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Existence and Nature of Low-Temperature Geothermal Systems in Eyjafjördur, N-Iceland, from a Geophysical Perspective

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ABSTRACT

Geothermal utilization in Iceland involves the exploitation of both low- and high-temperature resources for electricity generation as well as space heating and other direct uses. In Eyjafjördur, N-Iceland, the basaltic crust hosts low-temperature geothermal systems of which some have been harvested for half a century, while others have been discovered more recently. In this area, the basaltic crust is comprised of lava flows with thin sedimentary horizons, with the stratigraphic pile crosscut by basaltic dikes. Its permeability is almost entirely tied to vertical and sub-vertical faults and fractures, with the main heat source of these low-temperature geothermal resources being the background heat flow in Iceland.

We examine the existence and nature of the low-temperature geothermal systems in western Eyjafjördur, from the island of Hrísey in the north to Hjalteyri in the south. The analysis is mainly based on monitoring and evaluation of microseismicity in the area, using data from a local seismic network operated by Iceland GeoSurvey for the local utility service, Nordurorka, since 2017. The focus is on exploring how seismicity and active tectonics enhance permeability in the basaltic crust. We also consider, to some extent, results from magnetic and resistivity surveys for an improved understanding and updated conceptual model of these low-temperature geothermal systems.

1 INTRODUCTION

Iceland originates from the interaction of the divergent Mid-Atlantic plate boundary separating the North-American and Eurasian plates, and excessive mantle upwelling beneath central Iceland due to a mantle plume (Sigmundsson et al., 2020). The plume causes thermal uplift of a region at least 1000 km in radius, and elevated mantle temperatures cause considerably more melting than below a normal mid-ocean ridge (Darbyshire et al., 1998). These geodynamics result in a region of anomalously thick and hot crust in Iceland, rising more than 2 km above sea level, with the landscape shaped by volcanism and glaciations – as well as abundant geothermal resources, which play a major role in the economy of the country.

Geothermal systems in Iceland are in general classified as either low- or high-temperature resources, based on the measured temperature at 1 km depth. The high-temperature systems, which by definition have a reservoir temperature above 200°C at 1 km depth, are located within the volcanic zones that pass through central Iceland, while the low-temperature systems (reservoir temperature below 200°C at 1 km depth) are mainly located outside the volcanic zones and distributed all around the country, with the majority located in its western part, and the largest and most productive systems in SW-Iceland, on the flanks of the volcanic zones (Axelsson et al., 2010).

The low-temperature systems are located in tectonically active areas in Iceland, where faults and fractures are kept open by ongoing tectonic activity. The heat source for the low-temperature activity is believed to be the anomalously hot and thick crust of Iceland, with the active faults and fractures providing channels for water circulation and heat extraction within each system. A highly simplified conceptual model for these systems can be described as follows; precipitation falling in the highlands circulates through shallow groundwater flow down to the lowlands to a geothermal area, percolating into the bedrock through an open fracture or along a dike to a depth of a few km, where it extracts heat from the crust and ascends towards the surface due to reduced density (Bödvarsson, 1982; 1983; Björnsson et al., 1990; Axelsson et al., 2010).

In Bödvarsson's single-fracture model (Bödvarsson, 1983), the open fracture is assumed to be closed at depth but opening up with time and continuously migrating downward during the heat extraction process by cooling and contraction of the rock matrix. Theoretical calculations based on the Bödvarsson model indicate that the controlling factors for the existence of these low-temperature systems are the temperature and stress conditions in the crust, in particular the regional tectonics and the resulting local stress field (Axelsson, 1985).

Some of the low-temperature systems in Iceland have no surface manifestations, while others are more easily identified with hot or boiling springs at the surface. Both types have similar characteristics, while the ones devoid of surface manifestations have been discovered after surface exploration, including e.g., geological and tectonic mapping, shallow gradient well drilling, resistivity and magnetic surveying (Axelsson et al., 2005). In this study, we examine the existence and nature of the low-temperature geothermal systems in western Eyjafjördur, N-Iceland, with the focus on exploring how seismicity and active tectonics enhance permeability in the basaltic crust. The analysis is based on local seismic monitoring in the area since 2017, with examples from the island of Hrísey in the north and Hjalteyri in the south.

2 THE EYJAFJÖRDUR REGION

Eyjafjördur is a fjord in central N-Iceland, located just west of the Northern Volcanic Zone (Figure 1). Several low-temperature geothermal systems have been identified and harnessed, with the majority located in the western part of the fjord, and in the Eyjafjördur valley south of the fjord. The geothermal fields are operated by the local district heating company, Nordurorka Ltd. (NO), mostly owned by the municipality of Akureyri (e.g., Flóvenz et al., 1995).

2.1 Geology and tectonics

The Eyjafjördur region is made up of deeply dissected sequences of ca. 6-12 Ma subaerial basaltic lavas (e.g., Aronson and Saemundsson, 1975; Saemundsson et al., 1980), often referred to as the Eyjafjördur basalts, commonly separated by clastic interbeds consisting largely of wind-blown tephra mixed with ancient soils (Saemundsson, 1979; Saemundsson et al., 1980; Roaldset, 1983). The Eyjafjördur basalts originate in fissure swarms and central volcanoes of Miocene age, while silicic and intermediate formations are particularly associated with the presence of central (composite) volcanoes (including the Öxnadalur volcano along the Tröllaskagi peninsula and the Flateyjardalur volcano north of Grenivík (Figure 1). The stratigraphic pile is crosscut by series of subvertical basaltic dikes and faults. The dikes are in most cases nearly perpendicular to the basaltic lavas and were mainly formed by intrusions and faulting during rifting episodes in nearby volcanic systems at the time of the formation of the crust (Flóvenz et al., 2010). The permeability of the basaltic crust in the Eyjafjördur region is almost entirely controlled by vertical and sub-vertical faults and fractures.

The northernmost part of the fjord is strongly affected by the Tjörnes Fracture Zone (TFZ), which is a transform fault zone connecting the volcanic rift zone in NE-Iceland and the Kolbeinsey Ridge north of Iceland. The TFZ is believed to consist of three parallel major fault zones, trending WNW–ESE, based on historical seismic activity (e.g., Einarsson, 1991, 2008). The northernmost is the Grímsey Oblique Rift (GOR), in the middle is the Húsavík–Flatey Fault (HFF), and the southernmost is the Dalvík Lineament (DL), which is much less distinct than the other two in terms of seismicity, but is thought to run through Ljósavatnsskard, across Eyjafjördur, through the island of Hrísey and the town of Dalvík, and to the west to Skagafjördur fjord.

2.2 Geothermal fields

The background heat flow in Eyjafjördur is among the lowest observed in Iceland, with the regional temperature gradient being ~40-60°C/km (Flóvenz and Saemundsson, 1993). The basaltic lava pile in the area is deeply eroded by glacial erosion, and the primary permeability is generally very low, decreasing with depth (Flóvenz et al., 2010). The low-temperature geothermal systems in such a tectonic setting must therefore owe their existence to recent tectonic fracturing that creates paths for subsurface circulation of water.

In the Eyjafjördur region, numerous hot springs exist at the surface, indicative of the local, low-temperature geothermal reservoirs below. They show variable temperatures, ranging from 20 to 90°C, usually with quite low natural flow rate and chemical content (Flóvenz et al., 1995). Geothermal wells (500-2800 m deep) have been drilled into many of the fields, with very similar temperature characteristics observed for all fields, i.e., very high near-surface gradient that gradually lowers with depth, becoming nearly zero in many of the wells. Such behavior is explained by fluid convection in a near-vertical fracture system (Bödvarsson, 1982; Björnsson et al., 1990), and from heat flow analysis it has been concluded that the low-temperature geothermal systems in Eyjafjördur may have been active for tens of thousands of years (Flóvenz et al. 2010). During this time, a so-called self-sealing process has most likely been active, closing fractures at shallow depths due to precipitation of

secondary minerals during the cooling of the reservoir fluid – and at the same time, the process of downward propagation of the fractures has maintained the convection (Bödvarsson, 1982; Axelsson, 1985).

Presently, twelve low-temperature geothermal fields are harnessed by NO's district heating system, eleven of which are utilised for district heating in Eyjafjördur (https://www.no.is/is/veiturnar-okkar/hitaveita/vinnslusvaedi-hitaveitu) (Figure 1). The most productive of these eleven geothermal systems is the one on Hjalteyri, in western Eyjafjördur, and in general, the more productive areas are located on the western part of the fjord. The reason for this high capacity and good permeability, compared to other geothermal production areas in Eyjafjördur, is believed to be recent tectonic activity and fracturing caused by earthquakes along the Tjörnes Fracture Zone, thus enhancing permeability (Flóvenz et al., 2000). The Laugaland geothermal system in the Eyjafjördur valley, for example, is considerably less permeable compared to the systems in western Eyjafjördur, with the main reason being that it is located in a much less tectonically active area (Axelsson et al., 2010).

3 SEISMICITY

Seismic activity in Eyjafjördur has been sporadic since modern-day measurements began, with occasional earthquakes and small earthquake swarms (Figure 1). As previously mentioned, the DL is much less active than the other two fault zones of the TFZ. However, history shows that very large earthquakes of magnitude 6 or greater can occur, as evident by an event in 1934 near the town of Dalvík.

A common feature of the three fault zones of the TFZ is that seismic activity appears to occur on faults that cut across the strike of the belts (e.g., Rögnvaldsson et al., 1998), and seismicity on the DL seems primarily related to left-lateral strike-slip movement on short, parallel north-south trending faults that probably reflect a sort of "bookshelf" fracturing (Stefánsson, 1966; Rögnvaldsson et al., 1998; Gudnason et al., 2020). Unlike the HFF and GOR, no surface fractures are visible on the DL, despite earthquakes occurring along a ~30 km long zone (e.g., Rögnvaldsson et al., 1998; Einarsson, 2008).

The connection between seismic activity and the low-temperature geothermal areas identified in Eyjafjördur has been investigated over time, i.e., during geothermal exploration in Árskógsströnd in 1996, where the aim was to determine whether usable geothermal resources could be found closer to the populated areas on Árskógsströnd and at Ytri-Hagi (Flóvenz and Smárason, 1997). Evidence emerged of an active earthquake fault trending NNW-SSE, extending from the geothermal area in the southwestern part of the Hrísey island, across western Árskógsströnd, through Ytri-Hagi, and onto Arnarnes (Hjalteyri). This earthquake fault is clearly visible when plotting seismic activity in Eyjafjördur, as recorded by the SIL regional network of the Icelandic Meteorological Office, from the beginning of modern-day measurements in 1995 to the present (e.g., Gudnason et al., 2023) (orange dashed line in Figure 1). The orientation of this fault is roughly the same as that of the two fracture systems mapped near the geothermal area in Hrísey (Friðleifsson, 1989), and similar to the orientation of an active fault mapped using earthquake focal mechanism analysis northwest of Hrísey (Rögnvaldsson, 2000).

In chapters 3.2 and 3.3, we show examples of microseismicity recorded since 2016/2017 on this NNW-SSE trending earthquake fault, i.e., i) north of the island of Hrísey (3.2) and ii) at Hjalteyri (3.3).

3.1 Seismic monitoring network

Since early 2017, Iceland GeoSurvey (ÍSOR) has operated a local seismic monitoring network for NO in Eyjafjördur (yellow triangles, Figure 1). The current network consists of six permanent seismic stations; two on the east side of the fjord, three on the west side, and one at the head of the fjord. In addition, ÍSOR and NO have access to data from three seismic stations belonging to the SIL regional seismic network of the Icelandic Meteorological Office (IMO) in the area (blue triangles, Figure 1). All stations are streaming data in real-time.

The purpose of operating this local seismic network is to gather information about permeability in the bedrock of Eyjafjördur for improved understanding of the crust in this region, and to obtain data that could be useful for mapping low-temperature geothermal systems and their permeability, as well as monitoring the effects of production and re-injection on seismic activity.

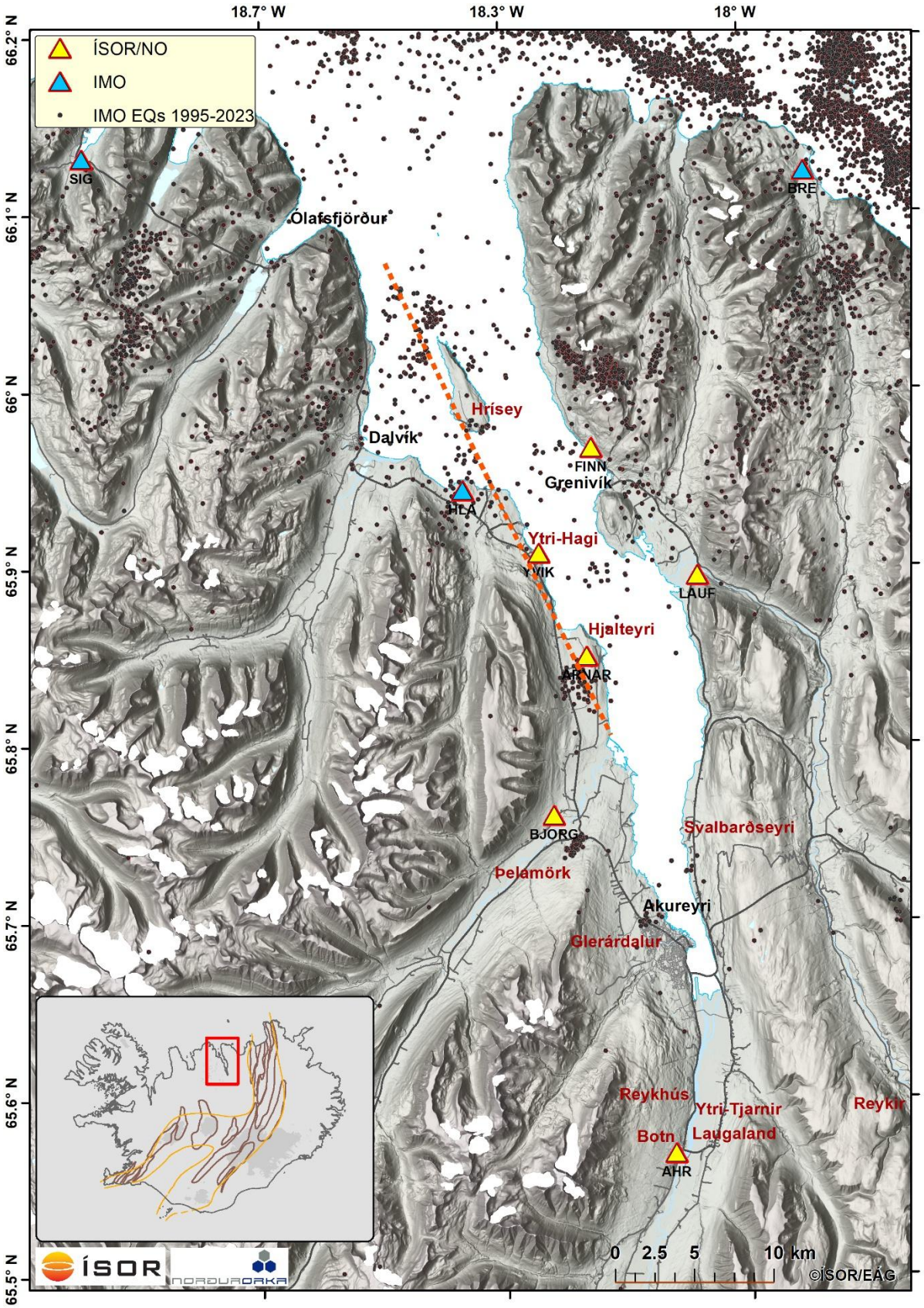


Figure 1. A map of Eyjafjördur and vicinity, showing the harnessed low-temperature geothermal fields (red colored text), towns and villages (black colored text) and the local seismic monitoring network, operated by ÍSOR for NO since 2017 (yellow triangles). Blue triangles are stations of the regional seismic network in Iceland, operated by IMO, that are part of the local monitoring network. Orange line shows the earthquake fault across the western part of the fjord, and seismicity recorded by IMO in 1995-2023 is shown as small, grey circles. The inset shows the location of the zoomed-in area in central N-Iceland (red box).

3.2 Hrísey

Hrísey is a small fishing village and island in central Eyjafjördur with around 180 inhabitants, living in the SW part of the island. The very dense bedrock in Hrísey is about 10-11 Ma (e.g., Friðleifsson, 1989), consisting of basaltic lavas and thin sedimentary interbeds (Einarsson et al., 1979). Subsurface water channels are assumed to be primarily along dikes and faults, with dikes being widespread in Hrísey, typically trending NNE and dipping towards NW (Friðleifsson, 1989). Two main fault trends are noted; an older NE-SW trend and a younger N-S to NW-SE trend assumed to be related to the DL (Friðleifsson, 1989). A large left-lateral SW-dipping strike-slip fault runs along Hrísey's eastern margin, which has been suggested to play an essential role in geothermal activity on the island (Friðleifsson, 1989). Natural geothermal hot springs are found at two locations. One is in the southwest part, with measured water temperature below 25°C (yellow star in Figure 2). A district heating system was installed in the village in 1973 after drilling of six wells close to this hot spring, with the deepest well drilled down to 1055 m (Flóvenz et al., 2010). Hot water was only encountered in a horizontal layer at ~100 m depth, with no major feed zones identified at deeper levels. Over time, inflow of fresh groundwater caused cooling and oxygen contamination in water from the well, leading to associated scaling and corrosion issues. After successful resistivity profiling in 1984, a 330 m deep production well was drilled, cutting the fracture feeding the horizontal layer and providing 77°C of hot water without oxygen and serious scaling problems (Björnsson and Flóvenz, 1985).

The other hot spring in Hrísey is found at the island's northern end, near a ~100 m thick dike named Laugarkambur that rises high above the land and slopes into the sea (orange star in Figure 2). A hot spring named Bekkur lies on the dike's eastern side, below the spring tide water level, thereby submerging at high tide (Hjartarson et al., 2017). Measured water temperature of the spring is up to 65°C, with natural flow of 0.4–0.5 L/s, but this geothermal area has not been studied in any detail (Einarsson et al., 1979).

Since modern-day measurements started, seismic activity has been recorded beneath and around Hrísey, demonstrating mainly occasional, deep earthquakes, indicative of active faults and fractures sustaining permeability. From late October 2020 to May 2022, however, swarm-like seismic activity occurred north of Hrísey, that can largely be divided into three separate swarms (Figure 2) (Gudnason et al., 2023). From the first swarm to the latest, seismic activity shifted progressively northward and is particularly notable for occurring at shallow depths, mostly less than 1 km. The majority of the earthquakes are microearthquakes (M_L<1), with a total number of ~80 earthquakes in all three swarms. Calculated focal mechanisms indicate that the movement was most likely left-lateral strike-slip on a NNW-SSE trending fault, and it is reasonable to assume that the earthquakes in these three swarms define a common fault plane or earthquake fault.

The swarm-like seismic activity occurs in an area north of Hrísey called Eyjahalar, where basaltic lavas beneath the seabed are intersected by vertical dikes trending NE or NNE. It is tempting to assume that this shallow seismic activity is caused by geothermal upflow, where an active earthquake fault with a NNW-SSE trend intersects the dikes beneath the seabed. Although it is difficult to identify any clear indicators of geothermal activity on the seabed in this area based on bathymetric surveys, there are small hydrothermal chimneys at two locations off Laugarkambur at about 30 m depth, along with the Bekkur hot spring in the intertidal zone (Figure 2). Therefore, it cannot be ruled out that hydrothermal chimneys may also be found in this area north of Hrísey.

Assuming that the earthquakes in these three swarms north of Hrísey define a common fault plane or earthquake fault, it is reasonable to assume that it could be an extension of the NNW-SSE trending earthquake fault that connects the previously mentioned low-temperature geothermal areas in western Eyjafjördur and is believed to play a key role in the activity of the geothermal systems in this region. Surface expression of this fault is believed to be observed along the eastern side of the island (described above, mapped by Friðleifsson, 1989). Head-on resistivity profiling measurements in Hrísey indicate that the geothermal activity trends NE or NNE and that geothermal upflow occurs where faults or dikes with this orientation intersect the NNW-SSE trending earthquake fault.

3.3 Hjalteyri

Hjalteyri is a small fishing village in central-western Eyjafjördur (e.g., Gautason et al., 2005). Geothermal prospecting in this area, which is lacking any geothermal surface manifestations, was initiated in 1999. During the next three years, geothermal exploration involved e.g., geological and tectonic mapping, shallow gradient well drilling, magnetic and resistivity surveying. A ground magnetic survey was carried out on three profiles perpendicular to the axis of the mapped thermal anomaly, and despite thick glacial sediments in the area, a distinct magnetic low was observed on all three profiles, interpreted as a reverse magnetised dike, or dike complex, trending ~N10°E.

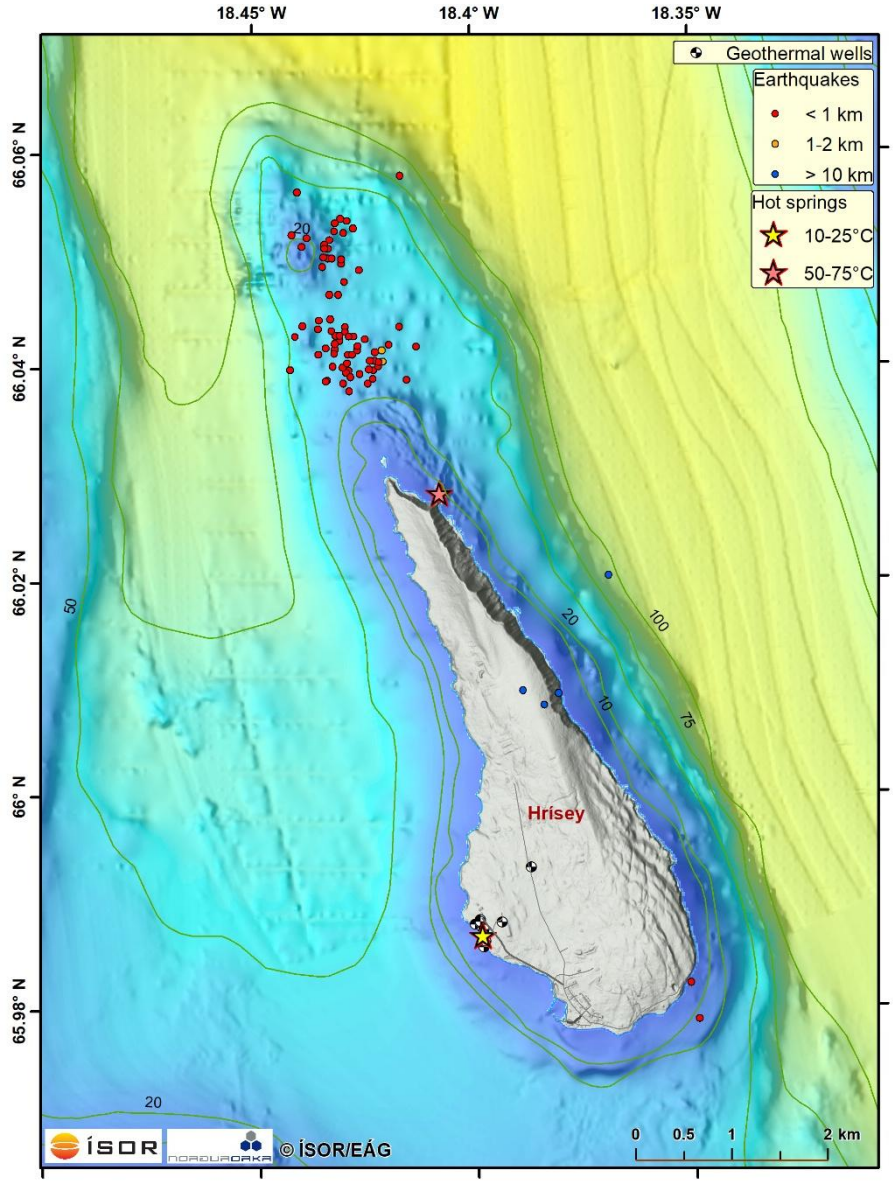


Figure 2. Earthquakes located north of Hrísey in Eyjafjördur during three separate swarms from October 2020 to May 2022 (Gudnason et al., 2023). Earthquakes are color-coded by depth, and geothermal wellheads are shown as black and white cross-circles. Geothermal hot springs in the southwest part and north of the island are marked with stars, colored according to temperature. The underlying seabed map was published by ÍSOR and is based on bathymetric depth measurements from the Icelandic Coast Guard, NO, the Marine Research Institute of Iceland and the OLEX database, with depth contours below sea level shown in green.

The results of the geothermal exploration suggested a significant low-temperature geothermal resource, and drilling of well HJ-19 to 1450 m yielded by far the most productive well in the Eyjafjördur region, and one of the more productive low-temperature wells in Iceland. The Hjalteyri low-temperature field is in fact the most productive geothermal system in the Eyjafjördur region. Production from the field started in 2003, and early model calculations indicated that the geothermal system should be able to yield an average of 200 L/s over the coming decades (Axelsson et al., 2003), while later calculations indicated a yield of 250-280 L/s (Axelsson and Egilson, 2017).

Similar to Hrísey, sporadic seismic activity has been recorded beneath Hjalteyri since modern-day measurements started, with mainly occasional, deep earthquakes, indicative of active faults and permeable fractures (Figure 3). In December 2016, just before the local seismic network of ÍSOR and NO was installed, a relatively large swarm of earthquakes occurred beneath Hjalteyri, recorded by the regional SIL network (grey events in Figure 3). A total of ~60 events occurred in one day, and the earthquakes were located at depths of ~9-13 km. The largest earthquake was a so-called foreshock, with a magnitude of 3.6 M_L at ~13 km depth. The focal

mechanism of the largest event indicates a combination of normal faulting and strike-slip movement, on a NW-SW trending fault, similar to the overall trend of the swarm (Figure 3).

Since this earthquake swarm, i.e., from 2017 onwards, only 15 occasional earthquakes have occurred beneath Hjalteyri (Figure 3) (Axelsson et al., 2024). These are mainly microearthquakes (< 1 M_L), with the two largest events only reaching 1.5 M_L. As elsewhere in the Eyjafjördur region, all earthquakes beneath Hjalteyri are deep, occurring between 8 and 14 km depth, i.e., in the lower part of the brittle crust. Focal mechanisms for seven of these events are indicative of right-lateral strike-slip movement on a NW/NNW-trending fault, which aligns well with the prevailing NW-SE fracture orientation observed in acoustic Televiewer images from wells HJ-19, 20 and 21.

Although all earthquakes at Hjalteyri occur deep beneath the geothermal system (> 8 km), they likely take place on active, permeable faults connected to the geothermal system, which suggests that the geothermal system may extend deep into the crust, although exactly how deep remains uncertain (Axelsson et al., 2024).

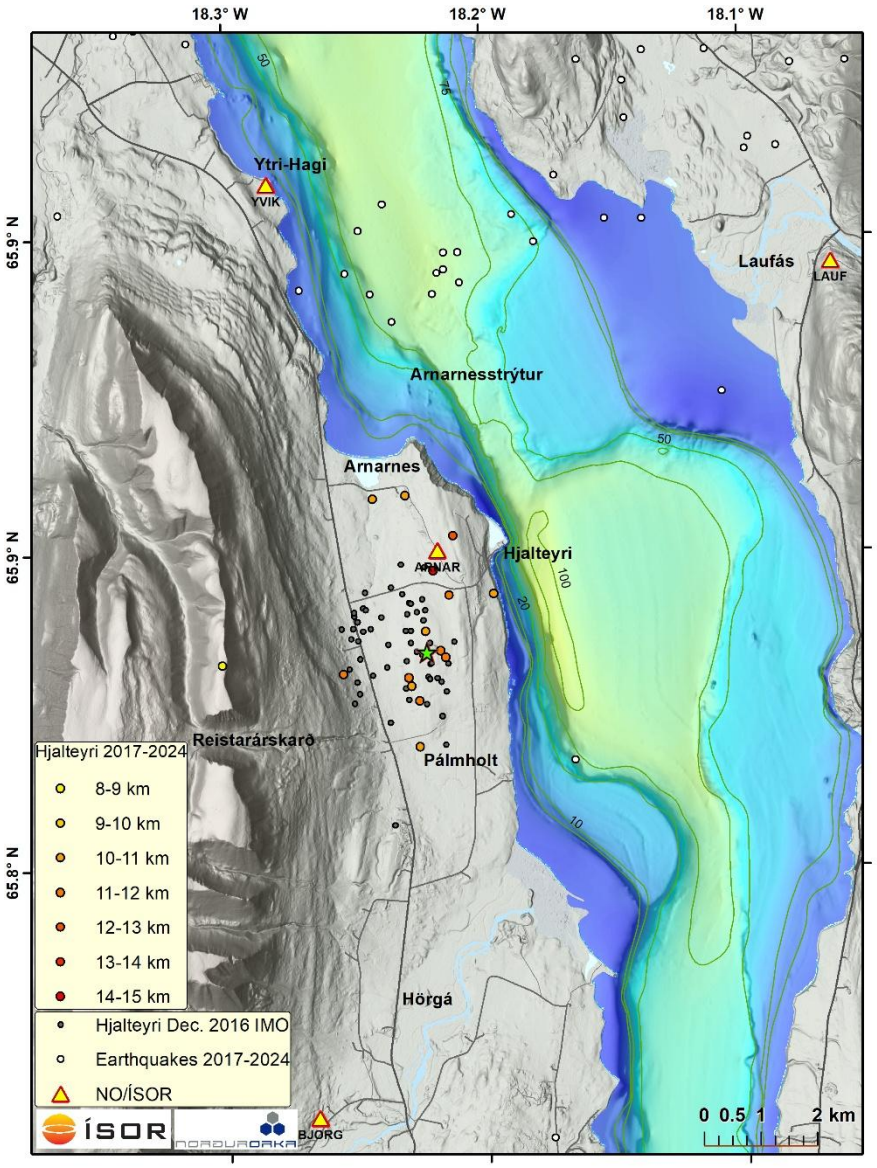


Figure 3. Earthquakes located at Hjalteyri and in the immediate vicinity from 2016 to 2024. Earthquakes located with the local monitoring network (NO/ÍSOR) at Hjalteyri from 2017–2024 are color-coded by depth, from 8 to 15 km (seismic stations shown with yellow triangles), while other earthquakes in the nearby area that occurred during the same period are shown in white. For comparison, an earthquake swarm that occurred in December 2016, located using the regional SIL network, is shown in grey. The largest earthquake of the swarm (3.6 M_L) is marked with a green star. The underlying seabed map was published by ÍSOR (same as in Fig. 2), and depth contours below sea level are shown in green.

4 DISCUSSION AND CONCLUSION

In general, ongoing tectonic activity is considered to play a major role in geothermal activity in Iceland, both concerning low- and high-temperature systems (Björnsson et al., 1990). Most tectonic movements are accompanied by earthquakes, and seismic activity along a fault is most likely necessary to maintain its permeability, and thus its importance as a flow channel for water in a geothermal system. By obtaining the best possible information about earthquakes, their nature and location, it is possible to identify which faults are moving, as well as their direction, and accordingly, where permeability and potential geothermal resources are likely to be found.

Although fracture systems forming geothermal systems in Iceland are generally considered active, experience has shown that seismic activity in geothermal areas varies greatly. In general, seismic activity is higher in high-temperature than low-temperature areas, likely due to the interplay of various factors, including greater geological activity combined with high temperature and pressure, related to proximity to the active volcanic zones. Examples show that in some geothermal areas, seismic activity appears to be persistent, such as in Krafla (e.g., Gudnason et al., 2025) within the active Northern Volcanic Zone, while in other areas, outside the volcanic zones, such as the Eyjafjördur region, earthquakes usually occur only occasionally, or in swarms, with years or even decades between swarms. In some areas, seismic activity is virtually absent; one example is Laugaland in the Eyjafjördur valley (Axelsson et al., 2000; Gudnason et al., 2020), situated approximately 40-50 km west of the plate boundary and south of the Dalvík Lineament. It should be noted, however, that earthquakes in geothermal areas are usually very small, so-called microearthquakes, and most are therefore only detectable with precise instruments and dense monitoring networks.

The low-temperature geothermal systems in Eyjafjördur are located in dense bedrock where the upflow of geothermal water is characterised by localized convection, with water flow paths confined to near-vertical fractures formed by tectonic movements, often associated with dikes (Björnsson et al., 1990; Axelsson et al., 2005). The controlling factors for the existence of these systems are the temperature and stress conditions in the crust, in particular the regional tectonics and the resulting local stress field (Axelsson, 1985). The most productive systems in Eyjafjördur are indeed located in the western part of the fjord, where good permeability is believed to be related to ongoing tectonic activity and fracturing caused by earthquakes along the Tjörnes Fracture Zone, in particular the Dalvík Lineament (Flóvenz et al., 2000).

An active earthquake fault trending NNW-SSE, extending from the geothermal area in the southwestern part of the Hrísey island through Ytri-Hagi and to Hjalteyri, is believed to be the connection between seismic activity and the identified low-temperature geothermal areas in western Eyjafjördur. In this study, we show examples of recent seismic activity on both ends of this fault, i.e., north of Hrísey and at Hjalteyri. In both cases, seismicity occurs both occasionally and during swarms on strike-slip faults with a NW/NNW-trend, and more importantly, where dikes trending NE/NNE intersect the earthquake faults, i.e., at the intersection of these two fracture trends. The earthquake zones are thus so-called step-over zones between a dike system with a NE/NNE-trend and an open fracture system with a NW/NNW-trend (Blischke et al., 2023) – creating the local conditions needed to enhance and sustain permeability in the basaltic crust.

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