Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Exploring Offshore Geothermal Fields around Iceland

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Keywords: Marine geology, submarine geothermal, geothermal chimneys, heat flow, vent field.

ABSTRACT

The Icelandic waters hold a number of geothermal fields, both low and high temperature, but none of them are harnessed (Fig. 1). Majority of the known low temperature sites (< 100°C at 1 km depth) are hot springs found in the tidal zone all around Iceland. In recent years geothermal sites have been discovered farther out. The best-known are the Ystavík and Arnarnes vents in Eyjafjörður, N-Iceland, where rows of geothermal chimneys are connected to active fissures and faults. All these low temperature vents are issuing more or less fresh water. Several offshore high temperature areas have also been discovered. They are related to the rift zones and volcanic activity of the Reykjanes Ridge, Kolbeinsey Ridge and the Tjörnes Fracture Zone. They are:

(1) The Kolbeinsey geothermal field, at around 100 m depth, 100 km off the north shore, near the islet of Kolbeinsey.

(2) The Grímsey geothermal vent field, at 400 m depth east of Grímsey island.

(3) The Eldey geothermal field, at 80-120 m depth, 12 km SW of Reykjanes.

(4) The Steinahóll geothermal field, at 160-300 m depth near the insular shelf break, some 120 km SW of Reykjanes.

The high temperature fields are all issuing hot brine. Because of the water pressure the seafloor boiling temperature is high. In the case of Grímsey vent field it is 250°C, similar to the core temperature of many onshore high temperature systems.

Some areas are inferred geothermal fields because of indirect indications of geothermal activity such as, gas bubbles on sea surface, geothermal altered material in core section, geothermal precipitates recovered from trawls and melted nylon trawls. Further mapping and exploration of the oceanic floor around Iceland in the coming years will certainly lead to discovery of unknown geothermal fields. Utilization of offshore geothermal energy might be possible in the future and the first steps have already been taken in that direction.

1. GEOTHERMAL GRADIENT AND HEAT FLOW

The geothermal gradient and heat flow in the sea floor around Iceland is poorly known. Very few measurements are available. Onshore, on the other hand, the gradient has been inspected carefully. In a broad sense the highest values are found close to the volcanic rift zones and the gradient decreases with distance from the spreading axis. Many exceptions are from this rule and local geothermal reservoirs are quite common. They are primarily convective systems associated with active tectonic fractures carrying heat from several km depths towards the surface. Inside the volcanic zones the heat sources seem to be hot intrusions, away from them the heat is extracted from the underlying crust (Flóvenz and Sæmundsson, 1993).

Hjartarson et al. (2014) published a heat flow map of Iceland and the NE-Atlantic region (Fig 2). The geothermal gradient on the sea floor is based on shallow holes sparsely distributed over large area and in fact there is a total loss of measurements west, east and southeast of Iceland. The data indicate large variations in heat flow ranging from less than 40 to over 300 mW/m^2 and sometimes even up to 500 mW/m^2. The spreading zones of Iceland and the Reykjanes and Kolbeinsey Ridges are prominent on the map with their high heat flow. A large “hot” area appears west of Reykjanes Ridge near Steinahóll geothermal site. Its existence is based on measurements in several ODP boreholes.

2. THE LITTORAL ZONE

Numerous hot springs are found in the littoral zone and shallow waters along Iceland’s coastline. These vents are nearly all low temperature. The littoral zone extends from the high-water mark, which is rarely inundated, to shoreline areas that are permanently submerged. The littoral zone always includes this intertidal zone, and the term is often used interchangeably. However, the meaning of littoral zone can extend well beyond the intertidal zone and that is the case here.

Benjamínsson (1988) documented hot springs in the littoral zone all around Iceland and mentioned several sites farther offshore. In his article 53 sites are mentioned, some of them unconfirmed (Fig 1). Very few sites have been added to his list. They are unevenly distributed around the country. Half of the tidal and littoral sites are in the Western Fjord region. No confirmed submarine activity has been found at or off the northeast, east and south coasts.

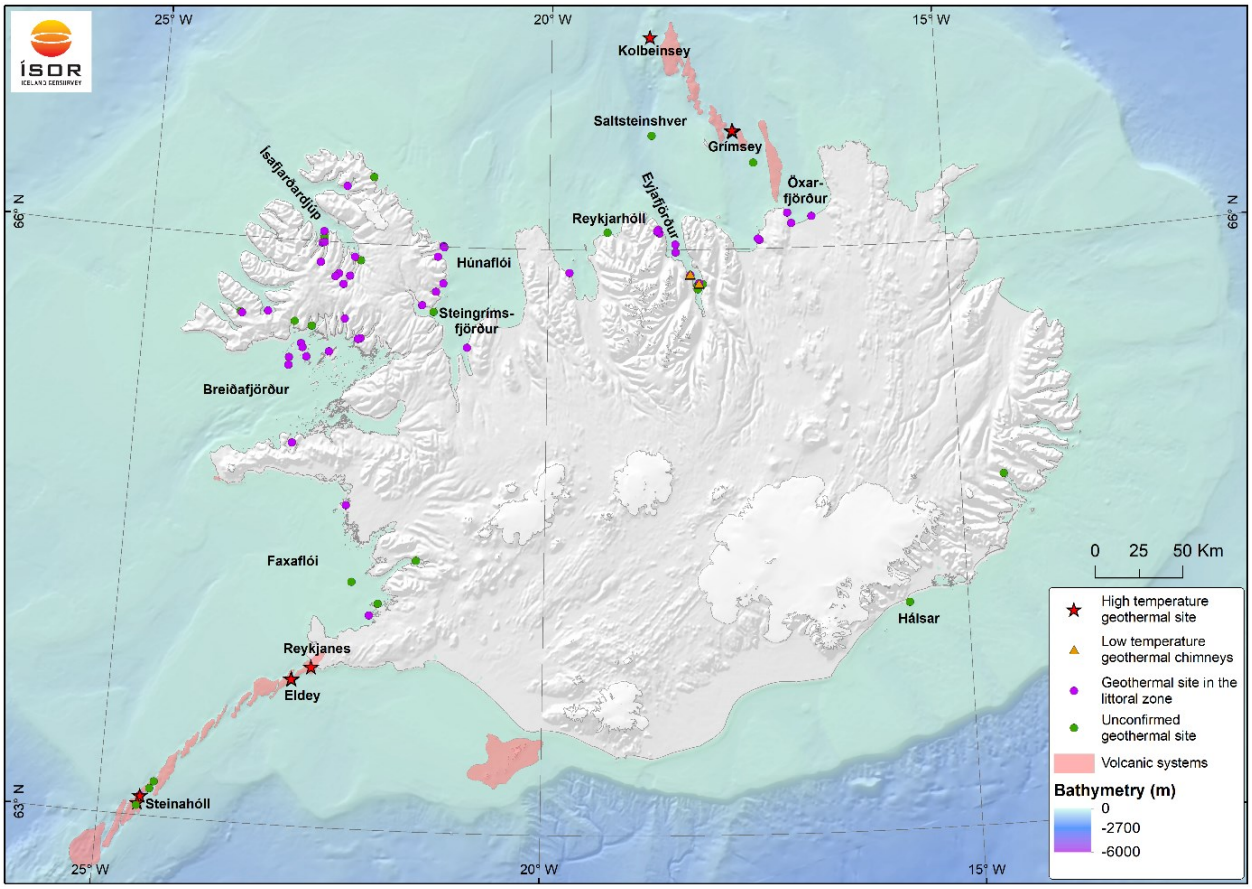

Figure 1: Geothermal sites within Icelandic water. Based on Benjamínsson, 1988 and Hjartarson et al., 2018.

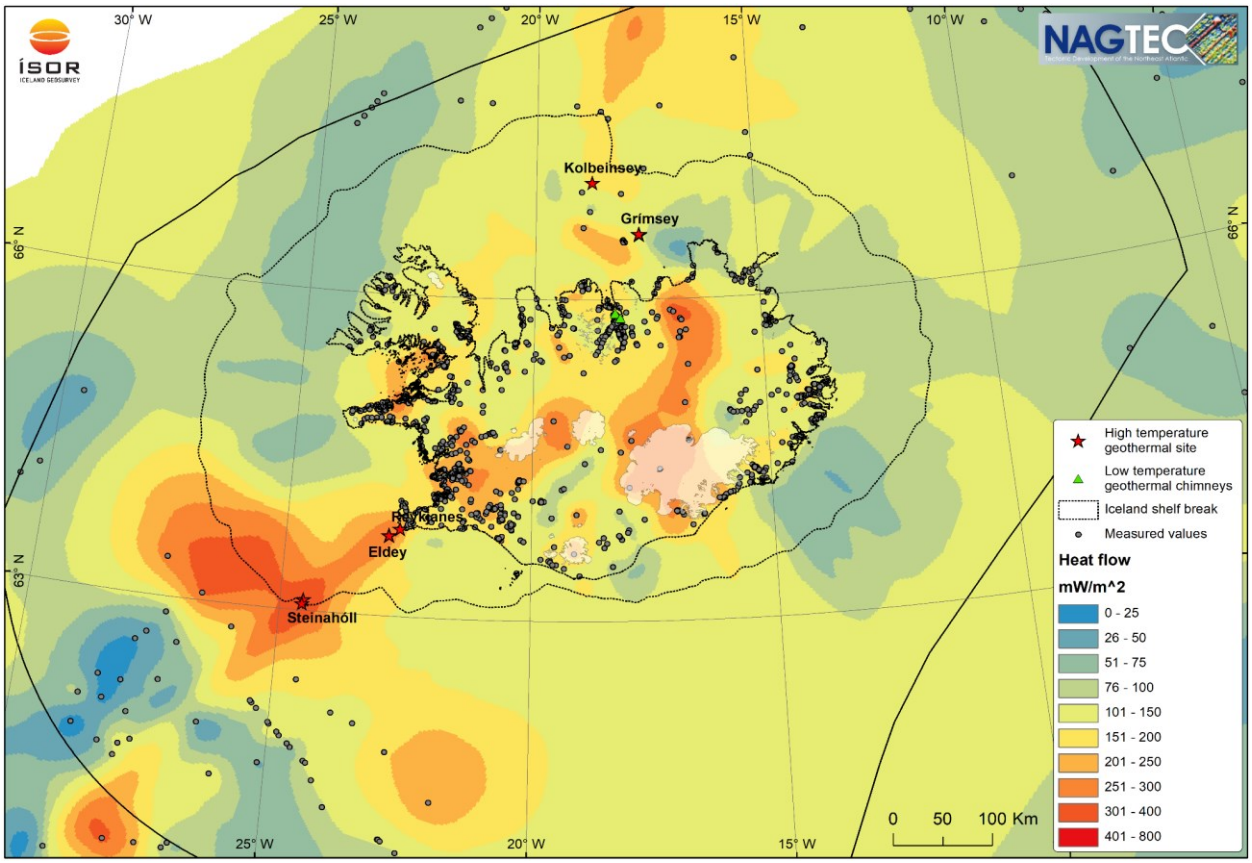

Figure 2: Heat flow map of Iceland and the surrounding sea. The spreading zones of Iceland and the Reykjanes and Kolbeinsey Ridges show increased heat flow. A large area with high heat flow appears west of Reykjanes Ridge near Steinahóll geothermal site. It is based on measurements in several boreholes. The map is modified from Hjartarson et al. 2014.

Hot springs occur on some islands and skerries, especially in Breiðafjörður but also in Vigur in Ísafjarðardjúp and in Hrísey island in Eyjafjörður. Twelve of the sites cannot be seen directly but are inferred from indirect evidence. The highest temperature measured, 100°C, was in Öxarfjörður. There, the geothermal area is suggested to represent a high temperature system (Ármannsson, 2016). The others reported are low temperature systems. The liquid is in most cases fresh geothermal water. In some case the salinity has been increased slightly because of intermixture with sea water. In some case deposits of geothermal minerals, sinter or geyserite, have been formed around the vents. in other case no such deposits exist because of wave erosion. The sinter is made of sand and gravel cemented by silica and calcite from the geothermal liquid.

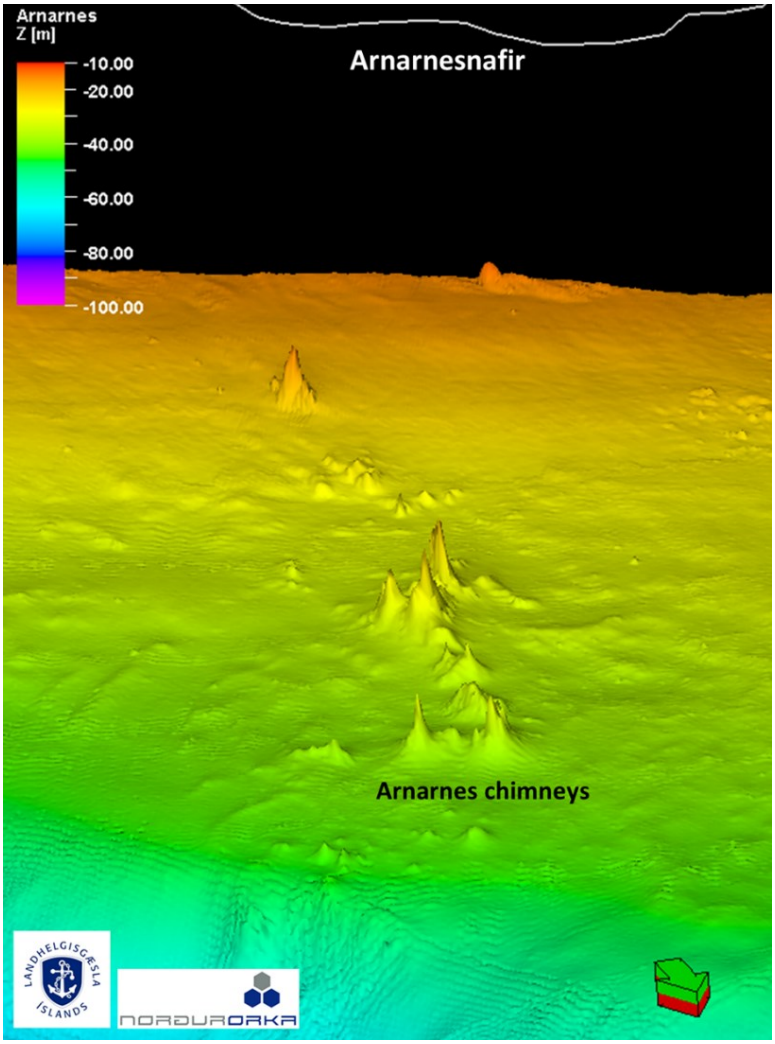

Figure 3: Multibeam image of Arnarnes chimneys in Eyjafjörður. Between 8-13 m high and 750 m long row of chimneys. Data resolution 2 m and 5 times vertical exaggeration.

3. GEOTHERMAL CHIMNEYS

For a long time, unclear information about submarine geothermal activity in several places around Iceland have existed (Benjamínsson, 1988). Only in the last few decades the presence of these activities has been confirmed. At the same time, it has been discovered that high clay chimneys can be formed around the geothermal vents. Around the turn of the century geothermal chimneys were discovered in two places in Eyjafjörður, called Arnarnes- and Ystuvíkurstrýtur (Arnarnes and Ystavík Chimneys) (Marteinsson et al., 2001; Gautason et al., 2005). They are made of smectite clay (saponite) that has been built up around the vents. The Eyjafjörður chimneys are up to 45 m high and form long rows (Fig. 3). Some of them are active, issuing clear and fresh fluid of 70-80°C, others are inactive. These clay chimneys create a unique environment with diverse habitats. A third possible site in Eyjafjörður is the still unconfirmed Gásastrýtur chimneys (Hjartarson et al., 2017). The Eyjafjörður chimneys with their fresh water differ from deep ocean high temperature vents where the upwelling liquid is saline and the deposits around the vents are made of anhydrate.

In several other places geothermal manifestations have been detected. The findings are unconfirmed and will be investigated in the future:

- Saltsteinshver in Eyjafjarðaráll west of Grímsey. Rumor among fishermen about geothermal manifestations at water depth 320 m (Sæmundsson, 2010).
- Off Reykjarhóll in Skagafjörður. Hot stones covered with geothermal precipitates caught in a trawl net (Benjamínsson, 1988).

- Steingrímsfjörður. Fragments of geothermal chimneys were caught in a fishing net. Water depth 70 m.
- Langadalsströnd, Ísafjarðardjúp. Gas bubbles rising from the seafloor at 130 m depth, detected by echo sounding (Benjamínsson, 1988).
- Faxaflói, east of Syðrahraun. Research vessel measured increased sea temperature in a limited area, > 40°C. (Information from Icelandic Coast Guard).
- Off Hálsar in Suðursveit. Gas bubbles rising from sandy sea floor at 36 m depth (Benjamínsson, 1988).
- Skjálfandadjúp, pair of possible chimneys, 15-20 m high, on top of small N-S trending ridge have been spotted in multibeam data at a depth of 190-200 m (Fig. 4). The area is outside the volcanic systems, 6 km southwest of the young seamount Mánárstapi. No faults or fissures are seen in the area and the sea floor is covered by thick sediments. In a recent research cruise (POS535) in the area a core was recovered next to these predicted chimneys with anhydrite and altered clays that is clear evidence of geothermal alteration.

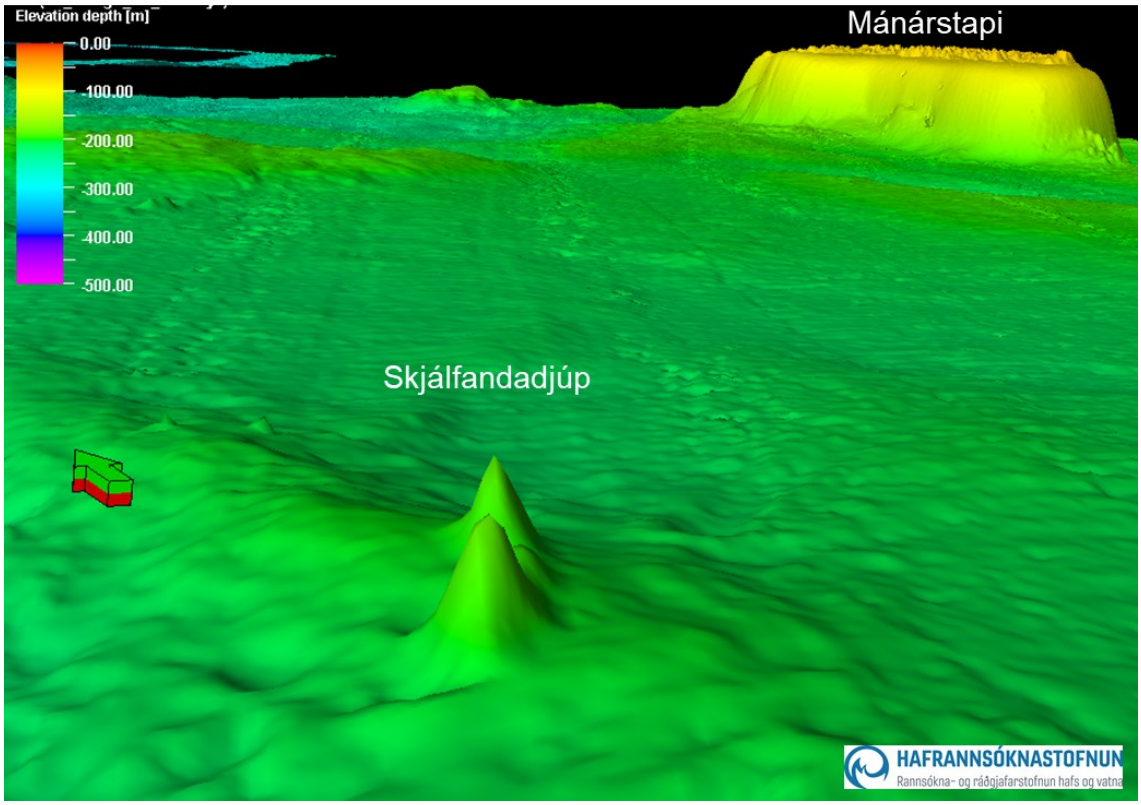

Figure 4: Multibeam image of possible geothermal chimneys, 15-20 m high, in Skjálfandadjúp trough. Mánárstapi seamount is in the background. Data resolution 20 m and 5 times vertical exaggeration.

4. HIGH TEMPERATURE SYSTEMS

The high temperature areas of Iceland have been considered by Ármannsson (2016) as 33, thereof 5 subglacial, 4 submarines and one or two partly submarine. Since then one site has been added to the list, the Eldey suspected area (Hjartarson et al., 2018). They are all related to the active volcanic belts of the country and most often to a special volcanic system (or a central volcano). The submarine systems are (from north to south): Kolbeinsey geothermal field, Grímsey geothermal field, Öxarfjörður partly submarine system, Eldey geothermal field and Steinahóll geothermal field.

The Kolbeinsey geothermal vent field was discovered already in 1974 (Benjamínsson, 1988). On echo sounders a plume of gas has been seen rising from the summit of a hill at 90 m depth. The location of the site is around 65 km NNW from Grímsey and 6.6 km south of the Kolbeinsey islet (Fig 5). The vent field is at around 100 m depth and the temperature of the geothermal fluid has been measured between 70-130°C (Botz et al.,1999). North-South oriented fissures and faults cross the active geothermal field and an eruptive fissure cuts it. The geothermal field is inside the rift area of the Kolbeinsey Ridge and is located on the rim of an axial rift valley. Ólafsson et al., 1990 studied the geochemistry of the Kolbeinsey field. They found geothermal precipitates of gypsum and barite with minor quartz and aragonite. Sulphide minerals found include major amounts of pyrite, minor amounts of marcasite and sphalerite and trace amounts of cubanite, covellite and bornite. The total gas concentration is as expected in high temperature areas with the CO_2 concentration most abundant. The isotopic composition of the CO_2 and He gas bubbles emitted from the geothermal vents show a definite mantle fingerprint (Botz et al., 1999). Mineral deposition is limited, which may indicate a young age of the field (see also Ármannsson, 2016).

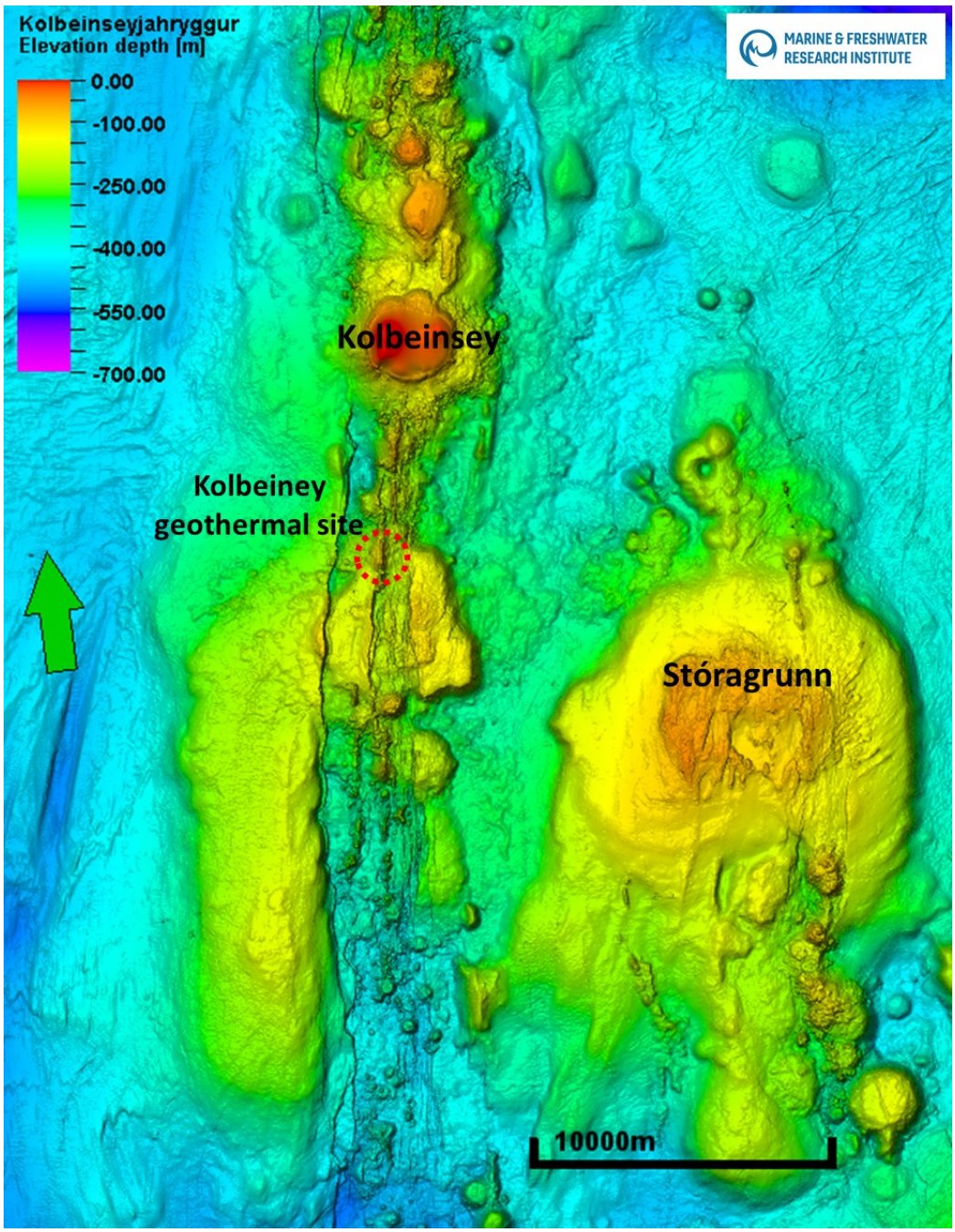

Figure 5: Kolbeinsey geothermal site. The vent field is at around 100 m depth. The temperature of the geothermal fluid has been measured between 70-130°C. North-South oriented fissures and faults cross the active geothermal field and an eruptive fissure cuts it. The geothermal field is inside the spreading rift area of the Kolbeinsey Ridge. Data resolution is 20 m and 5 times vertical exaggeration.

The Grímsey geothermal vent field has been extensively studied. Detailed bathymetry, mapping, chemical analyses, seismic study and coring has been conducted. Also dives with submersibles for temperature measurements, sampling, biological observations and photography (Ármannsson, 2016; Riedel et al., 2001; Hannington et al., 2001; Atkins, 2013; Kuhn et al., 2003). The first suspicions of geothermal activity in the Grímsey geothermal field was due to some geothermal material that had been recovered in bottom trawls and due to melted nylon nets. Later geothermal activity was hypothesized based on earthquake catalogue data. In 1997 an active geothermal field was confirmed. The vent field is located at about 400 m below sea level roughly 16 km east of Grímsey island (Hannington et al., 2001) (Fig 6). It is located between two active volcanic zones, Nafir and Skjálfandadjúp volcanic zones. It consists of about 20 large-diameter mounds, up to 10 m high, and 1-3 chimneys. Most of the mounds expel liquid at about 250°C, which is the boiling temperature at this depth. The entire field seems to be controlled by open system boiling. The geothermal vents are aligned in a northerly trend being approximately 1 km long and 350 m wide. The formation of large anhydrite deposits indicates that high temperature activity has been going on for long time. High levels of CH_4 and CO_2 have been measured around the vent field. No "smoke" is seen coming from any of the vents. This is indication of low concentrations of metals and sulphur in the geothermal liquid.

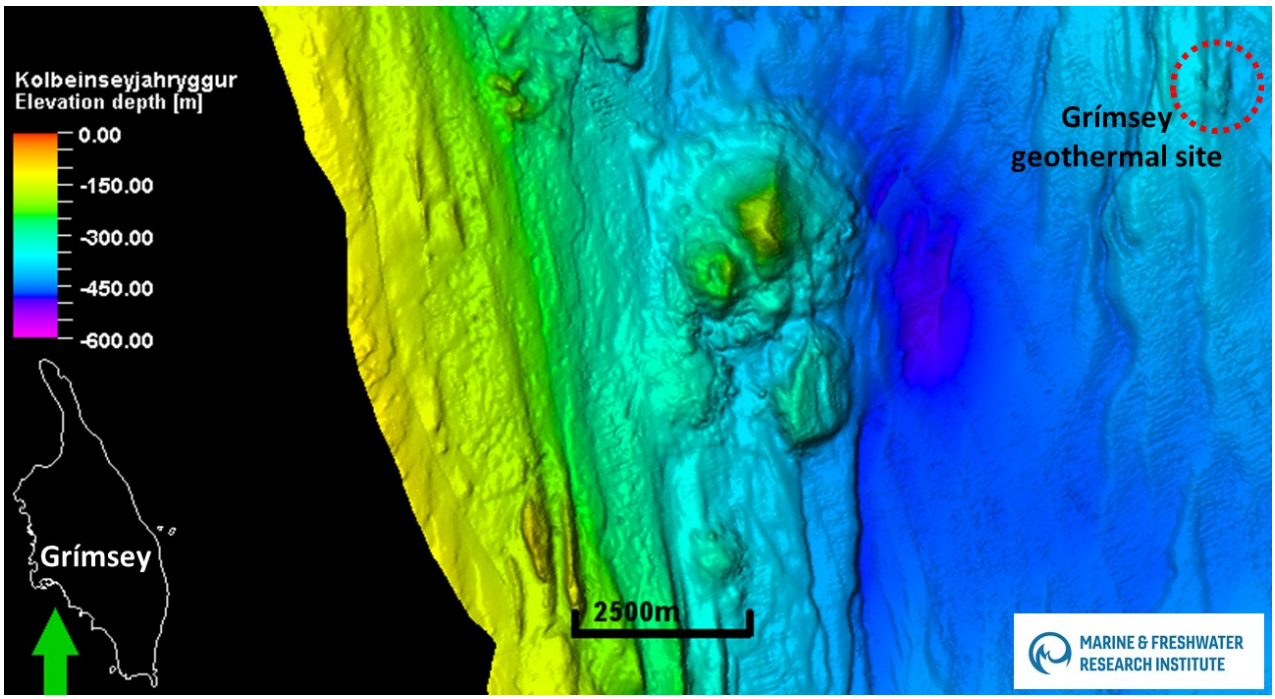

Figure 6: Grímsey geothermal site is located 16 km ENE off Grímsey at about 400 m depth. It consists of about 20 large-diameter mounds, up to 10 m high, and 2-3 higher chimneys. Data resolution is 5 m and 5 times vertical exaggeration.

Analyses reveal that the liquid is almost completely depleted of metals and has low salinity. The pH in the highest temperature vents is 5.9-6.8. Carbon dioxide (41%) and methane (24%) are the dominant gas species and of magmatic origin. More than 90% of the fluids released by geothermal venting are of a biogenic origin and derived from the upper mantle and the oceanic crust, respectively. Of the known submarine geothermal fields in Icelandic waters, Grímsey shows the largest amount of precipitates. The geochemical results suggest a highly magmatic heat source (Riedel et al., 2001; Hannington et al., 2001, Ármannsson, 2016).

Öxarfjörður High Temperature Area is located on the sandy shore of Öxarfjörður Bay reaching into the sea (Fig. 1). Therefore, it is partly submarine. Three active northward trending fissure swarms, the Theistareykir, Krafla and Fremrinámar fissure swarms, cross the shore in the region. There is the junction between the North Iceland spreading zone and the Tjörnes Fracture Zone, a right-lateral transform zone. The uppermost sediments in Öxarfjördur are due to Jökulsá glacial river delta which formed during the last 12,000-14,000 years. Geothermal surface manifestations are mainly located within the fissure swarms of Krafla. The highest surface temperature, 100°C, is found in the Skógalón hot spring area (Benjamínsson, 1988), 1000 m inland from the shore. In 1988 well ÆR-3 was drilled to 322 m depth and yields 45 L/s of 96°C hot water mainly from aquifers at 140 m depth. The temperature at the bottom is approx. 130°C. It is now the production well for the Öxarfjördur Heating Services. The fluid of all the Skógalón and Bakkahlaup wells is brackish, with chloride the major anion. Geothermometer temperatures suggest at least 180 °C in the roots of the system (Ármannsson, 2016).

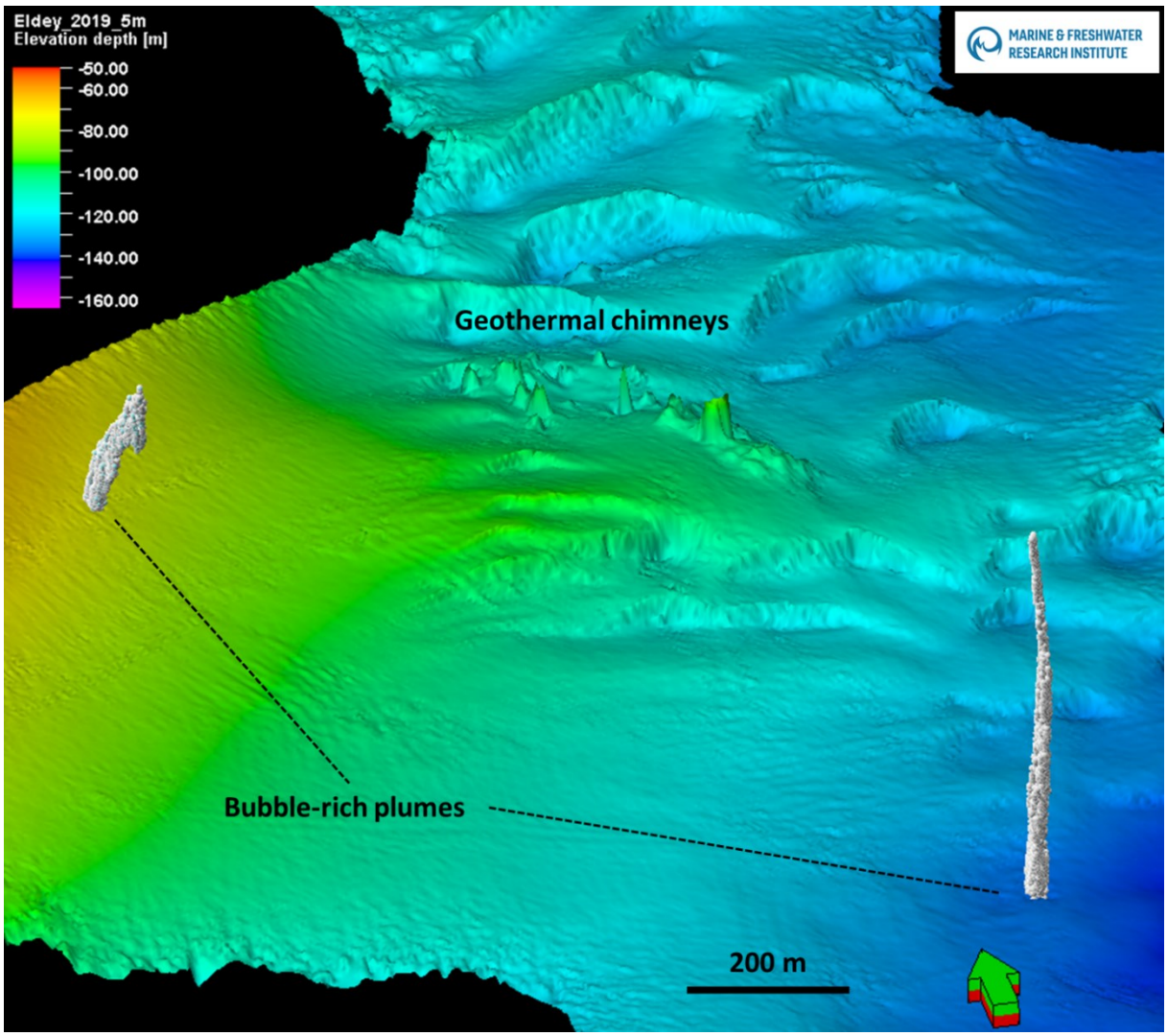

Figure 7: 3D view of the Eldey geothermal site, about 3 km ENE of Eldey island. In this new multibeam data, acquired in July 2019 by the Marine & Freshwater Research Institute, a row of 6-11 m high geothermal chimneys is seen along with two prominent upwelling bubble-rich plumes reaching high into the water column (37 m and 92 m high). Data resolution is 5 m and 5 times vertical exaggeration.

Eldey geothermal field. On the insular shelf the Reykjanes spreading Ridge consists of en-echelon arranged volcanic systems and fissure swarms. Eldey volcanic system is the one closest to the shore. Possible geothermal activity has been noted for years by gas bubbles rising to the sea surface in two localities 1-3 nm NE of Eldey, at less than 120 m depth, just outside of the nature reserve area of the island (Fig. 7). Hjartarson et al. (2018) suggested the sites to be hereto undiscovered high temperature area located 13 km towards southwest from the main land. A survey committed by the Marine & Freshwater Research Institute in July 2019 revealed two prominent upwelling bubble-rich plumes in the area. A row of about 10 geothermal chimneys also appeared on the new multibeam data, reaching up to 11 m in height (Fig. 7). Nothing is still known about the temperature or the discharge of the active vents.

Steinahóll geothermal field is inside a large volcanic system in Reykjanes ridge (Fig. 8). It is composed of volcanic ridges and hills, featuring craters and cones, with the shallowest peaks at around 160 m depth. Intense seismic swarms in 1989 and 1990 caused suspicion of volcanic unrest that led to the discovery of the vent field during a scientific cruise (Thors et al., 1992). In 1991 another scientific cruise, aimed at manganese oxide nodules and metal rich placers, mapped the Steinahóll area and then located the thermal area along with manganese rich sites that might be manifestation of a former geothermal activity. Later, a group of geothermal chimneys was discovered in the southern part of the field. They are 12-35 m high and form a 170 m long chain at water depth between 300 and 350 m. The Steinahóll geothermal field is near the center of the volcanic system, about 120 km SW from the tip of Reykjanes Peninsula at 160-350 m depth. Geothermal activity has been confirmed at two places. The site has been recognized for its bubble rich plumes that allow the vent field to be located very precisely. In one case a bottom trawl net used in the area was melted. However, the nature of the site is still poorly known. The size of the vent field is unknown, no direct measurements or fluid samples have been collected from the vents. The temperatures have not been measured but since gas bubbles rising from the vents are detected it could indicate that the fluid is boiling. The boiling temperature of sea water at this depth is around 220°C. Manganese nodules (containing todorokite and birnessite), gypsum and polymetallic sulphides, found by dredging in many localities on Steinahóll, indicate widespread active or inactive geothermal fields. According to Ármannsson (2016) the dissolved gas concentrations in water samples from plumes reach high values, higher than elsewhere on the Mid-Atlantic Ridge. The field reflects an interplay of magmatic and tectonic controls (German et al., 1994; German and Parson, 1998).

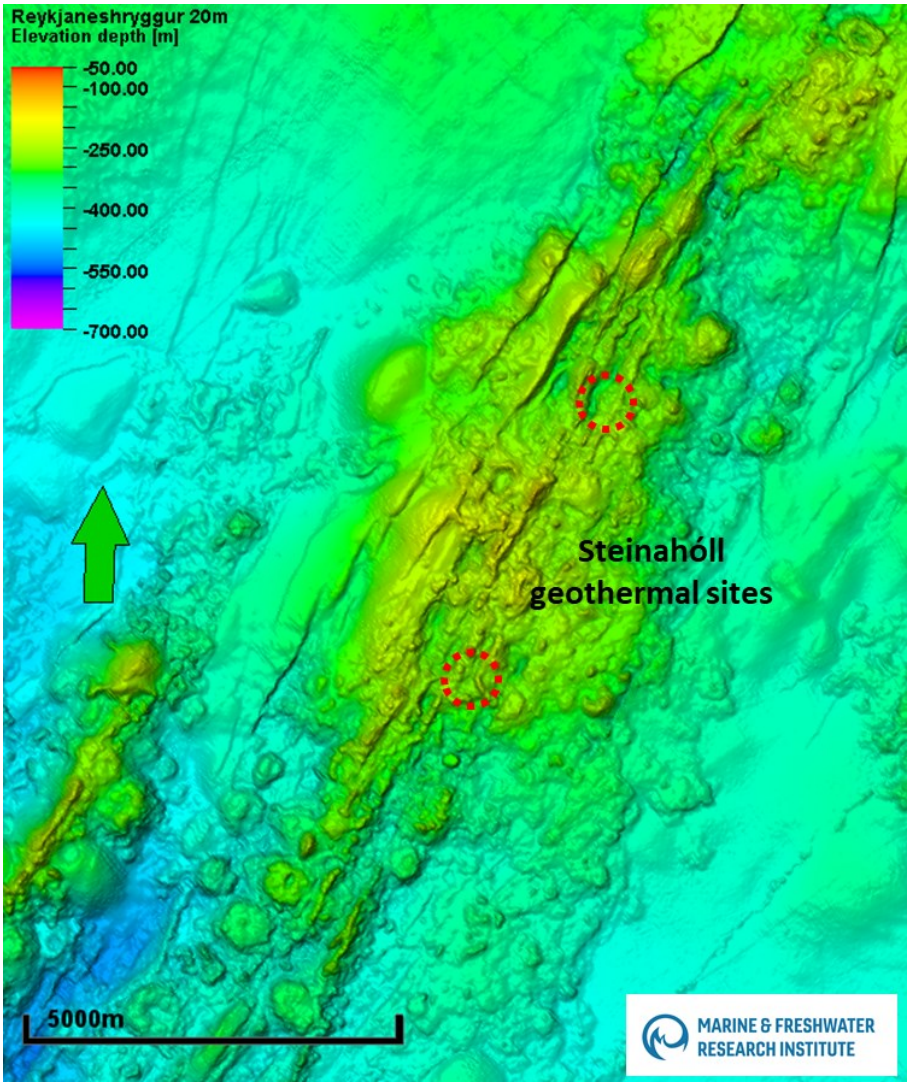

Figure 8: Steinahóll high temperature areas on Reykjanes Ridge. Data resolution is 20 m and 5 times vertical exaggeration.

5. UTILIZATION

The use of the littoral hot springs is pretty the same as the use of the onshore geothermal springs in Iceland. In some places (Hrísey) a production wells have been drilled for the local heating services and some places natural baths are in use (Drangsnes, Grettislaug). In ancient times some of the springs were used for cooking food such as eggs and fish (Benjamínsson, 1988)

In Eyjafjörður the geothermal chimneys have already economic importance in the tourist industry. The unique environment with its diverse habitats is popular tourist attractions.

Utilization of offshore high temperature geothermal energy might be possible in the future and the first steps have already been taken in that direction. In 2018 Iceland GeoSurvey (ÍSOR) conducted a reconnaissance geothermal study for the company North Tech Energy (NTE) on the sea floor within two exploration areas, one along the Reykjanes Ridge, and another one off the North Iceland coast (Hjartarson et al., 2018). The most promising sites have been listed up. The next step is to choose between them and then perform detailed geological and geophysical study. This work has been outlined already (Erlendsson et al., 2019). After such surveys, exploration drilling will be carried out in the field deemed the most promising in hosting a potential geothermal resource. Such drilling will hopefully be carried out shortly after the exploration surveys have identified the potential resource and drilling targets.

6. DISCUSSION

Further mapping and exploration of the oceanic floor around Iceland in the coming years will certainly lead to discovery of unknown geothermal fields. At the same time scientific and political discussion and debate about possible utilization will take place.

There are both advantages and disadvantages to the utilization of offshore geothermal resources, which relates to the environment as well as the financial- and technical feasibility of such endeavor. The exact utilization of the energy is not within the scope of this article, but it might be a conventional electrical production with a cable connection to the shore or even production of hydrogen fuel for energy transport.

In any case, if development of offshore geothermal power becomes feasible, it will open large additional possibilities for sustainable and clean energy production through geothermal than is already available today, world-wide.

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