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Subsurface characterization of the southern fringes of the Hellisheidi and Hverahlíd geothermal systems: Deep slim-well exploration drilling campaign

Dario I. Di Rienzo[1*], Ásdís Benediktsdóttir[1], Bjarni R. Kristjánsson[1], Thráinn Fridriksson[1]
Reykjavík Energy, Bæjarháls 1, 110 Reykjavík, Iceland[1*]
Dario.Ingi.Di.Rienzo@orkuveitan.is[*]

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ABSTRACT

The Hellisheidi-Hverahlíd geothermal systems are situated within the Hengill central volcano in southwest Iceland. The fields have been extensively developed over the last two decades, feeding the Hellisheidi power plant that accounts for a generation capacity of 303 MWe and 210 MWth for district heating in Reykjavík, making it Europe's largest geothermal plant on a single site. Reykjavík Energy and ON Power's mandate for increased power production has set the focus for the next years on the exploration of the southern fringes of the producing fields, specifically the areas of Gráuhnúkar-Meitlar and Nordurhálsar. Surface exploration has been completed, and an updated 3D resistivity model shows several shallow low-resistivity anomalies extending further south from the currently producing geothermal reservoirs. No surface manifestations are present in the Meitlar area and could thus represent a relatively young, fully sealed and hidden system at depth. The Gráuhnúkar-Meitlar area shows resistivity anomalies following the NE-SW structural trend of the Western Volcanic Zone and the Nordurhálsar plateau shows a narrower N-S trending anomaly. Deep slim-wells (>1500mTD) will be drilled for the first time and although not intended for production, these wells will offer a cost-effective and less invasive means of acquiring subsurface data and will be strategically sited to test resistivity-temperature correlation. The goal is to provide valuable inputs for resource capacity estimates for future drilling strategies. Subsurface characterization through geological-geophysical logs, geochemical samples of geothermal fluids and well completion testing will play a pivotal role in supporting decision-making in sustainable field development by reducing uncertainty in resource delineation.

1 INTRODUCTION

The Hengill volcanic region in southwest Iceland encompasses vast geothermal resources. The region hosts three main geothermal systems that are currently utilized for power production, Hellisheidi, Hverahlíd and Nesjavellir, by ON Power a subsidiary of Reykjavík Energy. The Hellisheidi geothermal power plant located on the southern flanks of the Hengill volcano, is a combined heat and power plant with an installed capacity of 303 MWe, as well as a 210 MWth plant for district heating. The electrical generation is made of six 45 MWe high pressure and one 33 MWe low pressure turbine generators.

The Hellisheidi power plant utilizes two geothermal fields that are believed to be separate systems (Gunnarsson et al., 2021), shown in Fig. 1. The Hellisheidi field located on the southwestern side of Mt. Hengill, with the Skardsmýrarfjall, Reykjafell and Gráuhnúkar hyaloclastite ridges bounded by a prominent NE-SW oriented fissure swarm on either side. The Hverahlíd field is located a couple of kilometers further east on the edge of the Hellisheidi plateau by the Hverahlíd escarpment, bounding the basalt plateau in Nordurhálsar.

The systems are liquid-dominated fractured geothermal systems. Production is mainly concentrated where temperatures are highest in the NW part of Skardsmýrarfjall, the eruptive fissures from Reykjafell to Skardsmýrarfjall and in Hverahlíd. The enthalpy of individual wells ranges from 1100 kJ/kg to dry steam enthalpy of about 2700 kJ/kg in Hverahlíd (Kristjánsson et al., 2016). The average enthalpy of produced fluid was 1580 kJ/kg in 2024. The average mass production in the field is around 62 kg/s/km^2, which corresponds to a power density of 14 MWe/km^2 (Gunnarsson et al., 2021).

Gráuhnúkar and Húsmúli are the two main reinjection fields utilized in Hellisheidi, as shown in Fig. 1. The Gráuhnúkar reinjection field is located SW of the production field and consists of six reinjection wells, with an average injection capacity of 300 l/s. Very high temperatures (>300°C) were recorded at the end of drilling in the deeper parts of the wells, which makes the area a prospect for future production (Kristjánsson et al., 2016).

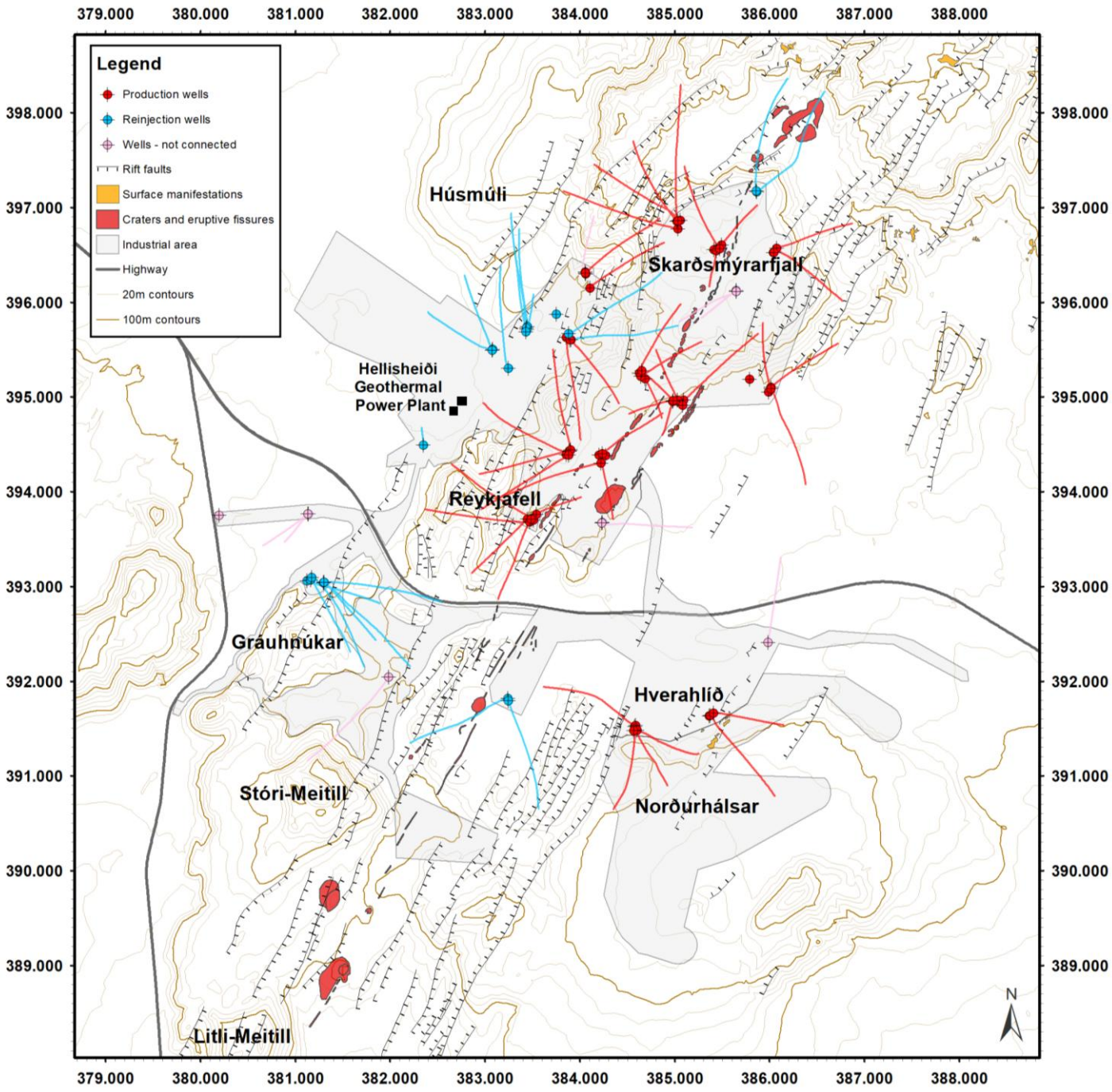


Figure 1. Regional map of Hellisheidi and Hverahlíd geothermal systems in the Hengill volcanic region.

2 GEOLOGICAL CONTEXT

The Hengill central volcano is located at a triple junction where two active volcanic rift zones, the divergent Western Volcanic Zone (WVZ) and the oblique Reykjanes Peninsula Rift (RPR), meet the South Iceland Seismic Zone (SISZ), a seismically active transform zone (Einarsson, 2008). The area has a pronounced fissure swarm with normal faults striking NE-NNE parallel to the WVZ. The fissure swarm is home to recent Holocene eruptions from 2,000, 5,800 and 10,000 years ago (Sæmundsson, 1995).These swarms are juxtaposed by several sets of strike-slip and oblique slip faults related to the interplay with the SISZ and the RPR along the triple junction, bringing in northernly and WNW striking dextral faults and ENE striking sinistral faults of the Riedel shear sets of conjugate fractures (Khodayar and Björnsson, 2008).

The bedrock of the geothermal systems consists mainly of basaltic lavas, hyaloclastites (tuffs, breccias and pillow lavas) and mainly basic intrusions (rarely acidic). The reservoir rock formations are heterogeneous with large variations in porosity and permeability. The porosity is high in hyaloclastites and lower in lavas and lowest

in intrusive dykes. Permeability is often secondary and fracture-controlled in lavas and intrusions, whereas it can be primary in horizontal dipping hyaloclastite formations.

3 CURRENT UNDERSTANDING OF THE SOUTHERN PART OF HELLISHEIDI AND HVERAHLÍD

This section will highlight the latest understanding of the southern fringes of the producing fields, specifically the areas of Gráuhnúkar-Meitlar and Nordurhálsar. This will be based on formation temperature from well data (shown in Fig. 2) and a newly developed 3D resistivity model from inversion of resistivity data (shown in Fig. 3).

3.1 Formation Temperature Model

3.1.1 Gráuhnúkar-Meitlar

The formation temperature in this area shown in Fig. 2 is based on five reinjection wells in Gráuhnúkar (HN-03, HN-05, HN-07, HN-08 and HN-10), one exploration well drilled towards Stóri-Meitill (HE-57) and another reinjection well further east (HE-55). The Gráuhnúkar reinjection site proved, at the time of drilling, to have much higher temperatures than anticipated (Helgadóttir et al., 2021). The wells directionally drilled towards the east encountered very high temperatures, the highest recorded in HN-05 centered at an upflow of 300°C at 1000m depth. Temperature, estimated by analyses of alteration minerals from drill cuttings, is lower than the measured formation temperature for HN-05 and HN-08. This suggests that the area in the center of reinjection has experienced recent heating. Further east, well HE-57 seems to be drilled along the easter boundary of the Gráuhnúkar upflow zone and shows a temperature reversal below 1500 m.b.s.l, whereas well HE-55 shows significant cooling when comparing alteration and actual formation temperature. This well was not feasible for production and has been utilized as an injection well. In well HE-55 this has been interpreted as cold water inflow within highly permeable volcanic fissures (Helgadóttir et al., 2021).

3.1.2 Nordurhálsar

The formation temperature in the Hverahlíd area is based on four production wells (HE-21, HE-36, HE-53, HE-54, and exploration well HE-26 to the north. The production wells encounter very high temperatures at shallow depths reaching 280-300°C at 550 m b.s.l., within a relatively narrow and highly productive part of the field. Enthalpies of these wells reach up to about 2700 kJ/kg with some wells producing fluids close to dry steam conditions. Only well HE-54 is directionally drilled beyond the ENE-trending Hverahlíd ridge and below the Nordurhálsar plateau at depth. Future slim-wells will help delineate the resource farther south toward the centre of the Nordurhálsar plateau.

3.2 3D MT Resistivity Model

A regional 3D resistivity MT model for the Hengill volcanic area was first published by Árnarson et al. (2010). In 2016 additional TEM/MT soundings pairs were acquired across the southern fissure swarms, resulting in new 3D resistivity models (Benediktsdóttir et al. 2021). These models show up-doming of the low-resistivity clay cap, outlining known and prospective geothermal systems. The bottom-of-clay (BOC) boundary (Fig. 3) marks the transition from the conductive clay cap, where smectites are dominant, to the resistive core at roughly 230°C, where epidote first forms. In locations where this boundary is closer to the surface, it is indicative of the presence of an active or fossil geothermal system at depth. Important is to note that the top of the clay clap is well determined but the BOC is less well resolved and should be interpreted carefully (Benediktsdóttir et al., 2021).

3.2.1 Gráuhnúkar-Meitlar

No surface manifestations are observed in Meitlar, suggesting a relatively young, sealed, and hidden geothermal system. The Gráuhnúkar–Meitlar anomaly follows the NE–SW structural trend of the Western Volcanic Zone (Fig. 3).

The Gráuhnúkar reinjection field lies southwest of the Reykjafell production area, on the western margin of the clay cap. Figure 4 shows a vertical cross-section through a 3D resistivity model across Gráuhnúkar. The injection wells extend, roughly, from west to east, entering the geothermal reservoir marked U4. Well data indicate that resistivity does not perfectly correspond with the current temperature regime, as formation temperature exceeds what is implied by alteration mineralogy, indicating a geothermal system that is heating up.

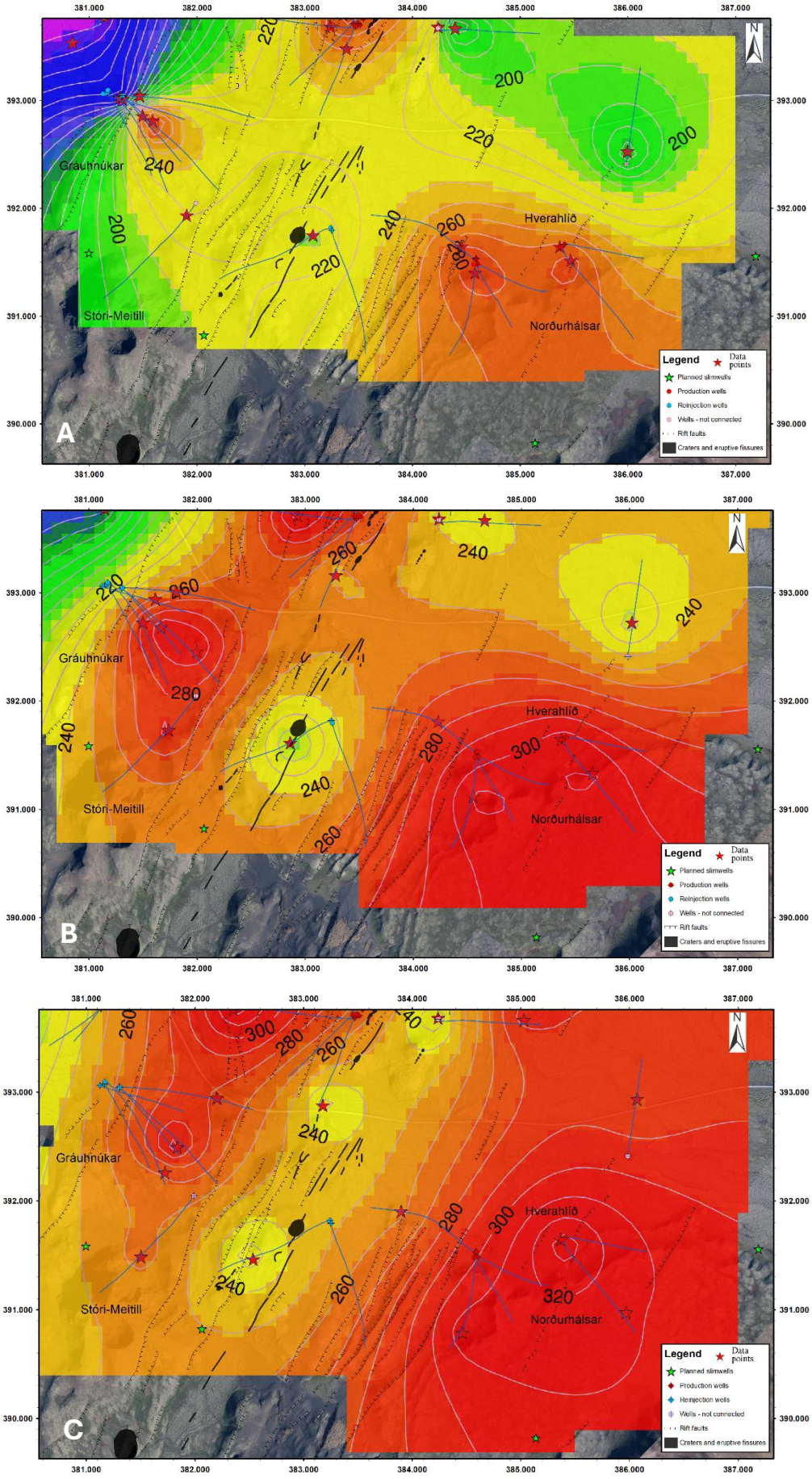


Figure 2. Formation temperature at 550m (A), 995m (B) and 1550m (C). Depths are below sea level.

The area between Stóri-Meitill and Litli-Meitill, often referred to as Meitlar (plural form of Meitill), has been considered as a separate geothermal system in literature due to its well-defined anomaly and shallow BOC values within a graben structure (e.g. Helgadóttir et al., 2021). However, the lack of surface manifestations may be indicative of a hidden geothermal system. Reinjection wells HE-55 and HE-18 do not intersect this sharp anomaly and raise the question whether the colder zone encountered in these wells extends further south. The northern edge of the Meitlar anomaly has a WNW trend aligning with mapped structures on surface.

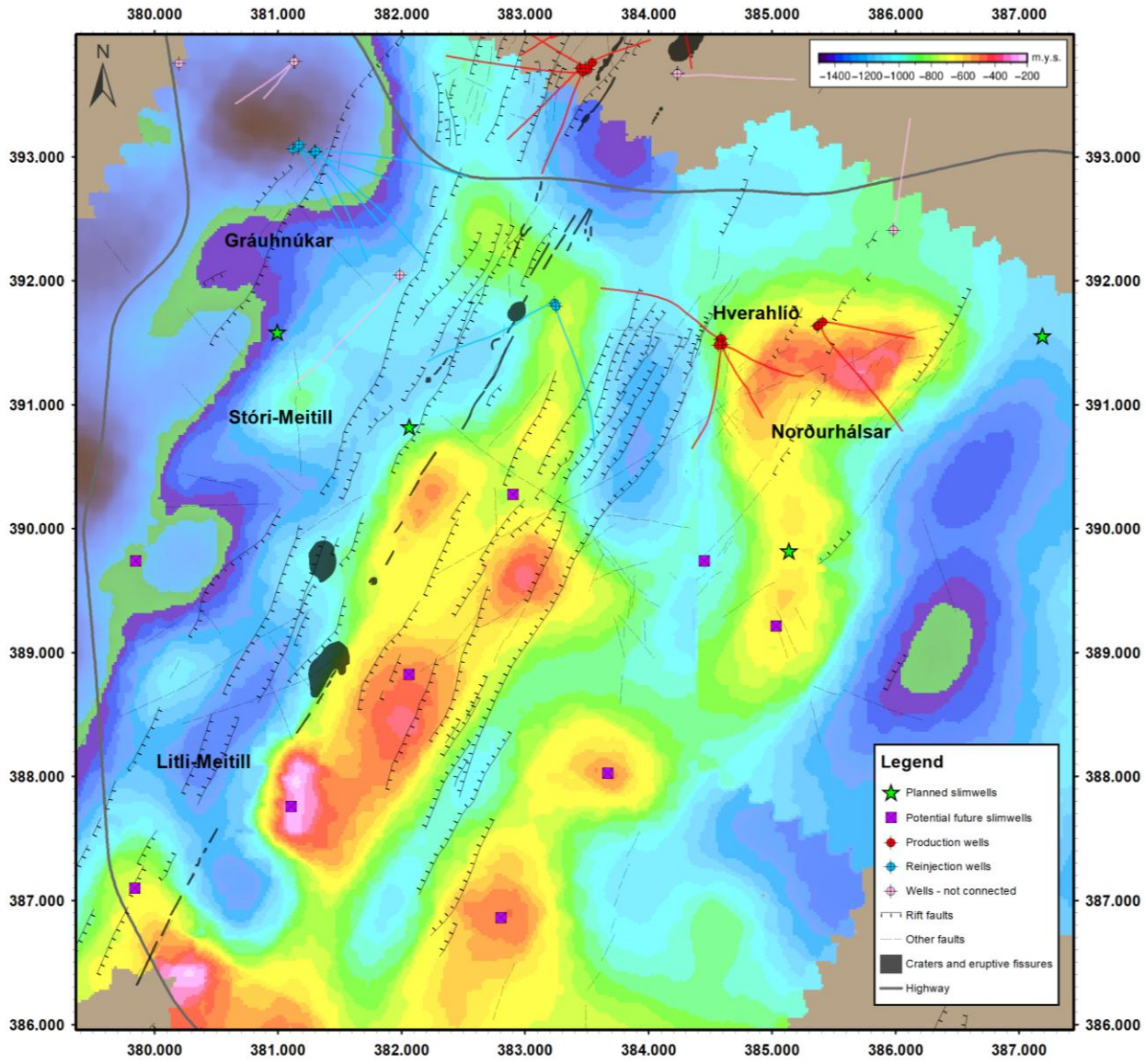


Figure 3. Bottom-of-clay (BOC) resistivity map from two 3D resistivity models by Bendiktsdóttir et al. (2021). Colour scale is meters below sea level. Planned and future slim-wells are displayed on the map, together with current wells, geological and geographic features.

3.2.2 Nordurhálsar

The Nordurhálsar plateau is part of an older basalt shield volcano overlain by the Skálafell hyaloclastites and the Trölladalur crater. The shallow resistivity anomaly in Hverahlíd is well constrained and is located where the rift trending normal faults intersect large ENE trending structures parallel to the edge of the Hverahlíd escarpment. The most powerful wells in Hverahlíd are drilled into the resistivity anomaly. To the west, formation temperatures and alteration minerals are in equilibrium, whereas farther east temperatures are higher than expected from mineralogy alone. The resistivity anomaly stretches south under Nordurhalsar and can be interpreted as an outflow zone from Hverahlíd or in alternative an indepenent upflow zone linked to hot intrusions below. The likely indication of the presence of intrusions is given by the Skálafell hyaloclasites and the Trölladalur crater just to the west. This hypothesis will be tested by drilling exploratory deep slim-wells in Nordurhálsar.

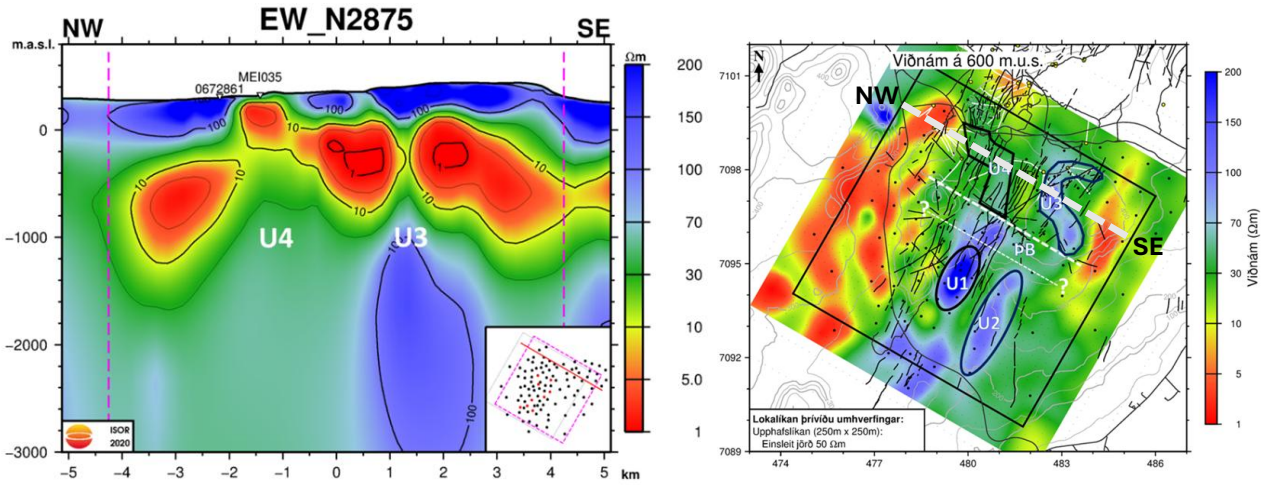


Figure 4. Three-dimensional resistivity model of the Meitlar area from Benediktsdóttir er al. (2021). Left: Vertical cross section through the model across Gráuhnúkar and towards western edge of Hverahlíd. Right: Depth slice through the model at 600 m b.s.l.; location of vertical cross-section shown as a thick white-dashed line.

4 DEEP SLIM-WELL EXPLORATION DRILLING CAMPAIGN

Reykjavík Energy and ON Power's mandate for increased power production has set the focus for the next years on the exploration of the southern fringes of the producing fields, specifically the areas of Gráuhnúkar-Meitlar for Hellisheidi and Nordurhálsar for Hverahlíd. Surface exploration has been completed, and the next phase will be conducting exploration test drilling via deep slim-wells.

Deep slim-wells have been widely used in the geothermal sector, especially in southeast Asia (e.g. Indonesia), United States, New Zealand and Central Latin America, for geothermal resource delineation in the early phases of resource exploration and development. Slim-wells can be more effective compared to conventional drilling in terms of reaching remote and difficult terrains, reducing the overall risk (cost) of failure in exploration drilling and improving probability of success of appraisal and production wells (Mackenzie et al., 2021). The expected cost savings are 3-4 times less than drilling a standard diameter well, so one can theoretically drill several slim-wells for the price of one larger well.

An ambitious test drilling campaign with a 100-ton hook load rig is programmed over the next three years, the first of its kind for Reykjavík Energy. Although not intended for production, the deep slim-wells will be strategically sited to test resistivity-temperature data correlation with the goal to provide valuable inputs for resource capacity estimates for future drilling strategies. The general design of the wells is a 13 3/8'' surface casing (0-70m), 9 5/8'' anchor casing (0-200m), 7'' production casing (0-650-800+m), 4 1/2'' slotted liner to ~1500mTD; and closed on the surface by ANSI Class 600 and 900 master valves. The wells aim to seal the clay cap and drill into the reservoir to confirm commercial temperature (primary objective) and test productivity (secondary objective).

Subsurface characterization will be through geological and geophysical well logs, geochemical samples of geothermal fluids and well completion testing, which will play a pivotal role in supporting decision-making in sustainable field development by reducing uncertainty in resource delineation.

The locations of planned wells are denoted as green stars in the Figures 2 and 3 in this paper. Based on formation temperature and resistivity models, the first planned wells in the Gráuhnúkar-Meitlar area are: one well in Gráuhnúkar, located in Stóri-Dalur valley further SW of the reinjection wells, and one well in Meitlar, directionally drilled into the first shallow resistivity anomaly at the northwestern extent (see Figs. 2-3). The first planned wells in the Hverahlíd-Nordurhalsar area are: one well in the middle of the Nordurhálsar resistivity anomaly, about 2km south of the current production wells; and one well further east of Hverahlíd (see Fig. 3), in order to test whether there has been any recent heating further east that might pose a difference between alteration mineralogy (and resistivity) and formation temperature, similarly to what is happening in Gráuhnúkar.

Once these wells are drilled and results processed, the current ideas for future drilling targets will be confirmed or revised. The exploration campaign is being carried out in phases, progressively moving further south as new

data are collected and interpreted. One potential next step is the prominent resistivity anomaly just east of Litli-Meitill, which appears to be a favorable target.

5 CONCLUSIONS

This paper presents an assessment of the current understanding of the southern part of the Hellisheidi (Gráuhnúkar-Meitlar) and Hverahlíd (Norduhálsar) geothermal systems in southwest Iceland, based on structural geology, subsurface temperature and resistivity models.

In Gráuhnkúkar-Meitlar, there are no surface manifestations present and the formation temperature from wells exceed what is implied by alteration mineralogy and resistivity models, indicating a relatively young, fully sealed geothermal system that is heating up. In Hverahlíd, there are visible surface manifestations, and the system is very productive with high reservoir enthalpies up to 2700 kJ/kg. The western part of the field has formation temperatures and alteration mineralogy in equilibrium, whereas farther east temperatures are higher than expected from mineralogy alone. The resistivity anomaly stretches further south under Nordurhálsar and can be interpreted either as an outflow zone or in alternative a secondary upflow zone linked to hot intrusions below.

To verify and update the conceptual model of these southern fringes, deep slim-wells (>1500mTD) will be drilled for the first time with the goal to produce valuable inputs for resource capacity estimates for future drilling strategies. A test drilling campaign is planned for the next years with four slim-wells currently scheduled to be drilled, two in each respective field, with additional potential targets already identified for future exploration. Subsurface characterization of well data will play a pivotal role in supporting decision-making in sustainable field development for possible future expansion in power production by reducing uncertainty in resource delineation.

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