the ridge and northeast on the western side of the ridge [14].

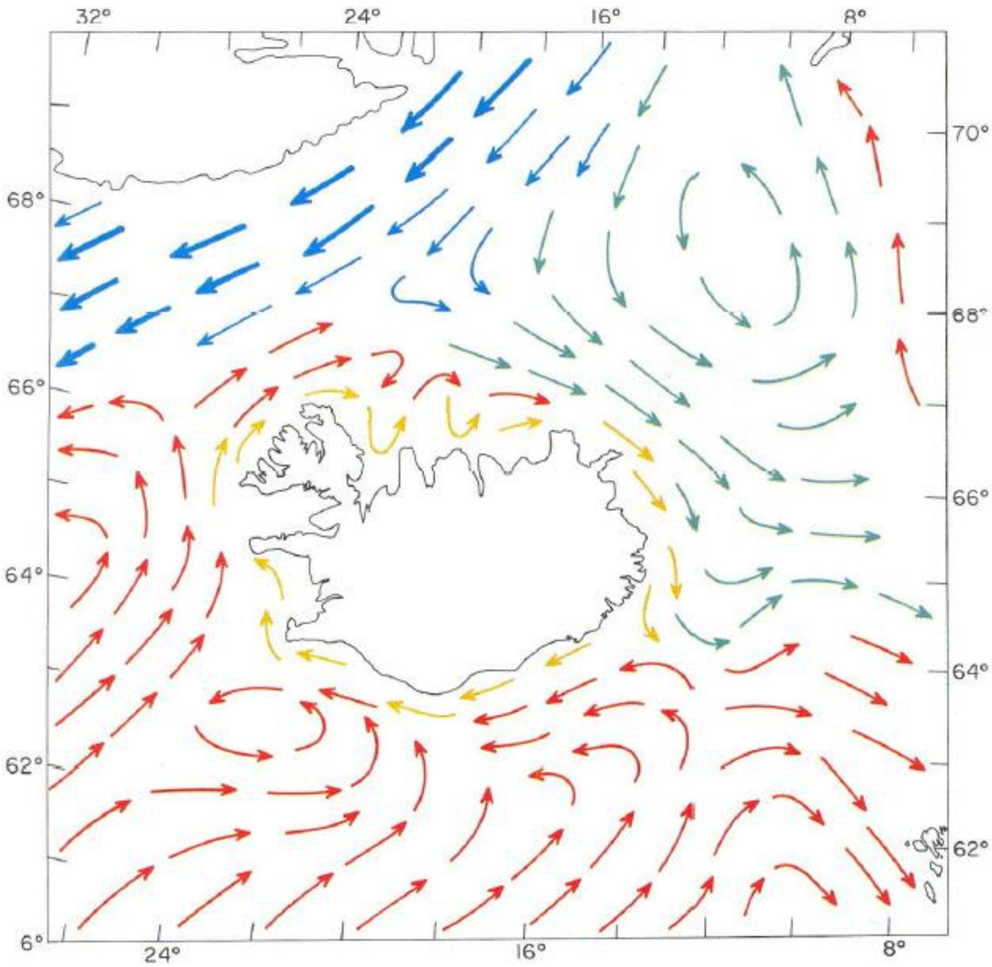

Figure 8) Map of regular ocean currents around Iceland. Red arrows are relatively warm currents, blue arrows are cold, and yellow are costal currents [20].

2.2 Past Studies on the Reykjanes Ridge

Section 2.2 outlines some geological and geophysical studies that have been conducted along the Reykjanes Ridge in the past. A short summary of each study and how the information might be useful for locating geothermal reservoirs along the Reykjanes Ridge is presented in the following section.

2.2.1 Reykjanes Iceland Seismic Experiment (RISE)

The RISE experiment was conducted in 1996 along the northern most 150 km of the Reykjanes Ridge [24]. Ocean Bottom Seismometers (OBSs) and on land seismometers were used to gain information about the crustal structures on the Reykjanes Ridge. 27 OBSs and 42 on land seismometers were used for this experiment. After the seismometers were in place shock waves were created in the crust using explosives. It was found that the top layer of rock has an average thickness of 0.5 km and the velocities recorded (1.9-2.5 km/s) indicate it consists of highly porous and fractured extrusive rocks [24]. Beneath that is a layer with an average thickness of 2.9 km and a high velocity gradient (1.0 s^{-1}), similar to what is seen on the Reykjanes peninsula [24]. The high velocity gradient could be attributed to crack and pore closure from lithostatic pressure, the precipitation of hydrothermal minerals, and/or increasing intensity of dikes with depth. The average thickness of the lower crust is 7.2-9.0 km and has an average velocity of 6.5-7.2 km/s [24]. The overall crust thickness is found to decrease from north to south [24].

This experiment has provided velocity and structural data about the crust of the northern Reykjanes Ridge. Of course, the actual structure is much more complex with intermediate layers and other heterogeneous features, but this experiment has helped to better understand the crustal structure. OBS readings played a very important role because they allowed for precise seismic wave arrival times to be recorded from the oceanic crust, which allowed for accurate velocities to be calculated. This is important because now any seismic events which occur on the ridge can be more accurately located since the velocities of the seismic waves at each depth are better understood. This study also helped to give an indication of the porosity and fault structure that can be expected beneath the surface. Ultimately, the knowledge gained from this study may provide additional information that could be useful for locating a potential offshore geothermal resource.

2.2.2 Micro-seismic Studies

Record keeping along the Reykjanes Ridge shows that there have been many small earthquakes on and around the Fuglasker seamount (Figure 9). This could indicate a potential geothermal heat source and/or hydrothermal activity. Seismic activity along the northern segment of the Reykjanes Ridge was low during the 1990's but began to increase in the year 2000, mainly around the Fuglasker seamount [12]. There have not been any hydrothermal vents confirmed on or around Fuglasker, but there have not been many ocean bottom investigations there either.

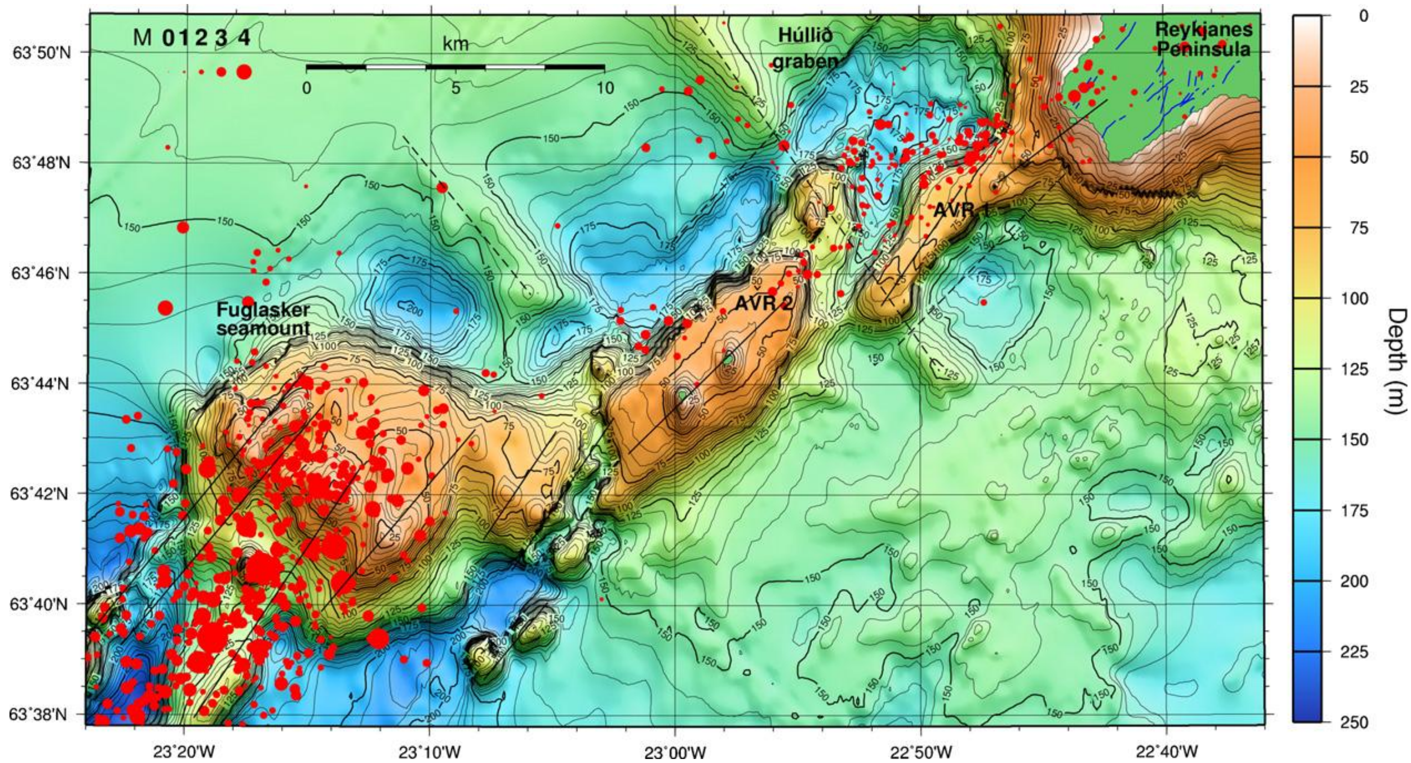

Figure 9) Map of seismic activity along the northern extent of the Reykjanes Ridge between 1990 and 2004. Red dots indicate earthquakes. A high concentration of seismic activity can be seen on and around the Fuglasker Seamount. The earthquakes farther south of the Fuglasker seamount are outside of the seismic networks accuracy zone so they can be inaccurate and therefore the map does not extend any farther south [12].

2.2.3 Ocean Drilling Projects

Two ocean drilling programs have drilled on and near the Reykjanes Ridge; the Deep Sea Drilling Project and the Ocean Drilling Program. These expeditions were both large projects with many drill sites in all the oceans around the world [25].

The Deep Sea Drilling Project was a series of scientific ocean drilling expeditions spanning from 1968 to 1983 [26]. During these expeditions a team of international scientists sailed around the earth and drilled for core samples in oceanic crust and conducted other various geophysical tests. Four bore holes were drilled in the vicinity of Iceland, sites 114, 407,408, and 409. The drill sites 407-409 run in a line perpendicular to the Reykjanes Ridge; only site 409 was located on the ridge axis (Figure 10). The primary goal of these drill sites was to investigate Iceland's geology and eruptive history. Site 114 is located about 100 km south east of the ridge axis and about 480 km south west of Iceland [27]. Site 407 is located west of the Reykjanes Ridge, about 385 km due west of the Reykjanes Peninsula [28]. Site 408 is located on the western flank of the Reykjanes Ridge about, 310 km west-southwest of the Reykjanes Peninsula [29]. The most relevant drill hole to this research is site 409. This drill hole is in the center of the Reykjanes Ridge; about 210 km from the tip of the Reykjanes Peninsula, and about 33 km from the inferred hydrothermal vent site Reykjanes Ridge Area A. The cores collected at this site revealed highly vesicular basalt, phyric and aphyric, with some unaltered olivine. Core samples at site 409 were collected down to 239 m [30]. No obvious evidence of hydrothermal activity or a geothermal heat source was mentioned in the reports.

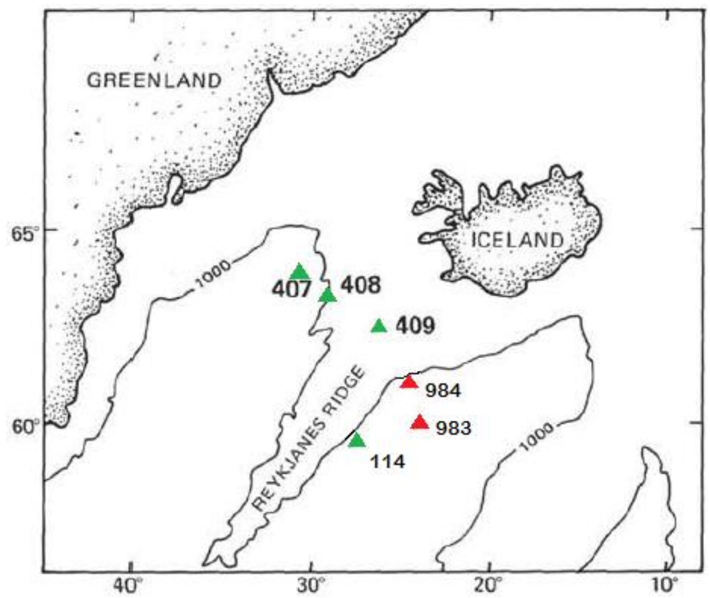

Figure 10) Green triangles are Deep Sea Drilling Project Sites. Red triangles are Ocean Drilling Program sites. Site 114 was drilled in 1972, sites 407, 408, and 409 were drilled in 1976, and sites 984 and 983 were drilled in 1995. Map modified from Wendell, 1979 [31].

The Ocean Drilling Program was a series of global expeditions that drilled into the ocean floor and took core samples to research the history of the ocean basins and learn about the crust beneath the ocean floor. During leg 162 of the program two drill sites, 983 and 984, were made east of the Reykjanes Ridge to study climate evolution and deep water circulation in the north Atlantic. Drilling of these sites was conducted in 1995. Site 983 is about 200 km from the ridge axis and site 984 is about 120 km from the ridge axis. The main goal for drilling these core samples was to investigate the sediment layers. No evidence of hydrothermal venting or other geothermal resources were mentioned in the reports for these drill sites [32],[33].

The Deep Sea Drilling Project and Ocean Drilling Program do not provide any indications of potential geothermal sites near Iceland. These projects are interesting though because they provide geologic information about the area. Cores from hole 409 offer some incentive as to what rock types drillers can expect in the upper-most crust along the ridge.

2.2.4 Dredging

In June 1971 four dredge samples were collected along the Reykjanes Ridge, during a cruise of the U.S.N.S. Lynch. All four of the dredges collected came from either the tops or sides of seamounts. The samples all consist of basalts and tuffs; typical rock types found at other mid-ocean ridges around the world. The names given to the dredges along the Reykjanes Ridge are D17, D18, D19, and D20. The descriptions and locations of the samples are shown in Table 1 and Figure 11. None of the dredged samples collected revealed any obvious evidence of hydrothermal activity. Detailed chemical composition of the rock samples is explained in Brooks et al. [15]. Chemically, there was nothing out of the ordinary about these samples; in fact their composition is very similar to average post glacial lavas on the Reykjanes Peninsula [15].

Table 1) Data for dredged samples along the Reykjanes Ridge [15].

Dredge number	Location	Depth (m)	Weight recovered (kg)	Rock type	Minerals
D17	63°38.6N 23°24.4W	67	25	Angular to sub rounded fragments of homogeneous basalt and palagonite tuff.	Phenocrysts of labradorite, magnesium olivine, and augite
D18	63°32.5N 23°39.9W	112	15	Angular fragments of homogenous pillow basalt	Phenocrysts of labradorite and augite
D19	63°25.2N 23°52.3W	68	50	Angular fragments of black homogenous basalt	Phenocrysts of labradorite, magnesium olivine, and augite
D20	63°17.6N 24°13.5W	99	15	Angular fragments of homogenous basalt, and some pillow basalt	Phenocrysts of labradorite and magnesium olivine

Figure 11) Google earth image showing the dredge locations along the Reykjanes Ridge

The research vessel Trident conducted dredge hauls along the Reykjanes Ridge in 1967 and 1971 (Figure 12) [34]. Nearly all the rocks pulled up were pieces of fresh pillow and slab basalts [34]. The samples were described as K-poor tholeiitic basalts [35]. Chemical analyses, including detailed sulfur analysis were conducted on the dredge samples. No anomalous measurements relating to hydrothermal activity were reported from these dredges [34].

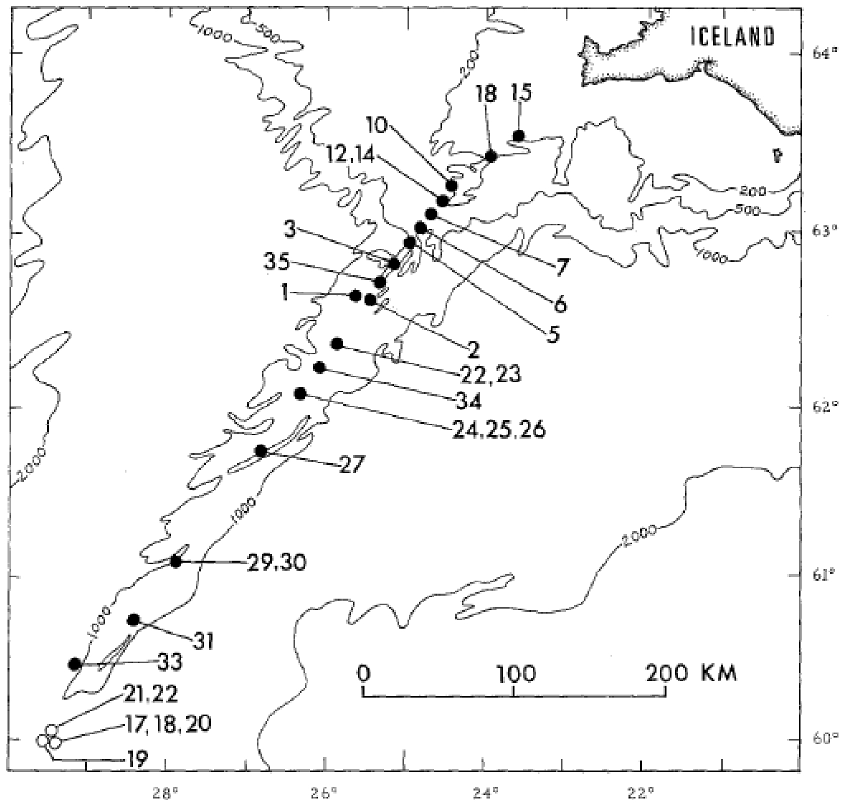

Figure 12) Map of dredge haul locations from the research vessel Trident. White circles are dredges from 1967 and black circles are from 1971 [34].

In 1994 the research vessel Charles Darwin recovered samples from 186 dredge sites along the Reykjanes ridge between 57.5°N and 63°N (Figure 13). Almost all of the material recovered from the dredges was crystalline basaltic pillows and slabs with glassy rinds; small amounts of hyaloclastite and pelagic sediment were recovered [36]. Major element analysis was done on the samples in the lab; detailed radiogenic isotopic analysis and X-ray fluorescence for detecting trace elements were performed. The report about these dredges does not make any mention about any hydrothermal material being recovered, nor does it say anything about evidence of hydrothermal activity being discovered [36].

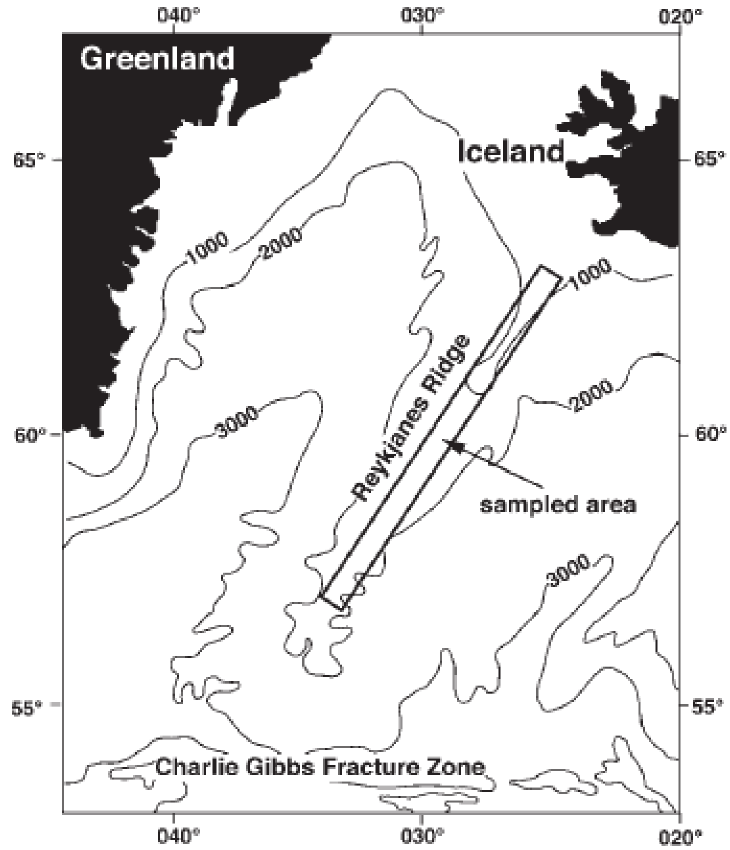

Figure 13) Sampling area from RSS Charles Darwin dredging cruise [36].

2.2.5 Reykjanes Ridge Crest: A Detailed Geophysical Study

The Reykjanes Ridge Crest study was a scientific expedition that took place in 1966 and utilized many different geophysical methods on and around the axis of the northern half of the Reykjanes Ridge. During the expedition water depth, magnetic, and gravity data were continuously recorded as the ship sailed. Core samples, dredges, water temperature, seismic refraction, and heat flow measurements were also conducted at many locations on and around the ridge axis [14].

During this expedition a marine magnetic survey was conducted over the Reykjanes Ridge. The survey revealed a magnetic high along the ridge axis with distinct bands of normal and reversed polarity off of the axis (Figure 14). This is no surprise now but back in 1966 when this survey was done the phenomenon was a very important discovery that helped to confirm the theory of mid-ocean spreading. The polarity reversals seen from magnetic data around the ridge also helped scientists learn about the ridge spreading rate, the time of crustal formation, and the earth's magnetic reversal interval, which are well known now [14]. These magnetic surveys however, do not reveal any obvious locations of hydrothermal activity or other offshore geothermal reservoirs.

Gravity measurements were made continuously during the expedition with a Graf Askania Gss2-12 sea gravimeter mounted on a gyro-stabilized platform [14]. The gravity surveys revealed free air gravity anomalies over the ridge ranging from +25 to +60 mgal [14]. A prominent feature of the gravity profiles is the gravity high along the ridge axis, and a gravitational low on each side of the ridge axis. The gravitational low coincides with the foot of an escarpment that runs along the ridge. These gravity data also show that there are several pockets of low, down to 25 mgal, anomalies off of the ridge axis. Gravity is not a primary method for locating geothermal resources however it can provides clues into the structure of the ridge.

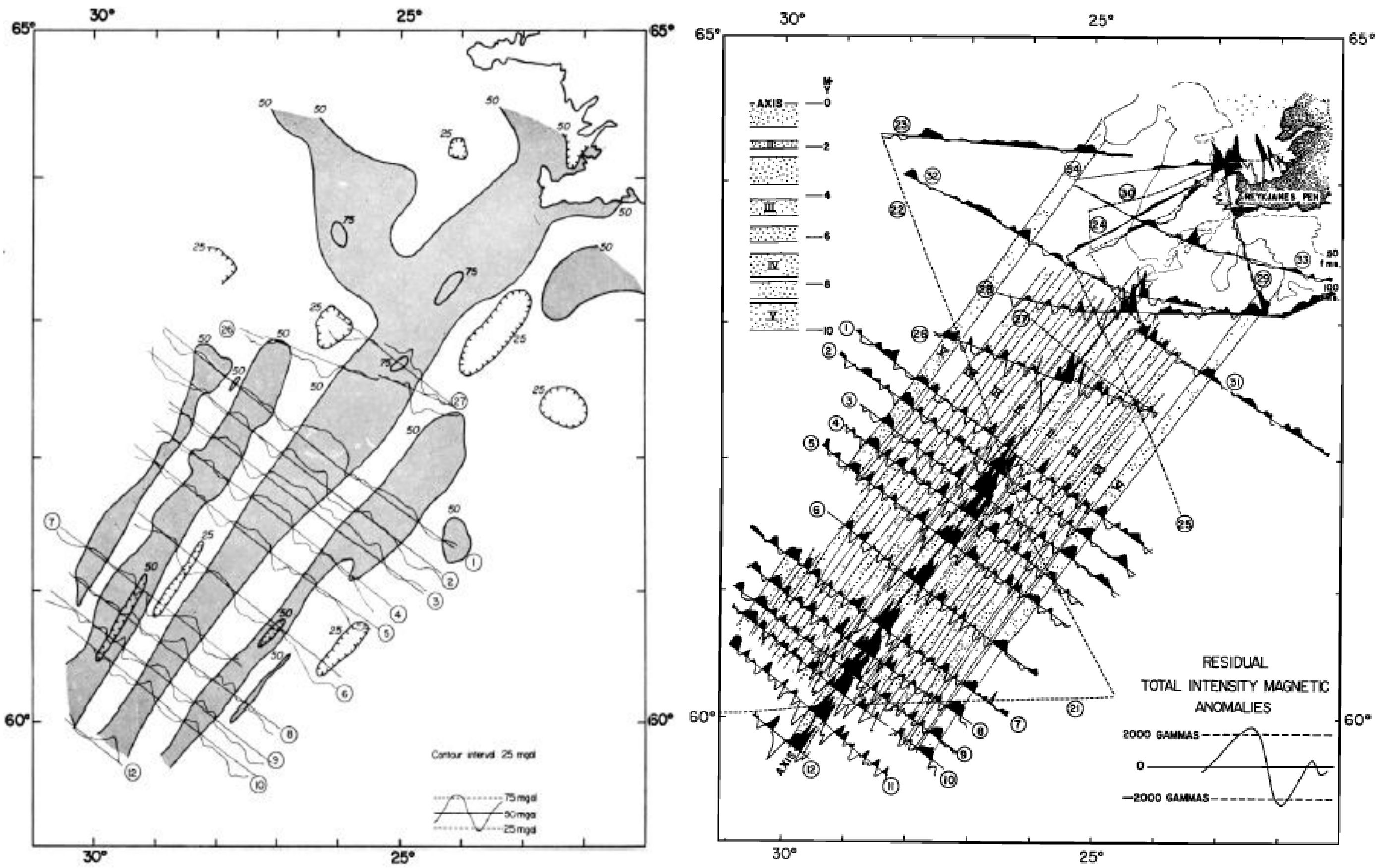

Figure 14) On the left: gravity map from the R.V. Vema cruise in 1966 [14]. The gravity profiles are plotted with the ship's track. The shaded areas represent gravity values greater than 50 mgal. A high gravity anomaly has been recorded over the ridge axis. On the right: magnetic map plotted with the ships tracks [14]. A magnetic high anomaly is recorded along the ridge axis.

During the Reykjanes Ridge crest survey heat flow measurements along the ridge were also conducted. The heat flow survey was done by taking measurements of the temperature gradient and conductivity in the sediment using 21 measuring stations [14]. The purpose was to determine geothermal flow from beneath the ridge and see how the heat flow changed at different distances from the ridge axis. The measurement device used was the Ewing thermograd apparatus, and the temperatures were measured up to 10-12 meters deep into the sediment [14]. Due to the sediment layer being very thin around the ridge axis the closest to the axis that these measurements could be made was about 10 km. Interestingly, low heat flow was recorded at about 75 km from the ridge axis and the maximum heat flow was recorded at about 25 km from the ridge axis [14]. Normally the highest heat flow should be recorded toward the center of the ridge. The anomaly may be due to the ground water circulation patterns or the unknown mantle plume configuration under the ridge. Overall, according to this study there is less heat flux near the Reykjanes Ridge than at other oceanic ridges [14]. This finding does not rule out the possibility of a high temperature heat source right at the center of the ridge, since the closest sensors to the center were 10 km away. Heat flow measurements similar to those done in this study might be beneficial for finding geothermal resources in the future if they are done in much more detail and cover the center of the Reykjanes Ridge.

Additionally, fourteen seismic refraction profiles were made during the Reykjanes Ridge crest survey. The seismic refraction data were collected by using expendable radio sonobuoys, which are dropped into the ocean and record seismic waves from just below the water's surface. Air guns and TNT blocks were used as sources for the seismic waves [14]. The profiles closest to the axis of the ridge reveal a top most layer that is 0.6-1.1 km thick with a velocity lower than 3 km/s. The second layer has a velocity of about 4.5 km/s, and the bottom layer has a velocity of about 7.4 km/s, the layer thicknesses are not clearly noted [14]. These figures do not agree exactly with the velocities found from the RISE experiment but they are very close. The difference could be due to the precise location of the profiles or possibly due to the different setup and methods of analysis that were used. Generally velocities appear to increase with increasing distance from the axis as the crust is older and denser further from the center of the ridge. Low seismic velocities at the center of the ridge suggest that the uppermost crust has very low density due to high porosity and faults [14].

Furthermore, dredging, photographs, and core samples taken near the ridge show that the basement rocks are usually bare basaltic pillow lavas [14]. Thus, the observed low velocities in the seismic readings could be due to a high porosity layer of pillow basalts overlying a more homogeneous consolidated basement layer. Dredge hauls over the axis of the Reykjanes Ridge pulled up primarily pillow basalts, which are highly magnetized, and very little to no sediment. The amount of sediment increases with increasing distance from the axis [14]. These findings are consistent with other studies of the Reykjanes Ridge and help contribute to the full understanding of the geology in this region.

A wealth of information about the geology of the Reykjanes Ridge was gained from this study, but none of the data reveal anything directly useful for locating an offshore geothermal power plant today. This study does however provide a better understanding of the structure of the Reykjanes Ridge.

2.2.6 Search for Hydrothermal Vents Along the Reykjanes Ridge

In 1993 there was a scientific cruise on the research vessel Bjarni Sæmundsson. It was sent out with the purpose of locating hydrothermal vents along the Reykjanes Ridge. During this cruise the Steinahóll vent field was confirmed (Section 2.3.1). The main instrument used on this cruise was called a CTD-nephelometer-transmissometer. It consisted of a Conductivity, Temperature, and Depth (CTD) sensor, a 25 cm path length SeaTech transmissometer, and a Chelsea Instruments AquaTracka III nephelometer, all within a large metal frame that holds water sampling bottles [37]. In simpler terms the instruments measure conductivity, temperature, depth, and light scattering which are discussed in section 3.1. The method they used was to stop the ship and drop the instrument straight down into the water column while making continuous measurements and collecting water samples for chemical analysis at various depths. Then they would retrieve the instrument and water samples, move on to the next station and drop the instrument straight down again. The water samples were analyzed for evidence of Si, CH_4, H_2, and Mn. The chemical analysis of the water was carried out using lab equipment on-board the ship. Measurements of total dissolved Mn and Si were determined using an auto analyzer system. Dissolved CH_4 and H_2 concentrations were measured using a portable gas chromatograph [17]. The shipboard scientific team also used a 38 kHz echo sounder to try and locate bubble rich plumes rising from the seafloor. Only one vent field called Steinahóll was discovered, which was already suspected to be there because of a major earthquake swarm that occurred in 1990 [38].

During this scientific expedition sampling stations were located along 750 km of the ridge and there were 175 sampling stations in total. 300 km of ridgeline were more extensively surveyed, these areas are marked A, B, C, and S in Figure 15. 23 CTD-nephelometer-transmissometer stations were made in area A, 45 in area B, 30 in area C, and 33 in area S. There were also 16 stations between areas S and A, 10 stations between areas A and B, and 10 stations between areas B and C [37]. Several stations were also made away from the center of the ridge. The stations done at the Steinahóll vent field were done in a dense grid for higher resolution. They found that the hydrothermal plume covered an area of approximately 4 X 6 miles [37].

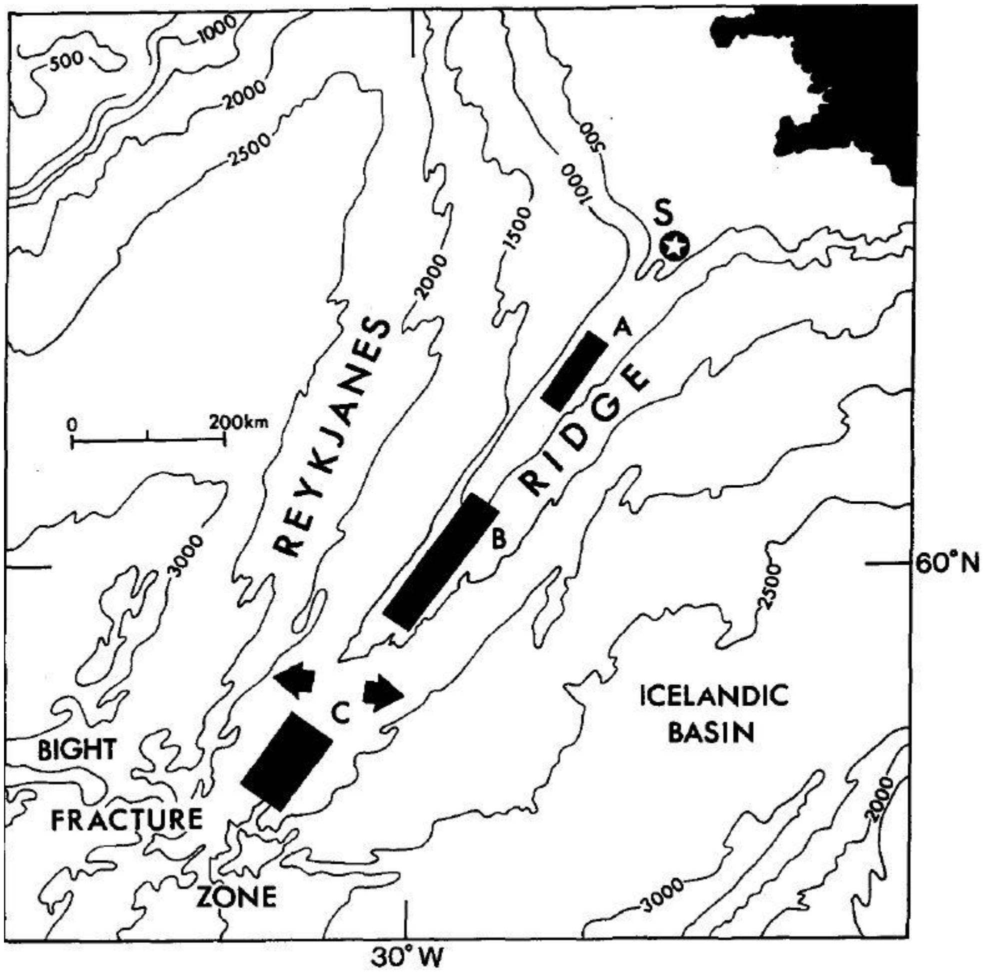

Figure 15) The area of study during the exploration for hydrothermal vents along the Reykjanes Ridge. The areas A, B, C, and S were more extensively surveyed, while the rest of the ridge was only surveyed using widely spaced CTD-nephelometer-transmissometer stations. The star marked S is the location of the Steinahóll vent field [17].

It appears from this study that the Reykjanes Ridge is not very active compared to Iceland and the rest of the Mid-Atlantic Ridge. Previous studies along the Mid-Atlantic ridge have shown that on average there is hydrothermal activity about every 150 km [17]. Surprisingly, during this entire expedition covering 750 km, only one vent field was discovered. In the article by German et al. [17], it was noted several times that there are far less known hydrothermal vents along the Reykjanes Ridge than along the rest of the Mid-Atlantic Ridge. The reason for this could be due to some unknown geologic irregularity between Iceland and the Mid-Atlantic Ridge. Another possibility is that some hydrothermal vents were simply undetected due to various factors. One theory for this mentioned that strong currents along the ridge cause hydrothermal evidence to dissipate quickly, thus making hydrothermal activity undetectable at the CTD-nephelometer-transmissometer stations [17]. It is possible that the CTD-nephelometer-transmissometer stations needed to be more frequent and vent fields could have been missed in the gaps between stations. Maybe more methods and different methods should be conducted before coming to the conclusion that there are not any other hydrothermal vents along the Reykjanes Ridge. It seems likely that there are other vents along the ridge but they are just more difficult to detect.

It is also possible that there really aren't any other hydrothermal vents on the Reykjanes Ridge. In a paper by Baker et al. [39], the Reykjanes Ridge is compared with a few similar hot spot related ridges. The other ridges in the comparison are the Galápagos Spreading Center, the South East Indian Ridge at Amsterdam Island and St. Paul Volcano, and the Ascension hot spot on the southern Mid-Atlantic Ridge. All of these Islands are similar to Iceland in the sense that they are located at hot spots on oceanic ridges. All of these locations are also noted to contain fewer high temperature hydrothermal vents that have been discovered on the nearby ridges compared with non-hot spot affected ridges. The reason for this pattern is unknown but there are several hypotheses. One hypothesis is reduced convective cooling, which means the higher temperature mantle causes the crust to be more ductile which in turn reduces fracturing and permeability thus decreasing hydrothermal fluids within the crust [10]. The next hypothesis is that there is low temperature cooling which could happen in two ways. One, higher porosity could cause there to be more fluid in the crust which dilutes the hydrothermal fluids causing there to a be more diffuse discharge thus lowering temperatures and the amount of metal precipitants; making it more difficult to detect hydrothermal activity. Two, the lower temperatures and metal precipitants are because of the shallow depths of the ridges which causes widespread low temperature phase separation [11]. Another hypothesis is that the hot spot influence over the ridges fluctuates and magma supply comes in brief episodes but most of the time the ridges are inactive [39]. If all four of these ridges are in time periods of low activity it would explain why they all share the same characteristic of having a relatively low pH at the few vents they do have. Whatever the explanation may be, the fact is that there have been far less high temperature hydrothermal vents found on the Reykjanes Ridge than ocean explorers expected, and a similar trend has occurred on comparable ridges around the world.

As a final point, it is possible that more high temperature hydrothermal vents exist on the Reykjanes Ridge and they just have not been found yet because they are more difficult to detect. They could be more difficult to detect for many reasons such as strong unusual currents, different chemistry, more diffuse venting or some other unknown factors. Further studies may find other hydrothermal vents; however it is possible there are no others. If there are no other high temperature hydrothermal vents along the Reykjanes Ridge it does not necessarily rule out the possibility of locating an offshore geothermal power plant there, but it may make the exploration process more challenging and the options fewer. On the plus side, most of the exploration for hydrothermal vents has been conducted far out at sea where the practicability of constructing a power plant is much less anyway. Less exploration has actually occurred near shore, so the possibility of finding suitable high temperature areas for offshore geothermal utilization still remains.

2.2.7 Magnetic Surveys

Aeromagnetic surveys have been conducted all over Iceland including the Reykjanes Ridge, maps are provided in Figure 16, Figure 17, and Figure 18. The maps show a positive magnetic anomaly trending along the Reykjanes Peninsula and extending into the ocean along the Reykjanes Ridge. The positive anomaly is surrounded by bands of alternating negative and positive magnetic anomalies which are caused by polarity reversals in the earth's magnetic field during the past as the tectonic plates spread. These magnetic maps do not reveal any obvious offshore geothermal resources, but they are indicative of where the youngest crust along the ridge is. The youngest crust has a high positive magnetic signature and marks where there would most likely be geothermal resources.

The majority of the magnetic data over land were collected from an airplane by Thorbjörn Sigurgeirsson from 1968-1980. In 1985-1986 L. Kristjansson and M. Sverrisson did a number of survey lines in order to fill the gaps, then G. Jonsson and L. Kristjansson added flight lines in 1990-1992 in order to replace old oceanic data that had been collected at sea [40].

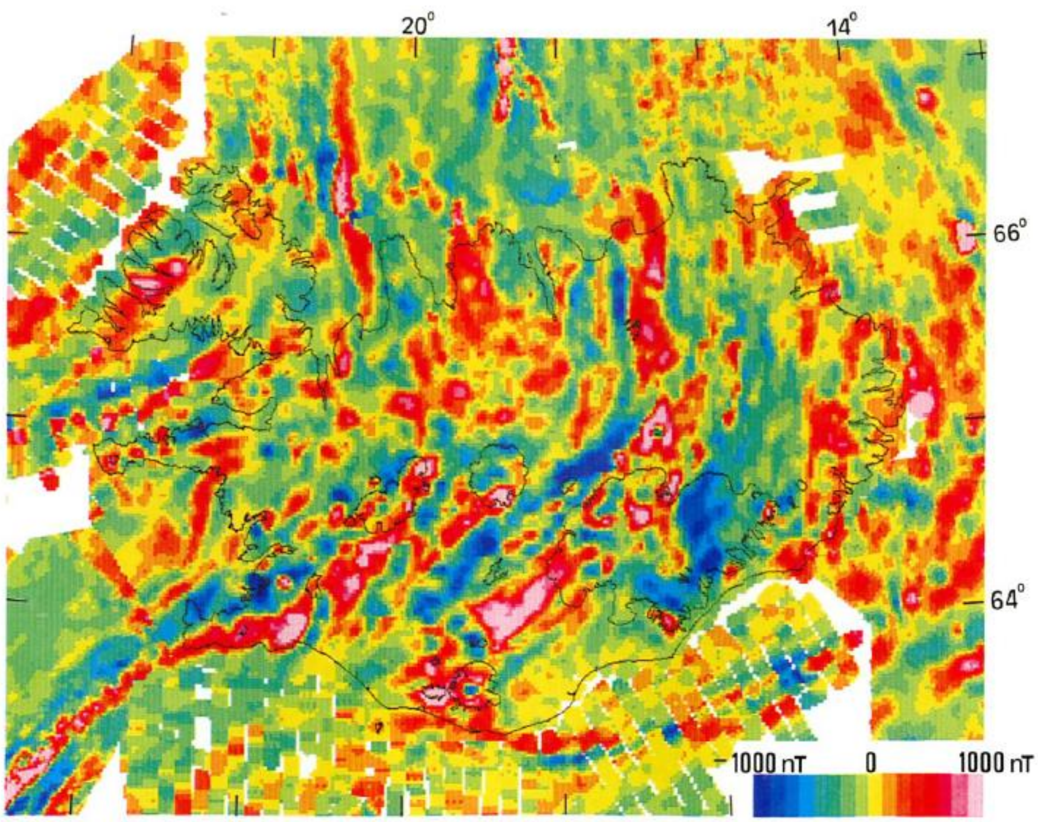

Figure 16) Compiled aero-magnetic surveys of Iceland. This map was created with the combination of data from several different scientists over the course of 24 years. Each color band represents a 125 nT interval. The survey altitude over Iceland was generally about 1 km above sea level [41].

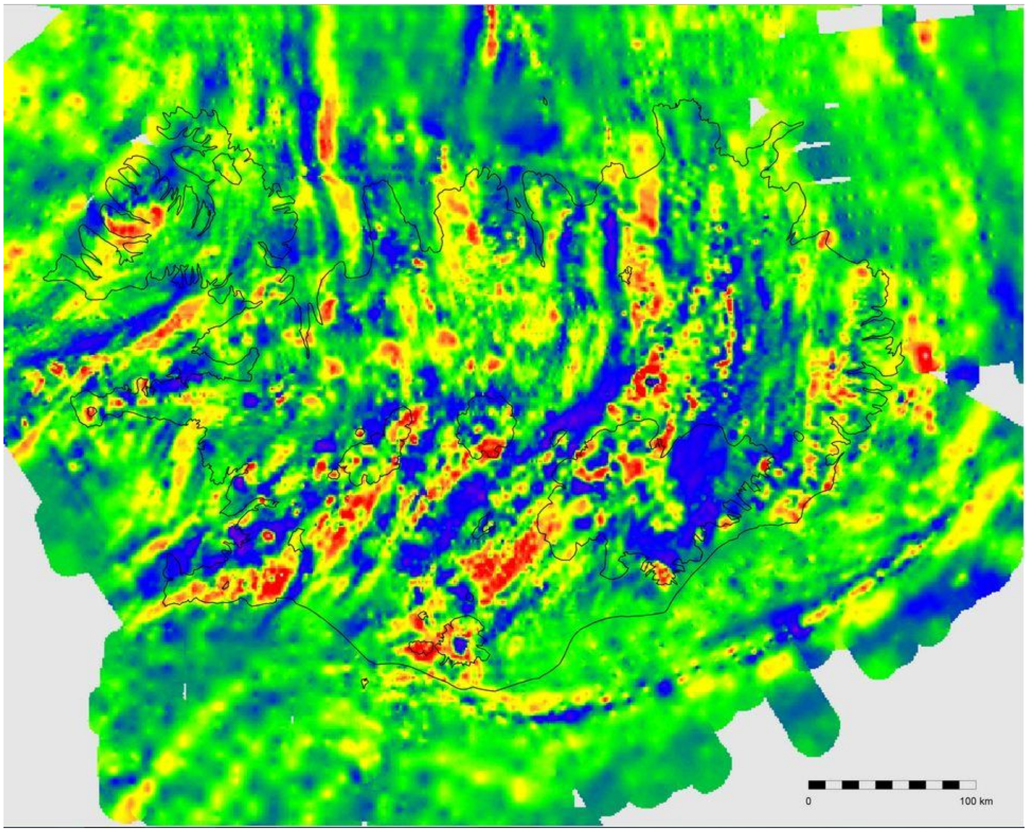

Figure 17) This map is a digitally enhanced version from the same compilation of surveys as in Figure 16 [42].

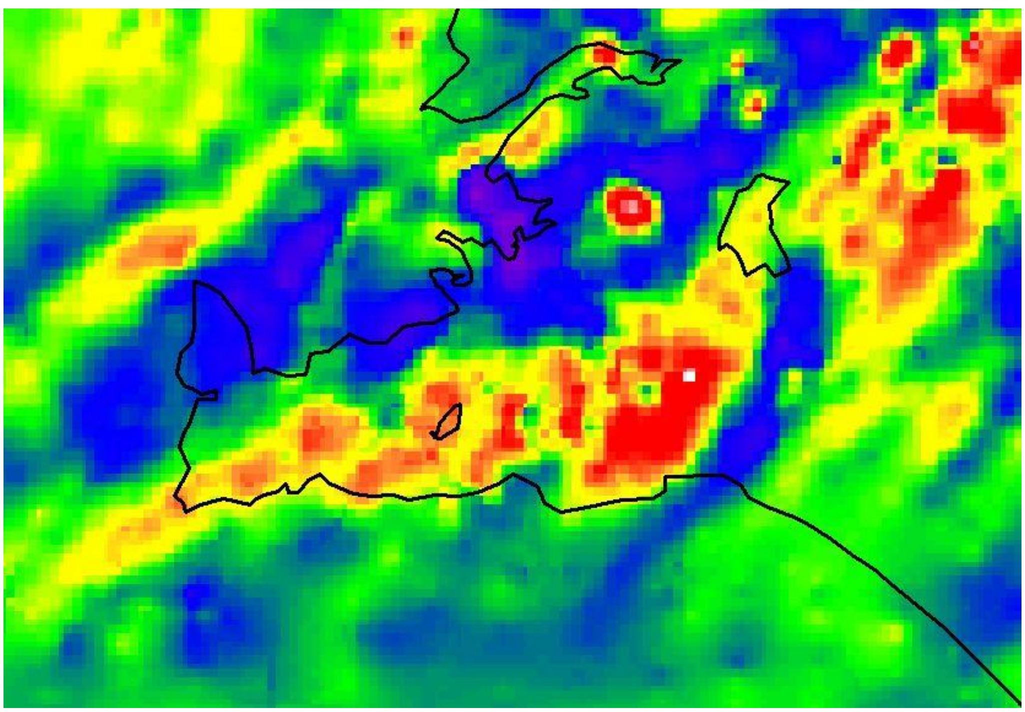

Figure 18) A zoomed in view, from Figure 17 of the Reykjanes Peninsula showing positive magnetic anomalies along the geothermally active zones of the peninsula [42].

Also, a couple of shipboard marine magnetic surveys were conducted south of Iceland; one in 1976 [43] and one in 2009 [44]. During the 1976 survey a Varian V-75 proton magnetometer was towed about 150 to 200 meters behind a ship. This survey covered a vast area in the waters of southern Iceland east of the Reykjanes Ridge. This survey only brushed the northern edge of the Reykjanes Ridge and the survey lines were spaced too far apart to create a reliable contour map [43]. The report about the 2009 magnetic survey does not specify exactly how the information was collected or what type of magnetometer was used but the survey did cover a large portion of the Reykjanes Ridge (Figure 19) [44]. Neither paper makes any mention for evidence of hydrothermal activity.

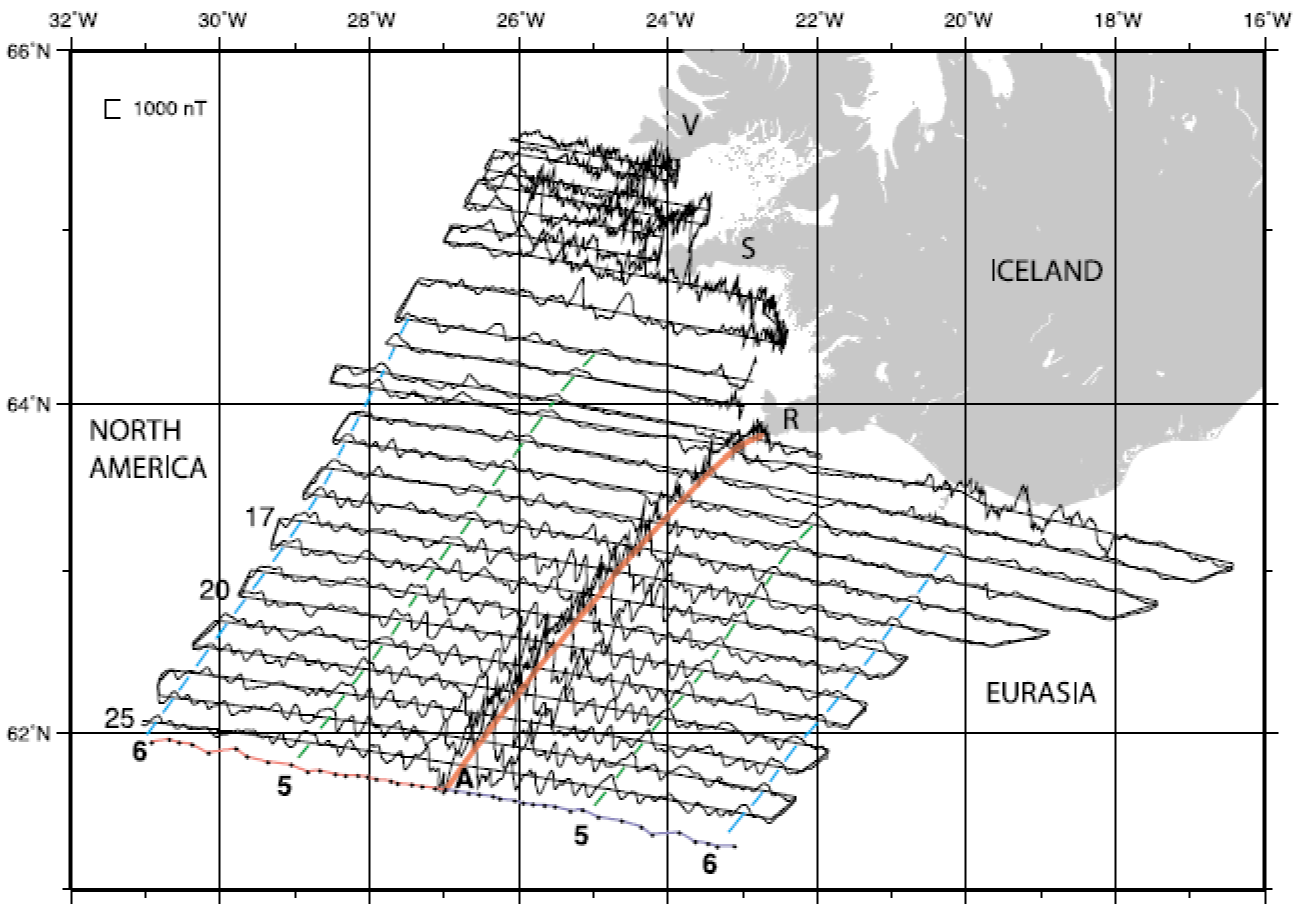

Figure 19) Marine magnetic data and track lines collected in 2009. The red line marks the ridge axis, the blue and green dotted lines are marking anomalies related to sea floor spreading [44].

2.2.8 Gravity Survey

Global marine gravity measurements have been derived via satellite. To date, eight high precision radar altimeter missions have provided valuable information used for creating marine gravity images around the earth [45]. One study conducted in 2009 used a combination of satellite derived gravity measurements and shipboard gravity measurements to create a nice gravity map of the region around Iceland (Figure 20) [44].

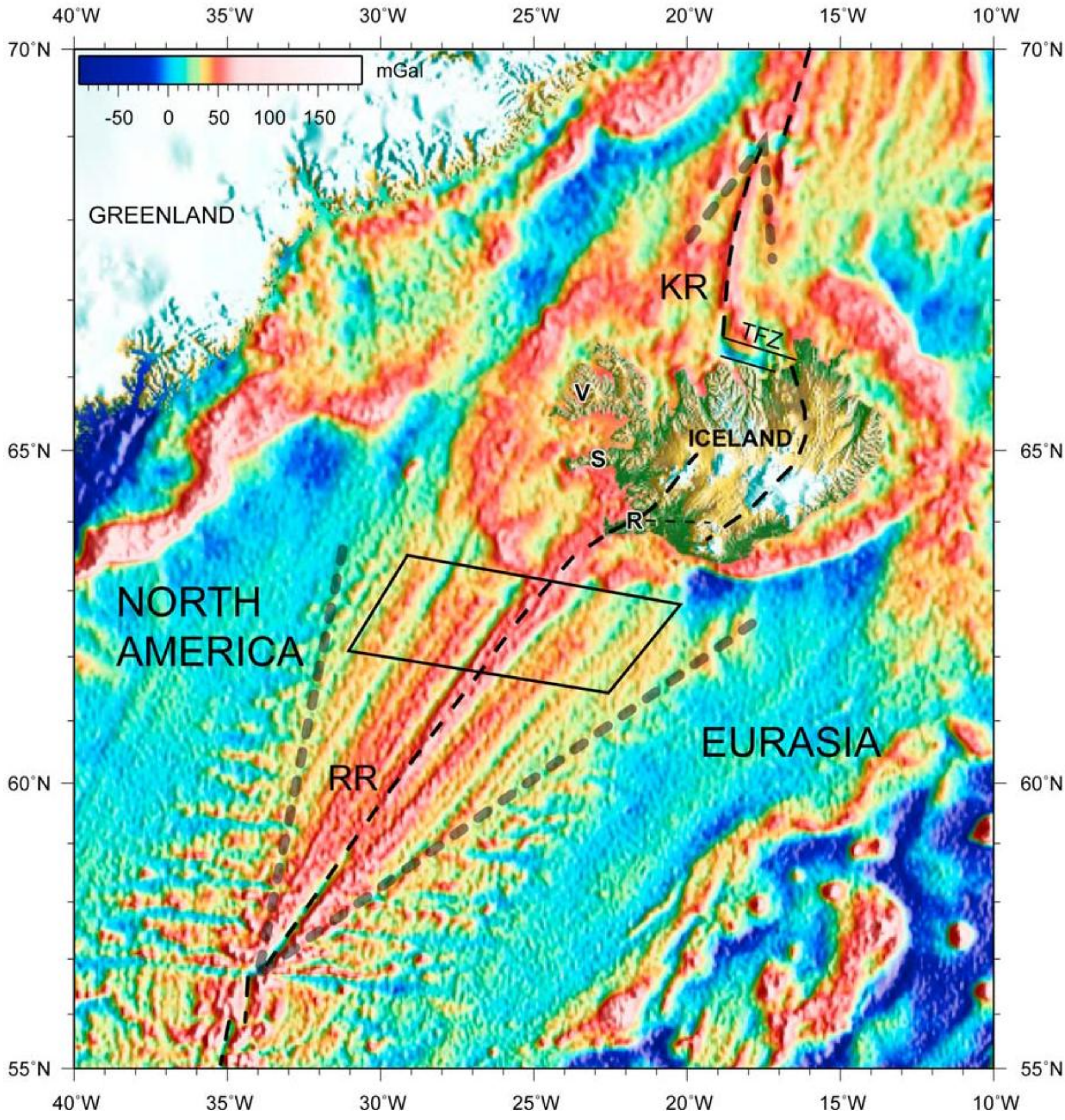

Figure 20) Satellite derived gravity map of the oceans around Iceland [44]. The box shows the area where shipboard gravity measurements were taken and compared with satellite derived gravity measurements; the two measurements matched up very well.

2.2.9 Reykjanes Axial Melt Experiment: Structural Synthesis from Electromagnetics and Seismics (RAMESSES) Study

The RAMESSES experiment was a geophysical study conducted in 1993 on the southern most part of Reykjanes Ridge at 57°45'N roughly 860 km from Iceland. In this study the following geophysical techniques were used: seismic experiments using OBSs, seismic reflection profiles, Controlled Source Electromagnetic (CSEM), Magneto-Telluric (MT), swath bathymetry, gravity, and magnetic [46]. Since this study was conducted so far from Iceland the information gained about the specific area is not of high interests for locating an offshore geothermal resource, so we will not go into detail about the findings. However, the CSEM and MT methods conducted are some of the few resistivity experiments that have been done over mid-ocean ridges, so the results of these surveys can give some insight as to whether or not they would be useful techniques to use for resistivity modeling of an offshore geothermal reservoir. These methods are discussed further in section 3.7.3.

2.3 Hydrothermal Vents Around Iceland

To begin the exploration process it is important to look for hydrothermal venting because these features are the most obvious indicators of a geothermal heat source in the ocean. When geothermal energy sources are located on land they are most often noticed due to surface features such as steam vents, geysers, and boiling pools that can be directly observed. In the ocean hydrothermal vents can be directly observed with underwater vehicles or towed cameras but it is not an easy task to find them because they cannot be seen from the surface. Also, underwater vehicles and towed cameras need to pass close to the vents because water visibility is limited and depends highly on depth and water clarity.

Some hydrothermal vents have already been found around Iceland but there is still a vast amount of unexplored ocean floor so the possibility of finding more exists. Section 2.3 discusses the hydrothermal vent fields that have been discovered around Iceland as well as some that are suspected but have not been visually confirmed.

2.3.1 Steinahóll Vent Field

To this day only one vent field called Steinahóll has been confirmed along the Reykjanes Ridge, it was first observed in 1993 via towed camera. A large earthquake swarm that occurred in 1990 aroused suspicion of Steinahóll three years before it was confirmed [17]. This earthquake swarm gave researchers clues that something unusual was happening around that location. Due to the distance from the nearest seismic stations, and the narrow angle between the earthquake swarm in relation to the seismometers, the calculated locations of the earthquakes had a high amount of error, so the first group of expeditions that went out to investigate had a large area to explore and nothing was found. Before the vents were discovered, trawlers conducted 12 dredge hauls around the area. They recovered fresh basalt, none of which was newly erupted or showed any evidence of hydrothermal alterations [38].

In June 1993 the Steinahóll vent field was confirmed during a scientific cruise. The sampling methods used on the cruise consisted of a CTD sensor, optical backscattering, swath bathymetry, deep-towed side-scan sonar, towed video and chemical analysis (Section 2.2.6). Strong evidence for hydrothermal activity around Steinahóll was indicated by high levels of total dissolvable Mn and high concentrations of dissolved CH_4 and H_2, there were also slightly higher levels of Si detected. The chemical levels found at Steinahóll are very similar to those found at the Trans-Atlantic Geotraverse (TAG) hydrothermal field; a black smoker area on the MAR at about 26°N. Gas bubbles from boiling have resulted in very high measurements of dissolved gasses. A higher concentration of H_2 and CH_4 than what is found at most other hydrothermal vents was observed [17]. Many samples were collected for chemical analysis of the water column. The CH_4, Mn, and H_2 information was looked at in great detail and an interpretation of the hydrothermal plumes flow dynamics was made in Ernst et al. 2000 [47]. The flow dynamics information helps to better understand how hydrothermal plumes behave in the water column.

The Steinahóll vent field is on the ridge axis and is about 120 km from the tip of the Reykjanes Peninsula (Figure 29). The depth of the vent field is about 250-350 m below sea level. One fascinating difference between Steinahóll and most other high temperature vent fields is that Steinahóll produces gas bubbles. The gas bubbles are thought to be produced due to the relatively shallow setting of the vent field. The shallow setting means less pressure which causes a lower boiling point at the vent field. This site has been recognized for these bubble rich plumes, which have been imaged using a high frequency 38 kHz echo sounder (Figure 21) [17]. This allows the vent field to be located very precisely.

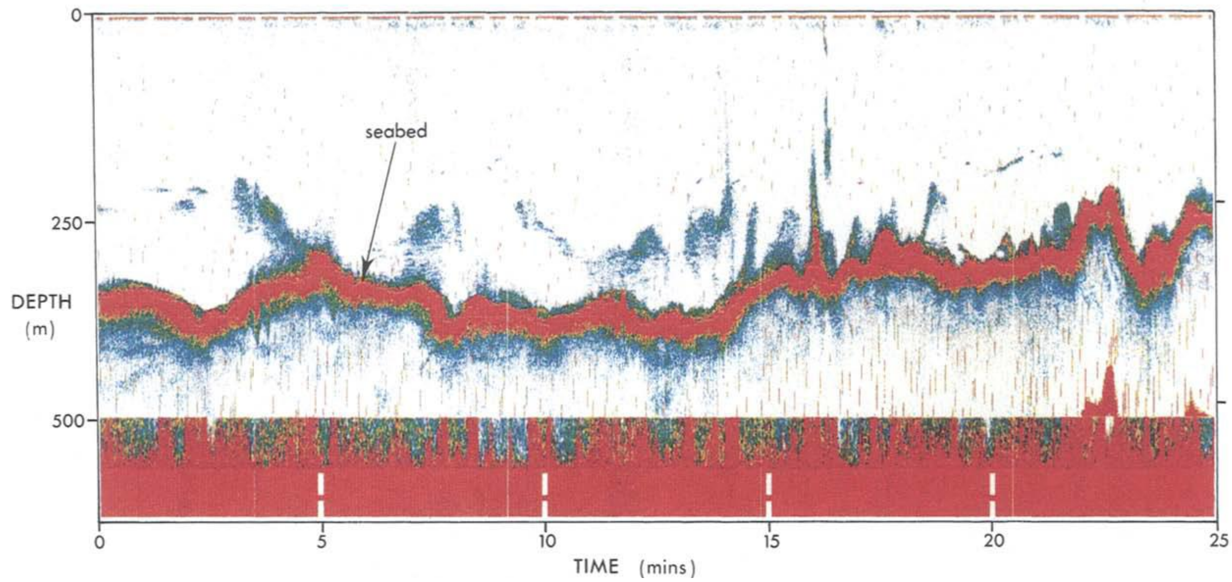

Figure 21) 38 kHz echo-sounder trace during a transect along the axis of the Reykjanes Ridge between 63°06.04'N and 63°06.10'N. The black marks above the seabed indicate traces of echo returns due to gas rich hydrothermal plumes rising from the ocean floor [17].

There is still a lot to learn about the Steinahóll vent field. For instance, no direct measurements or fluid samples have been taken from the vents, because underwater vehicles have not been down there yet. Also, very little is known about the size of the vent field and the surrounding geology. The temperature has not been measured but since gas bubbles rising from the vents are detected, the fluid is likely boiling when it exits the vents, so it is inferred to be about 220°C based on the boiling temperature of seawater at that depth (Figure 27). There is a possibility that the vent field has been explored in much more detail recently and these unknowns mentioned above are now known because in August 2012 a team on Paul Allen's yacht (The Octopus) conducted some studies in the waters around Iceland. A science crew got to use Paul Allen's yacht and submarines and it is rumored that they went down to the Steinahóll vent field. No papers have been published about this yet, so it is unknown what, if anything was learned about Steinahóll on this expedition.

2.3.2 Reykjanes Ridge Area A

Reykjanes Ridge area A is an unconfirmed hydrothermal vent field about 200 km from Iceland. This vent field appears on the "InterRidge Vents Database" but there is very little information about it. The area in question is at about 500 m deep [48]. Other than that, information is scarce because literature about this suspected vent field is un-published. Why hydrothermal venting there is suspected is not even provided on the InterRidge Vents Database. The most logical reason is that there were earthquake swarms there at some point in time which put it on the map.

2.3.3 Reykjanes Ridge Area B

On May 21st 1989 there was a major earthquake swarm on the Reykjanes Ridge at 59°44' N, 29°32' W the location is roughly 500 km southwest of Iceland and about 1000 m deep. This seismic event was detected on the world wide seismic network. There were a total of 40 teleseismic events with magnitudes between 4.0 and 5.5 [38]. The event prompted a quick response scientific team to investigate the area. The naval research laboratory had a P3 Orion aircraft fly over the area and deploy sonobouys and Expendable Bathythermographs (XBTs) in order to locate a possible underwater volcanic event. Thermal profiles were recorded with the XBTs in order to locate a hot anomaly in the water column but no anomalies were detected. The following year in 1990, Russian and American scientists teamed up and mobilized twin deep diving submersibles to study the area, however no hydrothermal venting or volcanic activity was located. No temperature or salinity measurements from the CTD giving any evidence of hydrothermal activity were recorded either. The submersibles and surface ships collected several sediment cores, basalt samples, biological samples, hours of CTD data, side scan sonar data, swath bathymetry data, magnetic data, water samples, photographs, and heat flow data [49].

Abundant fresh volcanic glass was found to be preserved in the rocks taken from this location. The development of palagonite was not observed [38], which indicates the volcanic glass was relatively young. Palagonite is an alteration mineral that occurs due to the interaction of volcanic glass with water. The rate of palagonitization is unclear and depends on many factors but after a rock is formed the alteration process begins immediately [50]. This means that on a geologic time scale the volcanic glass that was found was very young but its exact formation date is impossible to determine.

During the study in 1990, the sonar surveys that were conducted covered a 30 km stretch of the ridge in detail. These studies revealed a high number of small circular volcanoes and several volcanic ridges. The side scan sonar study also recorded three areas of very high backscattering which could be caused by steep slopes and/or relatively fresh lavas [49]. A magnetic survey covering an area of about 100 km^2 was also conducted during the 1990 cruise, but nothing more is said about the findings from the magnetic survey [38].

The area named Reykjanes Ridge Area B is an inferred hydrothermal or volcanic area, no absolute evidence of activity has been found yet. The submersible missions discovered lava flows and fault zones but the question remains; did these lava flows erupt from fissures during the 1989 seismic swarm event? The evidence shows that it is highly likely but it was not proven without a doubt [49].

2.3.4 Strytan and Arnarnesstrytur

Recently discovered within Eyjafjörður, are two hydrothermal vent fields (Figure 23) [51]. These hydrothermal vent areas are unique because they are the only known vents in the ocean which are at shallow enough depths for scuba divers to visit (Figure 22) [51]. The Strytan vent field consists of many hydrothermal chimneys spread around an area 200 m in radius, the largest and most significant structure being Strytan. Strytan is a gigantic hydrothermal cone extending from the sea floor and was discovered in 1997 by Erlendur Bogason [51], a commercial diver who now runs a scuba diving business which takes divers to these remarkable formations. Strytan rises 50 m up from the sea floor, its base lies at 65 mbsl and its top is at about 15 mbsl. Strytan ejects an estimated 100 liters/second of fresh water with a pH of 10 and a temperature of 75°C [51]. Seven years after Strytan was discovered another vent field with numerous small cones was discovered in Eyjafjörður this vent field was named Arnarnesstrytur. Arnarnesstrytur vent field lies at depths between 18 to 46 m and covers an area 400 m wide and 1000 m long [51]. Arnarnesstrytur also ejects fresh water with a pH of 10, but a slightly higher temperature of 79.5°C [51]. The geothermal fluid coming from the sea floor is anoxic with a salinity of about 0.1 times the salinity of seawater [52]. The chemical composition is variable. The cones at this location are built up mainly due to the precipitation of SiO_2 when it comes into contact with the cold seawater. These geothermal vent fields do not consist of black smokers. The maximum temperatures recorded are 79.5°C however the reservoir temperature is unknown [51]. The Silica geothermometer indicates temperatures of about 80°C. It appears that sea water does not penetrate the seafloor and get into the fresh water supply of these chimneys [52].

The hydrothermal vent area Strytan was long suspected because local fishermen had sometimes noticed a boiling disturbance on the water's surface [51]. In 1995 and 1996 a research vessel scanned the area in detail using multibeam sonar but they did not find Strytan; however they did find evidence of a small seamount in the area which raised more suspicion. Not long after that, in 1997, another expedition aiming to find the suspected vents took place utilizing the German submersible JEGO. This expedition found some hydrothermal activity and small cones below 45 m depth but did not locate the largest cone Strytan. Shortly after JEGO left the area the large cone Strytan was finally discovered. Erlendur Bogason located it on a scuba diving trip; he found the exact location because some local fishermen had noticed a disturbance on the water's surface [51]. The Arnarnesstrytur vent field was discovered in 2004 by the coast guard vessel named Baldur during a seafloor mapping mission for a proposed pipeline. They were utilizing multibeam sonar when the hydrothermal vent field was discovered [51].

These two low temperature vent fields are at shallow depths and very close to land; however they would not be feasible locations for an offshore geothermal power plant for several reasons. First, the temperatures are low; therefore, a power plant would need to operate via binary cycle utilizing a secondary fluid. It is possible that boreholes reaching depths of 1-2 km could reveal much hotter and high pressure fluids within the reservoir; however this would most likely destroy this magnificent and unique environment. Finally, building a power plant in these locations is out of the question because the Icelandic government has deemed these areas the first underwater protected areas in Iceland. There is however a borehole on land near Arnarnesstrytur which provides hot water to the town of Hjalteyri [51]. This borehole might be utilizing water from the same reservoir that supplies Arnarnesstrytur.

During my studies for this thesis I was fortunate enough to find the time to go scuba diving at Arnarnesstrytur. I dove with Erlendur Bogason who also trained and qualified me in dry suit scuba diving. The dives were more for recreational purposes rather than scientific; however the experience allowed me to learn a lot about these vents and see firsthand what hydrothermal venting on the seafloor looks like. Diving in Iceland at such an incredible and unique location is an experience I will never forget and I am very thankful to have had the opportunity to do it and relate it to my studies. Figure 22 shows just a few of the many pictures I took during the dives.

Figure 22) A) Me on the left and Erlendur Bogason on the right about to descend down to Arnarnesstrytur. B) A Wolf Fish at the site; many animals are attracted to this site because of the warm water. C) Hydrothermal minerals formed by the precipitation of SiO rich geothermal fluid [51]. The hot water rising from the rocks causes shimmering. D) A large hydrothermal stalagmite at Arnarnesstrytur which formed from many years of precipitated materials building up. The SiO in the hot geothermal fluid mixes with cold Mg rich seawater to form smectite [51]. This process slowly builds up these geothermal chimneys over many years.

Figure 23) Google earth map showing the locations of the Hydrothermal vents Strytan and Arnarnesstrytur within Eyjafjörður.

2.3.5 Grímsey Hydrothermal Field

Another geothermal field confirmed by the German submersible JEGO in 1997 was the Grímsey field. This hydrothermal vent field is located at about 400 m below sea level and roughly 16 km east of the island Grímsey, northern Iceland (Figure 29). There are around 20 large mounds in the Grímsey hydrothermal area most of which expel water at about 250°C. The thermally active area spans about 1 km^2 and primarily consists of shimmering water and extensive mounds of white anhydrite and talc. The buildup of large anhydrite deposits indicates that high temperature venting has been going on for a very long time. Actively boiling vents occur on most of the mounds and the widespread shimmering water indicates that the entire field is thermally active. [53].

The first suspicions of hydrothermal activity in that area was due to some hydrothermal material that had been recovered in fishing nets [53]. Then the vent field was hypothesized based on some interpretations of seismic reflection recordings and earthquake catalog data. The data indicated complex fault structures and a potential heat source in the subsurface. Furthermore, the locations of "polarity reversal anomalies" in the seismic seafloor reflection data coincided with other evidence of hydrothermal activity (Figure 24) [53].

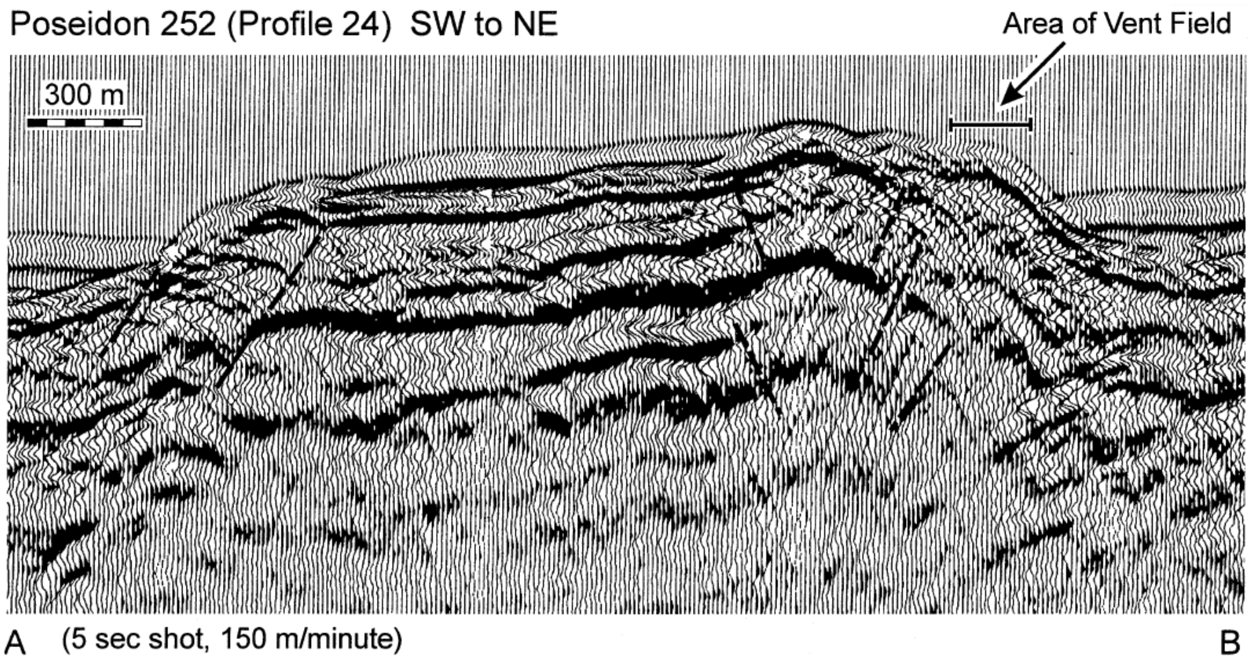

Figure 24) A Seismic reflection profile from the Grímsey field. Phase reversals in the record beneath the Grímsey field might correspond to subsurface gas accumulations in the sediments [53].

After that, a more precise location for the hydrothermal vents was discovered by measuring the concentration of dissolved gasses in the water column. High levels of CH_4 and CO_2 were measured around the vent field. Besides boiling water, most of the hydrothermal gas consists of CO_2, which dissolves as it rises to the surface. The CH_4 also remains dissolved in the water as it rises to the surface. The molecular composition of the gas and the isotopic composition of methane measured indicate a mostly abiogenic source possibly due to "Fischer-Tropsch reactions at 250-500°C mixed with thermogenic hydrocarbons" [54]. The gas geochemical results suggest that the origin of more than 90% of the hydrothermal fluids are derived from the upper mantle and oceanic crust [54]. After the vent field was found chemical measurements were taken from the fluid at the mouth of the vents. There is no smoke coming from any of the vents indicating that there are low concentrations of metals and sulfur in the fluid. The measurements revealed that the fluids are almost completely depleted of metals and have low salinity. The measurements from the highest temperature vent fluids reveal a pH between 5.9 and 6.8, and a high alkalinity (ability to neutralize acids) of 2.4-3.0 mEq/l. There were observations of phase separation within the vents, which are supported by calculations of seawater chlorinity. The dominant gasses measured from the vents are CH_4 and CO_2. The high CO_2 concentrations suggest a highly magmatic heat source [53].

In addition, 12 and 18 kHz echo sounding was used to detect gas bubbles in the water column above the vent field. The active hydrothermal vents were easily located by using the echo sounder because there are plenty of gas bubbles due to the boiling. The gas bubbles cause strong acoustic scattering which can be seen in Figure 25 [53].

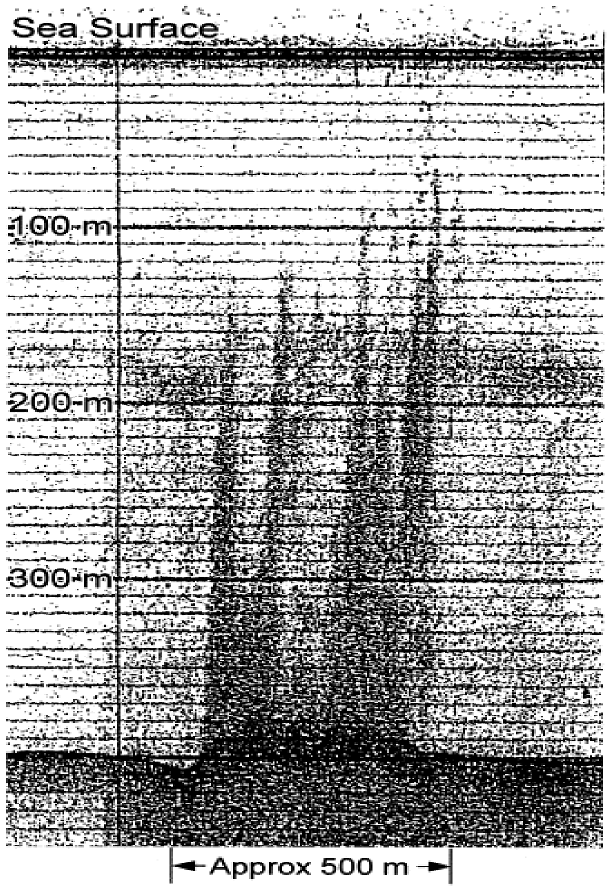

Figure 25) An exceptional profile from an 18 kHz echo sounder as the ship traveled over the Grímsey vent field. Obvious acoustic scattering from the bubble rich plumes that rise from the vents can be seen [53].

Core samples have also been taken from the Grímsey field. Seventeen core samples in total, which were between 3 to 5 meters deep in the sediments. All of the core samples were absent of burrows and any other signs of biologic activity [53]. The temperature of each core sample was recorded upon recovery. The cores with the highest temperatures map out an area of very high heat flow which surrounds the main hydrothermal mounds (Figure 26) and may possibly outline an area where boiling occurs beneath the sea floor [53]. Almost all the temperature measurements at the vents were between 248 and 251°C, which is close to the boiling point of seawater at the depth of the vents (Figure 27). Very few of the vents have temperatures less than 250°C; this implies that the temperature of the entire field is controlled by open system boiling and agrees with the findings from the core sample measurements [53].

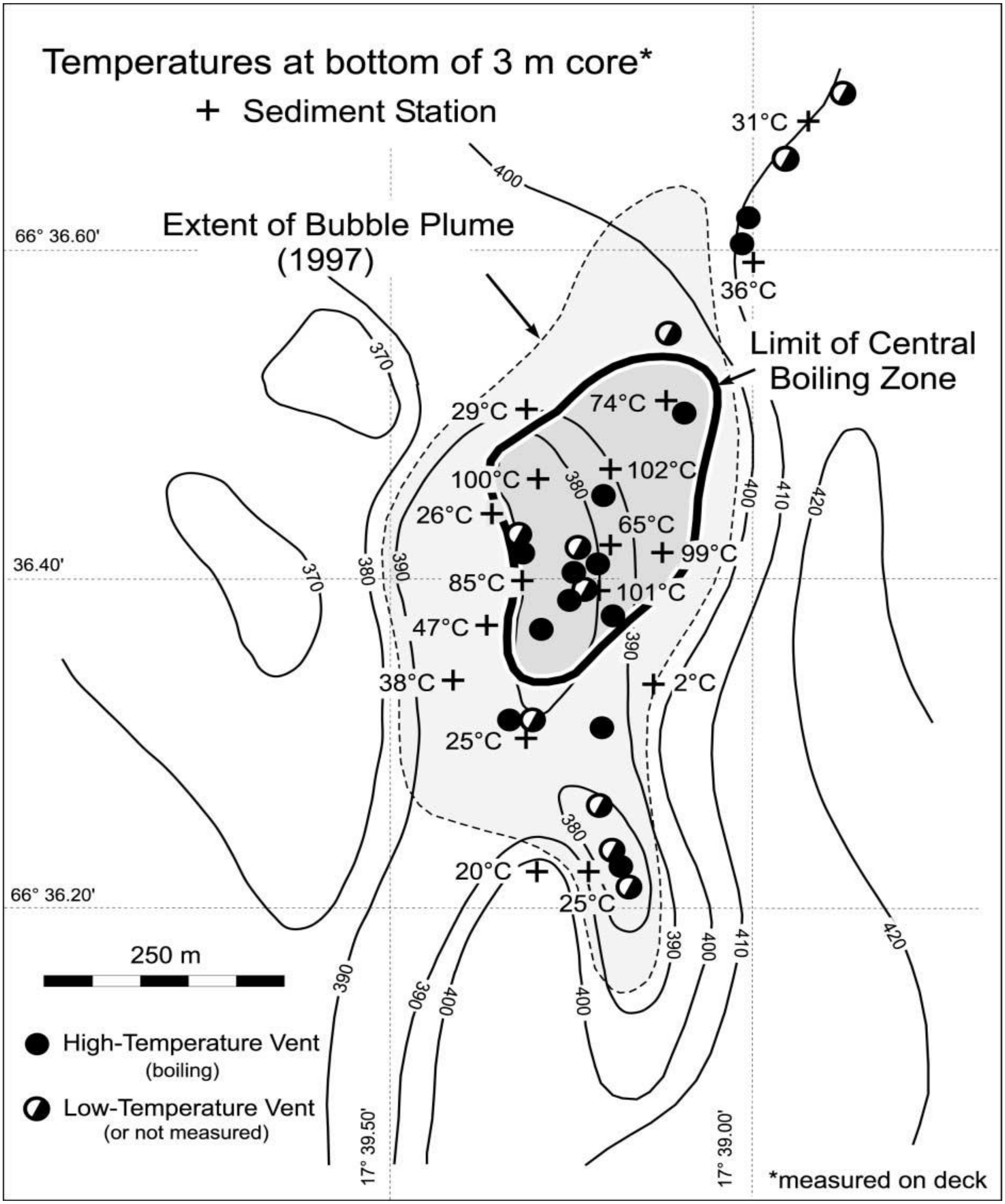

Figure 26) Map of the Grímsey hydrothermal vent field with bathymetric lines of 10 m intervals [53]. The light shaded area with the dotted line is the extent of the bubble rich plume recorded from the 18 kHz echo sounder. The + symbol shows the locations of the core sample along with the temperatures recorded upon recovery of the core on the ship. The dark shaded area in the center shows the extent of what is thought to be the central boiling zone.

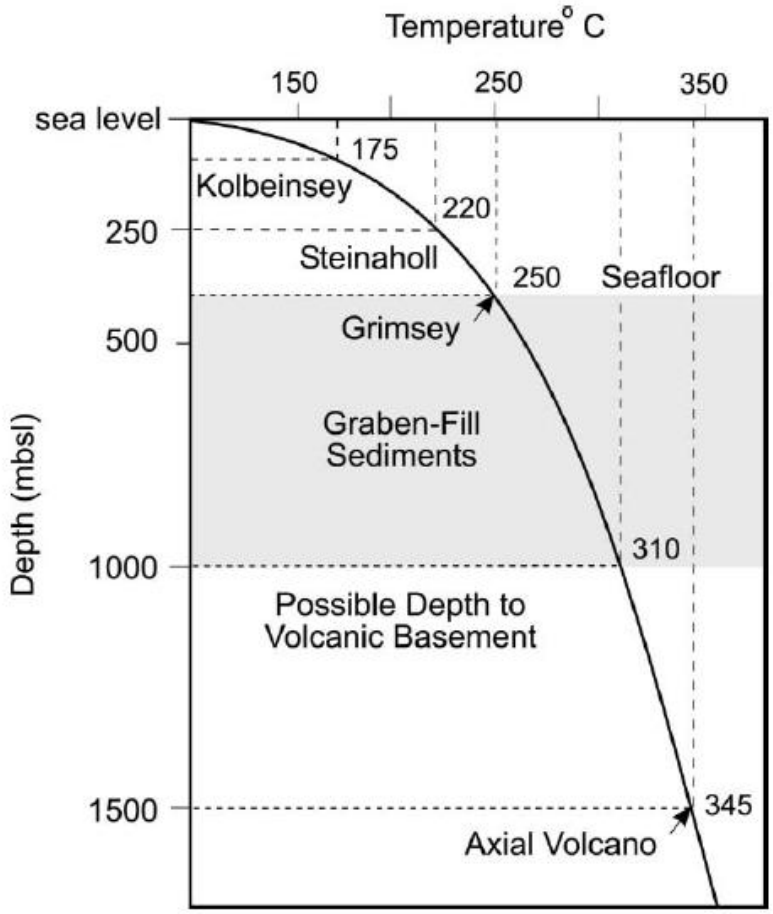

Figure 27) The temperature to depth boiling curve showing where the Kolbeinsey, Steinahóll, and Grímsey vent fields are situated. Based on this boiling curve for seawater the temperatures at the boundary between the sediment and basalt layers at Grímsey could be up to 300°C depending on the depth of the volcanic basement. The depth to the volcanic basement has not been confirmed; it is estimated in this figure based on basement depths in nearby valleys [53].

In summary, despite being discovered very recently the Grímsey hydrothermal vent field has been extensively studied. There has been detailed bathymetry, mapping, chemical analysis, seismic studies, and coring that has been conducted. Also, many dives with submersibles have gone down to measure temperatures, collect rock samples, take pictures, and observe biologic activity. All of these previous studies have revealed loads of valuable information about this hydrothermal area which is very beneficial to any future geothermal companies who may decide that this would be a good location for an offshore geothermal power plant.

2.3.6 Kolbeinsey Hydrothermal Area

The Kolbeinsey hydrothermal vent field is located north of Iceland, roughly 65 km north northwest from Grímsey and 100 km from the mainland (Figure 29). The vent field was postulated in 1974 because gas bubbles were seen rising to the surface. Then, the vent field was confirmed in 1987 by the submersible GEO. During the GEO expedition videos, pictures, rock samples, water samples, and biological samples were taken from the site. The vent field lies at about 100 m depth and the hydrothermal fluids have been measured to be between

70-110°C. It is possible that temperatures are higher because the submersible could not reach some areas to take measurements, but gas bubbles, possibly from boiling, could be seen rising from some craters. At this depth the boiling point of seawater is about 175°C (Figure 27), so it is possible that the temperature could be up to 175°C in these areas. Water samples taken from the vents contained He, H_2S, Mn, and SiO_2. Detailed bathymetry, side scan sonar and echo soundings have also been conducted in the area [55].

2.3.7 Squid Forest

Another hydrothermal vent field discovered near Iceland is called the Squid Forest. It is approximately 170 km north of Iceland (Figure 29) and lies at about 900 m depth. This vent field is not of interest for geothermal energy exploration because the field is inactive. It was discovered in 1999 by the remotely operated vehicle Aglantha [48]. The field lies in a depression on a small volcanic ridge and consists of about 30 extinct hydrothermal chimneys, some of which have collapsed [48].

2.3.8 Other Unconfirmed/Unnamed Vents and Hot Springs

There are at least two cases of documented but unconfirmed and un-named areas where hydrothermal venting might be occurring along the Reykjanes Ridge. They are near the small island of Eldey. The reason hydrothermal venting is believed to be occurring near Eldey is because sonar scattering anomalies have been seen there; likely due to rising bubbles [21]. One of these areas is 1.3 nautical miles east-north east of Eldey (Figure 28). An attempt to collect dredge samples from the area was unsuccessful due to the strong currents [21]. It is likely that other areas like this exist along the Reykjanes Ridge but they have not been found or they are undocumented.

Another location of interest is the area just south of the smaller island of Grímsey in Steingrímsfjörður. There is recent speculation that there might be some hydrothermal chimneys in this area because a local fishing captain reported finding a strange rock in his fishing nets. The rock is 30-40 cm on the sides and has many open pathways which are smooth on the inside [56]. It is likely that the rock is from a geothermal stalagmite and the smooth pathways were formed from the flow of hot water. There are also known geothermal sources nearby this area; the closest town to where this rock was found is Drangsnes, which has a geothermal well that supplies hot water to the town [57].

2.3.9 Coastal and Tidal Zone Hot Springs

Along the coastlines of Iceland there have been many hot springs found in the tidal zone and shallow waters (Figure 28) [21]. These vents are all low temperature but they could be linked to deeper high temperature fields.

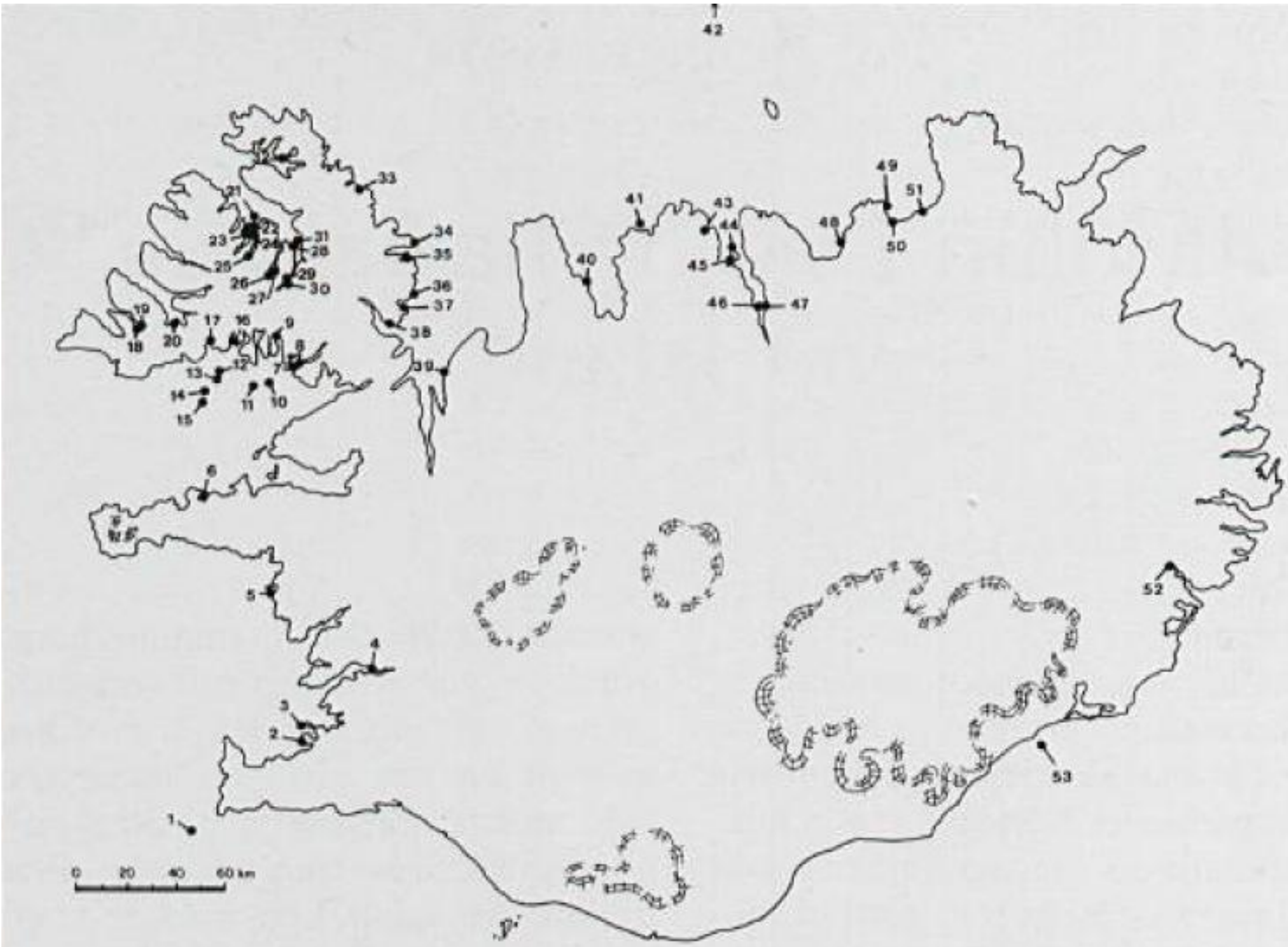

Figure 28) Locations of tidal zone hot springs documented around Iceland. Number 1 marks the area of the suspected vent 1.3 nautical miles east north east of the island Eldey [21].

2.3.10 Hydrothermal Vents Around Iceland

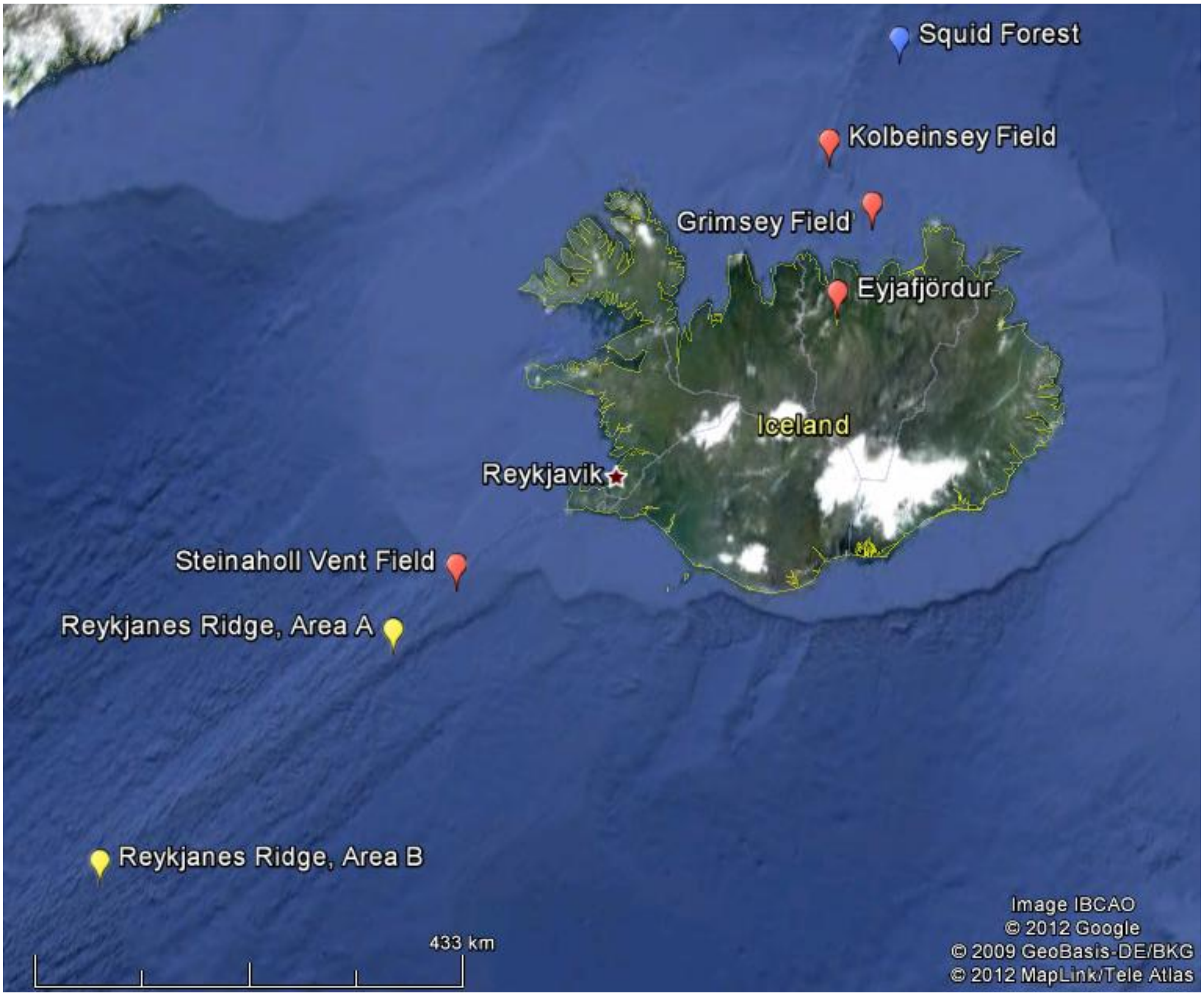

Figure 29) Google earth map of all the documented hydrothermal vent fields near Iceland [48]. Red markers indicate confirmed vent fields, yellow markers indicate inferred vent fields, and the blue marker indicates an extinct vent field. The Eyjafjörður marker includes Strytan and Arnarnesstrytur.

Table 2) Comparison of hydrothermal vent field characteristics around Iceland as well as the Marsili seamount and two other highly studied vent fields. The Brothers Volcano and the TAG hydrothermal vent field were added into these tables for a comparison of vent fields in other parts of the world that have been extensively studied.

Vent field	Location	Distance from nearest land (km)	Depth (m)	Maximum temperature (°C)	References
Steinahóll	Lat 63.100 Lon -24.533	120	250-350	220 inferred from depth boiling curve	[48]
Reykjanes Ridge Area A	Lat 62.450 Lon -25.433	200	500		[48]
Reykjanes Ridge Area B	Lat 59.816 Lon -29.683	580	1000		[48]
Strytan	Lat 65.850 Lon -18.133	3	15-65	75	[48], [51]
Arnarnesstrytur	Lat 65.870 Lon -18.220	1	18-46	79.5	[48], [51]
Grímsey	Lat 66.606 Lon -17.654	16 from the island of Grímsey 50 from mainland of Iceland	400	250	[48], [54]
Kolbeinsey	Lat 67.083 Lon -18.716	65 from the island of Grímsey 100 from mainland of Iceland	100	131 measured; 180 inferred from depth boiling curve	[48], [55]
Squid Forest	Lat 68.000 Lon -17.500	160 from the island of Grímsey 170 from mainland of Iceland	900		[48]
Marsili	Lat 39.260 Lon 14.378	115	400-800		[48]
Trans-Atlantic Geotraverse (TAG)	Lat 26.136 Lon -44.826	2000	3600	368	[48], [58]
Brothers Volcano	Lat -34.866 Lon 179.066	300	1150-1800		[48]

Table 3) Comparison of hydrothermal vent field characteristics continued

Vent field	Chemistry	Approximant thermally active seafloor area	Other observations	References
Steinahóll	High concentrations of H_2 and CH_4 (Higher than at most other vent fields)		High productivity of gas bubbles	[17]
Reykjanes Ridge Area A				
Reykjanes Ridge Area B				
Strytan	pH = 10; Fresh water, 0.1 times the salinity of seawater; Fresh water, dissolved SiO_2, variable chemical composition	Circle of 200 m radius	Approximately 100 l/s of fresh water flows from the largest cone Strytan	[51], [52]
Arnarnesstrytur	pH = 10; Fresh water, 0.1 times the salinity of seawater; Fresh water, dissolved SiO_2, variable chemical composition	0.4 km^2	numerous cones built up mainly due to the precipitation of SiO_2	[51]
Grímsey	pH = 5.9-6.8; Low salinity; CO_2 and CH_4 are dominant gasses, no smoke so there are low amounts of metals and sulfur in the fluid	1 km^2	Field consists of mostly shimmering water and extensive patches of white anhydrite and talc. Low biologic activity	[53]
Kolbeinsey	High levels of CO_2, CO, and CH_4, water samples also contained He, H_2S, Mn, and SiO_2			[55]
Squid Forest			Consists of about 30 extinct hydrothermal cones	[48]
Marsili	high levels of dissolved CO_2, CO, and CH_4; high $^3He/^4He$ ratios recorded			[5], [59]
Trans-Atlantic Geotraverse (TAG)	These vents are black smokers so there are many metals in the fluid. Mn, Fe, S, Si	5 km^2	First high temperature hydrothermal vents discovered on the Mid Atlantic Ridge	[58], [60]
Brothers Volcano		13 X 8 km^2 area of volcano	Four separate hydrothermal vent fields found in the volcano's area	[61]

Table 4) Discovery and exploration methods used at each hydrothermal area

Vent field	First evidence leading to further investigation of hydrothermal vents	Year and how it was confirmed	Exploration methods used	References
Steinahóll	An earthquake swarm in 1990 prompted an expedition to investigate the area	In 1993 it was confirmed via towed video	CTD sensor, optical backscattering sensor, swath bathymetry, deep-towed side-scan sonar (38 kHz echo sounder), dredging, and chemical analysis	[17], [38]
Reykjanes Ridge Area A	Most likely suspected due to seismic activity	Unconfirmed		[48]
Reykjanes Ridge Area B	Major earthquake swarm	Vent field is highly likely to exist but has not been confirmed without a doubt.	Sonobouys, XBT's, submersibles, CTD, water samples, photographs, heat flow data, side scan sonar, swath bathymetry, magnetic survey, sediment cores, Basalt samples and Biological samples were taken	[38], [49]
Strytan	Gas bubbles seen at surface	1997, Scuba diving	Multibeam sonar, submersible dives, scuba diving	[51]
Arnarnesstrytur	Multibeam sonar	2004, Scuba diving	Multibeam sonar, scuba diving	[51]
Grímsey	Hydrothermal material recovered in fishing nets	1997, Submersible JEGO	Seismic reflection, earthquake catalog data, chemical analysis, swath bathymetry, 12 and 18 kHz echo sounding, 17 core samples taken, dredging, submersible dives	[54], [53]
Kolbeinsey	Gas bubbles seen at surface	1987, Submersible GEO	Swath bathymetry, side scan sonar, echo soundings, videos, pictures, rock samples, water samples, and biological samples have been taken	[55]
Squid Forest		1999, Remotely operated vehicle Aglantha	ROV	[48]
Marsili	An iron rich rock sample collected in 1988 revealed evidence of hydrothermal activity. The rock sample was believed to be a hydrothermal precipitate.	2006, Remotely operated vehicle Cherokee	Detailed bathymetry, chirp sub bottom profiling, CTD, optical backscattering, heat flow measurements, chemical analysis, He isotope measurements, seismic reflection, towed magnetic survey, gravity survey, OBS/H, OBMs, spontaneous potential, towed camera, dredging, and core samples	[5], [59], [62]
Trans-Atlantic Geotraverse (TAG)	Dredge samples, water temperature measurements, chemical analysis, and metalliferous layers found in sediment cores	1985 towed camera	Detailed bathymetry, side scan sonar, chemical analysis, dredging, near bottom magnetic survey, 17 core samples taken, submersible dives	[58], [60]
Brothers Volcano	Dredged sulfide samples found	1998 towed camera	Swath bathymetry, dredging, plume mapping cruises with MAPR, eH sensor, optical backscattering, CTD, pH sensor, submersible dives, towed camera, OBS/H, AUV dives equipped with multibeam side scan sonar, and near bottom magnetic survey	[61]

2.4 The Marsili Project

Currently, Italy is leading the world in offshore geothermal exploration. Geophysical research in the Southern Tyrrhenian Basin, just north of Sicily, has revealed a potential target for the world's first offshore geothermal power plant. This target is on the Marsili Seamount which is an underwater volcano about 115 km from the Italian coast; its base lies at about 3000 m deep and its summit is at about 500 m deep. It is Europe's largest volcano, even larger than Mount Etna [59]. According to the Marsili project website, Italy plans on producing electricity from an offshore platform similar to an offshore oil platform by 2015 [5].

A lot of geophysical research is being done on the Marsili volcano in preparation for the world's first offshore geothermal power plant. The existence of this volcano has been known for a long time but extensive geophysical research has only begun recently because of this idea to utilize its energy. All the exploration techniques used are listed in Table 4.

One of the first methods used to study the volcano's energy potential was heat flow measurements. The measurements taken determined that the most heat flow was at the volcanoes summit. Next, magnetic and gravity surveys were conducted and they both agreed that there is an anomaly at the summit. The internal structure of the volcano has been roughly inferred mainly from the gravity data. Also, from these gravity data the porosity of the volcano has been tentatively estimated to be more than 10% by volume [59].

A few different magnetic surveys were conducted at the Marsili Seamount. One research team used a Marine Magnetics SeaSpy magnetometer which was kept 120 m off the port side of the ship and the measurements were processed with Marine Magnetics SeaLink software. Another research team used two Geometrics Mod-G811 magnetometers in a gradiometric configuration 150+150 m off of the starboard side of the research vessel and the information was processed using OASIS GEOSOFT software [59]. Both of these surveys showed a very low magnetic anomaly in the center of the volcanic crest. The low magnetic anomalies are believed to be caused by rocks which have very low magnetic properties, most likely because of demagnetization due to hydrothermal activity. No black smokers have been confirmed but hydrothermal circulation below the volcanoes surface is believed to be breaking down the magnetic minerals thus reducing the magnetization. In addition, this low magnetic anomaly can also be associated with a shallow Curie isotherm. The isotherm is thought to be located at around 4-5 km below the volcanoes summit. If this is true it would suggest that there is a temperature of more than 600°C at the base of the volcano [59]. This would also mean that there is a possibility of magmatic activity in the seamount. The high temperatures inferred by these data agree with the high heat flow measurements found on Marsili and suggest that there is an intense and shallow heat source [59]. Another type of magnetic survey mentioned on the Marsili project website was a study using many Ocean Bottom Magnetometers (OBMs) to monitor the magnetic and electrical characteristics of the rocks [5]. No other details about this study were provided though.

Chemical analysis has been conducted in the water column above Marsili. It was found that the $^3He/^4He$ isotope ratio showed much higher levels of ^3He directly above Marsili than in the surrounding waters. The chemical analysis also showed high levels of dissolved CO_2, CO, and CH_4, with respect to the rest of the sea, which was a clear indicator of hydrothermal activity at the top of Marsili. The chemical analysis was carried out by towing and CTD sensor with a rosette for collecting water samples, over the seamount ridge and using the tow-yo method. The tow-yo method involves raising and lowering the CTD instrument in the water column, like a yo-yo, as the ship moves along [63].

There has also been chemical testing for Fe, Mn, Zn, Pb, Cu and other sulfide minerals [59]. Bottom sampling, dredging and core samples have been taken. Fifteen dredging samples were taken, some of which show alteration features which indicated hydrothermal activity. A core sample of about a meter in length and 0.015 m in diameter was taken from near the top of the volcano, it revealed unique tephra and mud deposits, but nothing more is said about it [59].

Several seismic studies were done on the seamount. A broadband Ocean Bottom Seismometer with Hydrophones (OBS/H) was placed on top of the seamounts ridge line at 790 mbsl for nine days. Over 1000 seismic signals were recorded during the nine days. High fracturing in the rocks is shown from the seismic observations recorded in the OBS/H data. Seismic events that were not strong enough for the onshore network to pick up were seen by this OBS/H. Even though it was only out there for nine days enough tectonic events were recorded to show a great deal of local activity occurring [59]. A very high frequency of seismic noise was recorded by the OBS/H which also supports the idea that there is hydrothermal activity within the volcano. Seismic noise levels between 2-20 Hz can generally indicate hydrothermal activity this low frequency noise can often be caused from the collapse of bubbles in ascending hydrothermal fluids [59]. Three years later another study using OBS/H was done; this time the sensor was placed on top of the seamount for 9 months. Data gathered from this study helped geophysics to identify where the hypocenters of seismic events were located. They found that many micro-seismic events were occurring at very shallow depths, which is an indicator of hydrothermal fluid movements beneath the surface [63]. High resolution seismic reflection has been conducted in the area as well. The method used for the seismic reflection was called chirp sub-bottom profiling [59]. Chirp sub bottom profiling utilizes an instrument called 3D Chirp which is towed from a ship. This powerful imaging device that can scan the upper 10’s of meters of the subsurface in three dimensions with high resolution

[64]. Active seismic tomography techniques have also been done in order to image the deep geologic structure beneath the volcano and model the geothermal field to locate the main reservoir [5].

Other surveys that have been done at Marsili include: direct observation via underwater cameras, collection of Bio and Magneto stratigraphical data, environmental monitoring, and detailed bathymetry. Stratigraphical information was collected to help understand the history and learn the ages of different strata in the area[59]. The environmental monitoring included observations of water currents, biological activity, and climate patterns [5], all of which will be important to know when planning the construction of the offshore platform.

Overall, the Marsili Seamount has been extensively studied and it has been determined that a very high geothermal potential exists in the submarine volcano. In a few years if everything goes as planned the first offshore geothermal pilot plant will become operational providing more renewable energy to Italy.

2.5 The IMPULSA Project

An offshore geothermal research project is taking place off the coast of Mexico in the Gulf of California. This project is called the IMPULSA project and is being researched by the Universidad Nacional Autonoma de México. The goal of the IMPULSA project is to utilize renewable sources for the desalinization of seawater. Part of their research investigates the utilization of geothermal energy from hydrothermal vents in order to power the desalinization plant. Unlike the Marsili project they plan to construct a submarine power station that will utilize the hydrothermal fluids directly from the vent sites (Figure 30). Currently prototype models are being tested in a shallow low-temperature hydrothermal system called Bahia. This area was chosen because it is in shallow calm waters so it is easy to work and scuba dive at. At Bahia diffuse hydrothermal fluids rise from the seabed at 5-15 mbsl and there are also springs and bubbling vents located in the intertidal zone. The seabed fluids are 87°C with a pH of 5.9 and the fluids in the tidal zone are 62°C with a pH of 6.7 [65].

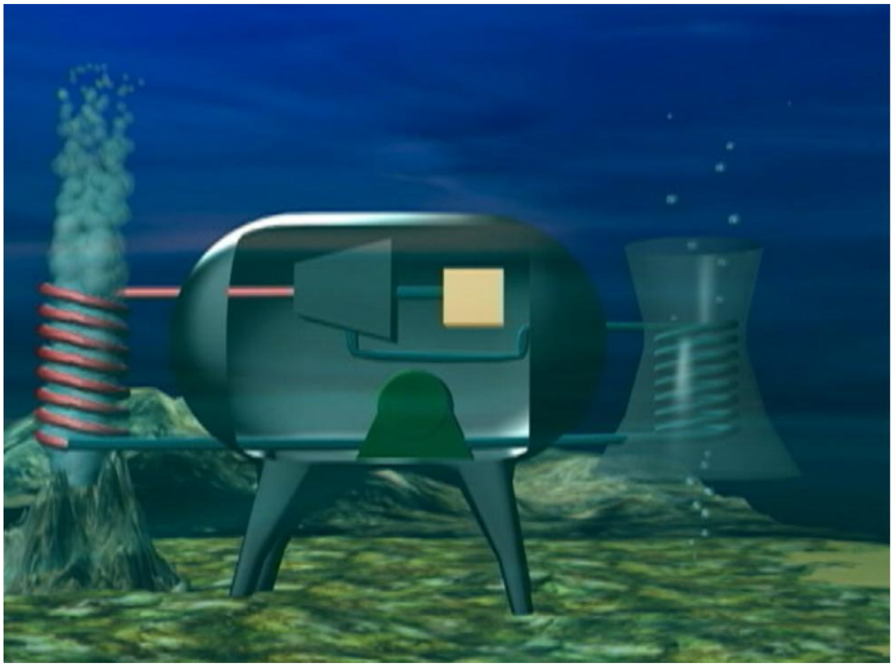

Figure 30) Conceptual drawing of one possible design for a submarine power station that is installed directly over a hydrothermal vent [65].

The goal of the IMPULSA project is to eventually install a commercial power station at the Guaymas Basin hydrothermal vents. The Guaymas Basin hydrothermal vents were discovered in 1980 via deep towed CTD and dredging, and then confirmed by the submersible Alvin in 1982 [48]. The Guaymas vent field lies at 2000 mbsl and has temperatures of around 360°C [66]. Since their plan does not require drilling and the power plant will simply utilize the venting fluids upon surfacing, few geophysical methods to try and map the reservoir have been carried out compared to the Marsili project. Right now it is undetermined when the power station will be installed and become operational.

3 Exploration Methods

This section discusses the geophysical techniques that are relevant to geothermal exploration, hydrothermal vent exploration, and general marine geophysical exploration, including offshore hydrocarbon exploration. All of these techniques have been looked into in order to evaluate and decide which methods will be the most practical for future offshore geothermal exploration.

3.1 Common Methods for Locating Hydrothermal Vents

Exploration for offshore geothermal energy will logically begin with finding hydrothermal venting on the ocean floor. High temperature hydrothermal vents are the only visual evidence of geothermal heat sources beneath the ocean floor, so locating these features is important for finding a good location to build an offshore power plant. Locating a geothermal power plant on land normally begins with finding areas which have surface features such as fumaroles and boiling pools; analogues to hydrothermal vents. These types of features indicate a shallow heat source. On land, they are easily found with simple geologic reconnaissance and direct observations, but in the ocean it is not that simple. Exploration in the ocean is difficult because the ocean is vast and inaccessible, so hydrothermal vents can only be observed with the aid of different technologies which are usually very expensive. Direct observations require submersibles or towed cameras and getting to vent sites usually requires a large ocean worthy ship. Section 3.1 discusses the various methods and technology being used for finding hydrothermal vents.

3.1.1 Sound Navigation and Ranging (Sonar)

Sonar is a technique that uses acoustic signals that propagate through the water. There are two main types of sonar: active and passive. Active sonar sends out a pulse of sound and listens for return echoes. The time it takes for the sound waves to return can be calculated into distances. This technique is most commonly used to map the ocean floor. Passive sonar is simply listening for sounds in the water and is most commonly used for monitoring ocean traffic. Passive sonar is an important tool used onboard military ships for locating and identifying submarines and other war vessels. There are many different types of sonar methods used for different proposes and some techniques are effective for locating hydrothermal vents.

The most commonly used sonar for mapping the ocean floor is called multibeam swath bathymetry or echo sounding. It can be set up to map a very wide strip of the ocean floor as the ship travels or it can be set up to map a narrower strip in more detail. Swath bathymetry can be a useful method for locating hydrothermal vents if they are rich in gas bubbles because the gas-rich fluid rising from the ocean floor causes acoustic scattering; which can be seen in the sonar profile (Figure 21 Figure 25). The gas bubbles emerging from some hydrothermal vents scatter the sound waves; making it very difficult to depict the topography beneath the rising plume. Seismic reflection studies are also affected by the rising gasses; sometimes producing polarity reversals or very weak positive amplitudes in the seismic data [54].

Another sonar technique called side scan sonar looks at the backscattering strength of multibeam data and is useful for learning about rock types and structures on the ocean floor. Backscattering analysis detects the intensity of the returned sound wave. The sound pulses are transmitted from either a tow-fish or a hull-mounted transmitter. The surface the acoustic wave reflects from will determine the amplitude of the return wave. Materials that are smooth and hard have a stronger return signal, while softer or rugged materials such as sedimentary rock or aa-lavas will return a weaker signal. Side scan sonar data can reveal plenty of information about the ocean floor and is often used to locate shipwrecks or archeological sites. The different intensity in backscatter can also help to identify different lava flow events from each other, also landslides and faults can be visible in side scan sonar data [12]. This technique is beneficial for learning about the material and texture of the ocean floor, which can help researchers deduce where hydrothermal sources might exist.

Passive sonar has not been used for finding hydrothermal vents, but it is possible that it might be useful. Passive towed array sonar is something that is mainly used on navy ships to detect submarines from long-range. There are several passive types of arrays such as the Tactical Towed Array Surveillance System (TACTASS), or the Surveillance Towed Array Sensor System (SURTASS). Both of these systems were designed for the purpose of finding submarines but possibly a similar hydrophone array could be used to detect sound of particular frequencies characteristic of hydrothermal vents. The arrays consist of many hydrophones and 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. The shift in frequency would occur as the array passes the vents, thus giving away the location of the vents after a couple of passes. This idea has not been tested for the purposes of locating hydrothermal venting and it is unknown if venting would produce clear and strong enough sound waves in the water to be detected by an array of this type. Also, it could be a difficult technique to use when there is other shipping traffic in the area because there might be too much noise in the water to isolate the frequencies from a vent.

3.1.2 Chemical Analysis

Chemical analysis of the water column is an important and useful method for locating hydrothermal vents. There are several chemical methods that can be used to detect evidence of hydrothermal venting such as measuring isotope ratios, dissolved gasses, and reduced chemical compounds. Hydrothermal vents produce many chemicals and dissolved gasses that are in elevated levels compared to ordinary sea water. They often contain high levels of trace gasses derived from the mantle such as ^3He and carbon bearing gasses such as abiogenic CH_4, and CO_2 which are formed in the mantle and deep crust [54]. These fluids enriched with gasses and various dissolved substances form buoyant plumes that rise through the water column. There are a few different types of sensors and methods used to detect these chemicals.

Analyzing water samples for high ratios of $^3He/^4He$ isotopes in the water column is a useful indicator of hydrothermal activity [54]. Hydrothermal vents often expel a higher amount of ^3He than is in the ambient water increasing the $^3He/^4He$ ratio in the vicinity of hydrothermal vents. Large scale plumes can sometimes release enough ^3He such that it can be detected up to 1000 km away [54]. Many research vessels have labs onboard which can carry out this type of chemical analysis. This type of measurement was used during the exploration of the Marsili Seamount and helped to confirm the presence of hydrothermal activity there. The highest ratio of $^{3}He/^{4}He$ was found near the top of the seamount and strongly reinforced the suspicion of hydrothermal activity there [67]. This method is useful because a high $^{3}He/^{4}He$ anomaly can be detected at great distances from a hydrothermal vent site which can be an advantageous when searching a vast area. A disadvantage of this method compared to some other chemical methods is that it requires analysis in the lab, so there will always be a slight delay in obtaining the results.

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 [37]. These substances can be measured directly in the water column using various sensors that are dropped into the water from the ship. They can also be measured from water samples in the lab. After the seismic episode at the Steinahóll vent field, water samples from the area were collected and analyzed in the lab on-board the ship. Researchers measured for CH_4, Si, H_2, and Mn and elevated levels of these dissolved chemicals produced evidence that helped in locating the vent field [37].

There are several different instruments used for real-time chemical measurements in the water column including electrochemical redox (eH), methane, and pH sensors. There is also an instrument suit called System Used to Assess Vented Emissions (SUAVE). This instrument has the ability to detect dissolved chemicals such as iron, manganese, and hydrogen sulfide [68]. It provides a live feed of data and can be mounted to an underwater vehicle or towed behind a ship. It is also designed to be integrated with a CTD instrument.

An eH sensor, also called an Oxidation-Reduction Potential (ORP) sensor, is commonly used. This sensor detects the presence of reduced (oxygen poor) chemical compounds such as H_2S and Fe^{2+} which rise into the ocean waters from hydrothermal vents [69], [39]. The measurements are similar to a pH measurement. It works by measuring the equilibrium electrode potential (e) between a platinum black electrode in the seawater and a reference which is an Ag-AgCl electrode in a saturated KCl solution [39]. The absolute value of e is not always the same from site to site, so in order to detect hydrothermal plumes the Δe value between the ambient water and an anomaly is used to determine the presence of reduced chemicals from a hydrothermal plume [39]. This sensor is built into the Miniature Autonomous Plume Recorder (MAPR) instrument suit and can also be mounted on a CTD instrument as an auxiliary sensor. The instrument can be towed from a ship a few hundred meters above the sea floor and is commonly used via the tow-yo method. The sensor can also be mounted to an underwater vehicle [39].

Other real time sensors typically used are methane sensors and pH sensors. These simple and inexpensive sensors can be easily used in conjunction with other devices. Methane is a byproduct of high temperature hydrothermal venting [70], so a simple methane sensor will show anomalies which are associated with hydrothermal vents. A pH sensor can also pick up anomalies in the water caused by hydrothermal fluids because the fluid often has a different pH than the ambient water. These sensors can be mounted to underwater vehicles and they are easily integrated with a CTD and towed from a ship [70].

Hydrothermal fluids also contain many different metals that precipitate out of the fluid once it comes in contact with the cold seawater. This is what causes the smoke many hydrothermal vents are known for. Hydrothermal vents precipitate mainly sulfide minerals containing copper, zinc, and iron [71]. Dredge sample containing high levels of these sulfides can be an indicator that hydrothermal vents are nearby.

To sum up, most hydrothermal vents leave some sort of chemical signature, thus chemical analysis is a significant method that gives researchers valuable information about hydrothermal fluids and helps in locating where a vent site might be. Chemical sensing instruments can always be used in conjunction with many other types of sensors, so it is a method that is very commonly used.

3.1.3 Optical Sensors

Light Backscattering Sensors (LBSS), also known as optical backscattering sensors, are simple yet highly sensitive instruments commonly used for locating hydrothermal vents. At many hydrothermal vents, visible clouds of precipitating minerals form and an LBSS can detect these suspended particles. Field studies have shown that the LBSS has a high accuracy for detecting hydrothermal vents dominated by metal precipitants [70].

The LBSS consists of a Light-Emitting Diode (LED) and a detector; mounted side by side in the instrument housing [72]. The LED shoots a beam of light out into the water and particles in the water scatter the light, some of which will be reflected toward the detector. The detector is calibrated to determine how much of the light is received. Water containing a high level of metal precipitants will scatter more of the light into the detector. The instrument measures relative backscattering of light rather than absolute, so measurements can differ from sensor to sensor [72]. The light backscattering measurements are in terms of Naphelometric Turbidity Units (NTU). The light backscattering anomaly caused by a hydrothermal plume is then recorded in units above the ambient called ΔNTU [73].

Optical sensors 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. An LBSS is usually towed or lowered from a ship; it is integrated with the MAPR instrument suit and can be used as an auxiliary sensor with a CTD instrument [70].

3.1.4 Cameras

A simple and straight forward piece of equipment is the towed camera; often the first method for obtaining visual confirmation of hydrothermal vents. Cameras are towed behind a ship and can be used in conjunction with a suit of other sensors. Having a camera in the water can help guide a mission, gives researchers valuable visual information, and allows for video and photographs to be obtained from vent sites. Having a camera in the water is also very important to biologists who are studying the unique life forms at deep hydrothermal vents [74].

Cameras are also mounted to submarines and Remotely Operated Vehicles (ROVs). They are vital to navigation and very important for studying hydrothermal vents up close. Getting visuals of a hydrothermal vent site helps to determine the size and can give clues into the chemistry and temperature. Capturing a vent field on camera is the most direct and satisfying way to confirm its existence.

3.1.5 Dredging

Collecting rock samples from dredging is a useful method for finding evidence of hydrothermal venting because rocks near vents can be affected by hydrothermal activity. The presence of sulfide minerals in the rocks are the most common indicator of possible hydrothermal activity. In some cases alteration is due to CO_2 rich hydrothermal fluids reacting with hot mineral surfaces, causing serpentinization of ultramafic rocks [54]. Obtaining rock samples from hydrothermal vents has sometime happened by accident from fishing vessels, like in the case of the Grímsey vent field [53] and the suspected vent in Steingrímsfjörður [56]. In the case of the Grímsey vent field, a rock sample discovered in fishing nets triggered further investigation of the area.

Collecting rock samples is also important after a vent field has been discovered as researchers can learn about the chemistry, geology, biology, and sometimes infer the temperature. When deciding on a site for a geothermal power plant it will definitely be important to retrieve rock samples from the location.

3.1.6 Conductivity, Temperature, Depth (CTD) Sensors

CTD sensors are the most routine instrument used when searching for hydrothermal vents [75]. A CTD measures the conductivity, temperature, and pressure of seawater; the pressure measurement is then used to calculate depth. Data from the CTD can also be used to calculate other parameters such as salinity, density, and sound velocity [75]. Salinity is the concentration of salt and other inorganic compounds in seawater. Conductivity is a measure of how well a medium conducts electricity and in seawater; it is directly related to salinity. Data are collected about how conductivity and temperature fluctuate in the water column with relation to depth. CTD data can also be used to calculate seawater density which can then be used to infer ocean currents [75]. This instrument package is usually lowered or towed from a ship via a conducting 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 [75].

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 [76]. CTDs are commonly attached to a large metal frame called a rosette (Figure 31), which holds water sample bottles that can be remotely controlled to close so they collect water samples from different depths in the water column [75].

Figure 31) A CTD with a rosette frame and 24 water sampling bottles. Photograph by Dr. Robin Robertson aboard the R/V Nathaniel B. Palmer [77].

3.1.7 Miniature Autonomous Plume Recorder (MAPR)

MAPR is a small inexpensive instrument package similar to a CTD (Figure 32). 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. It is designed for use with a software package that is a point and click user interface, so the instruments configuration and information processing can be easily controlled. The simplicity of this instrument and software make it more robust and versatile for practical use. The MAPR has been widely used to detect hydrothermal plumes on dredging and coring missions [73]. Multiple MAPR's can even be used on the same cable so that a larger vertical length of the water column can be scanned in one pass [39].

The instrument package has an optical backscattering sensor, an eH sensor, a temperature sensor, and a pressure sensor. As discussed previously, the optical backscattering and eH sensors are very useful for locating evidence of hydrothermal venting. The temperature sensor is useful but it can have trouble detecting weak non-buoyant hydrothermal plumes because the temperature anomaly is too small [73]. The pressure sensor is simply a means of calculating the depth of the instrument. Being able to see these data in real-time makes this instrument very useful because it can then help to direct the ship closer to any suspected hydrothermal vents and they can be located much quicker.

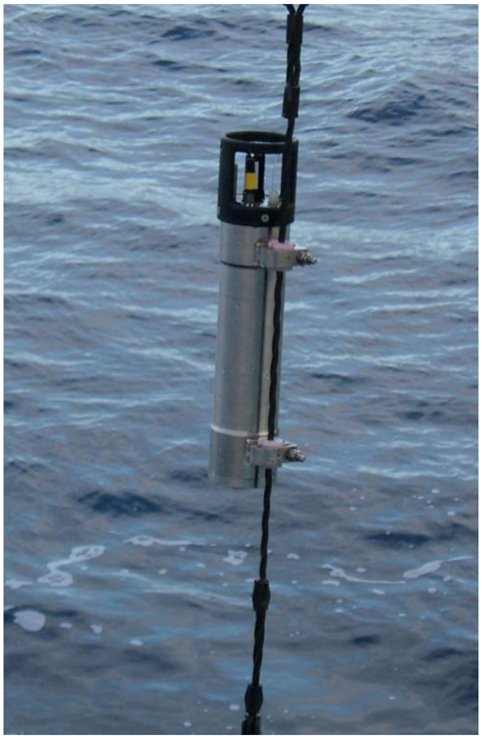

Figure 32) MAPR instrument attached to a cable and being lowered into the water for deployment [69].

3.1.8 Scuba Diving

Scuba diving would be a very straight forward way for people to collect rock samples, water samples, take measurements, and confirm the presence of hydrothermal vents. The problem is that safe scuba diving is limited to depths of around 100 m [78], and most hydrothermal vents are much deeper than that. The next best means for visiting a hydrothermal vent is by submarine. Scuba diving is a simple and direct exploration method for relatively shallow areas, but it becomes dangerous with depth, thus an impractical exploration method for finding geothermal resources.

3.1.9 Manned Submersible Exploration

Submersibles are the best platform for exploration as far as obtaining concrete data and direct measurements. A submersible can carry various sensors, retrieve water samples for chemical analysis, retrieve rock samples, get temperature readings at the vent mouth, conduct magnetic surveys, take pictures, observe the living organisms, and observe the surroundings. Submarines provide the only means for humans to witness deep hydrothermal vents first-hand. The visibility through a viewport in a submarine compared to looking at an image provided by a camera is far superior; it has been noted that researchers often see much more from a submarine view port than through a camera mounted on an ROV [79]. The use of submersibles have also been a very good way of conducting very detailed magnetic surveys because the magnetometer can be brought very close to the ocean floor [60]. The disadvantages of submersibles are that they have limited depth, range, bottom time, and they are expensive to operate. For example, the Alvin cost around 40,000 USD per day to operate, has a depth limit of 4500 m, a top speed of 3.4 km/hr, and a bottom time of roughly 4 hours [80]. Due to these limitations the vent field must be accurately located before sending a submersible down. Once a vent field is confirmed sending a submersible down can be highly useful.

Figure 33) Launching of the submersible Alvin [80].

3.1.10 Remotely Operated Vehicle (ROV)

An ROV is an underwater vehicle similar to a submarine only it is unmanned (Figure 34). ROVs are remotely controlled from a surface ship and connected by a long cable, which allows the operator on the surface to have a live feed. An ROV is capable of doing any of the tasks that a submersible can do, the only disadvantage being that its maneuverability is somewhat restricted due to the possibility of entanglement with the cable connecting it to the ship [81]. Otherwise, ROVs are advantageous compared to submarines for a couple of reasons. First, there is less risk involved because sending humans down in submersibles holds inherent dangers and ROVs are easier to be designed for the deepest depths of the ocean. Second, they can operate for virtually unlimited time because of the cabled connection to the ship. The only limitations are the amount of time the operator(s) can handle working or how long the surface vessel can stay. ROVs are typically equipped with cameras and lights for detailed photographic surveys. Other sensors such as magnetometers, sonar equipment, CTD, MAPR, etc. can also be carried by an ROV. ROVs are very useful for collecting water and rock samples, doing detailed mapping of complex terrain, and conducting in-situ experiments. ROVs have been widely used on deep sea missions in recent years and they are very important and useful tools to have when searching for hydrothermal vents and conducting other deep sea exploration [81].

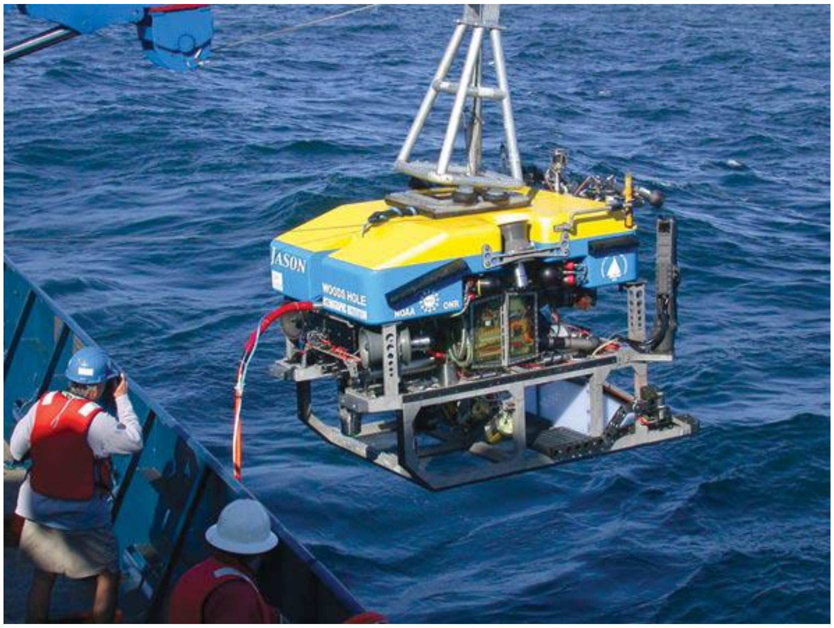

Figure 34) An ROV being deployed for hydrothermal vent exploration [81].

3.1.11 Autonomous Underwater Vehicle (AUV)

An AUV (Figure 35) is similar to an ROV except it is controlled by an internal computer. The internal computer is pre-programmed with a mission and then the AUV is sent into the ocean where it will carry out the mission on its own. Then the information collected is retrieved when the AUV is recovered on the surface. AUVs can operate at great depths depending on the specific design and they are usually only limited by battery life [81]. Hydrothermal vent exploration has become more efficient because of AUVs and when AUVs and ROVs are used together much more research can be accomplished. There have been several cruises in recent years where AUVs and ROVs are used together with great success. Sometimes an AUV is sent out first and the findings will help guide researchers to the most interesting locations for the ROV to be deployed. Then the ROV can examine the site up close, gather samples, and conduct experiments. Other times an AUV and an ROV are used simultaneously [81]. This way both vehicles are in use and valuable time at sea is used as efficiently as possible. In this sense an AUV allows the research team to multi-task and achieve higher quality results.

AUVs are very useful because they bridge the gap between large area but low resolution surveys, conducted from the surface, and very fine detailed but localized surveys, conducted by ROVs and submersibles [61]. AUVs can cover a larger distance than ROVs and submersibles while still being positioned close to the seafloor. AUVs have onboard sonar navigation that provides real-time bottom information [81], so the pre-programmed commands usually make it maintain a certain altitude above the sea floor. AUVs have been programmed to conduct detailed bathymetry surveys, multibeam backscatter surveys, and detailed magnetic surveys; they can also be fitted with other sensors such as a CTD or MAPR [61].

Figure 35) An AUV being deployed for hydrothermal vent exploration [81].

Compared to an ROV, an AUV has the advantage of not being tethered to the surface ship by a cable; however, communications with the vehicle while underwater is severely limited. Once released the vehicle functions on pre programmed settings, but some simple commands can be sent to the AUV via acoustic signals. Acoustic communication is still in development and limited by the relatively slow speed of sound waves compared to radio waves or electrical signals. In some situations communicating with the AUV by sonar is useful. For example, when AUV and ROV operations are being done at the same time the AUV can be programmed to land on the ocean floor and wait after finishing its survey. This can ensure it stays in a planned, safe location until it is convenient for the research team to go retrieve it. Once the researchers are ready for retrieval an acoustic signal is sent to the AUV triggering it to surface [81].

Overall, both ROVs and AUVs are extremely useful tools for underwater exploration of hydrothermal vents. They can be outfitted with many types of sensors and gather a large amounts of information. AUVs are great for detailed yet larger area surveys on a scale of meters to kilometers [81]. They are convenient to use because they simply follow their pre-programmed commands, so they don't take up as much of the research team's attention once released. ROVs are great for detailed mapping in areas with complex terrain and hazards that an AUV would not recognize. ROVs usually work well for mapping in ranges of around 100's of meters [81]. These vehicles are very beneficial to a research team when they can be used collectively.

3.1.12 Summary of Techniques and Equipment for Locating Hydrothermal Vents

Table 5) Methods and instruments for hydrothermal vent exploration

Method/ instrument	Details
Passive sonar	Not normally used for locating hydrothermal vents. In theory it could be a useful method assuming acoustic noise from hydrothermal venting can be monitored from a towed array of hydrophones.
Swath bathymetry/ multibeam sonar	Measures water depth. Used for mapping the topography of the ocean floor.
Side scan sonar	Backscattering measurements, measures the strength of return echoes for detecting geologic structures and objects on ocean floor.
Chemical analysis	Several methods and instruments: $^{3}He/\ ^{4}He$ isotope ratio, eH sensor, methane sensor, pH sensor, SUAVE instrument suit. Used for finding evidence of hydrothermal fluids in the water column. Inexpensive and can be used in conjunction with many other instruments.
Light scattering sensor	Detects metals that precipitate from hydrothermal fluids. Simple and inexpensive. Built into the MAPR instrument suit.
Cameras	Most important tool for confirming a hydrothermal vent. Allows for visual study of the geology and biology at vent site.
Dredging	Inexpensive and easy method for collecting rock samples. Geological analysis can then give clues as to whether hydrothermal activity exists or once occurred at the sample location.

Table 6) Common instrument suits used for hydrothermal vent exploration

Instrument	Equipped sensors	Details
Conductivity, Temperature, and Depth (CTD) sensor	Conductivity, Temperature, Pressure	Most widely used instrument suite for hydrothermal vent exploration. Can be integrated with many auxiliary sensors and can be used in conjunction with a rosette for collecting water samples.
Miniature Autonomous Plume Recorder (MAPR)	eH, optical back scattering, temperature, pressure	Small, inexpensive, dependable, very easy to use and deploy, can be used alongside other towed instruments. Multiple MAPRs can be connected to one tow line and towed at different depths.
System Used to Assess Vented Emissions (SUAVE)	iron, manganese, and hydrogen sulfide sensors	Used for chemical analysis of the water column.

Table 7) Vehicles used for hydrothermal vent exploration

Vehicle	Details
Surface ship	Essential for any hydrothermal vent exploration. Transports crew and equipment to site. Can conduct sonar surveys and tow many instruments. Covers much more area than any underwater vehicle. Good for broad studies of large areas.
Manned submersible	Important for very detailed studies of complex areas. Good for collecting samples, making measurements, and taking detailed pictures and videos. Short-range and limited bottom time.
Remotely Operated Vehicle (ROV)	Virtually all the same capabilities of a manned submersible. Important for detailed studies, measurements, and sample collection. Often used for detailed photography and fine scale bathymetry. Live feed to surface ship via cable. Unlimited bottom time.
Autonomous Underwater Vehicle (AUV)	Good for preliminary studies of a large area. Used for detailed mapping. Pre programmed to perform a mission, data are collected after mission. Bottom time limited by battery life.

3.2 Heat Flow Measurements

Measurements of heat flow from the ocean floor are a longstanding method that has been used for scientific studies. The instruments most commonly used are coring devices with two thermal elements set at a known distance apart [82]. The coring device penetrates a few meters into the ocean floor and then temperatures are measured at two different depths. Thermal conductivity of the sediment between the two measuring devices is estimated and then heat flow can be calculated. This method can be preformed anywhere but is much easier to conduct in sediments. It is more difficult to measure in basaltic rocks because the rocks are harder, so more extensive coring techniques need to be used to get the measuring device into the ground. Heat flow measurements are useful but sometimes can produce unexpected and highly variable results due to unpredictable hydrothermal flow patterns in the subsurface [82].

3.3 Seismic Methods

Seismic techniques are the most commonly used geophysical techniques as far as the amount of survey activity and the wide range of applications [83]. Seismic methods are the most common method used in the oil and gas industry, especially for offshore hydrocarbon exploration. There are two main types of seismic surveys: active and passive. Active seismic surveys use man-made waves created by a controlled source and passive surveys use waves created by natural seismic events. Active seismic methods have been used since the early 1920's and passive were being used well before that [83].

3.3.1 Historic Earthquake Data

Earthquake activity recorded over time and large earthquake swarms can be monitored and used for locating potential geothermal heat sources. Geothermally active sites tend to have a high frequency of seismic activity [18], so earthquake maps such as Figure 9 could show helpful clues as to where to look for offshore geothermal energy. Observing large earthquake swarm events has also proven to be useful for locating hydrothermal vents as with the case of Steinahóll; however, not all large earthquake swarms are an indication of potential heat sources. Seismic monitoring can also be useful to learn about the porosity of the crust because fluid within the pore space causes S wave velocity to be slower compared to P wave velocity [84]. In ocean areas where there are many small earthquakes it can indicate that there might be space in the rocks where fluid is flowing [59]. Historic earthquake data can be used to map out fault planes as well [18]. If earthquake epicenter positions and depths can be accurately located, then after enough data are collected, the earthquakes can be plotted in a 3D graph and the fault planes in the area will start to become visible. Knowing the strike and dip of the faults in a geothermal area is very useful when determining where to drill.

3.3.2 Micro-Seismic Monitoring

In order to gain valuable knowledge from micro-seismic activity, especially about fault planes, very accurate locations for micro-seismic events need to be known. Currently in Iceland oceanic earthquake data are not as accurate as could be, because all the seismometers in the SIL network are located on land. This causes earthquakes that occur far out in the ocean to have a narrow angle between seismometers, so position calculations will have higher error. In order to locate micro-seismic events that take place offshore more accurately, OBSs would need to be placed in the oceans around Iceland. OBSs would also help to detect micro-seismic events in the ocean that may not be detected by the seismometers on land. If OBSs were placed along the Reykjanes Ridge for a period of time and linked with the SIL network then offshore micro-earthquakes could begin to be more accurately cataloged. This would help to enhance the understanding of possible resources along the ridge.

Once a possible offshore geothermal location has been found, seismic evidence from OBSs can help define the geothermal reservoir as well. For example, OBSs were used on the Marsili Seamount and they helped to reveal valuable data about the subsurface activity. The OBSs gave indications of high porosity and the data showed evidence that fluid is flowing within the seamount [59], which is essential to know before building a geothermal power plant.

An OBS network set up around a potential reservoir to monitor micro-seismic events may also be beneficial for locating well sites. In a lecture by Simiyu, 2009 [84], potential well sites on land at the Menengai-Olbanita area in Kenya were determined based on a technique using a seismic network to monitor micro-seismic events. Utilizing micro-seismic data collected by the densely spaced network of seismometers, Simiyu was able to determine zones of the highest heat flow. This was done by comparing the S wave and P wave arrival times. In areas with high heat, fluid, and pore space, S waves are slowed down more than P waves. The velocity ratio of these waves (Vp/Vs) was then mapped and areas of higher heat flow became visible. The process and data analysis is far more complex than that, but the point is, a network of OBSs set up around a potential reservoir could be used as one technique to define fault planes and suggest drilling areas within an offshore reservoir.

3.3.3 Seismic Reflection and Refraction

Seismic reflection and refraction are active techniques and are the most common methods used for offshore oil and gas exploration [83]. They are very useful for mapping out sedimentary layers and sub-surface geologic structures, including structures in a geothermal setting; however they are not normally a primary method for geothermal exploration on land because structures are very complex so interpretation is difficult [85].

Marine refraction and reflection surveys are generally carried out in the same way. The basic method involves towing an array of hydrophones behind a ship then generating an acoustic pulse in the water. The source of the acoustic waves is usually generated from a powerful air gun in the water. The shock waves travel through the water and propagate into the ocean crust and then return back to surface where they are received by the hydrophones (Figure 36). The concept is very similar to sonar only the waves penetrate deeper into the crust. Reflection surveys are the most widely used and well known technique, especially in the oil industry [83]. Reflection seismology interprets the data from the seismic waves that are reflected off of subsurface boundaries between layers of different velocities. Refraction surveys are a bit more complex; they analyze the seismic waves which are refracted or bent in the subsurface and travel along layers of different velocities [83]. Reflected seismic waves are analogous to light waves being reflected off of a mirror and refracted seismic waves are analogous to light bent by a prism. Both of these methods use similar field equipment but the main differences between them lies in how they are preformed and the analysis of the data.

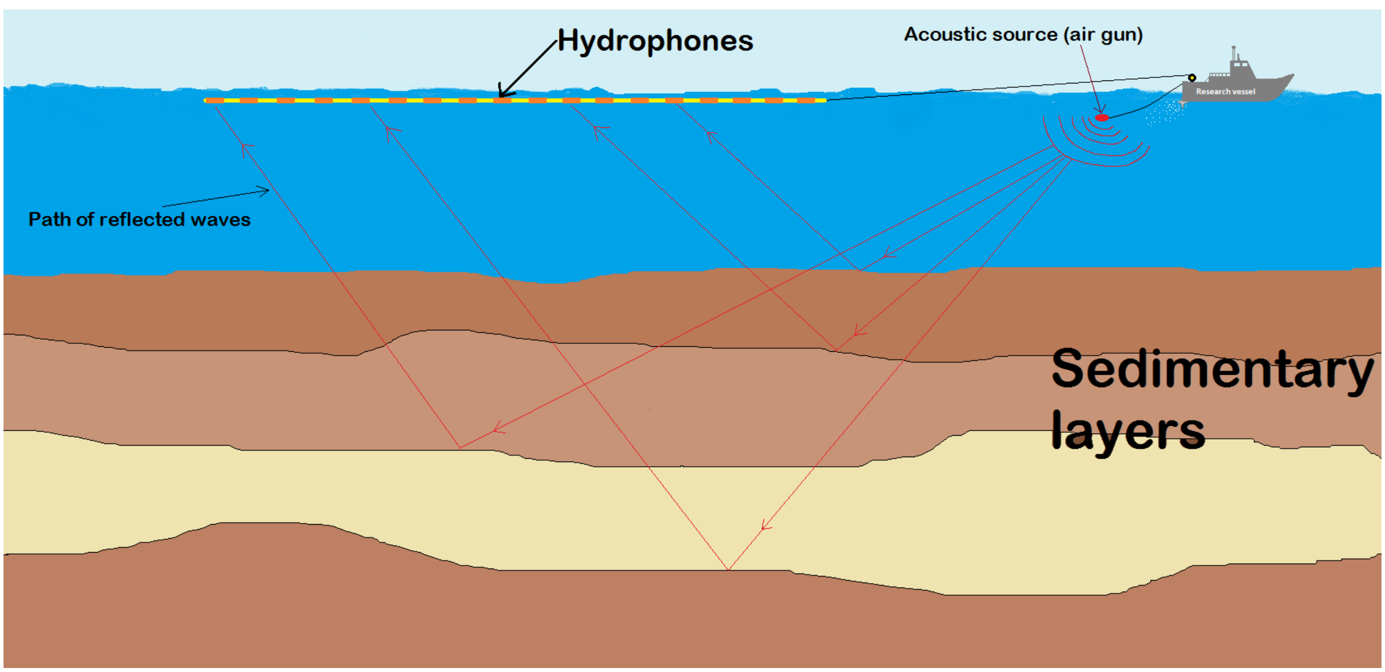

Figure 36) Conceptual drawing of a marine seismic reflection survey

Seismic reflection surveys have been used for geothermal exploration on the Marsili Seamount. A technique called 3D chirp sub-bottom profiling was used there (Section 2.4) [59]. Seismic reflection was also used during exploration of the Grímsey vent field (Section 2.3.5) and it was noted that phase reversals were seen in the seismic data. One proposal is that there is a relation between gas accumulations from hydrothermal vents and polarity reversals in the seismic reflection signal [54]. Another anomaly noticed when doing reflection surveys at hydrothermal vent sites is that hydrothermal alterations beneath the surface can appear as local reductions in reflectivity, or commonly called dim spots in the profiles. These dim spots are possibly caused by an inversion in the velocity structure and might be indicators of hydrothermal mineralization within pore spaces and/or impedance caused by free gasses [54]. A seismic study in Yellowstone Lake also revealed that local reductions occur directly beneath hydrothermal vents. These anomalies in the Yellowstone Lake were interpreted as gas pockets, gas charged fluids, or hydrothermally altered zones [86]. Seismic reflection has not been commonly used for hydrothermal vent exploration but these findings support the idea that it might be useful for locating hydrothermal vents around Iceland.

3.4 Magnetic Methods

There are several types of magnetometers in use: the fluxgate magnetometer, the proton precession magnetometer, and the optically-pumped magnetometer [82]. The most commonly used instrument for magnetic surveys is the proton magnetometer. This device utilizes a container surrounded by a coil and filled with a liquid rich in hydrogen atoms, such as kerosene or water. When current is passed through the coil it generates a magnetic field forcing the protons to align to the artificial magnetic field created. Next, the current is switched off, causing the protons to spin back into alignment with the natural magnetic field. The frequency of the protons spiraling back into their natural orientation is measured and provides an accurate reading of the strength of the total geomagnetic field [83]. The fluxgate magnetometer has also been commonly used during submersible magnetic surveys. Fluxgate magnetometers have the advantage of measuring vector components of the magnetic field [82].

Magnetic surveys can be used for many purposes, to find structural/tectonic trends, age relationships between crustal areas, to estimate sizes and thicknesses of rock formations, and to find unusual magnetic properties which can then be linked to other geologic features [41]. Magnetic surveys are a very useful tool for locating hydrothermal activity and learning about hydrothermal fluid flow because the magnetic properties of the rocks are affected by the hydrothermal fluids [60].

In general, freshly erupted basalts that are rapidly cooled are strongly magnetic because they usually contain significant amounts of magnetite or titanomagnetite [61]. In addition, since they are relatively young rocks they have only been exposed demagnetization processes for a short period of time [59]. For these reasons most young mid-ocean ridge basalts are highly magnetized but laboratory studies have shown that magnetic minerals in oceanic crust are highly susceptible to alteration from hydrothermal fluids [60]. Acidic hydrothermal fluid circulation drastically decreases the magnetization of the rocks by changing the original minerals into less magnetic minerals such as pyrite [61]. The alteration process can cause secondary minerals which are less magnetic to replace the original minerals resulting in a localized low magnetic anomaly where hydrothermal fluids have affected the rocks. Hydrothermal fluids can also cause leeching out of the iron content in the rocks, thus causing demagnetization [87]. The overall magnetic signature left behind is a magnetic low anomaly often contained within a magnetic high area.

Another way that the rocks can become demagnetized is due to elevated temperature. If the rocks in a hydrothermal area contain high amounts of titanomagnetite then demagnetization due to high temperatures can take place because titanomagnetite has a low Curie temperature of 150-200°C [61]. This type of thermal demagnetization usually occurs on a large scale. If the high temperatures diminish then magnetization returns, but demagnetization due to mineral alterations will remain even after the heat source is gone [61]. More evolved areas tend to have a higher concentration of magnetite so the Curie temperature will be much higher. The Curie temperature of magnetite is about 580°C [88]. The depth to the bottom of the magnetic sources (the Curie point isotherm) can sometimes be estimated from magnetic survey data, and using this technique the depth where temperatures reach around 580°C can then be inferred.

3.4.1 Ground Magnetic Surveys

Magnetic surveys on land have been done for a long time and for many different purposes, including geothermal exploration (Figure 37). Magnetic surveys are normally used for locating iron ore, and hidden structures such as dikes or faults. In geothermal exploration it can be used for finding areas of reduced magnetization caused by hydrothermal fluids [85]. An on-land magnetic survey is conducted by carrying a magnetometer across the landscape and walking many profiles. The profile spacing and length varies depending on the geology and the specific goal of the survey. The same concepts apply to a land magnetic survey as would apply to a marine survey concerning the magnetic low anomaly of interest. Section 4 describes the land magnetic survey that was conducted for this thesis.

Figure 37) Equipment used for a ground magnetic survey. The magnetometer is on a pole roughly 2.5 meters above the ground. A GPS is at the very top of the pole. The computer is strapped around the stomach.

3.4.2 Aero-Magnetic Surveys

Aeromagnetic surveys are conducted from the air using a magnetometer installed on an airplane or helicopter (Figure 38). This type of survey is useful for getting broad information about the magnetic characteristics of a region. Aeromagnetic surveys are the most efficient magnetic technique for covering a large region and can be used over land and sea. The problem with this type of survey is that it has low resolution, so small features such as localized magnetic low anomalies, caused by hydrothermal activity, are usually too small to be found from the air. In order to see smaller localized anomalies the magnetometer must be closer to the ground.

Figure 38) A total field magnetometer installed onto the back of an aircraft [89].

3.4.3 Marine Surface Ship Surveys

A marine magnetic survey can be done in several ways. The simplest way is to collect magnetic readings from the surface. For marine surveys the magnetometer (Figure 39) must be towed at least two ship lengths behind the vessel to prevent the ship from affecting the magnetic readings [83]. This method could detect a magnetic anomaly if the volume of hydrothermal alteration is large and/or the depth of the alteration is shallow enough. For ocean depths greater than 1 km, surface data becomes less useful because the resolution diminishes fast with distance, thus making any detailed mapping impractical [90].

Another method is to tow the magnetometer from the ship and let it sink to a depth where it is much closer to the ocean bottom. A magnetometer with controllable fins towed from a ship could help create better resolution in the data because the altitude of the instrument above the seafloor could be controlled (Figure 40). There has been no information found concerning whether towed marine magnetometers with control fins have been used yet.

Figure 39) Marine magnetometer; this instrument is about 2 meters in length and is towed by a cable. While in tow the instrument transmits magnetic measurements to a computer onboard the ship [91].

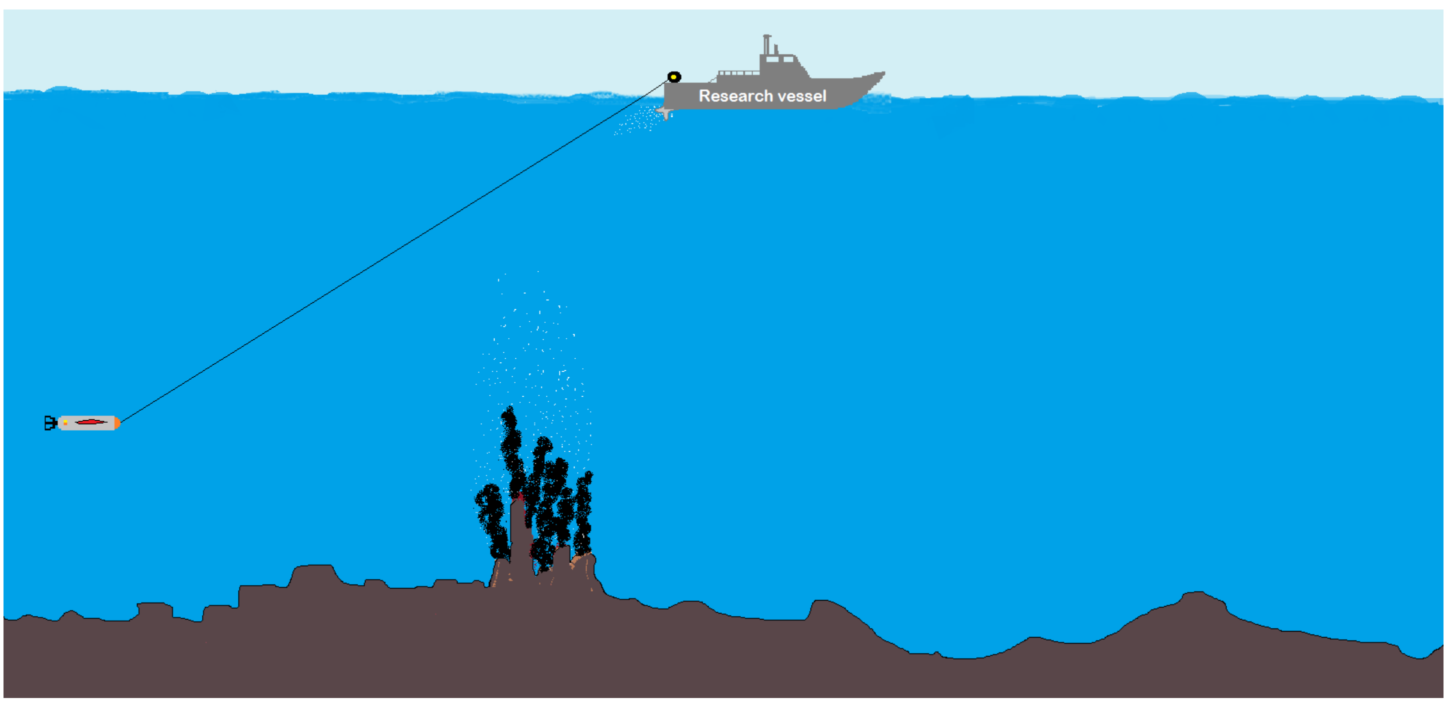

Figure 40) Conceptual drawing of a marine magnetic survey using a towed magnetometer with depth control fins. When the magnetometer passes over the hydrothermal vents low magnetic readings are expected.

3.4.4 Marine Underwater Vehicle Surveys

In order to get very fine detailed magnetic data of the ocean floor underwater vehicles are used. One example of a magnetic survey done from a submersible with great success was at the TAG hydrothermal vents [60]. Prior to the discovery of the TAG hydrothermal field a magnetic survey from the surface revealed an elongated magnetic low stretching along the Mid-Atlantic Ridge. After the TAG hydrothermal vents were discovered it increased interest in the idea that hydrothermal activity can cause significant demagnetization in oceanic crust. Tivey et al., 1993 stated "The mapping and analysis of 3D magnetic anomalies shows considerable promise in locating significant hydrothermal deposits on the deep seafloor" [60]. In 1990 the submersible Alvin was used for the magnetic survey at the TAG vent field, the survey covered an area of 350 X 400 m. The instrument used was a three-axis fluxgate magnetometer which was mounted onto the sample basket of the Alvin [60]. Using 3D analysis, the interpretation showed a distinct magnetic low anomaly at the hydrothermal vents. The detailed magnetic study even shows narrow alteration pipes in the subsurface which likely feed the hydrothermal vents. These types of clues are very useful for determining the location of hydrothermal up flow zones and possibly locating the magma heat source; however only drilling would confirm those models [60].

ROVs and AUVs have also been used for magnetic surveys with success. They have the advantage of collecting high resolution data while having a greater range than a manned submersible [90]. When a magnetic survey is done by an underwater vehicle the magnetometer is mounted directly onto the vehicle. In order to correct for magnetic effects caused by the vehicle, calibrations of the sinusoidal variation from the magnetic field data are made. This is achieved by spinning the vehicle during the descent and ascent [90].

3.4.5 Magnetic Methods Summary

Table 8) Summary of the magnetic methods useful for offshore exploration

Method	Range	Resolution
Aeromagnetic	Long	Low
surface ship	Medium/Long	Medium
ROV and AUV	Medium/short	High
Manned submersible	Short	High

3.5 Gravity

Gravity measurements require extremely precise instruments that measure minute variations in the earth's gravitational field, caused by contrasts in densities between formations. A detailed gravity survey can be useful for supporting magnetic and resistivity surveys by detecting anomalies caused by shallow heat sources and providing information that can be used to infer the porosity of the rocks [85]. Shallow heat sources and porous rock can be inferred because hot areas are less dense than cold areas and water within pore space is less dense than solid rock. In the geothermal industry gravity surveys are also used to monitor the fluid mass extraction due to fluctuations in the water table during utilization of geothermal reservoirs [85].

Ocean gravity surveys are most often conducted from a ship. Gravity meters used onboard ships are mounted to gyro-stabilized platforms (Figure 41) in order to reduce movement caused by waves [92]. The accuracy of marine gravity measurements are about 1-5 μms^{-2} which is an order of magnitude less accurate than gravity measurements made on land [93]. Gravity measurements are sometimes taken from aircraft and have an accuracy range of around 50 μms^{-2} [93]. Gravity measurements can be made from submersibles as well, but are un-common in part because of the difficulty of keeping the submersible at one precise depth [93]. Underwater gravity meters that can come to a rest on the ground have been used in shallow waters and have accuracies similar to land gravity measurements [93]. It might be possible to design a similar instrument for deeper ocean applications that would be useful for offshore geothermal exploration.

Figure 41) Marine gravity meter [92]

An indirect way of deriving ocean basin gravity measurements is from radar altimeter data collected via satellite. The radar altimeter is used to measure the ocean surface topography very precisely and the static gravity field values are calculated based on the slope of the ocean surface. Extremely precise measurements from the satellite along with complex mathematical models have resulted in widespread gravity field maps of the ocean floor. Using this method it is possible to learn about the topography and gravity of the ocean floor because seamounts and other ocean floor features have an influence on the water's surface. Due to the slightly larger or smaller gravity anomaly from a seamount or trench, a small bulge or dip on the ocean's surface can be detected with the radar altimeter (Figure 42) [94]. The accuracy of the satellite derived gravity data are about the same as shipboard gravity data [45].

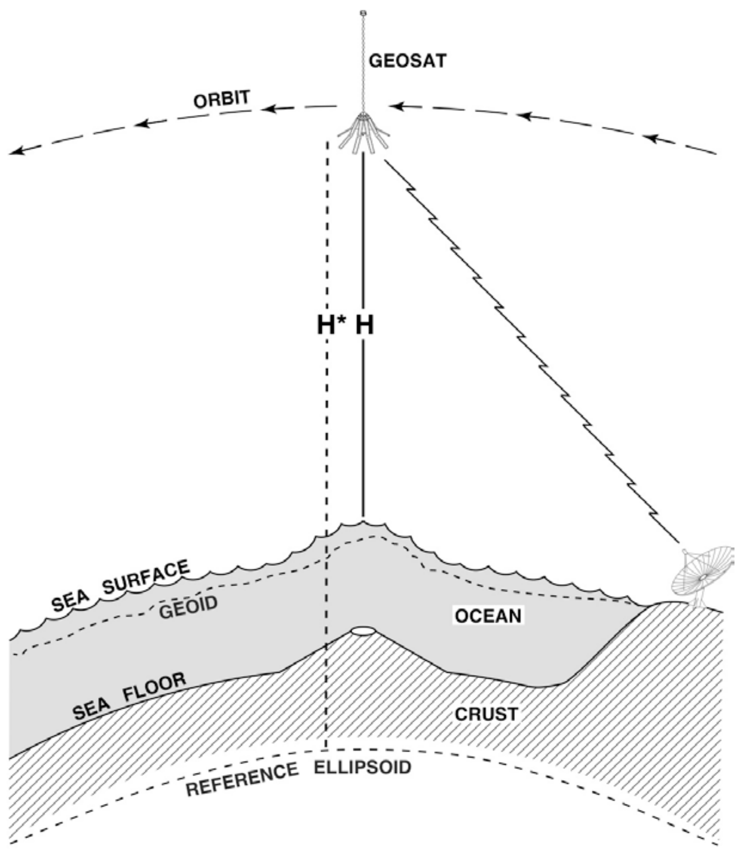

Figure 42) Conceptual drawing of how radar altimetry is used to deduce ocean floor bathymetry and gravity anomalies [94].

3.6 Electrical Methods

The goal of electrical methods is to learn about resistivity structures in the subsurface. Resistivity methods are the most important geophysical techniques being used for geothermal exploration on land right now [85]. Geophysicists looking for geothermal resources carry out these surveys and look for shallow layers of low resistivity which is an indication of clay alterations caused by high temperature fluids. The clay alterations are caused by the interactions between hot geothermal fluids with rocks [95]. Beneath the layer of low resistivity there is sometimes a basement layer of higher resistivity, an epidote-chlorite zone, that forms a dome shape, and is an indicator of temperatures greater than 250°C [96]. It is important to note that resistivity data does not directly indicate heat, it indicates where rocks have been altered from a heat source; thus, a low resistivity structure can be left behind even after a geothermal heat source has gone extinct.

In marine geothermal environments low resistivity anomalies can be caused by the presence of seawater in highly porous basalt, hydrothermal activity, and/or the presence of melt [97]. The overall resistivity of basalt saturated with seawater depends strongly on the resistivity of seawater; and the resistivity of seawater varies with temperature. Seawater at about 2°C has a resistivity of 0.3 Ωm and seawater at 350°C has a resistivity of 0.04 Ωm; beyond 350°C the resistivity increases [97]. There are many techniques used to obtain resistivity data from the subsurface and they are divided into two main techniques; electrical methods and electromagnetic methods (Section 3.7).

3.6.1 Direct Current (DC) Method

DC methods were the most commonly used method for geothermal exploration up until the 1980's, but now their application is not as common and electromagnetic methods are routine [85]. DC methods involve generating a current and injecting it directly into the earth via a pair of electrodes (dipole) that is placed in the ground. Then the voltage between a second pair of electrodes is measured. There are many different electrode configurations that can provide resistivity information from varying depths. The voltage and current measured at the surface can be converted into an apparent resistivity giving information about the resistivity structures below [98]. DC methods are the most common and inexpensive way to conduct a resistivity survey on land.

3.6.2 Induced Polarization (IP)

The IP method is similar to the DC method in the sense that it uses electrodes that are placed into the ground to send a current and record the resistivity. IP methods use AC or DC currents to record the capacitance as well as the conductivity of the rock [98]. Capacitance is recorded by abruptly turning off the current and recording the electrical decay over time. IP methods are most commonly used for metal exploration [83].

3.6.3 Self Potential (SP)

Self potential, also called spontaneous potential is a similar method to IP only it is passive. Electrodes are still placed into the ground but the SP method uses naturally occurring ground currents to detect resistivity structures in the ground. Ground penetration is only about 30 m [83], but SP is inexpensive and fast to set up.

SP methods are commonly used for mineral exploration and identifying ground water flow. SP is also sometimes used for geothermal exploration [83].

3.6.4 Marine Electrical Resistivity Methods

Electrical resistivity is a very useful form of exploration for geothermal resources on land, so it would be very beneficial to have a way of conducting a resistivity survey at sea. Land based techniques are very difficult to perform underwater because placing the electrodes into the ground would require scuba diving or underwater vehicles, so it would be much more complicated, time consuming, and expensive. There is also the problem of the salt water being conductive, so the electrical current is not only directed into the ground like it is for a land survey. Marine electrical techniques have not been used for offshore geothermal exploration but they have been used for offshore hydrocarbon and metal exploration. Marine resistivity techniques are still in research and development stages and will most likely need to be modified in order to be practical for offshore geothermal exploration.

The most common type of marine electrical resistivity equipment is towed array systems. They are basically a modified version of the DC method used on land [99]. The first commercial design, Cable Burial Assessment Survey System (C-BASS) was released in the early 1990's [100]. C-BASS was capable of working at more than 2000 mbsl and taking continuous multi-electrode resistivity measurements of the top few meters of seafloor [100]. Most of the practical applications for towed electrical resistivity systems are preformed in shallow fresh water. This is because fresh water is less conductive and the high conductivity of salt water causes very high currents to be needed in order to penetrate into the seabed [99]. Also, the conductive seawater makes it difficult to distinguish which signals travel through the ground and which travel through the water. There are several different types of arrays and methods being experimented with right now. The most commonly used arrays have been towed horizontally but it has been found that horizontal arrays are inefficient, making it difficult to penetrate downward into the rock [99]. The use of vertical arrays have recently been experimented with and they are found to improve data quality; however accurate information seems to be limited to very shallow marine environments and problems with keeping the array perfectly vertical slows down the data collection process drastically [99].

One company leading in marine electrical resistivity techniques is Advanced Geosciences Inc. (AGI). According to the AGI website, their towed systems have been used in lakes, canals, and shallow straits with great success [101]. AGI also has a system in development for deep salt water applications. It is called the SuperString Ocean Bottom Electrical Imaging System (OBEI) (Figure 43). This system requires a surface vessel and an ROV. The ship on the surface tows an array consisting of electrodes while the ROV guides it along the bottom. The ROV is needed to keep the array straight and to prevent it from being dragged over jagged rocks. The array must be kept very close to the bottom so the current can penetrate through the conductive salt water into the earth. There must be a large current to be adequate for a deep salt water environment, so with OBEI the transmitter has an output of 10 kW [102]. According to AGI an OBEI system specifically designed to work in an offshore geothermal environment such as the Grímsey or Steinahóll vent fields would be possible [102].

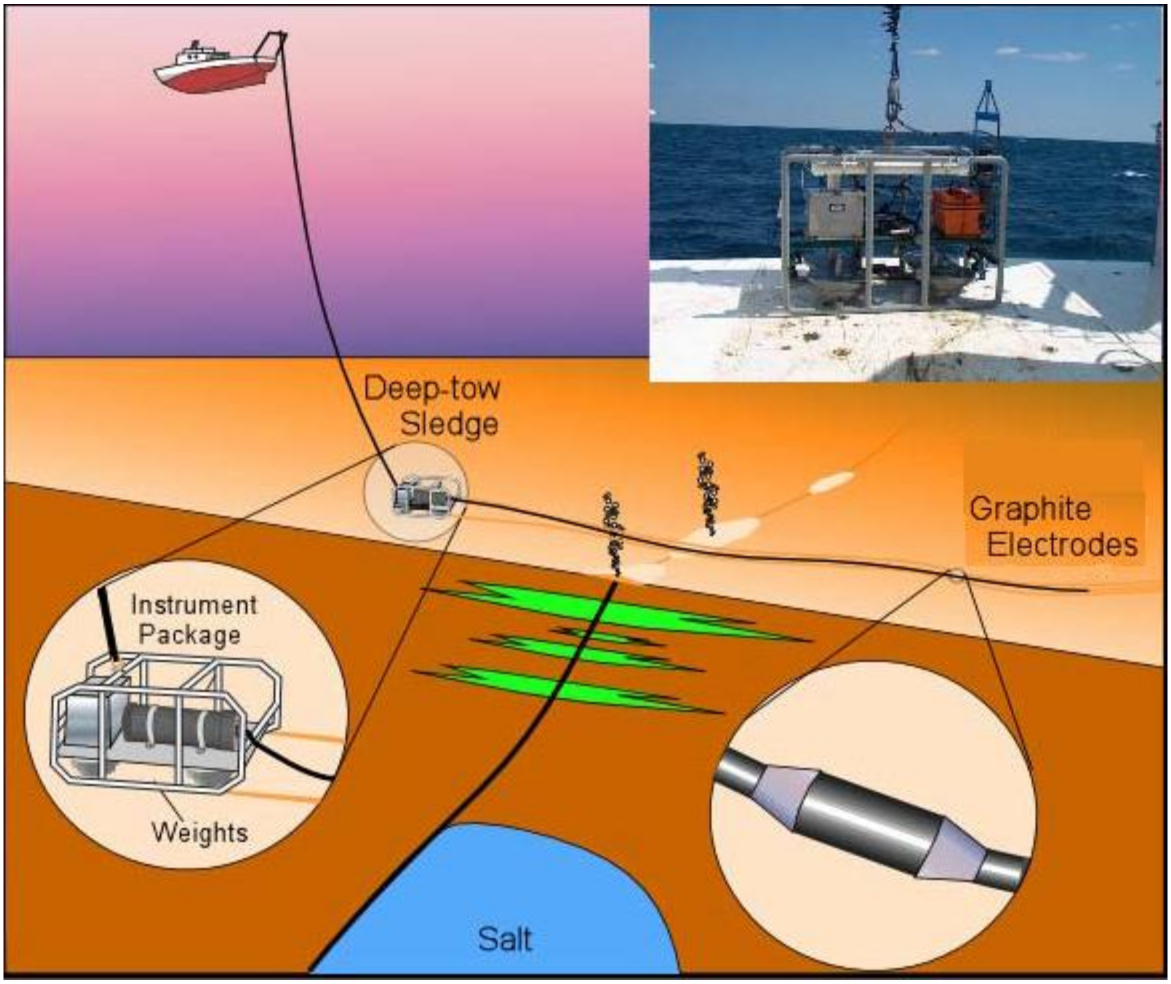

Figure 43) Conceptual animation of a marine resistivity survey used in the oil and gas industry. Inset is a photograph of the deep tow sledge unit [103].

3.7 Electromagnetic (EM) Methods

The goal of EM methods is the same as electric methods; to identify resistivity structures in the subsurface. Electromagnetic methods do this indirectly by measuring a small secondary electromagnetic field induced by a larger primary electromagnetic field. There are many variations of EM methods on land. EM methods, specifically Transient Electromagnetic (TEM) and Magneto-Telluric (MT), are presently the preferred resistivity methods for geothermal exploration on land. Some marine EM methods are in development and are most commonly used for hydrocarbon exploration and locating metal objects buried in lakes or rivers.

3.7.1 Transient Electromagnetic (TEM)

The TEM method, also called the Time Domain Electromagnetic (TDEM) method, began to be used in the geothermal industry in the 1980's [85]. One configuration of this method is the use of a big loop with current transmitted through it, creating a magnetic field in the ground. Then the current is abruptly turned off, which causes a secondary field of eddy currents in the ground to decay with time. The decay rate is then monitored by measuring the voltage induced in a receiver coil, usually located inside the large loop. Current distribution and decay rate are dependent on the resistivity of the rock below. High currents are required in order for there to be a strong enough magnetic field through the transmitting loop [85]. This method is useful for analyzing the upper 1 km of crust [85].

3.7.2 Magneto-Telluric (MT)

The MT method uses alternating currents induced from the earth's natural electromagnetic field. The field is time dependent and can therefore induce electrical currents in the conductive earth. For this method the signal from the fluctuating magnetic field and the electrical field on the surface are measured. With these measurements it is possible to learn about the resistivity structure below the site where the measurements are taken. The MT method is not as precise as TEM, but can see much deeper into the earth. The MT method can probe hundreds of kilometers below the surface [96], and because of the large range the MT technique is currently the resistivity method of choice for most geothermal exploration companies [104].

3.7.3 Controlled-Source Electromagnetic Sounding (CSEM)

CSEM is a fairly new technique that has been very successful in the offshore oil and gas industry. ExxonMobile and Statoil began testing this method in the early 1990's, but the majority of CSEM research has taken place in the last 12 years [105] [106]. This method is designed for use at sea and involves setting up Ocean Bottom Electro-Magnetometers (OBEMs) on the ocean floor. An OBEM is a self-contained sensor and information recorder that can measure small electric and magnetic fluctuations on the ocean bottom [107]. A CSEM survey begins by deploying OBEMs over the area of interest, and then a ship towing an electromagnetic dipole transmitter along the seafloor makes passes by the OBEMs (Figure 44). This induces an electrical field into the ocean floor around where the OBEMs are placed. The transmitter is towed as close as possible to the seafloor without risking damage from hitting jagged rocks on the bottom; the tow depth is usually between 25-100 m above the seafloor [106]. A close tow to the bottom maximizes coupling with the seafloor and minimizes coupling with the air [106]. The transmitters are towed horizontally, they are 50-300 m long, and emit up to 1000 amps of current into the seawater [106]. CSEM methods have proven useful in waters 1000+ meters deep, but in shallow waters there has not been as much success due to coupling with the air-water boundary [108]. Research into improving shallow water results is ongoing.

The use of an electromagnetic transmitter to induce current makes this method similar to the TEM method, but an OBEM can also record the earth's natural magnetic fluctuations, so this method can be used actively and passively. Once the active portion of the survey is done it is beneficial to leave the OBEMs on the bottom to record natural signals and conduct a marine MT survey as well [105]. Once the survey is completed the OBEMs are triggered to release themselves from their anchors and the sensor floats to the surface for recovery. The release is either triggered by a timer or an acoustic signal sent out from the research vessel [82].

The interpretation of CSEM information requires sophisticated modeling and inversion techniques but the basic idea is that the ratio of the electric field and magnetic field recorded by the OBEM can be used to determine the resistivity of subsurface structures. An OBEM situated over resistive seafloor structures will record a larger electric field than those placed over conductive structures [108].

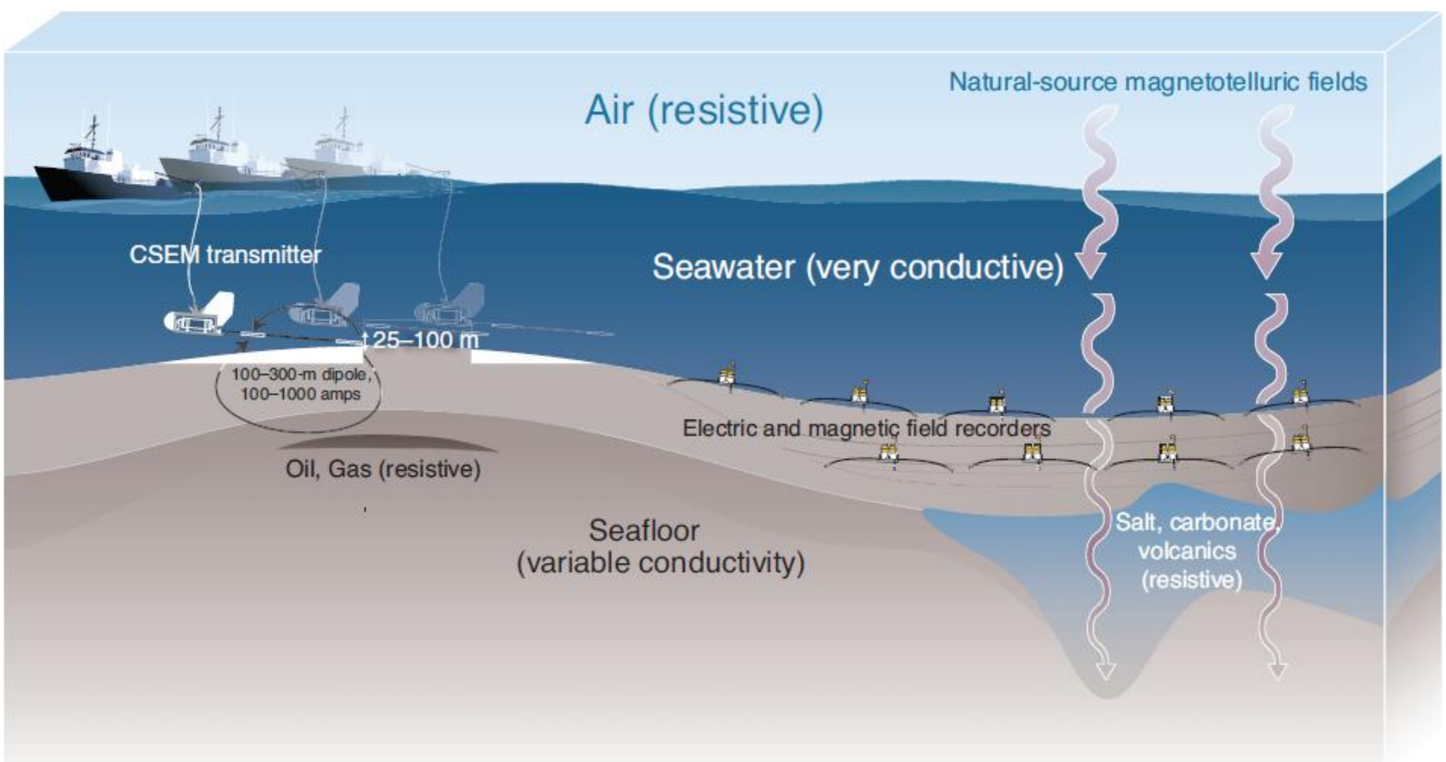

Figure 44) Conceptual drawing of how a CSEM survey is carried out for hydrocarbon exploration [106].

Most of the literature on CSEM and marine MT surveys are about hydrocarbon exploration in sedimentary dominated regions; however the RAMESSES experiment (Section 2.2.9) is one of the few where CSEM and MT surveys were conducted over a basalt dominated mid ocean ridge [97]. During the RAMESSES experiment the CSEM survey was conducted in 1800 m deep waters over the Reykjanes Ridge. A horizontal dipole, 100 meters long, was towed at heights of 50-80 m above the seafloor, at distances of up to 15 km from the OBEMs. The upper crust of the ridge axis was found to have a very low resistivity of 1 Ω m, which is explained by the rock being highly fractured and saturated with seawater. A steep resistivity gradient was also noted because at 500 m depth the resistivity was 10 Ω m. The results of this survey provided quality resistivity data from the ridge axis down to roughly 2 km depth where a low resistivity anomaly of 2.5 Ω m was encountered and interpreted to be a body of melt [97].

3.7.4 Multi Transient Electromagnetic (MTEM) Method

The MTEM method is similar to the CSEM method except MTEM is a time domain pursuit while CSEM is a frequency domain pursuit. Also MTEM sends out an impulsive source, which generates a broadband electromagnetic signal; while CSEM creates an electromagnetic field with only a few fundamental frequencies [109]. The MTEM method records a continuous frequency spectrum data set. The data set includes the earth response and the system response for source and receivers, which are very important for learning about the subsurface electrical properties [109]. MTEM is designed for use at sea and on land while CSEM is designed solely for at sea purposes. In theory, both methods should produce equal results; however MTEM is more successful at shallow depths, while CSEM has had some difficulties being used at less than 1000 m depth [98]. The MTEM method has mainly been used for offshore oil and gas exploration and to my knowledge has not been used for geothermal or hydrothermal vent exploration.

An MTEM survey requires two ships (Figure 45). One ship is equipped with an Ocean Bottom Cable (OBC) which has the electromagnetic signal receivers. The OBC is set down on the seabed in a straight line and remains at rest while the other ship towing the electromagnetic source is in motion. The distance between the source and the receivers is directly proportional to the depth that can be explored. This method is very convenient because the equipment used can provide real-time results in the field [109].

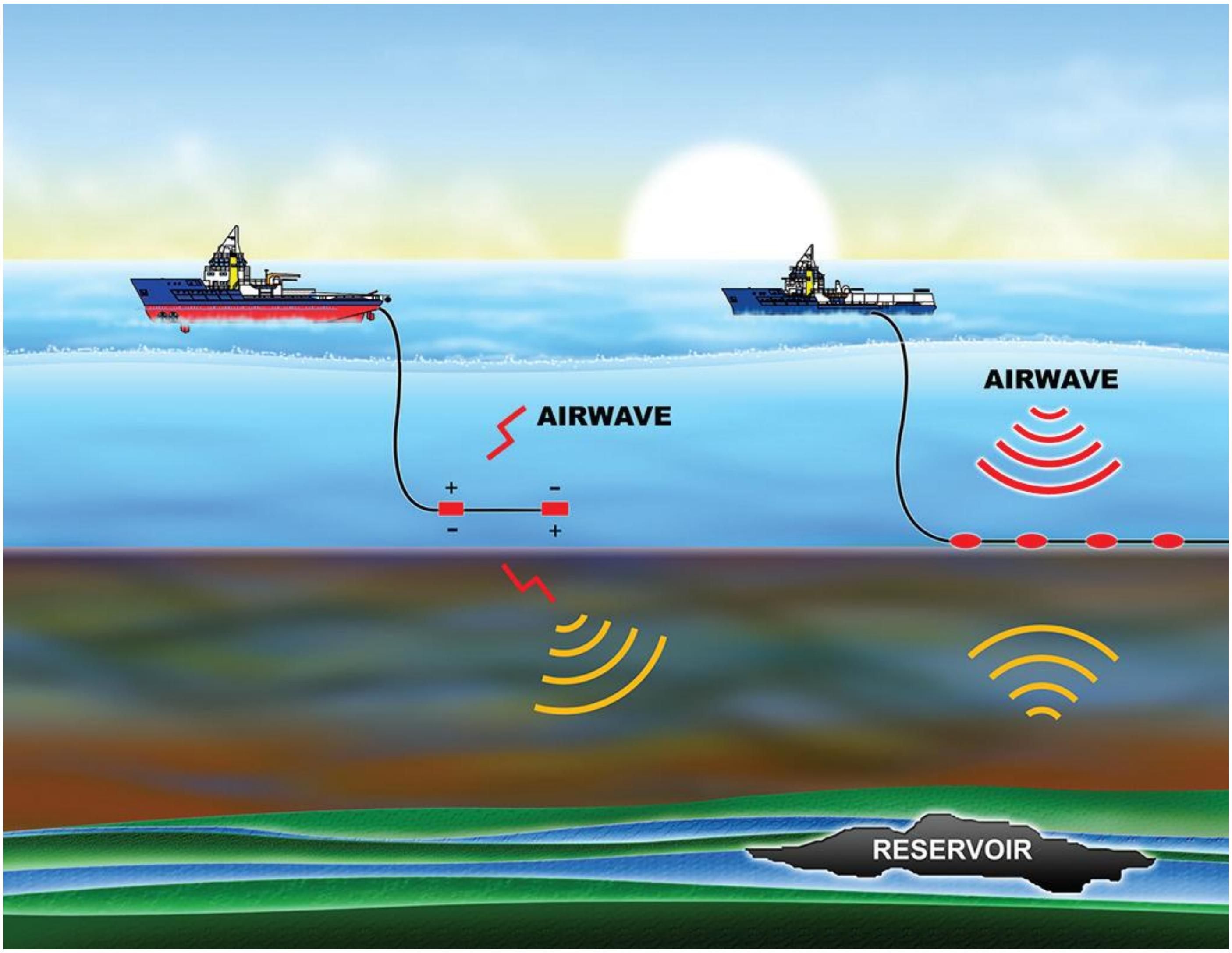

Figure 45) Conceptual drawing of how an MTEM survey is carried out for hydrocarbon exploration [98].

3.7.5 Magnetometric Resistivity (MMR) Method

The MMR method (Figure 46) is similar to the DC method except in MMR the potential electrodes are replaced by highly sensitive magnetic field detectors. A component of the magnetic field, caused by low frequency current in the ground is measured, rather than a component of the electric field. This method is a type of electrical method useful for mapping lateral changes in conductivity on land and underwater. It has been found to provide reliable data for the upper few kilometers of crust in some cases [110]. This method has been used for mapping regional geology, searching for nuclear waste disposal sites, geothermal resource exploration, and most recently to study electrical conductivity of deep oceanic crust [110].

Marine applications of the MMR method have been used to estimate electrical resistivity of the uppermost oceanic crust using OBMs. This method uses a vertical array for the electric current rather than a horizontal array. The vertical array covers a small area but allows for high resolution and deeper penetration compared to a horizontal array [111]. The OBMs are placed on the ocean floor, then current is transmitted into the crust by the vertical dipole and the OBMs record fluctuations of a component of the azimuthal magnetic field induced by the electrical current [82]. Once the readings are made the vertical dipole is raised from the ocean floor and moved to a new location where current is fed into the seafloor again. The resistivity of the oceanic crust is dependent on the amount of fluid within the crust, the distribution of the fluid, the temperature, and the salinity [112]. Due to these factors the electrical resistivity can potentially be used to deduce the volume and temperature of hydrothermal circulation fluid within the shallow crust. Lower resistivity readings beneath a ridge crest are often an indicator of hot fluids beneath the surface [112].

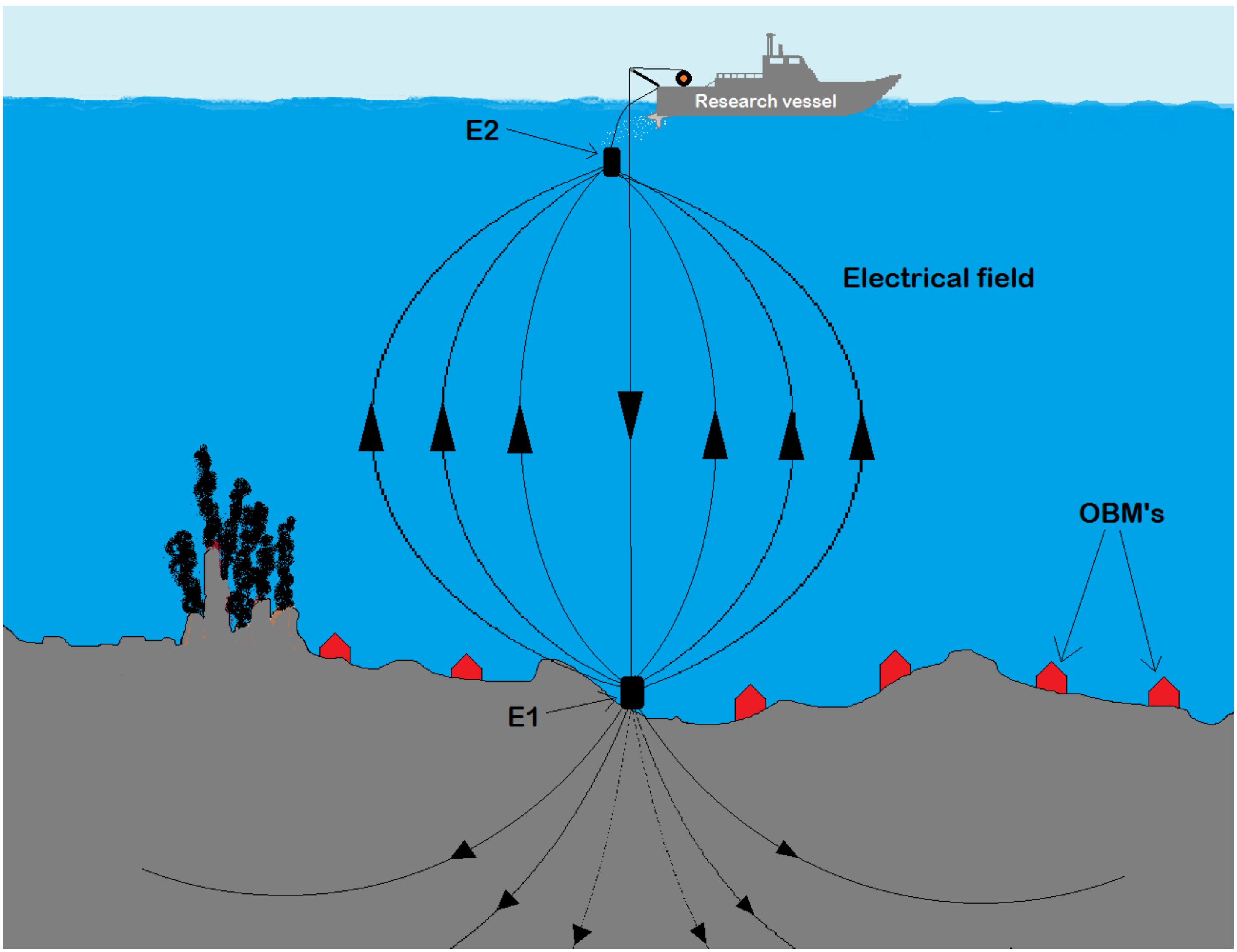

Figure 46) Conceptual drawing of the MMR method. Current is fed into the seafloor with a vertical bipole source and OBMs record a component of the azimuthal magnetic field induced by the electric current.

MMR Surveys have been conducted on sections of the Juan de Fuca Ridge with successful results. The studies found low resistivity anomalies beneath areas of highly active hydrothermal venting. The resistivity zones indicated that hot fluids flowing within the porous rocks extend to depths of at least 1 km [113].

3.7.6 Airborne Electro-Magnetotelluric (EMT)

A recent method experimented with in the offshore oil and gas industry is a type of MT survey conducted via aircraft. The method has been named airborne EMT and uses natural electromagnetic currents induced upon the earth from the interaction of the ionosphere with the sun. The company that invented and patented the technology for this method is called eField Exploration LLP. Airborne EMT is carried out using a typical survey aircraft. The company's patented system involves mounting electric field sensors in the wingtip pods [114]. The sensors have three orthogonal sensors orientated along the X, Y, and Z axes and they are attached to angular motion sensors that compensate for the motion of the aircraft [114]. In order for the electric field sensors to supply accurate telluric current readings, a total field magnetometer is mounted onto an 8 foot long tail stinger [114]. The magnetometer provides a telluric phase and amplitude reference for the electric field sensors [114].

A successful survey carried out in the Norwegian Sea in 2008 has given this method a very optimistic future for offshore oil and gas exploration. The survey showed that this method can detect hydrocarbons below waters 300 m deep and up to 6 km beneath the seafloor [114]. In addition, airborne EMT can cover about 260 km^2 per day, so time and money consumption is less compared to conventional marine methods like seismic or CSEM [114]. The Norwegian survey was completed in one week, while conventional marine methods would have taken months at several times the cost [114].

Airborne EMT methods have been successful for locating offshore hydrocarbon deposits because hydrocarbons have a high resistivity compared to water [114]. There is also an effect called Natural Field Induced Polarization (NFIP), caused by the flow of current between hydrocarbons and water. The NFIP effect helps anomalies to be seen by the airborne EMT system, which aids geophysicists in identifying where the hydrocarbon deposits might be during interpretation [114]. Whether or not this method can be modified to be useful for offshore geothermal exploration is unknown and would require a great deal of research.

3.8 Radiometric

The radiometric, also called Gamma Ray Spectrometry (GRS), method detects radioactive elements, the most common being uranium, thorium, and potassium. This method is usually used on land because it is limited by the attenuation of gamma rays in water. Nevertheless, marine equipment for this method has been developed, but in order for it to be effective the sensors must be on or very close to the seafloor; within 20 cm [115]. Depth penetration of GRS devices is minimal, only penetrating a few centimeters into the ground [116]. This method can be used in shallow and very deep oceanic waters. The sensor is small and can be towed from a ship or mounted to an underwater vehicle. Most marine applications have been for geological mapping, but some studies have been conducted around active hydrothermal vents [115]. One study on core samples from an ODP drill site at the PACMANUS hydrothermal vent field suggested that uranium enrichment could be related to the hydrothermal activity [117].

3.9 Remote Sensing via Satellite

There are many remote sensing techniques being used over land today but only a couple are useful for learning about the ocean floor. Remote sensing methods carried out from satellites cannot penetrate the ocean's surface, except for one method called Light Detection and Ranging (LiDAR). LiDAR is a remote sensing technique that uses high energy pulsed laser beams to measure the distance of objects. The concept is similar to sonar only an optical source is used rather than an acoustic source. The laser beams used are typically in the visible and near infrared wavelengths [104]. LiDAR is used over land for many purposes such as: mapping of topography, faults, rock types, archeology etc. Marine applications include monitoring of surface water pollution, bathymetry of shallow coastal topography, and backscatter scans; similar to side scan sonar. LiDAR surveys of bathymetry from satellite or aircraft is limited to shallow waters; about 60 m deep and is highly influenced by water clarity and turbidity [118]. A LiDAR survey with the instrument mounted to a ship hull can have a depth range of up to 100 m in good water conditions [118].

Thermal imaging is another remote sensing tool that in theory could have some use; however infrared wave lengths do not penetrate the ocean surface [119], so if an anomaly from a geothermal source in the ocean were to be detected the hot water must reach the surface. This might be possible in shallow waters, but the amount of hydrothermal fluid emitted from a vent field is small compared to the ocean, so this method seems unlikely to be practical.

Another remote sensing instrument useful for learning about the ocean floor is the radar altimeter discussed previously in Section 3.5.

4 Magnetic Survey Field Work

Section 4 discusses the magnetic field work conducted on land in the summer of 2012. This section is written as a separate small report within the main thesis. After Section 4 we will return to the topic of offshore geothermal exploration.

4.1 Introduction

As part of this thesis a magnetic survey was conducted in the Eldvörp geothermal area during the summer of 2012. The purpose of this field work was to learn how a magnetic survey is done and to learn about the principles behind a magnetic survey. Of course a magnetic study done somewhere on the Reykjanes Ridge would have been more valuable to this thesis, but due to lack of funds it was not possible to obtain a research vessel and all necessary equipment to carry out a marine magnetic survey. Nevertheless, this field work was conducted for the purpose of becoming familiar with magnetic surveying and to learn about the theory behind it. This was important to this thesis because magnetic studies are an effective method in the exploration and assessment of offshore geothermal resources.

The Eldvörp area was chosen for conducting this field work because before this study no magnetic surveys had been conducted there; at least none which have been documented and are available. Eldvörp is a row of craters on the Reykjanes Peninsula where a high temperature geothermal area exists among the craters (Figure 47). It is located between the Svartsengi and Reykjanes geothermal areas where a positive magnetic anomaly is seen in Figure 48.

The row of craters spans roughly 4-5 km and runs in a northeast-southwest direction. One crater is of particular interest because steam is seen rising from inside the crater and the immediate area surrounding the crater. The area is of some interest as a possible location for another geothermal power plant. One exploratory well has been drilled in this location but it is not connected to any power plant at this time. The purpose of this field work was not to conduct a full survey and analysis of the data; however the information collected may contribute to future studies for that purpose. It was very interesting to learn how a magnetic survey is carried out and to create new, possibly useful data for future geothermal exploration.

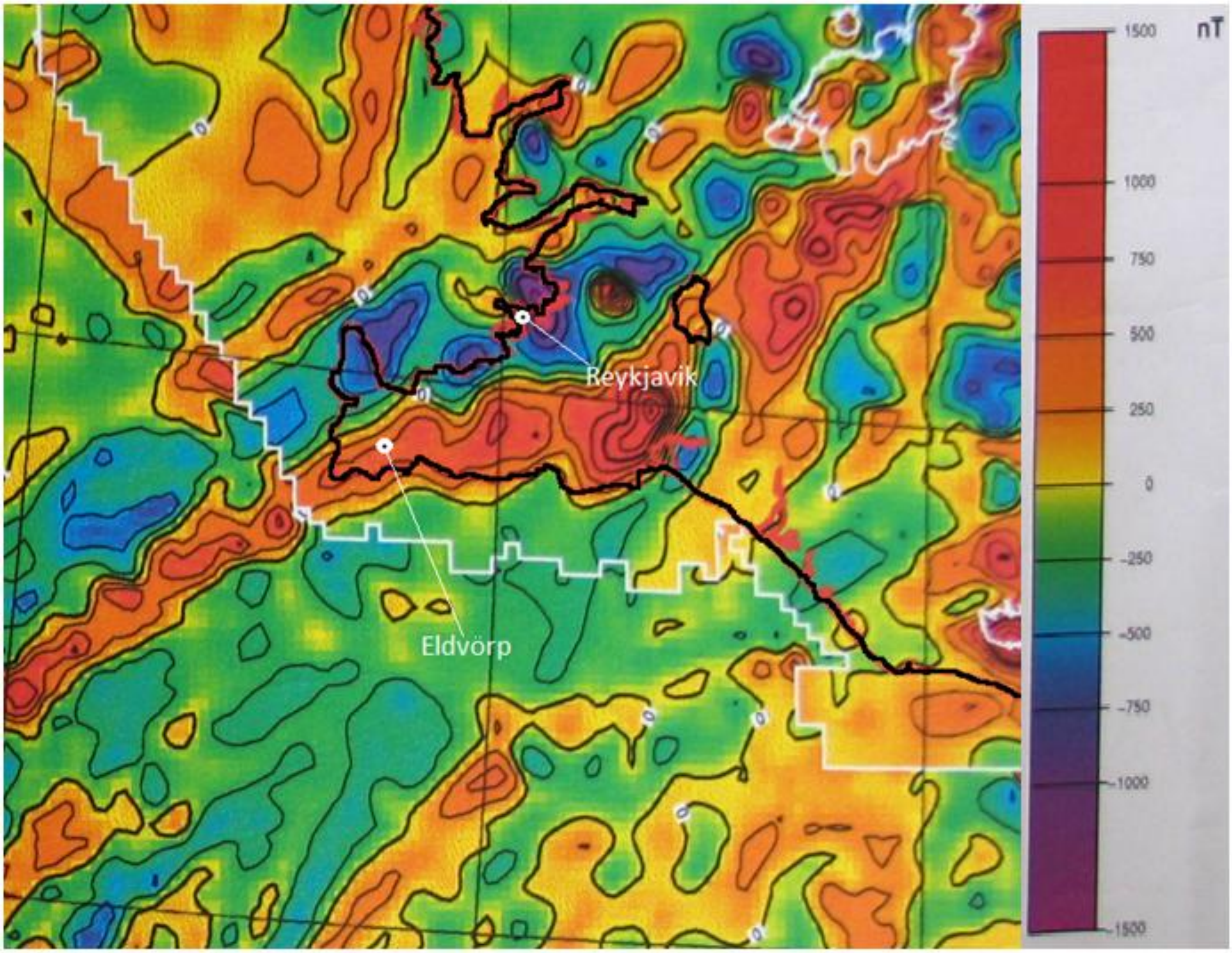

Figure 47) Aero magnetic map of Iceland [120] modified to clearly show the location of Eldvörp. Contour interval is 250 nT. This map does not show enough detail to be of any use for locating hydrothermal vents; however it does show a clear magnetic high along the Reykjanes Ridge, so is indicative of a general location geothermal activity might take place. Eldvörp lies in the center of the magnetic high anomaly that is characteristic of the Mid-Atlantic Ridge.

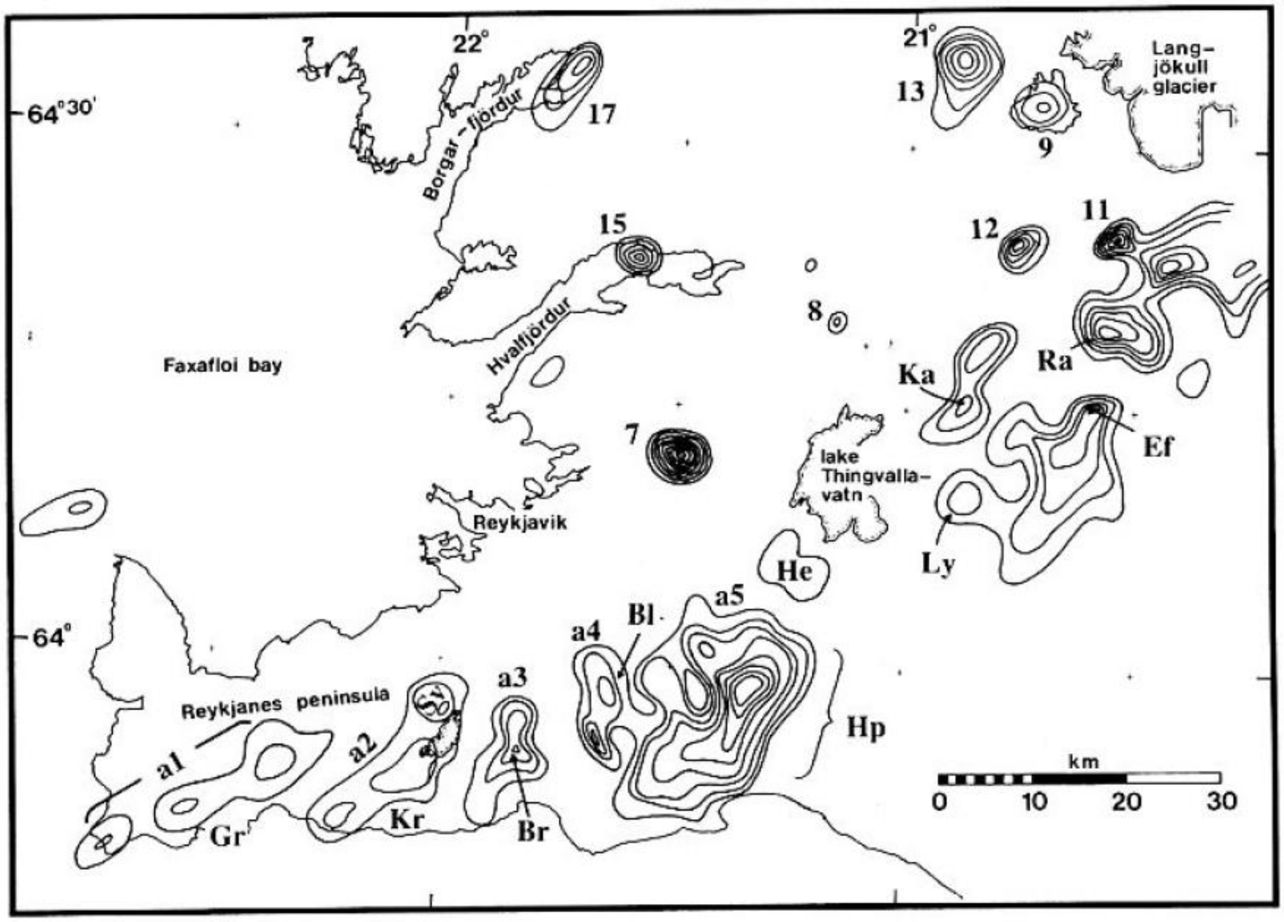

Figure 48) A contour map of geomagnetic intensity in the region of the Reykjanes Peninsula. Only positive anomalies are shown. The lowest contour is +600 nT and the contour interval is 200 nT [41].

Magnetic surveys can be used at sea in a similar manner as on land, only the magnetometer is towed from a ship, or mounted on an underwater vehicle. For the data interpretation the same principles apply as far as seeking magnetic low anomalies, within magnetic high areas, which might indicate hydrothermal activity and a geothermal heat source. The magnetic anomalies caused by hydrothermal fluids percolating through rocks are most likely similar on land and in the ocean because the same processes are involved. The hydrothermal fluids are generally corrosive to the parent rocks and alter the minerals to a less magnetic state, thus creating a magnetic low anomaly where strong hydrothermal activity has occurred. This phenomenon alters the rocks permanently [61], so inactive hydrothermal areas will be detected as well as active ones using this method.

4.2 Methods

The field work was carried out over 4 non-consecutive days. In total 11 profiles were done (Figure 49); 2 long profiles (C and D), 2 medium profiles (A and B), and 7 short profiles (E-K). The two medium profiles were done first in order to become familiar with the area and determine how the field work should be conducted. In the first day a lot was learned; we figured out how the gear works and how the rest of the surveys should be accomplished. After that the 2 long profiles were done. These profiles cut across a majority of the Reykjanes Peninsula and each one took a full day to complete. The long profiles were done in order to get a broad understanding of the magnetic field around the Reykjanes Peninsula. On the last day we did the short profiles in order to narrow in on the specific area of interest. All of the field work was conducted with two people, one person to carry the magnetometer and one person to take notes.

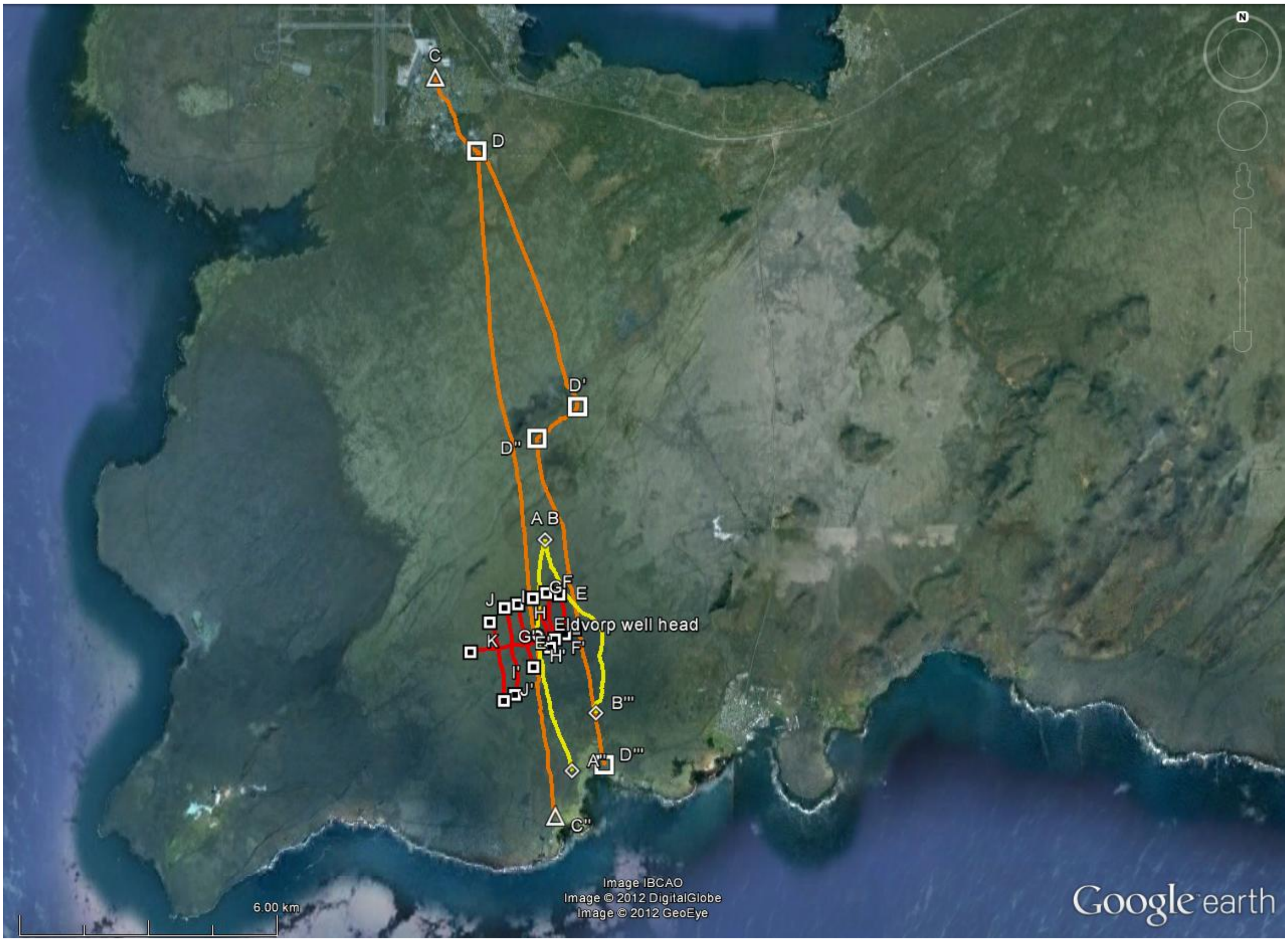

Figure 49) Zoomed out view of all profiles

The instrument used for this field work was the GSM-19T Proton Magnetometer produced by GEM Systems and we borrowed the equipment from ISOR. The gear included a magnetometer which is carried on a pole so it stays roughly 2.5 meters above the ground, a computer which straps around the chest, a small GPS unit which plugs into the computer, and several large external batteries (Figure 37). The computer was set up to record the magnetic field and GPS position every 2 seconds during the trek.

The first day of field work was on July 18th 2012 and profiles A and B were completed (Figure 50). Profile A was heading north and profile B was heading south. The first day of field work was a learning experience. The methods we used throughout the day changed as we became familiar with how the gear worked and what we needed to do in order to cover enough ground. At the beginning of the day we measured our profile distance as we went, using a 50 meter rope, and writing the magnetic measurement down every 50 meters. This technique did not last long because progress was extremely slow due to the rope getting caught up on rocks, causing us to stop many times. We decided to abandon that method and rely solely on the GPS data recorded by the computer. Luckily, the GPS functioned correctly for the most part; there were only a few short periods during the entire field work when it did not record properly. Once we abandoned the rope the survey moved along much quicker. We decided to only stop and write notes when passing something of geologic significance or any metal objects that could influence the magnetic readings. After looking at the data from the first day we realized one mistake was made. Each time we stopped we left the computer running, so it continued to record data even though we were not walking. This caused a stack up of data to accumulate in one location, which ultimately created biases in the data graphed. This was easily fixed by deleting the excess data recorded; however the process was time consuming. In the rest of the profiles we learned how to pause the computer during stops and restart it when we continued to walk. Another thing we changed after the first day was how we carried the sensor. During the first day the sensor and pole was carried by hand, which was very tiresome because the climb over the jagged terrain was not hands free. For the rest of the profiles the sensor was fastened to and carried on an external-frame backpack. The pole used to hold the sensor high above the ground was simply attached to the frame of the backpack so the operator could hike with their hands free. This made walking much easier, climbing safer, kept the sensor at a consistent height, and helped keep the profiles straighter. Profiles A and B were basically practice profiles so we could learn how to obtain consistent high quality data in the succeeding surveys.

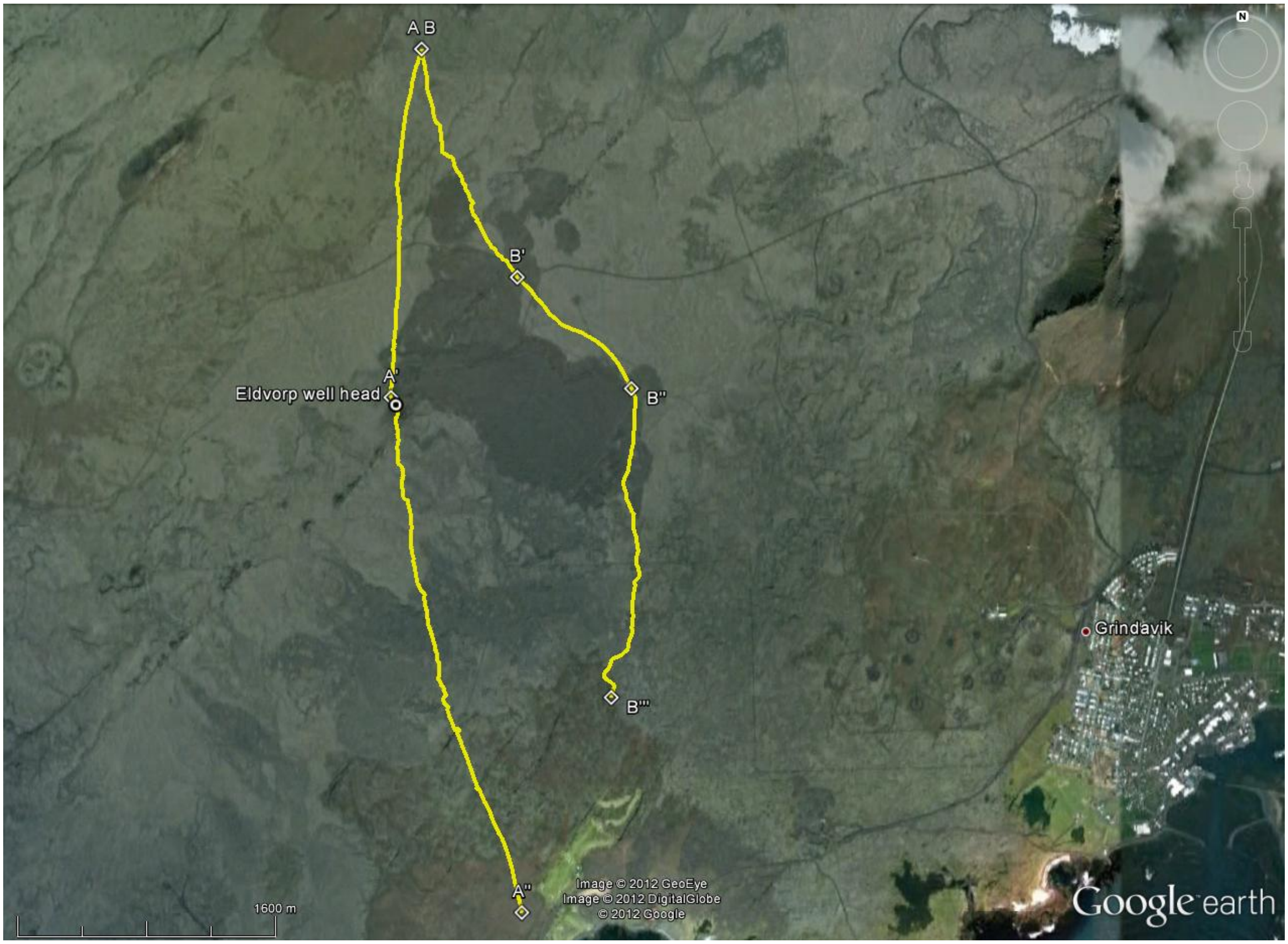

Figure 50) Profiles A and B, July 18th 2012

The second day of field work was on July 28th 2012 and profile C was made (Figure 51). This profile was done going from north to south and is over 17 km long. The field work began in Ásbrú, where there are many buildings in the surrounding area, so the first 2 km of the profile consisted of many influences from manmade structures. Profile C intersected within about 70 m of the crater with steam rising out of it and a magnetic low spike was recorded at this location. Unfortunately, during the last 4 hours of the field work a geomagnetic disturbance occurred (Figure 52). The disturbance was recorded by the Leirvogur Magnetic Observatory in Iceland. The record shows that there was a disruption in the magnetic field of up to approximately 250 nT in the horizontal direction and approximately 150 nT in the vertical direction, in effect causing an error in the total field of up to 205 nT during the disturbance. This disruption was not corrected for in the analysis because it was beyond the scope of this thesis. There was also one GPS malfunction during the end of this profile. The GPS stopped recording for about 3 minutes. All of the GPS discrepancies that occurred during the field work were corrected for in the analysis by assuming a straight path and taking an average distance traveled per time interval for the time period where there is a gap in GPS data.

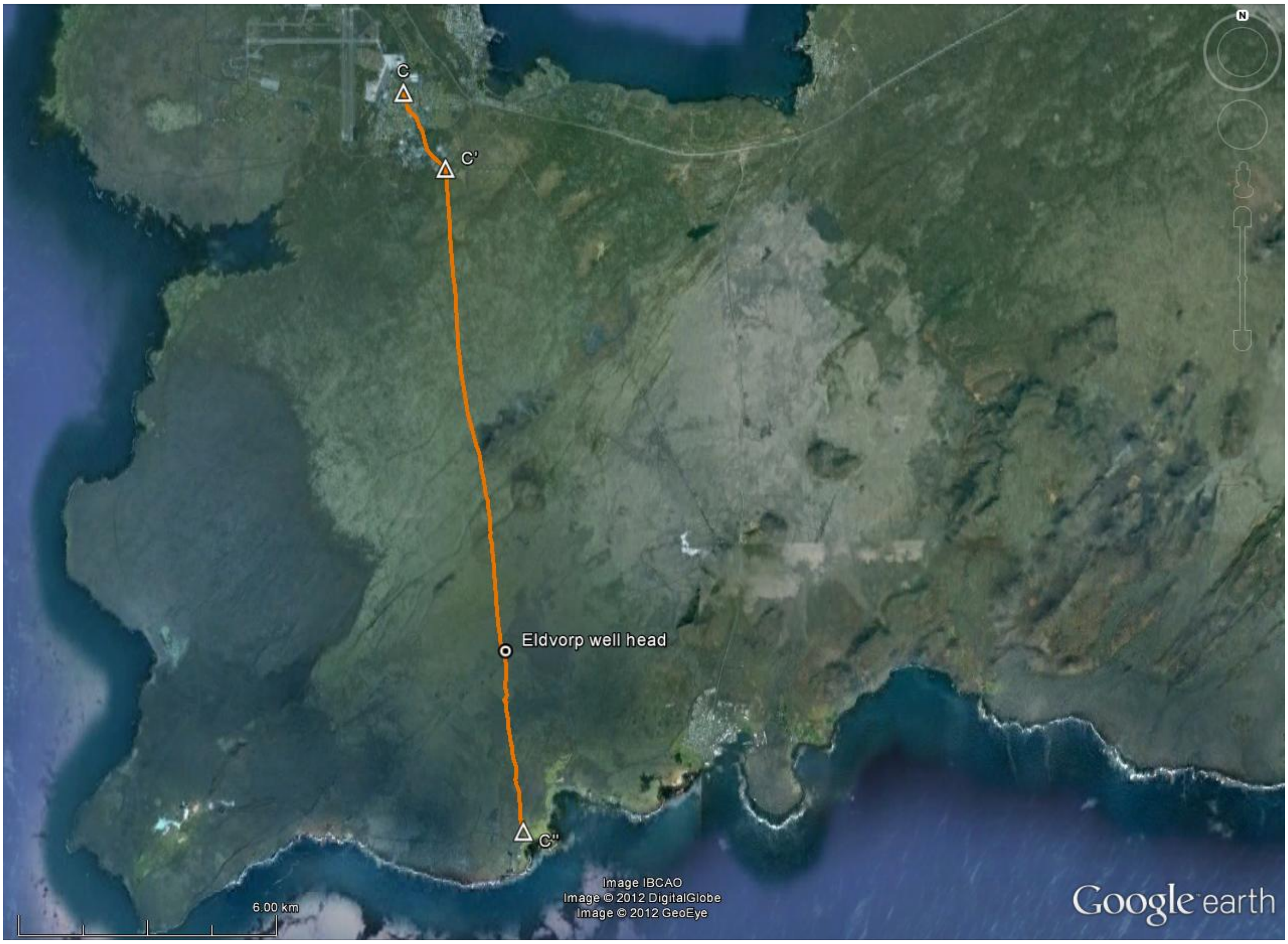

Figure 51) Profile C, July 28th 2012

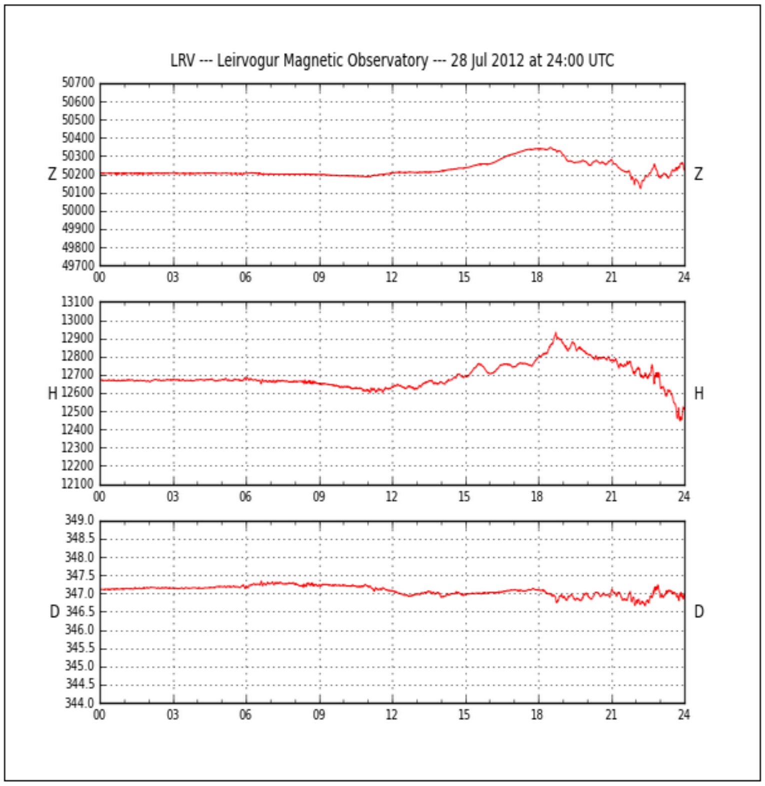

Figure 52) Magnetic observatory data from July 28th 2012 [121].

The third day of field work was on July 31st and profile D was made (Figure 53). This profile was done going from south to north and is about 15 km long. This profile ran about 900 m from the crater with steam but it is unclear if any low anomalies related to the geothermal activities were recorded on this pass. During this profile there were also two discrepancies where the GPS stopped recording. There is also one point during the GPS malfunction where a couple of erroneous readings were recorded which caused a small zig zag; as seen in the profile map just north east of the Eldvörp well head. This slight zig zag does not accurately represent the actual path taken. In the middle of profile D it was impossible to continue on a straight path because of a mountain and mining area that we had to go around. Due to this obstacle the profile has been broken down into three segments as seen in Figure 53. Between D’ and D’’ we followed a road that went parallel to some power lines, so the data collected during this leg of the profile is most likely of no use.

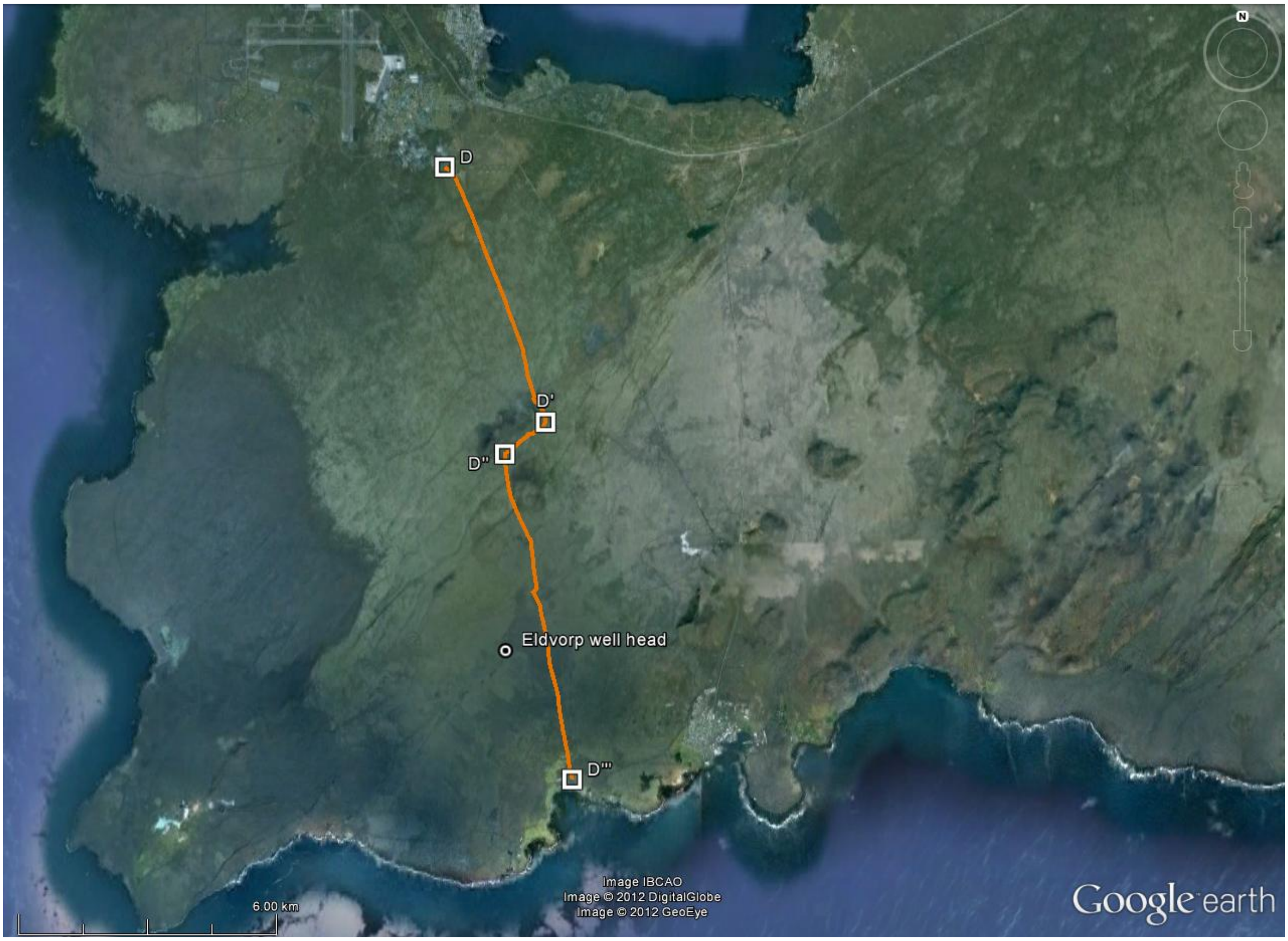

Figure 53) Profile D July 31st 2012

The last day of field work was conducted on August 14th 2012 and short profiles E-K were made (Figure 54). Each profile is 1-2 km long except for K which is 2.5 km. We started with profile E heading south, then F heading north, G heading south, H heading north and so on. After finishing north-south profiles, we made profile K heading east, which cuts across the other profiles. The purpose of all the short profiles was to collect detailed information about the Eldvörp area. The purpose of profile K was to cross all the other profiles and reinforce the data to help get a better understanding of the area. Profile K went just to the south of the crater with steam rising out and an obvious magnetic low anomaly was recorded. All of the profiles except for F went well. During profile F there was an equipment malfunction and the computer did not record any data for about 120 m.

The best effort was made to do the profiles parallel to each other, but they are not perfect. We found that it was quite difficult to remain in a straight path over the rugged terrain, also in some areas no reference points were visible, so estimates of the correct direction had to be made. The profiles also turned out unevenly spaced due to the extremely difficult terrain. The landscape immediately surrounding the Eldvörp row of craters is mostly aa-lava flows that consisted of extremely jagged and loose rocks. That landscape was very disorientating and difficult to walk on.

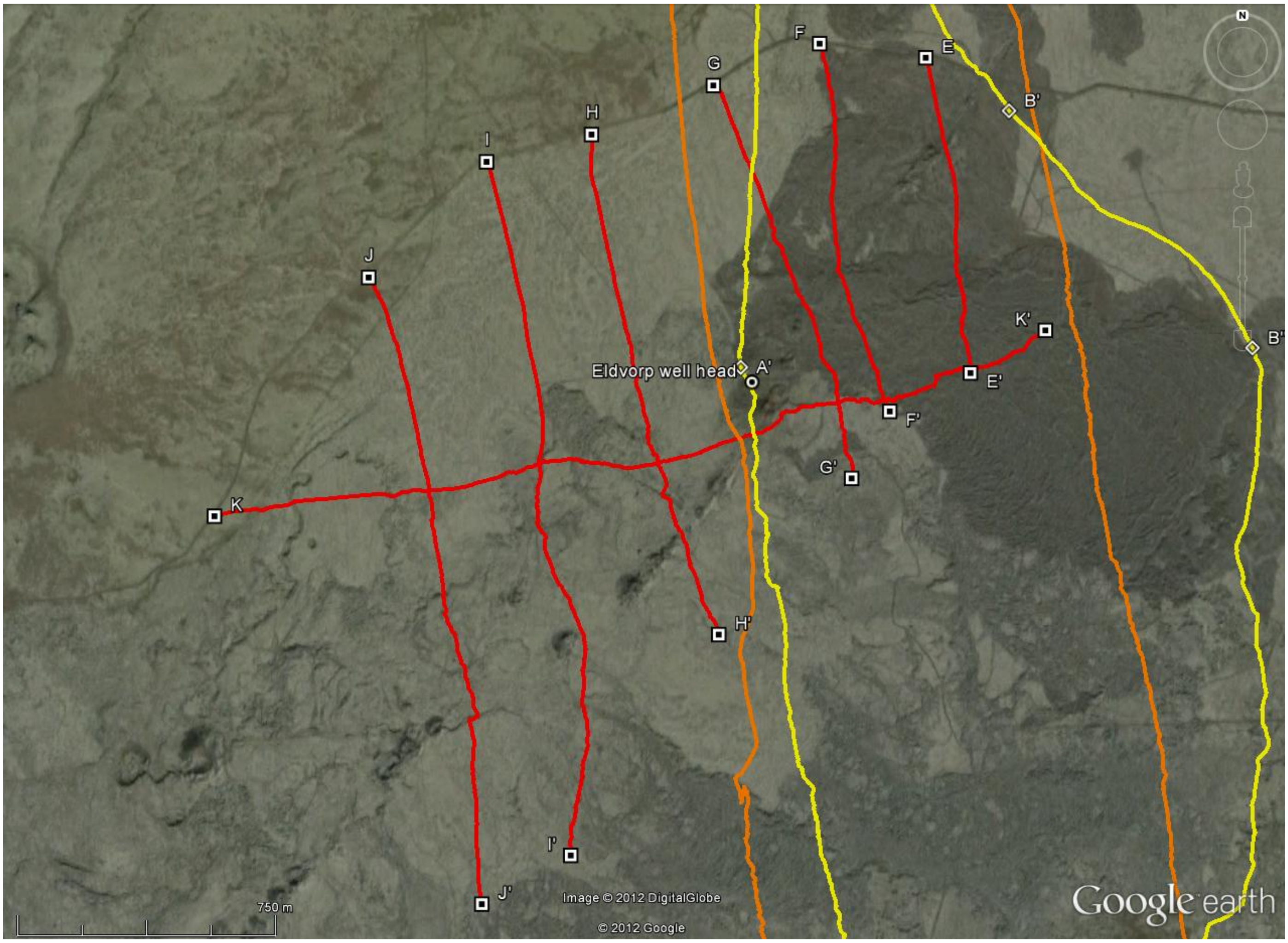

Figure 54) Close in view of Eldvörp. Profiles E-K (red), profiles A and B (yellow), profile C (left orange), and profile D (right orange).

4.3 Results

After each day of field work the recorded information was uploaded from the magnetometer computer onto a program called GEMLink 5.3, which is provided by the manufacturers of the equipment. This program turned out to be difficult to use, so it was decided to do the analysis and graphs using Microsoft Excel. The GPS data were converted into KMZ files so the profile tracks could be displayed in Google earth. This conversion was done via free online software provided on a website called GPS Visualizer [122].

The data recorded by the magnetometer's computer were: GPS coordinates, time, magnetic reading, and quality. After importing all the data into Microsoft Excel the first step was to eliminate all the erroneous low quality measurements. The measurement quality was recorded onto the computer on a scale from 0 to 99; all off the chart data with quality less than 99 were eliminated from the graphs. The eliminated data were between about 5-15% of the total data recorded, depending on the profile and the terrain covered. There was more bad data recorded over the rugged aa-lava flows compared to the smooth terrain, probably due to the magnetometer not being carried as smoothly. Next, the distance travelled was calculated based on the GPS coordinates. The GPS coordinates were recorded in decimal degrees so the distance travelled was calculated in meters, using the following formulas:

1) $(Lat1 - Lat2) * 111474 = D_1$
2) $(Lon1 - Lon2) * 49194 = D_2$
3) $\sqrt{{D_1}^2 + {D_2}^2} = D_t$

Where Lat1 and Lon1 are the coordinates of the starting point of each profile and Lat2 and Lon2 are the coordinates of the magnetic measurement point. The number 111474 is the distance in meters of 1 degree latitude and 49194 is the distance in meter of 1 degree longitude [123]; both numbers are based on Eldvörp's approximate latitude of 63.85°. Equation 1 calculates the latitudinal (north-south) distance and equation 2 the longitudinal (east-west) distance. Equation 3 gives the straight line distance between the two points. Once the distance was calculated graphs of the magnetic measurements vs. distance along the profile were created. All of the data and graphs were orientated such that all profiles are shown running from north to south. Running averages of N=5 and N=25 magnetic measurements were added to the graphs in order to smooth out the data. After that, significant geologic features and metal objects previously noted in the field were located on the graphs and labeled so any anomalies could be easily correlated with the features in the field. The points where profiles intersected are also labeled on the graphs.

The following figures are the graphs for each profile. Profile's A-D have a large amount of data and are very long, so they have been split into multiple segments for easier viewing.

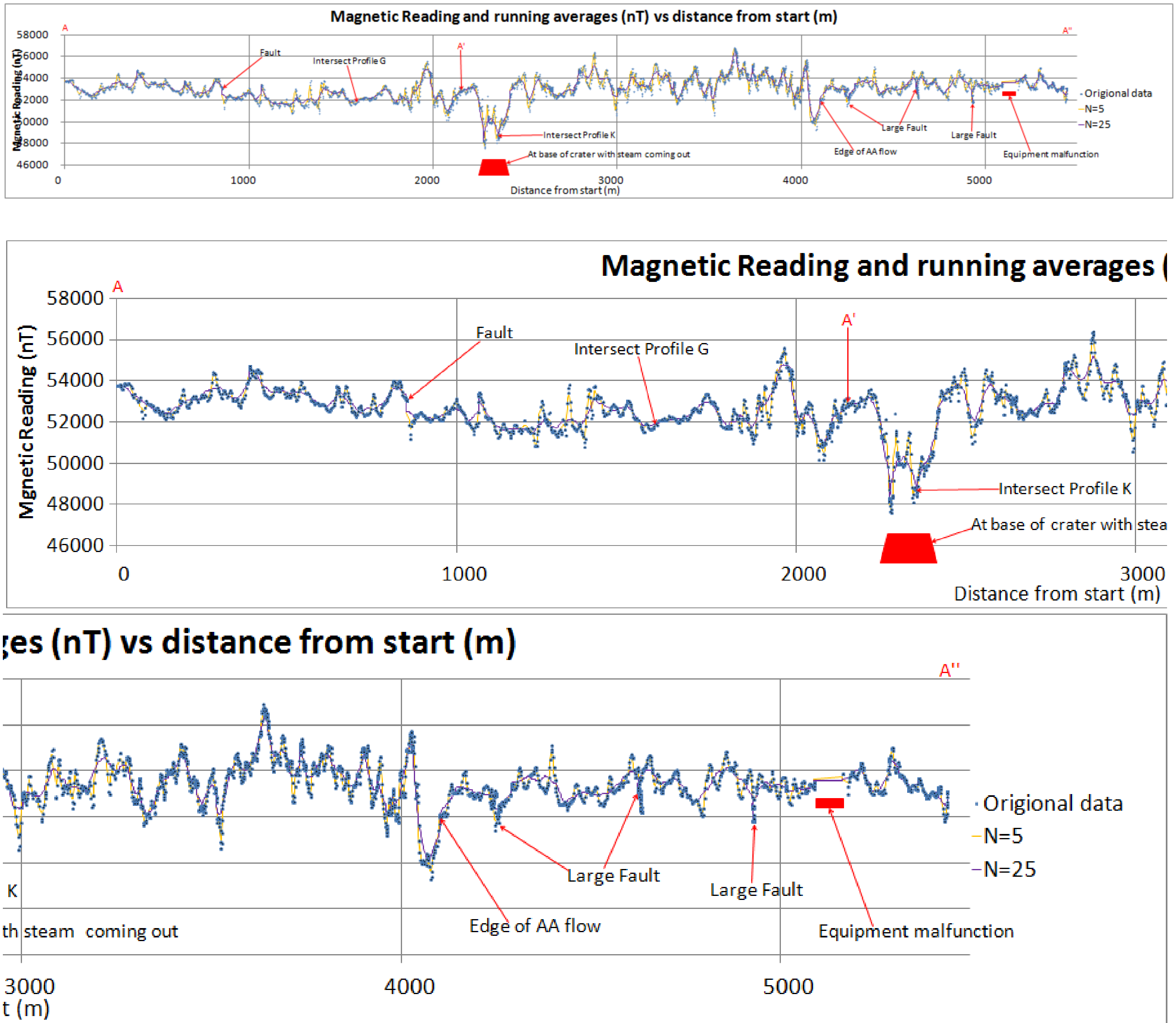

Figure 55) Profile A in whole at the top, then split into two segments for a more detailed view.

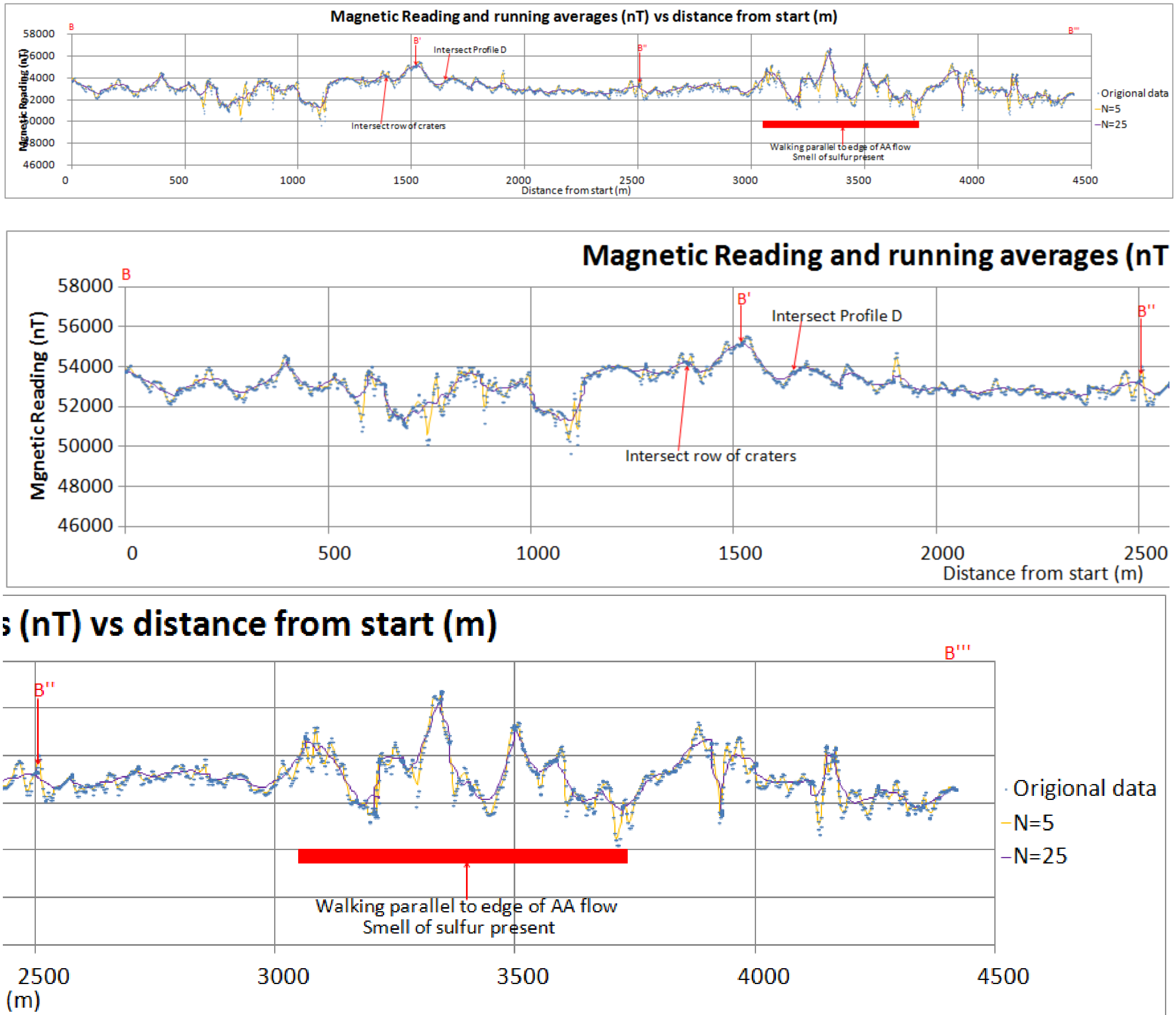

Figure 56) Profile B in whole at the top, then split into two segments for a more detailed view.

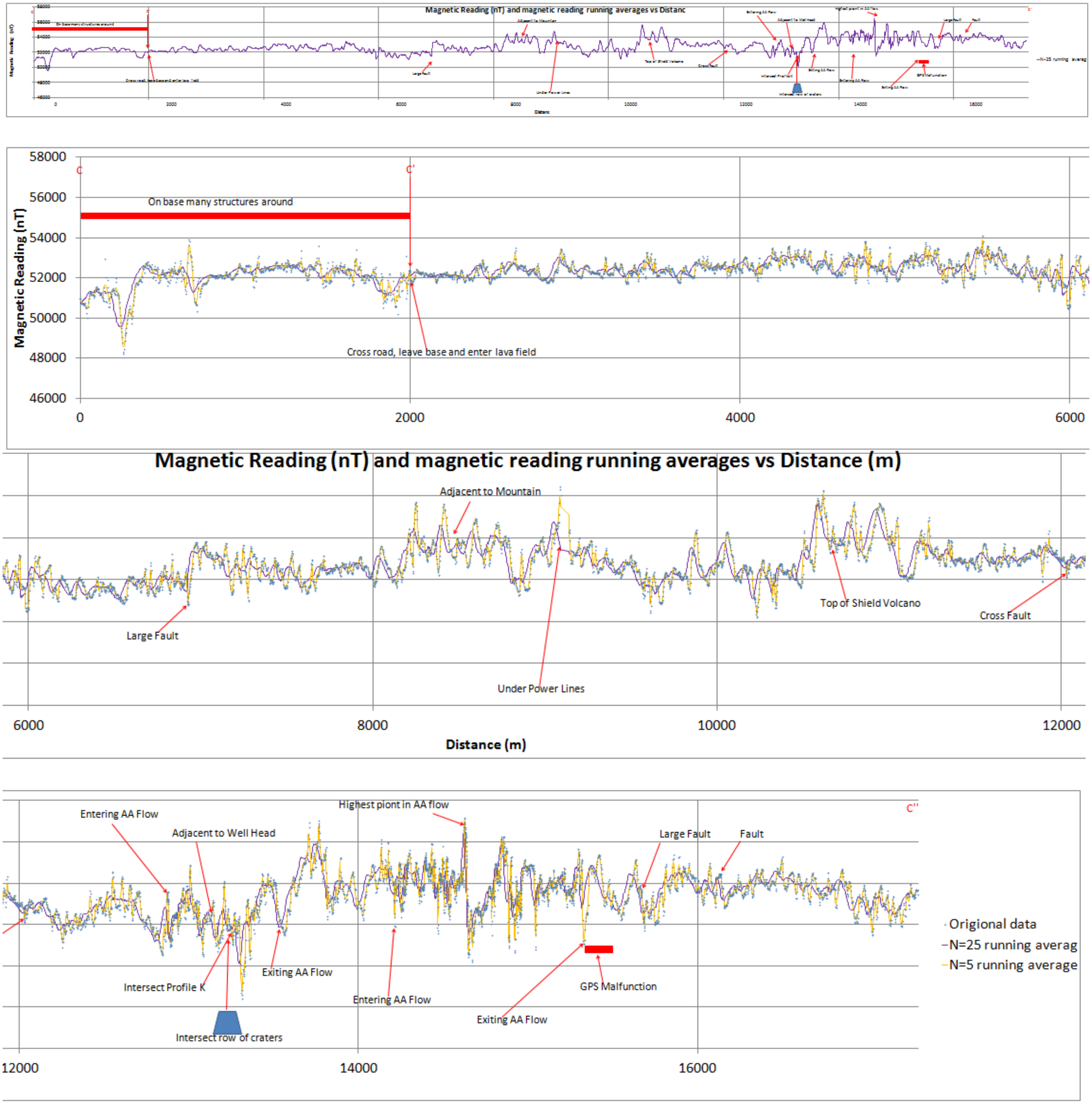

Figure 57) Profile C in whole at the top, then split into three segments for a more detailed view.

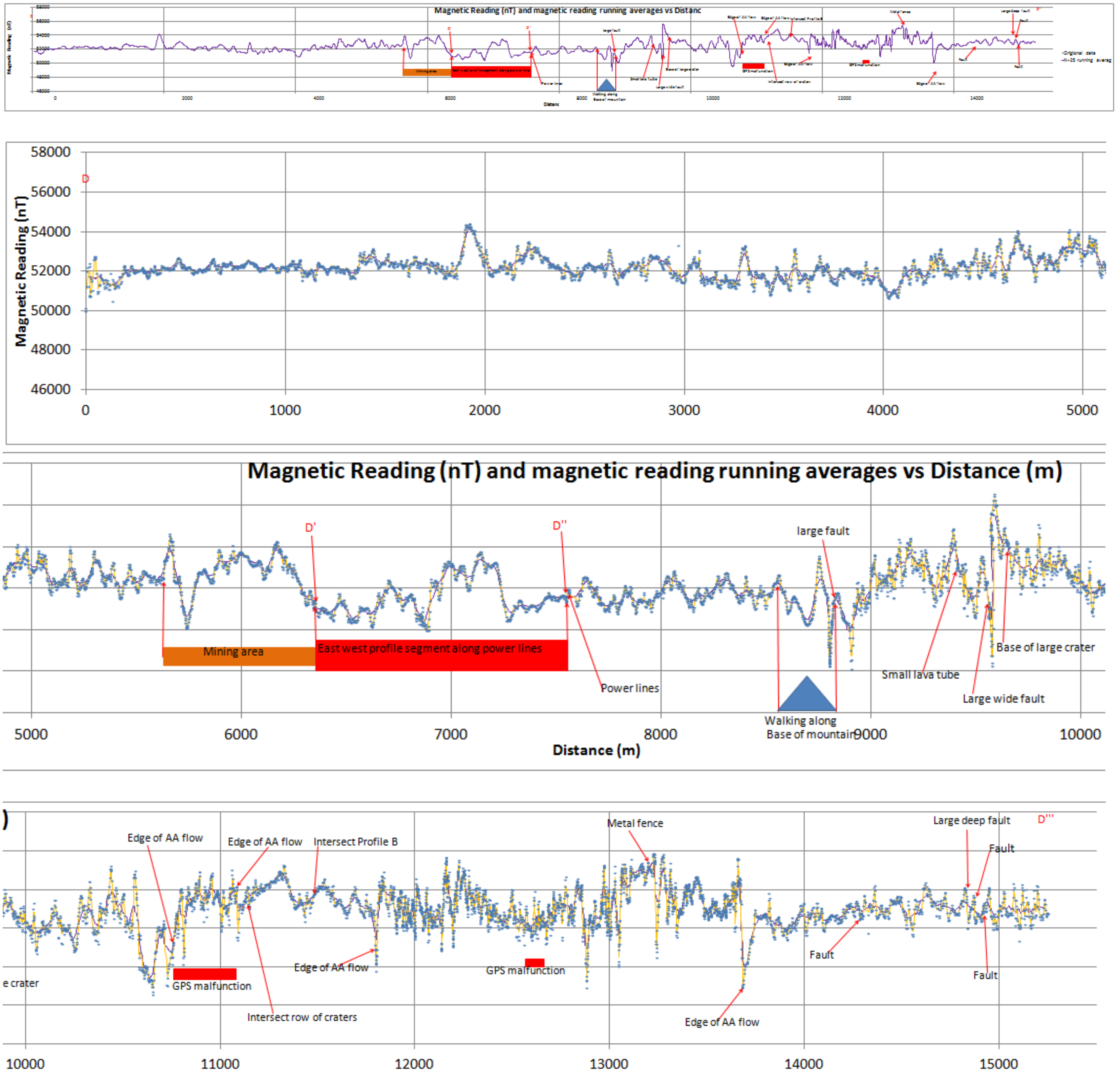

Figure 58) Profile D in whole at the top, then split into three segments for a more detailed view.

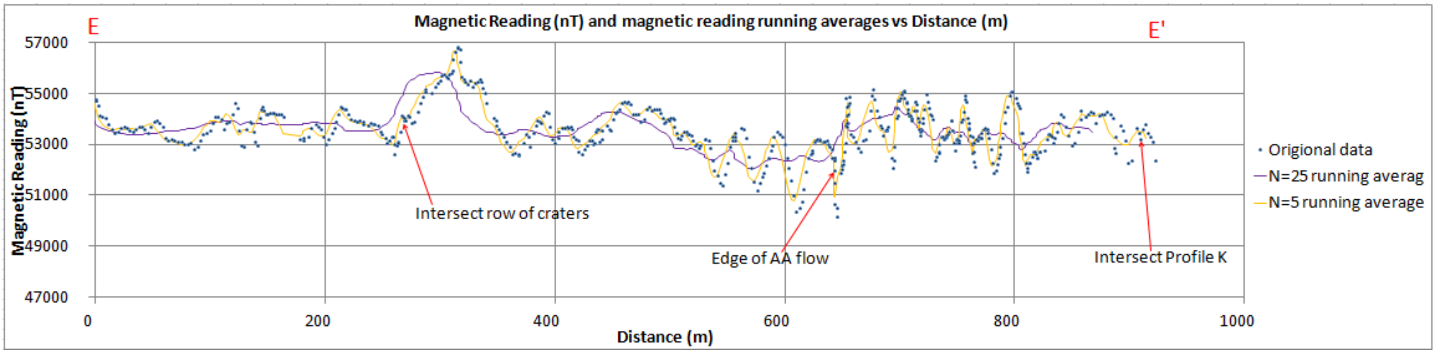

Figure 59) profile E

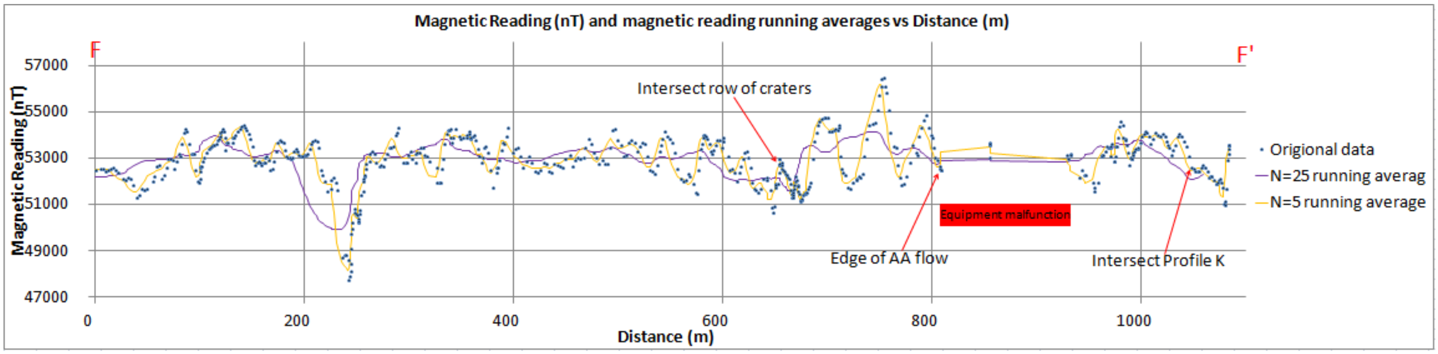

Figure 60) Profile F

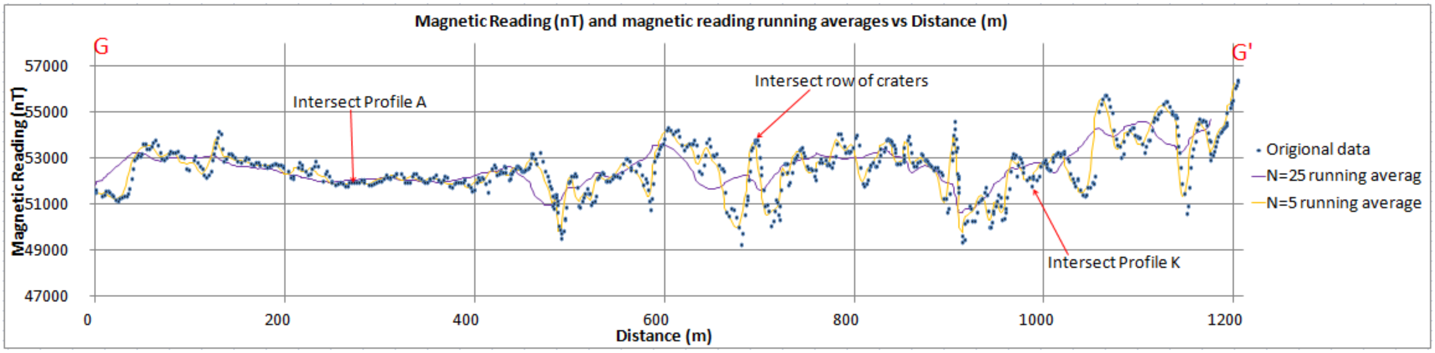

Figure 61) Profile G

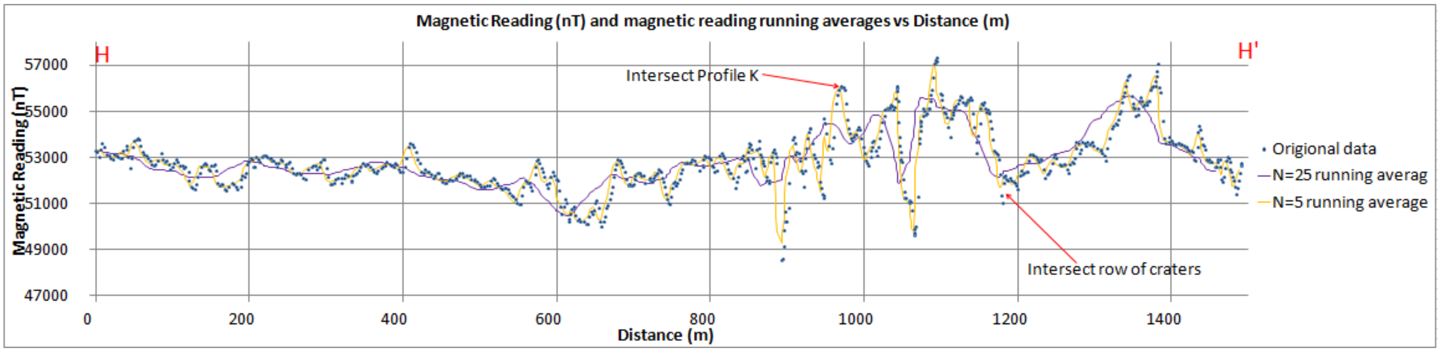

Figure 62) Profile H

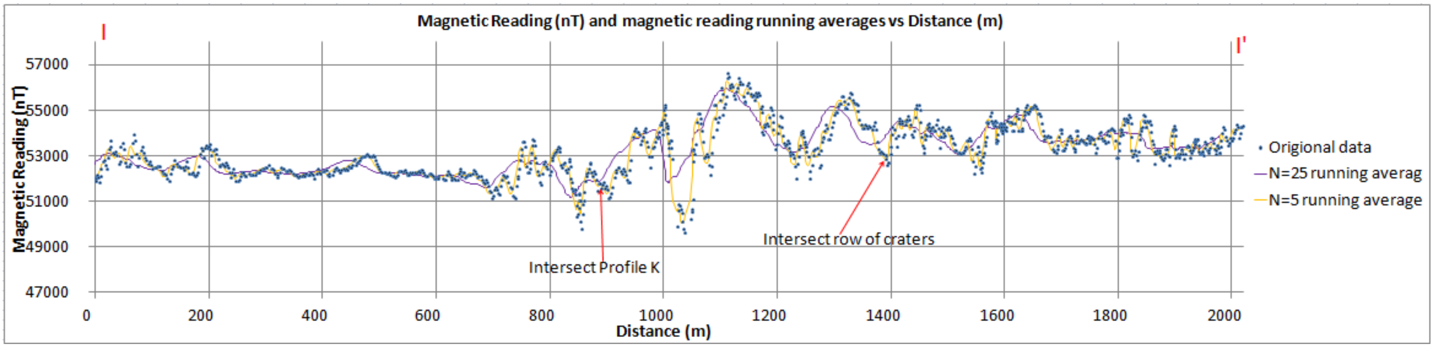

Figure 63) Profile I

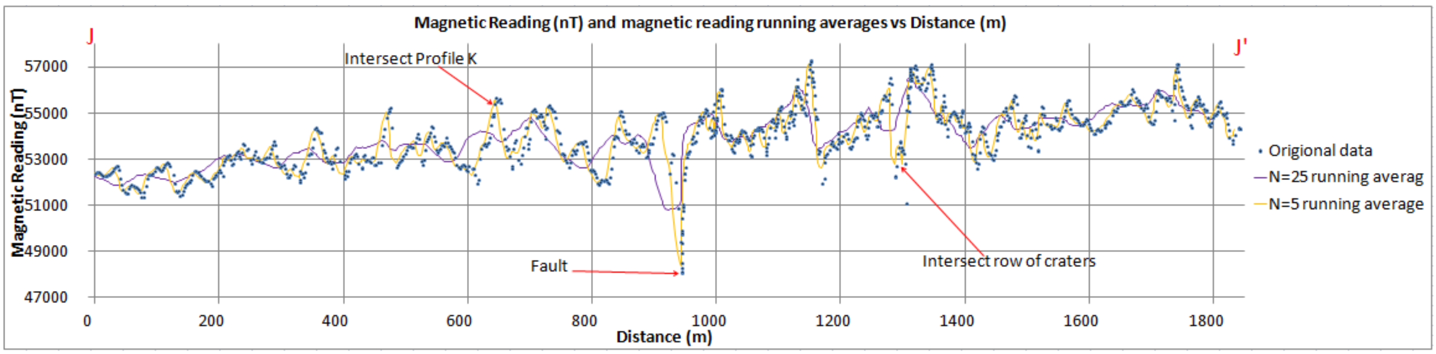

Figure 64) Profile J

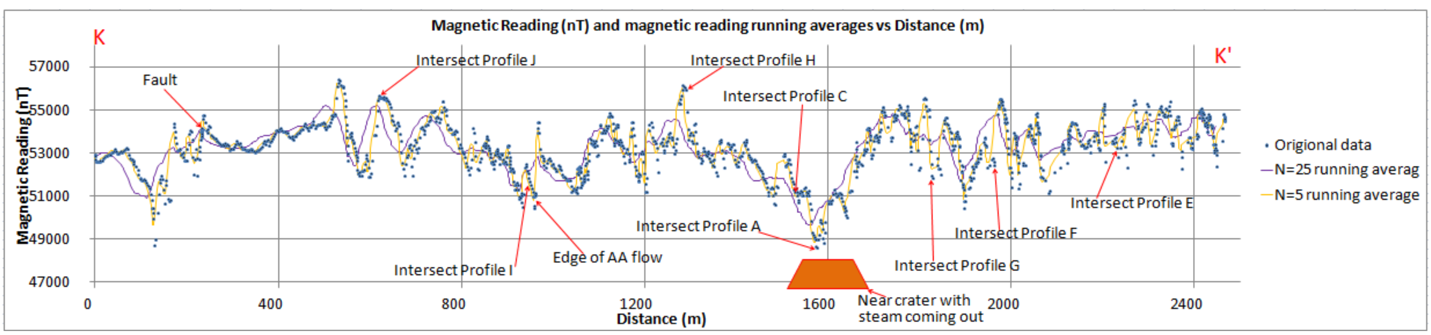

Figure 65) Profile K

4.4 Discussion

The data produced during these magnetic surveys had a high amount of noise and fluctuations due to the probes short distance of only 2.5 m from the highly magnetic terrain. High fluctuations were especially noticeable when passing faults and the edges of lava flows. The terrain in the Eldvörp area consisted of both pahoehoe and irregular aa-lavas, which were difficult to perform surface magnetic measurements on due to the strongly magnetized basalt. Based on aeromagnetic data (Figure 47) it was expected to see a general magnetic high in the Eldvörp area, and despite the difficulties, this can be seen in the longest profiles C and D. Although the measurements fluctuate the general readings are highest when crossing the row of craters as expected.

We were looking for localized magnetic lows within the magnetic high area around the craters, and some indications of localized lows were recorded. These indications of low magnetic anomalies can be seen near the crater with steam coming out, and are most evident in profiles A and K. The general magnetic high in the Eldvörp area is probably due to normally magnetized rocks in the basement and strongly magnetized feeding dikes. The localized magnetic lows may be caused by reduced magnetization from local hydrothermal alterations of the rock.

A more detailed analysis of the data collected would require much more involved processing techniques along with correlation to the topography, which is outside the scope of this thesis and could in fact be another thesis on its own.

5 Results

There is still a lot unknown about offshore geothermal resources around Iceland because only a small percentage of the ocean floor has been thoroughly explored; however with what is currently known, a few offshore geothermal resources are recognized and a number of potential resources are suspected (Figure 66). There are also many hot springs around Iceland that have been found in the tidal zones (Figure 28). 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.

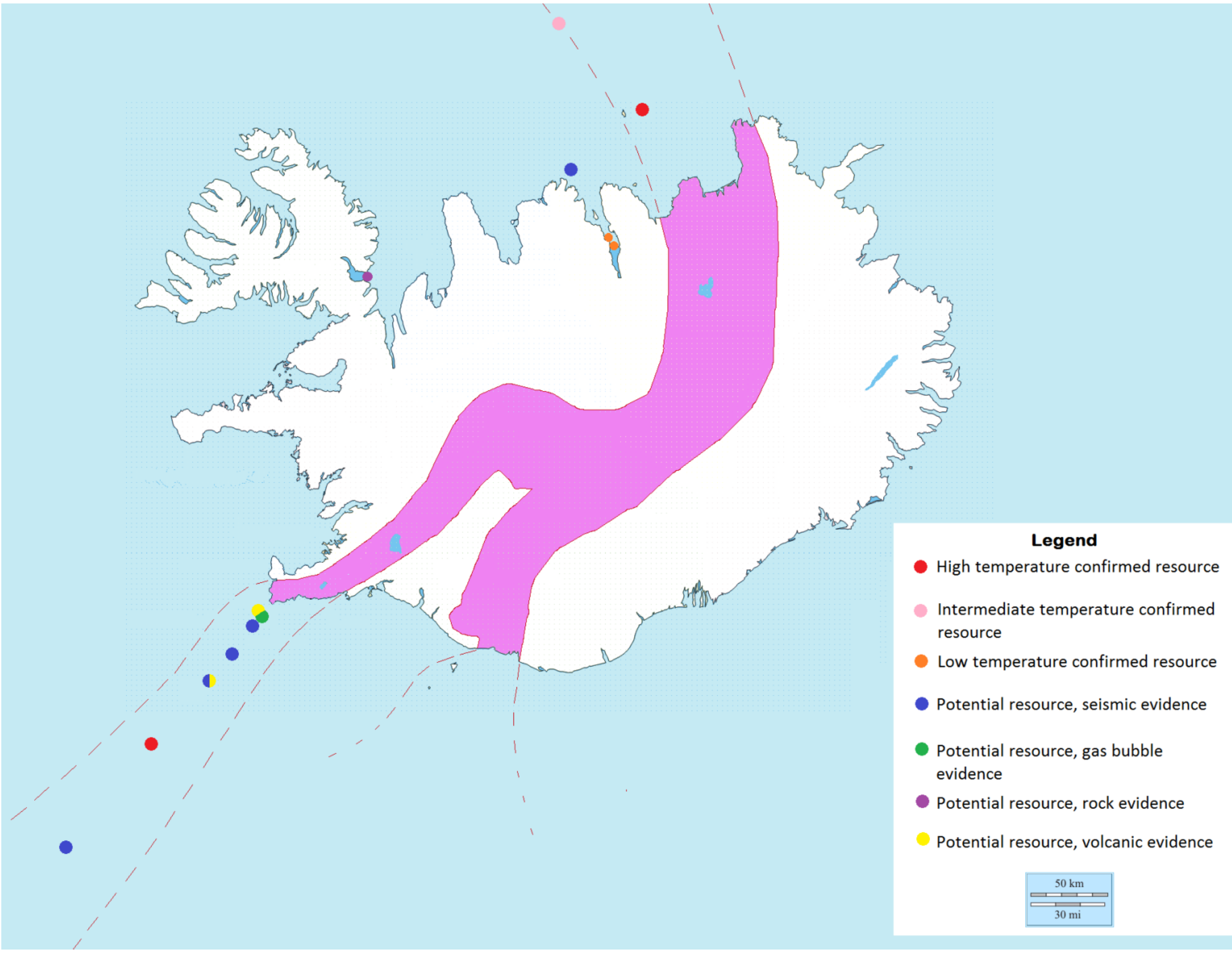

Figure 66) Map of confirmed and potential offshore geothermal resources around Iceland. The purple area is the active rift zone that runs through Iceland based on Figure 2 [7]. The dotted lines extending from the active rift zones are the inferred high temperature zones in the ocean. The potential resources from seismic evidence (blue dots) are either from earthquake swarms [19] or micro-seismic data collected over many years at the Fuglasker seamount [12]. The potential resource from gas bubble evidence (green dot) is from scattering in sonar profiles, which is thought to be caused by gas bubbles [21]. The potential resource from rock evidence (purple dot) is referring to a hydrothermally altered rock found in Steingrímsfjörður [56]. 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 [12].

5.1 Confirmed Resources

There are five confirmed offshore resources near Iceland (Table 9) and all have hydrothermal venting occurring. Based on what is currently known, these hydrothermal vents are the only clear-cut places where offshore geothermal energy production will be possible. All of these locations will still require more studies before proper reservoir models and energy potential estimates can be made.

5.1.1 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), building a geothermal power plant at Steinahóll would be a technical and economical challenge. Considering there is very little experience in the offshore geothermal field, building in far open seas would be risky. There are also plenty of unknowns about Steinahóll; the vent field has not been mapped, the size of the hydrothermally active zone on the sea floor is unknown, the temperatures have not been directly measured, and the vent fluid has not been sampled. If the Steinahóll vent field is to be considered for geothermal power production many more studies would be needed. It would probably be wise to utilize a location much closer to land until offshore geothermal has become a more established technology.

5.1.2 Grímsey

Although the Grímsey resource is not located along the Reykjanes Ridge, it is the most compelling site for an offshore geothermal power plant based on current knowledge. It has by far been the most extensively surveyed offshore resource around Iceland. The Grímsey hydrothermal field would certainly be a good candidate for further geologic and geophysical research to determine the reservoirs temperature, size, and energy content. From what can be seen on the ocean floor, 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 [53]. Furthermore, due to the close proximity to land (16 km from the island of Grímsey and 50 km from Iceland) and depth (400 m), the Grímsey hydrothermal vent field is the most feasible location, out of the known resources, for an offshore geothermal power plant. In addition, there is a very low presents of observed biologic activity at Grímsey; thus environmental impact would be less significant.

Another positive factor about the Grímsey vent field is that it offers a renewable source of energy for the island of Grímsey which has been a pressing issue for many years. One problem with this idea is the island of Grímsey only has 76 inhabitants as of January 2012 [124], so the power plant would not service many people which might make this offshore geothermal power plant not economically feasible. On the other hand, it could be possible to install an underwater cable from Grímsey to northern Iceland if a large enough amount of energy can be produced to make such a project worthwhile.

5.1.3 Kolbeinsey

North of Iceland the Kolbeinsey vent field is not a good candidate for utilization because it is largely outcompeted by the Grímsey vent field. This makes the site unappealing for further geophysical studies.

Kolbeinsey could possibly be a useful in the distant future, but for now the Grímsey field is a better choice because it is closer to land, appears to be larger, has higher temperatures, and has been more extensively studied compared to Kolbeinsey, making it a much better destination for further geophysical studies at this time.

5.1.4 Eyjafjörður

The two vent sites in Eyjafjörður, although very close to land and sheltered in the fiord, are not good locations 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, so production would be minimal.

Table 9) Summary of confirmed resources in order of highest interest

Site	Location	Distance to land (km)	Depth (m)	Temperature (°C)
Grímsey	North of Iceland	16 from Grímsey 50 from Iceland	400	250 (measured)
Steinahóll	Reykjanes Ridge	120	250-350	220 (inferred)
Kolbeinsey	North of Iceland	65 from Grímsey 100 from Iceland	100	131 (measured) 180 (inferred)
Arnarnesstrytur	In Eyjafjörður	1	18-46	79.5 (measured)
Strytan	In Eyjafjörður	3	15-65	75 (measured)

5.2 Potential Resources

Potential resources are locations where some evidence for a geothermal resource has been reported but nothing has been confirmed yet. These areas are only suspected of having a geothermal heat source and need to be explored further before determining whether or not they can be considered viable resources. There are a handful potential sites that have been revealed during the background review of this thesis (Table 10).

5.2.1 Eldey

Near the Island of Eldey (Figure 67), some fisherman have noticed anomalous scattering in their sonar (discussed in Section 2.3.8). The scattering is thought to be caused by rising bubbles from speculated hydrothermal venting; however no other evidence of hydrothermal venting has been identified [21]. In addition to the gas bubbles, the most recent confirmed volcanic activity occurred near the island of Eldey in 1926 [12]. This further supports the idea that there could be a geothermal heat source somewhere near the island. Further investigation of the seas surrounding Eldey might reveal new discoveries of hydrothermal vent fields. If a large enough geothermal reservoir is discovered near Eldey it would be a good location for an offshore geothermal power plant because Eldey is only about 14 km from Iceland and water depths are no more than 150 m [125].

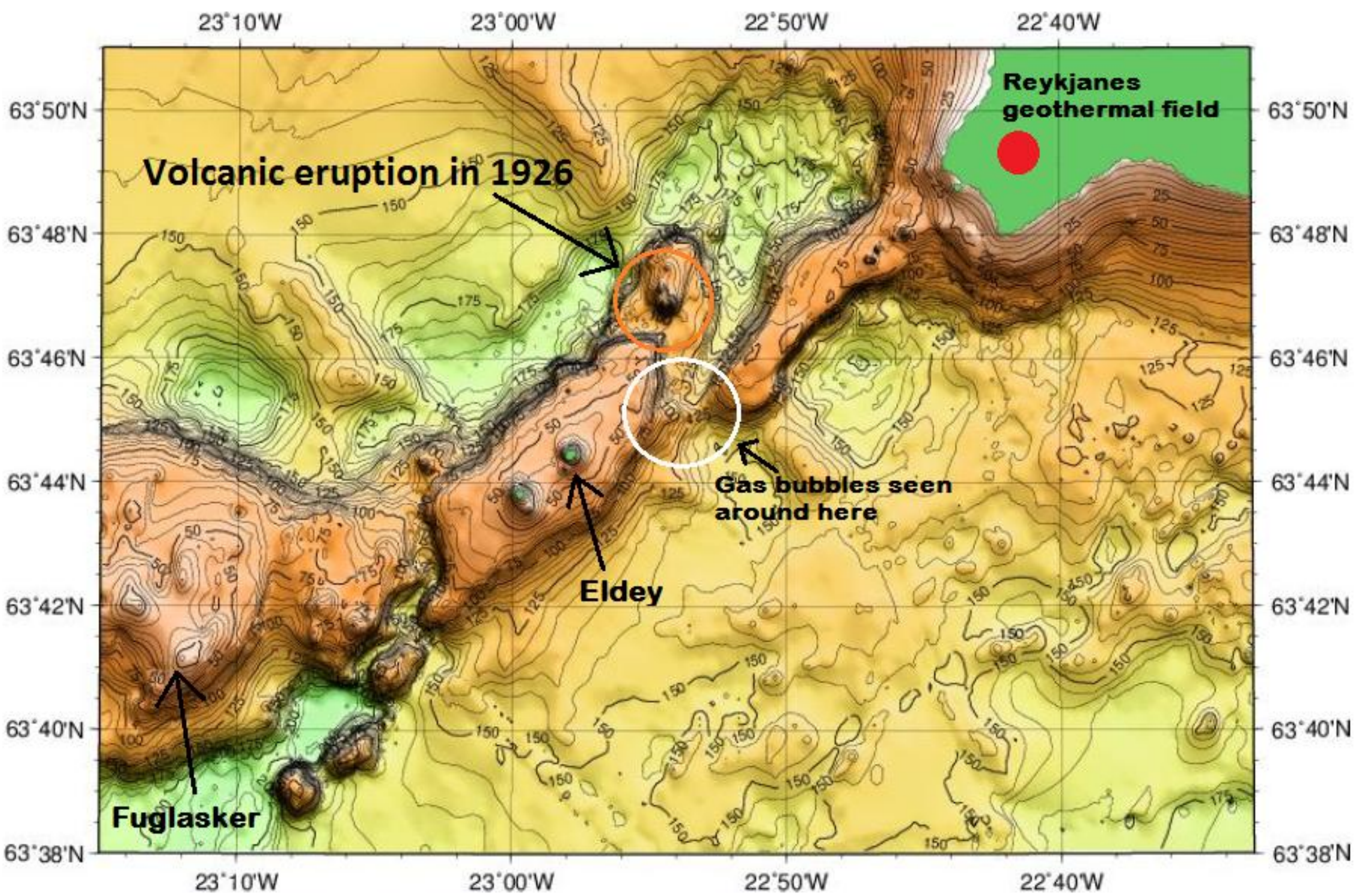

Figure 67) Locations of three potential resource areas, the Fuglasker Seamount and two areas near Eldey, where further exploration would be beneficial. Map modified from [125], gas bubble evidence is from [21], and volcanic eruption date is from [12].

5.2.2 Fuglasker

The Fuglasker Seamount has shown high numbers of micro-seismic events over the course of many years (Figure 9) [12], which is a common characteristic for geothermal fields in Iceland[18] and may indicate hydrothermal circulation in the ground [63]. Further exploration on and around the Fuglasker seamount is necessary for confirming or denying the possibility of a resource. If a high energy resource is discovered under the seamount it would be a good location for a geothermal power plant because the seamount is only about 25 km from land. Also, the seamount is at relatively shallow depths; the base is approximately 180 mbsl and the summit is approximately 40 mbsl [12].

5.2.3 Eldeyjarboði

The Eldeyjarboði seamount is of interest because it may have erupted in 1970 [12]; however that has not been confirmed. Additionally, a small earthquake swarm occurred at Eldeyjarboði on February 8th 2012 (Figure 68) [19], indicating that some interesting activity may be occurring in the area. Eldeyjarboði is about 65 km from land; the base is approximately 180 mbsl and the summit is approximately 60 mbsl. Further exploration of this area would be worthwhile; however the distance from land makes Eldeyjarboði a less attractive site compared to Eldey and Fuglasker.

5.2.4 Reykjanes Earthquake Swarms

There have been two locations along the Reykjanes Ridge in the last year where small earthquake swarms have occurred (Figure 68). The first occurred February 8th at the Eldeyjarboði Seamount and then on September 16th another occurred about halfway between Eldeyjarboði and Fuglasker [19]. Investigating locations where large earthquake swarms occur has proven successful in the past when researchers discovered the Steinahóll vent field. Continued record keeping of earthquake swarms may someday help to identify other locations with potential heat sources. The earthquake swarm that occurred between Eldeyjarboði and Fuglasker, although small, might be worth investigating, especially if a research team is already going to investigate the Eldeyjarboði Seamount.

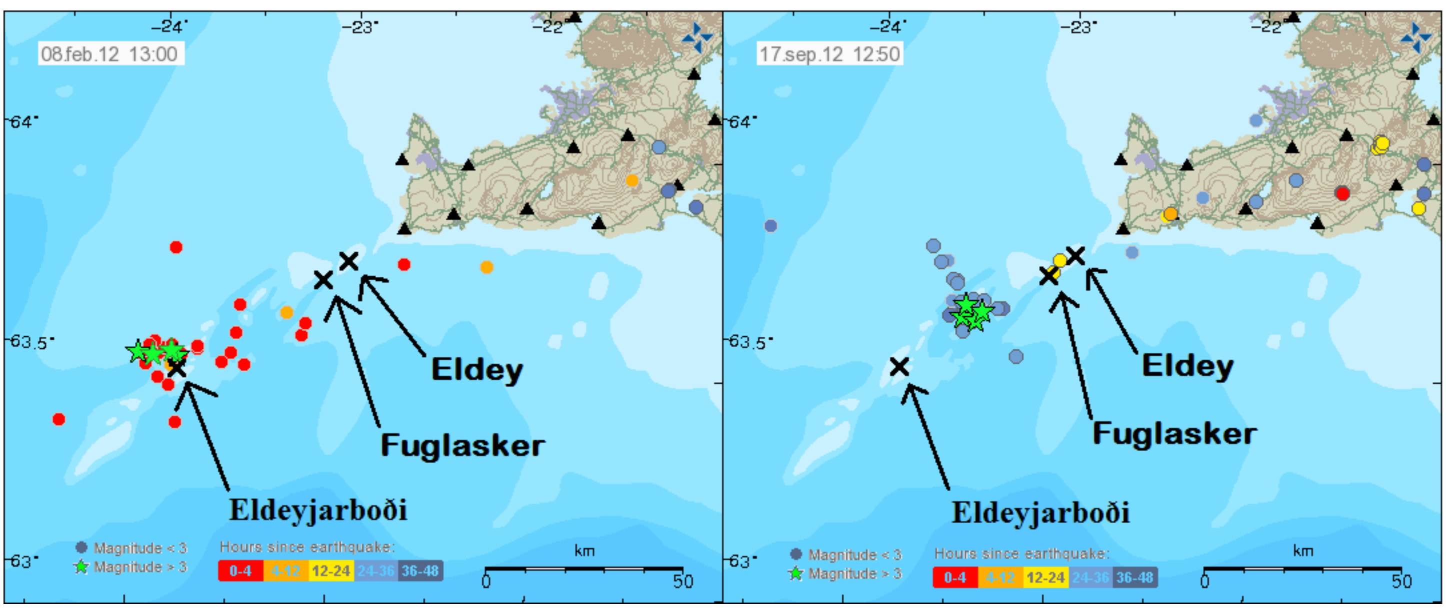

Figure 68) Comparison of two small earthquake swarms that occurred on the Reykjanes Ridge in 2012. Maps modified from [19].

5.2.5 Reykjanes Ridge Area's A and B

The inferred hydrothermal vent sites area's A and B are not strong areas of interest for an offshore power plant. There may be resources there; however these areas are very far from land and even if a resource was confirmed the Steinahóll vent field is much closer, and would probably be a higher priority.

5.2.6 Tjörnes Earthquake Swarms

There has been a large ongoing earthquake swarm in the Tjörnes fracture zone (northern Iceland) for the latter part of 2012. Thousands of earthquakes have occurred in the area since September 2012 [19]. The peak intensity of this swarm occurred on October 21st 2012, when a 5.6 earthquake struck (Figure 69). 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 [126]. On the other hand, the earthquake swarm going on right now has had a very high frequency of earthquakes for over 3 months, so it might be possible there is more than simple plate motion going on down there. The high number of earthquakes and longevity of this event might be due to seafloor volcanism; however we will not know until further studies are conducted. This location would be worthy of further exploration, and if a geothermal resource was found it would be in a very nice location because the majority of seismic events are only about 10-15 km from land and the depth range in the is around 100-300 mbsl [127].

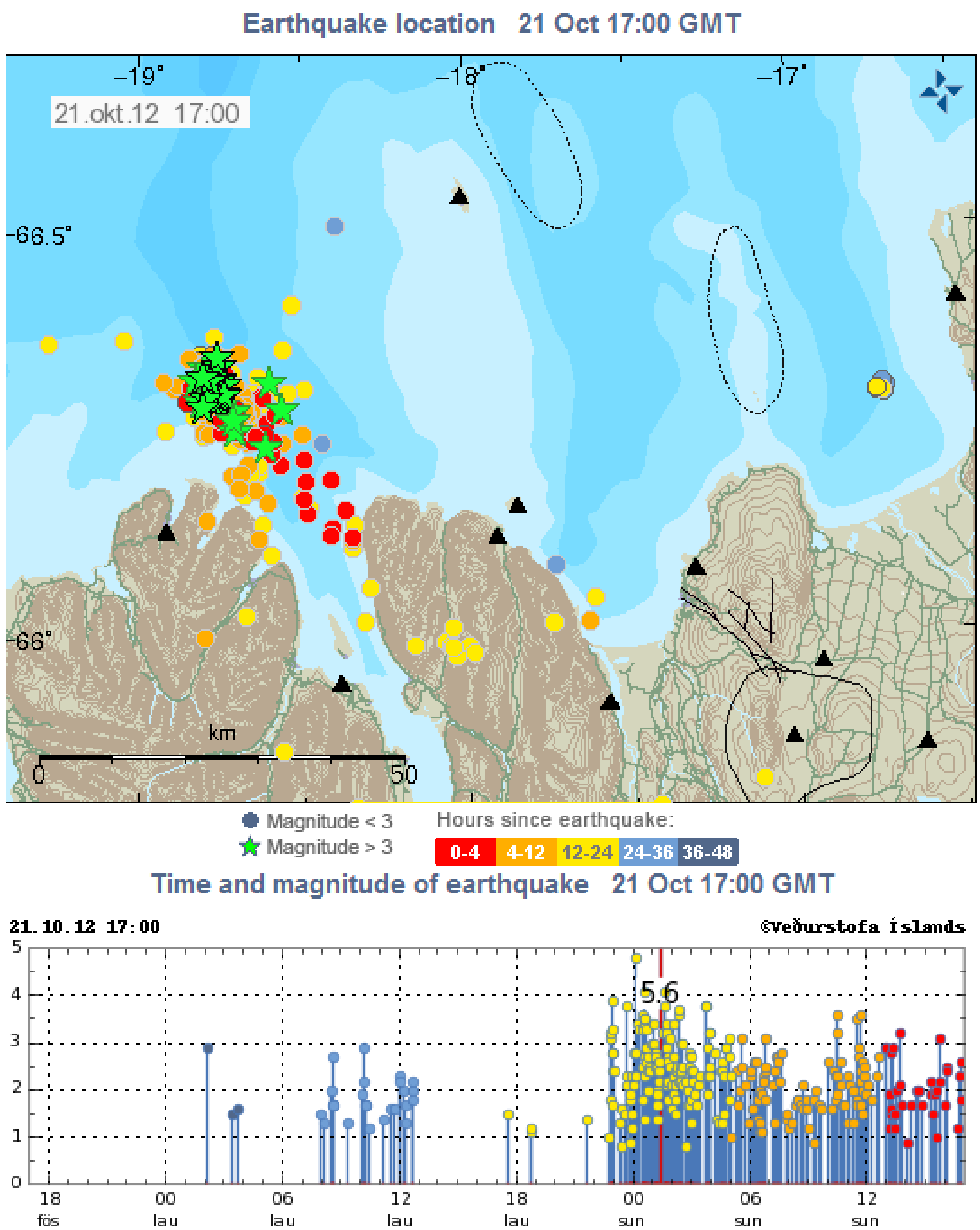

Figure 69) Large earthquake swarm in the Tjörnes fracture zone recorded by the SIL network on October 21st 2012 [19].

5.2.7 Steingrímsfjörður

A rock affected by hydrothermal activity, found in Steingrímsfjörður, indicates potential vents in the fiord [56]. 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. The problem is that this area does not seem likely to have a high temperature resource because it is far from Iceland's main rifting zone [7]. 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. Also, a low temperature resource could be used for district heating purposes in the nearby towns such as Drangsnes.

5.2.8 Squid Forest

It is possible that there is still heat beneath the extinct hydrothermal area; however the Squid Forest is not a logical place for further exploration of offshore geothermal resources at this time. The reasons are, it is a very far distance north of Iceland (170 km), in deep waters (900 m), and the area is dormant. Also, the Grímsey field would have a much higher priority for further exploration in the north because of the much closer proximity to Iceland and Grímsey is a confirmed, active, high temperature reservoir.

Table 10) Summary of potential resources in order of highest interest of further geophysical exploration

Site	Estimated distance from land (km)	Estimated 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
Steingrímsfjörður	0-3	1-100 (estimated in Google earth) [127]	Rock found with hydrothermal alterations
Tjörnes fracture zone earthquake swarm	10-15	100-300 (estimated in Google earth) [127]	Large ongoing earthquake swarm
Reykjanes Ridge area A	200	500	Earthquake swarm
Reykjanes Ridge area B	580	1000	Earthquake swarm
Squid Forest	170	900	Dormant chimneys

5.3 Exploration Strategy

There are many exploration techniques for locating, delineating, and characterizing offshore geothermal areas. Each area of interest will need different methods depending on what is already known and what still needs to be known. For the confirmed resources, the exploration techniques can be designed for a small area and will focus on determining parameters for building a reservoir model such as the reservoir boundaries, structure, temperature, energy content, permeability, and chemistry. The exploration strategy for the potential resources will be much different; their location is not exactly known, so a much larger area will need to be covered and different techniques focused on locating a heat source and hydrothermal venting will be used. There is also the strong possibility of finding new undiscovered resources around Iceland. Finding clues for locating completely new ocean resources will require exploration strategies that can efficiently cover very large areas.

5.3.1 Iceland's Research Vessels

There are two research vessels owned by Iceland's Marine Research Institute (Figure 70). One is named Arni Fridriksson, and the other is named Bjarni Sæmundsson. The Arni Fridriksson is 70 m long and costs about 15,000 EUR per day to rent. The Bjarni Sæmundsson is 55 m long and costs about 11,500 EUR per day to rent [128]. Both vessels are equipped with CTD sensors, model SBE911 from Seabird Electronics, as standard equipment [128]. The SBE911 has a depth range of 6800m and is capable of being integrated with auxiliary sensors and working with a rosette for collecting water samples [129]. Both ships are capable of towing a magnetic sensor and a camera, but this equipment is not provided by the marine institute. The ships are also capable of collecting dredge samples; however the dredging equipment is not standard onboard and would need to be provided. The Arni Fridriksson is equipped with a multibeam echo sounder, the EM 300 from Kongsberg Maritime [128]. The EM 300 has a range of 10 to 5000 m deep, can emit a swath of up to 5000 m wide, and the nominal operational frequency is 30 kHz [130]. This type of sonar would be very useful for conducting a detailed survey of the bathymetry wherever offshore geothermal studies are conducted. These vessels are made for offshore research and are capable of conducting missions needed for offshore geothermal exploration.

Figure 70) Two research vessels owned by the Icelandic Marine Research Institute, moored in Reykjavik harbor; the Bjarni Sæmundsson in front and the Arni Fridriksson in back.

5.3.2 Strategies for the Confirmed Resources

The confirmed resources of highest interest are Grímsey and Steinahóll as discussed before. Since the locations are known the next step is to gather information that can be used 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 which have not been done yet are magnetic and resistivity. Of course, before utilization, as many different geophysical studies should be conducted as feasibly possible in order to build a realistic reservoir model, determine the energy content, and locate the best sites for boreholes.

Magnetic: Obtaining a detailed magnetic model of a geothermal area is very useful before utilization [85]. The most ideal methods at the confirmed resource sites are submarine or ROV magnetic surveys. 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 the entire area, and it will provide high resolution data. Utilizing an AUV would also be very effective especially at Steinahóll because the extent of the area is unknown and AUVs can survey a larger area. 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 (585°C). In shallow waters, near shore, magnetic measurements can be conducted from surface boats relatively easily and inexpensively.

Resistivity: Gaining a resistivity model of a geothermal area is very important in the geothermal industry and nicely compliments a magnetic survey. Resistivity models are essential information to have on land when estimating the size, location, and geometry of a reservoir and deciding on a drilling location [85]. Obviously the main problem with using electrical and electromagnetic methods to explore the ocean floor is the conductive seawater, so different methods are needed in ocean environments. There are three very similar types of EM marine resistivity techniques that I believe would be best for geothermal exploration at Grímsey, Steinahóll, or any other potential sites around Iceland. Those methods are CSEM, MTEM, and MMR (Table 11). The MMR and MTEM methods would be the most ideal for depths less than 1000 m because CSEM has trouble in shallower depths [108]. MMR would be the best method in rugged ridge terrain because it utilizes a vertical array. The vertical array can be lowered and raised easier than a horizontal array, but it takes more time to use. The methods that use horizontal arrays can still be done, but it will depend on the topography of the area as the array needs to stay close to the ocean bottom without hitting rocks and getting damaged. Perhaps CSEM and MTEM can be modified to use a vertical array; then the methods would become basically the same as MMR, only with OBEMs rather than just OBMs. CSEM, MTEM, and MMR methods are also top choices because they have the advantage of being capable of collecting passive MT data for analysis. The best technique to use will depend on the topography revealed from a detailed bathymetry survey, time and budget constraints, and the size of the survey area.

Other resistivity methods that might work are OBEI and airborne EMT. The OBEI method could be experimented with; however this method has not been proven in deep saltwater environments and can only be done with a horizontal array that must stay very close to the sea bottom. The only other marine resistivity method that does not use a horizontal towed array is the airborne EMT method, but this is still highly experimental and at this stage in development requires highly resistive hydrocarbons and the NFIP effect caused by the hydrocarbon water interface in order for any anomalies to be seen through the seawater. Much more research would need to be done for airborne EMT to be adapted to geothermal exploration, if it is even possible.

Table 11) Comparison of potentially useful marine resistivity methods. The CSEM, MTEM, and MMR methods can be used to conduct passive MT surveys as well. This is done by leaving the ocean bottom sensors on the seafloor and collecting natural signals for some time after the controlled source has been removed.

Method	Array type	Sensor type	Vessel requirements	Uses
Controlled Source Electromagnetic (CSEM)	Horizontal	OBEMs	1 vessel	Mostly used in offshore oil and gas exploration. It has been tested over southern part of Reykjanes Ridge with success, finding resistivity data down to 2 km.
Multi Transient Electromagnetic (MTEM)	Horizontal	OBC with electromagnetic signal receivers	2 vessels	Mostly used for offshore oil and gas exploration. Unknown if it has been used for other applications.
Magnetometric Resistivity (MMR)	Vertical	OBMs	1 vessel	Used for oceanic crust studies. Has been used at hydrothermal vents along the Juan de Fuca Ridge with successful results which indicated hot hydrothermal fluids were flowing at depths of at least 1 km.
SuperString Ocean Bottom Electrical Imaging System (OBEI)	Horizontal	Electrical sensor array	1 vessel and 1 ROV	AGI claims it could be used for offshore geothermal, but it has not been tested yet that we know of.

A potential problem with conducting electrical and electromagnetic studies to model a geothermal reservoir at hydrothermal vent areas is that they often contain large sulphide deposits [82]. Sulphide is highly conductive, so a resistivity survey over large sulphide deposits might cause very limited depth penetration with current techniques. On the other hand, this effect could be useful when exploring for unknown hydrothermal vent sites because finding a very low resistivity anomaly on the ocean bottom could indicate hydrothermal venting is present. The problem with using resistivity as a technique for discovering new resources is that the techniques would be difficult to conduct efficiently over very large expanses of the seafloor.

Fluid chemistry: An essential parameter of the geothermal reservoir that needs to be known before utilization can take place is fluid chemistry. 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. Detailed analysis of fluid samples will provide information on dissolved minerals, dissolved gasses, non-condensable gasses, pH etc. Reservoir temperature estimations could also be inferred from the chemical analysis.

Seismic: A useful reservoir modeling technique for offshore geothermal exploration is seismic. Some seismic reflection surveys have been done at Grímsey but a more detailed seismic survey using OBSs would be beneficial for learning about the fault structures in the area. Micro-seismic monitoring and analysis using OBSs placed around the hydrothermal vent fields for days to months would help in learning about the tectonic structures and possibly hydrothermal flow. Hydrothermal vents are commonly linked with nearby tectonic structures and subsurface faults, which often provide the easiest pathways for the flow of hydrothermal fluids [131], so it would be very beneficial to map out all faults, dikes, and impermeable layers that could possibly divert these hot fluids away from the main heat source. Knowing the fault structures will help to better understand where the geothermal source is located thus providing a better guess as for where to drill the first exploratory wells.

Seismic refraction and reflection techniques can also be helpful but are not commonly used because high temperature geothermal systems are often within or associated with volcanic systems which consist of irregular and complex geological structures which makes interpretation very difficult and depth penetration shallow [85]. On the other hand, in certain environments seismic reflection and refraction methods might be beneficial, so it is important to have them in mind and if funding allows they would certainly not hurt.

Heat flow measurements: Measurements of the heat flow are not essential to reservoir modeling but if they can be carried out easily they would help. Heat flow measurements are much easier to carry out if there are sediments covering the seafloor around the vents such as at Grímsey. If the seafloor only consists of fresh basalt then heat flow measurements may not be worth the trouble.

Gravity: A detailed gravity survey of Steinahóll and Grímsey is not essential before utilization, but would help to compliment the other surveys and provide a more complete reservoir model. If funding allowed for a gravity survey, the most ideal method would be using underwater gravity meters; however a shipboard gravity survey would also suffice and be much less expensive and time consuming.

5.3.3 Strategies for the Potential Resources

The potential resources of most interest are the ones closest to land along the Reykjanes Ridge because they are in ideal locations for a future power plant. The top locations for further investigation are Eldey, Fuglasker, and then Eldeyjarboði. On land, the first good indicators for locating a potential geothermal resource are surface alterations, steam vents, hot springs, geysers, boiling pools, etc., so an expedition to search for active hydrothermal venting in these areas would be best. This expedition should utilize as many of the techniques described in Section 3.1 as possible. 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, optical backscatter sensor, 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. After water samples are retrieved they should be analyzed for $^{3}He/^{4}He$ isotope ratios dissolved substances. 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 sent down 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. In the geothermal industry the term "blind system" is used to describe an area with geothermal potential but has little to no surface activity [104]. It is possible that there are blind systems in these areas, so some other exploration methods could be used if nothing is found. Other methods that might be useful are micro-seismic monitoring with OBSs, gravity, or heat flow measurements.

If any other potential resources, such as the Tjörnes fracture zone or Steingrímsfjörður are going to be studied the same exploration strategy discussed above would apply. If a new resource is confirmed from any of the potential resources further exploration strategies discussed in Section 5.3.2 would then apply before utilization is decided.

5.3.4 Strategies for Discovering New Resources

There may be many resources in unexplored regions of the ocean where no evidence of hydrothermal activity has been found. The exploration strategy for regions not yet explored should use the same instruments as the exploration strategy for the potential resources; except surveys should be designed to scan very large expanses of the ocean. A ship towing an array of sensors like the one described in the previous section would be useful, but instead of using an AUV for the magnetic portion of the survey, a towed marine magnetometer (Figure 40) would cover more ground. A magnetic survey from a ship could even provide high resolution data if the towed magnetometer has control fins, because then the altitude of the instrument above the bottom can be managed. The use of this technique could be very beneficial for the exploration of new offshore geothermal resources, because geomagnetic anomalies reveal valuable information about the distribution of hydrothermal vents [132]. Overall, for large areas which have not been surveyed in detail, such as sections of the Reykjanes Ridge, a magnetic survey with a towed marine magnetometer would be highly useful. When exploring a large area for new unknown sites it is important that profiles are designed to efficiently cover as large of an area as possible, without leaving significant gaps between profiles.

Regions near shore on the Reykjanes Ridge should definitely be surveyed more. Also, further exploration within the estimated offshore high temperature rift zones (Figure 66) could reveal new vent fields. 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 also be beneficial for further exploration to be conducted near the coastlines of Iceland around areas where tidal hot springs have been found, especially those within the high temperature rift zones such as numbers 48-51 in Figure 28, which are in Skjálfandi and Öxarfjörður, northeast Iceland. It is possible that these tidal hot springs could be 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.

6 Conclusions

(1) Based on what is known now, 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, which is comparable in size to other high temperature resources on land in Iceland [53]. Grímsey is also the closest known offshore resource to Iceland.

(2) Along the Reykjanes Ridge, the only confirmed resource is the Steinahóll hydrothermal vent field. The reservoir size is unknown and the temperatures and fluids have not been directly measured. The vent field lies at 120 km from land, which will make utilization more challenging and expensive compared to Grímsey.

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

(4) The most practical methods for exploring the potential resources involve searching for evidence of hydrothermal venting. The common methods for locating hydrothermal vents (Section 3.1) are well established and should be the first techniques used for further exploration into locating new resources. Magnetic techniques and monitoring of seismic activity with OBS are also useful techniques for detecting possible hydrothermal activity. The most important techniques and sensors to use for locating new hydrothermal vent areas are as follows:

- CTD sensor
- MAPR sensor
- Chemical analysis
- Light scattering sensor
- Sonar
- Cameras
- Magnetic
- Seismic monitoring
- Dredging

(5) Before utilizing confirmed resources, reservoir models need to be constructed. The best geophysical methods for offshore geothermal reservoir modeling are as follows: The importance of each method and the order they are preformed should be evaluated on a case by case basis depending on the site.

- Magnetic
- Seismic monitoring with OBS
- Electromagnetic
- Chemical
- Heat flow measurements
- Gravity

(6) 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.

(7) Resistivity techniques are highly valuable in geothermal exploration and can be used in marine environments as well. However, the methods are still under research and have not been used specifically for offshore geothermal exploration. CSEM, MTEM and MMR methods seem like they could be useful after some modifications which will depend on the terrain and water depth.

(8) Chemical analysis will help to construct a more complete reservoir model because it is useful for inferring reservoir temperatures. The chemistry of hydrothermal fluids is obviously essential information to know when designing a power plant as well, so at some point fluid samples need to be collected.

(9) Heat flow measurements and shipboard gravity techniques are not primary methods for offshore geothermal exploration but can be used to help support magnetic, seismic, and resistivity data.

(10) Offshore geothermal energy production does appear to be feasible off the shores of Iceland because resources are available. This research does not take into account the economics of offshore geothermal production, so a geothermal energy production estimate and a profitability analysis would be needed before such a project can be claimed to be economically feasible. From a purely engineering standpoint and by comparison with the Marsili project, Grímsey and Steinahóll would be technologically feasible locations for utilization based on the resources locations, temperatures, and depths.

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