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Well Siting in the Gráuhnúkar-Meitlar Field in the Hengill Area, SW-Iceland

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ABSTRACT

The reinjection site of Gráuhnúkar at the Hellisheiði high-temperature field in SW-Iceland proved, at the time of drilling, to have much higher temperature than anticipated. Despite the reinjection the area has, due to its anomalous temperatures, since been regarded as a potential production area for Reykjavík Energy along with the Meitlar area to the south. Interdisciplinary work on well siting commenced with gathering and comparing available data from the area. The dominating fractures in the area are the NE-SW striking fractures belonging to the Hengill fissure swarm. However, other fractures with different strikes have been noted in the landscape. Those fractures need further analyses. Resistivity model of the area has been made using a 3D inversion of static shift corrected MT measurements. The bottom of the low resistivity layer, where high resistivity is noted below, is believed to indicate the outlines of the geothermal system in Gráuhnúkar-Meitlar. The depth to the change of low restivity to high resistivity (25 Ωm was used here as a reference) seems to form a ridge, following a graben with a similar strike to the Hengill fissure swarm. In the northern part of the Gráuhnúkar-Meitlar area six reinjection wells and two exploration wells have been drilled. The formation temperature in the area is based on those wells. This leaves large unknown areas temperature wise, particularly in the Meitlar area to the south. Temperature in Gráuhnúkar is 260°C at 1000 m b.s. and is currently regarded as the hottest area. Comparison of the first appearance of certain alteration minerals in drill cuttings from the wells to the formation temperature indicates that the centre of the reinjection area has experienced recent upheating. The area to the east of Gráuhnúkar has, however, experienced cooling and is not feasible for production drilling. Comparison of available data suggests feasible targets to the east and northeast of mount Litli-Meitlar. It is, however, difficult to predict whether the resistivity model shows the current temperature regime or if the temperature of the system has changed. Drilling will reveal if the resistivity model corresponds with the current temperature.

1. INTRODUCTION

During drilling, the reinjection site of Gráuhnúkar in the southwestern part of the Hengill high temperature area in SW-Iceland, proved to have much higher temperature than anticipated. The area has, due to its anomalous temperatures, since been regarded as a potential production area for Reykjavík Energy, despite the reinjection. The evaluation of the geothermal system at Gráuhnúkar and the nearby Meitlar area was therefore requested by Reykjavík Energy in order to minimize the risk of well siting.

2. GEOLOGY OF THE AREA

The Hengill fissure swarm, which is 60-70 km long and 5-10 km wide, has a prominent NE-SW strike and extends from Þingvellir in the northeast towards just south of Litli-Meitill in the southwest. Prominent faults are rare southwest of Hengill although there are a few that can be traced for a considerable length, e.g. the Húsmúli fault which lies north of Sleggja to the southwest through Kolviðarhóll, Litla-Reykjafell and from there to Gráuhnúkar (Figure 1). Another prominent fault, with a throw to the east, is named after Búasteinn west of Þverfell mountain. It reaches south through Reykjafell towards Stóri-Meitill and has a 40 m throw to the east at surface. The third prominent fault is at the top of Hellisskarð whereby it holds its name (Sæmundsson and Friðleifsson, 2004). This fault has no less than 40 m throw to the west at surface. These faults make up the edges of a rather narrow graben, the Reykjafell graben. Results from borehole studies suggest that the throw of the graben is even more than 40 m at depth (Harðarson and Kristinsson, 2012).

The bedrock in the Gráuhnúkar area consists mostly of hyaloclastite rocks, including pillow lava. Some of it is overlain by dolerite of which the largest volume sits between the two Meitill mountains (Millimeitlastapi). Gráuhnúkar is the oldest one, heavily eroded and in part covered by glacial sediments. Among the oldest formations are pillow lavas in Lakahnúkar also appearing in a ridge north of Stóri-Meitill mountain. Hyaloclastite with a dolerite hat on top of both of the Meitill mountains are the youngest formations. Stakihnúkur, west of Stóri-Meitill, as well as a ridge running northeast along the eastern slopes of Gráuhnúkar, is made of picrite. Picrite is rather common in the Reykjanes peninsula and is found in a few places in the Hengill volcanic system (Sæmundsson, 2010).

Five eruptions are known to have occurred in the Hengill volcanic system of which three occur in the Gráuhnúkar area. In addition, there are two lavas from the Brennisteinsfjöll-Bláfjöll volcanic system at the western edge of the area. The oldest Hellisheiði-lava is around 10.000 years old and occurs in two places along the westernmost fault edge of the Lakahnúkar formation. Craters, belonging to the same lava field, are seen 500 m to the southwest. Two patches of a 5700 year old lava can be seen between Stóri-Meitill and the hills of Hveradalir. The youngest Hellisheiði lava field is around 2000 years old and lies against the Gráuhnúkar area to the east and north but also to the west, where a section of the Svínahraun lava has partly covered it.

Apart from the dominating NE-SW striking fractures other indications of fractures and faults in the landscape have been noted (Harðarson and Kristinsson, 2012; Ágústsson, 1998). These are marked as red dashed lines in Figure 1. These need further analyses as well as field studies to confirm them as real tectonic features.

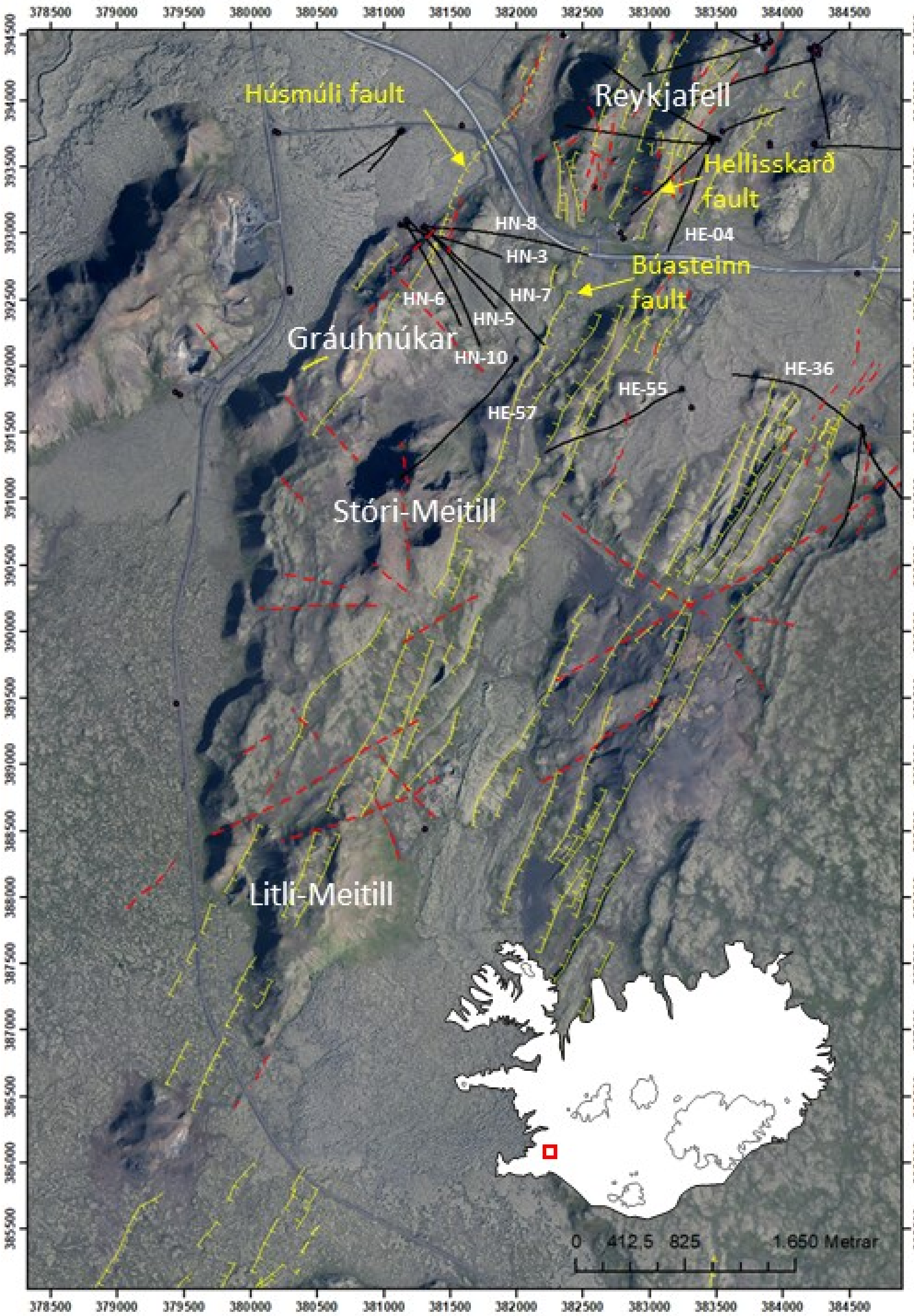

Figure 1: Aerial photographs suggest that fractures in the area may be more variable than the main NNE-SSW strike of the fissure swarm of the Hengill central volcano. Yellow lines show the governing fractures of the fissure swarm from geological maps and revisions (Sæmundsson, 1995; Sæmundsson and Friðleifsson, 2004; Sæmundsson et al., 1990) and the red lines show possible fractures interpreted from aerial photos.

3. RESISTIVITY MODEL

Resistivity model of the area has been made using a 3D interpretation of MT measurements, corrected for static shift using TEM measurements. The bottom of the low resistivity layer, where high resistivity is noted below, is believed to show the outlines of the geothermal system in Gráuhnúkar-Meitlar and the boundary was therefore mapped (Figure 2). The geometry of the boundary forms a ridge which follows a graben east with NNE-SSW strike, similar to the Hengill fissure swarm. It is most prominent east of mounts Stóri-Meitill and Litli-Meitill. In the northernmost part of the area the "ridge" seems to shift towards the NW, still following a similar strike. There are slight indications of a N-S trend, similar to the fracture trend of the South Iceland Seismic Zone (SISZ), as well as a hint of a NW-SE trend just southeast of Stóri-Meitill.

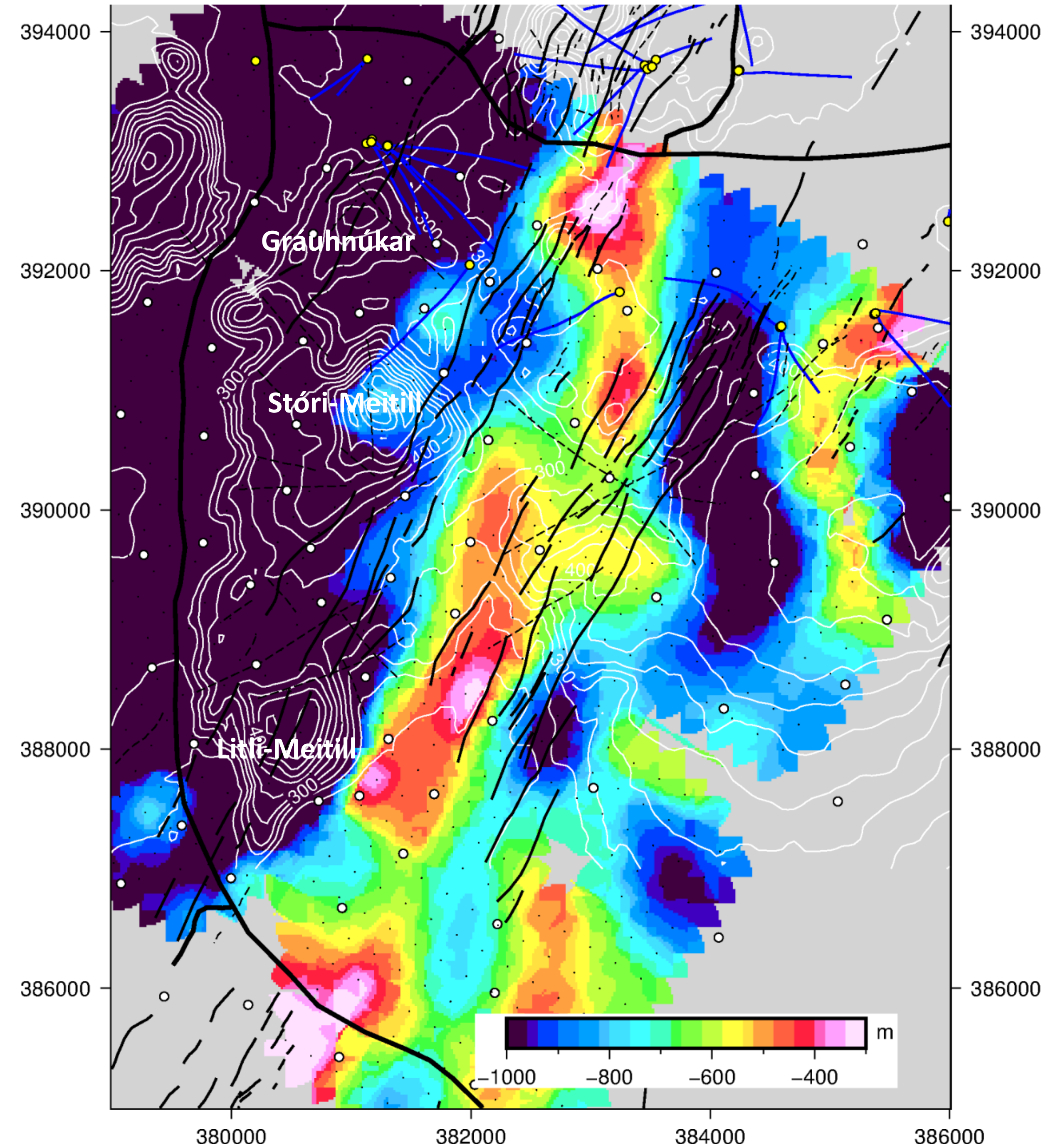

Figure 2: Depth to the bottom of the upper low resistivity layer based on resistivity measurements. Wells are shown with blue lines, black solid lines show the governing fractures of the fissure swarm from geological maps and revisions (Sæmundsson, 1995; Sæmundsson and Friðleifsson, 2004; Sæmundsson et al., 1990) and the black dotted lines show possible fractures interpreted from aerial photos.

4. WELLS AND TEMPERATURE

Six reinjection wells have been drilled in the Gráuhnúkar area, in the northwestern part of the are Gráuhnúkar-Meitill area. These are HN-3, HN-4, HN-5, HN-6, HN-7, HN-8 and HN-10 (Figure 1). In addition, two exploration wells have been drilled just east of Gráuhnúkar, HE-57 and HE-55. Figure 3 shows the expected formation temperature in the area at 500 and 1000 m depth b.s. (Gunnar Gunnarsson, personal communication). At around 1000 m b.s. the temperature is 260°C in Gráuhnúkar. The wells southeast of Gráuhnúkar, however, have lower temperatures. Well HE-57 is drilled to the southwest beneath mount Stóri-Meitill and shows lower temperature than the reinjection wells although it may possibly be used for production. On the other hand, well HE-55, which is located east of HE-57, does not have temperature high enough for electricity production.

No chemical samples from the reinjection wells in Gráuhnúkar exist as they were never tested. This is also the case with HE-55. The quartz geothermometer points to a temperature of 275°C in well HE-57 and the Na/K geothermometer gives 265°C. Generally, there is a better concordance between measured temperature at the main feed zones of wells in Hellisheiði and the quartz geothermometer rather than the Na/K geothermometer.

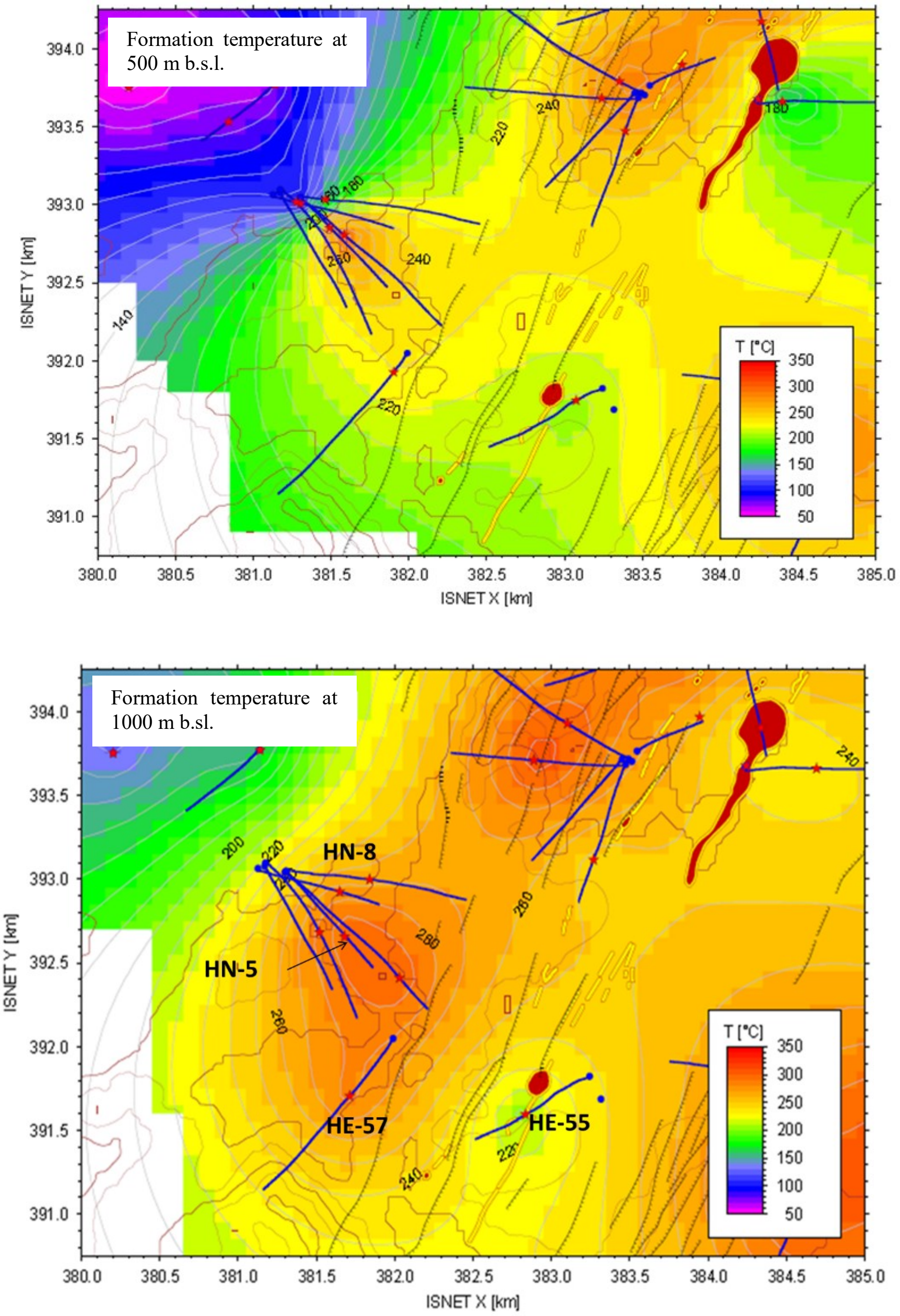

Figure 3: Formation temperature in the Gráuhnúkar area at 500 m b.s. (upper) and 1000 m b.s. (lower) (Gunnarsson, personal communication).

In Figure 4 the formation temperature of four wells in the area is compared with the alteration temperature. The alteration temperature is estimated using the first appearance of temperature dependent alteration minerals in drill cuttings from the wells. The northernmost reinjection wells in Gráuhnúkar (HN-8 and HN-3) seem to have a similar or just a little bit lower alteration temperature than formation temperature (Helgadóttir, 2011a; 2012). A little bit further to the south (HN-5 and HN-7) the alteration temperature is lower than the formation temperature (Helgadóttir, 2011a; 2012). The southernmost wells (HN-6 and HN-10) show similar temperatures for the most part, except for the middle part of the wells where alteration temperature is lower than the formation temperature (Helgadóttir, 2011b). The temperature data suggest that the centre of the Gráuhnúkar area, where wells HN-5 and HN-7 are drilled, has not yet adjusted to the current formation temperature and other parts of the system are in equilibrium.

Formation temperature in well HE-57 is lower than the alteration temperature below 1200 m measured depth (Snæbjörnsdóttir et al., unpublished report). Well HE-55, east of HE-57, shows an alteration temperature that is considerably higher than the current formation temperature. The alteration temperature in HE-55 is based on preliminary data that have not been analysed as thoroughly as the other wells (Guðfinnsson et al., 2010a; 2010b). The data does, nevertheless, indicate that this part of the system has cooled significantly since the height of geothermal activity. Temperatures in wells HE-04 and HE-36 are shown in Figure 5, as examples from the northern and northeastern margin of the Gráuhnúkar-Meitill area. Both wells show reversal in temperature although well HE-36 is nevertheless quite hot (280°C at bottom). Alteration temperature in HE-36 is lower than the formation temperature at a depth of 800 to 1350 m MD. Below 1350 m the formation temperature is lower than the alteration temperature, suggesting that cooling occurs when the well reaches the eastern margin of the Hengill fissure swarm (Níelsson, 2011).

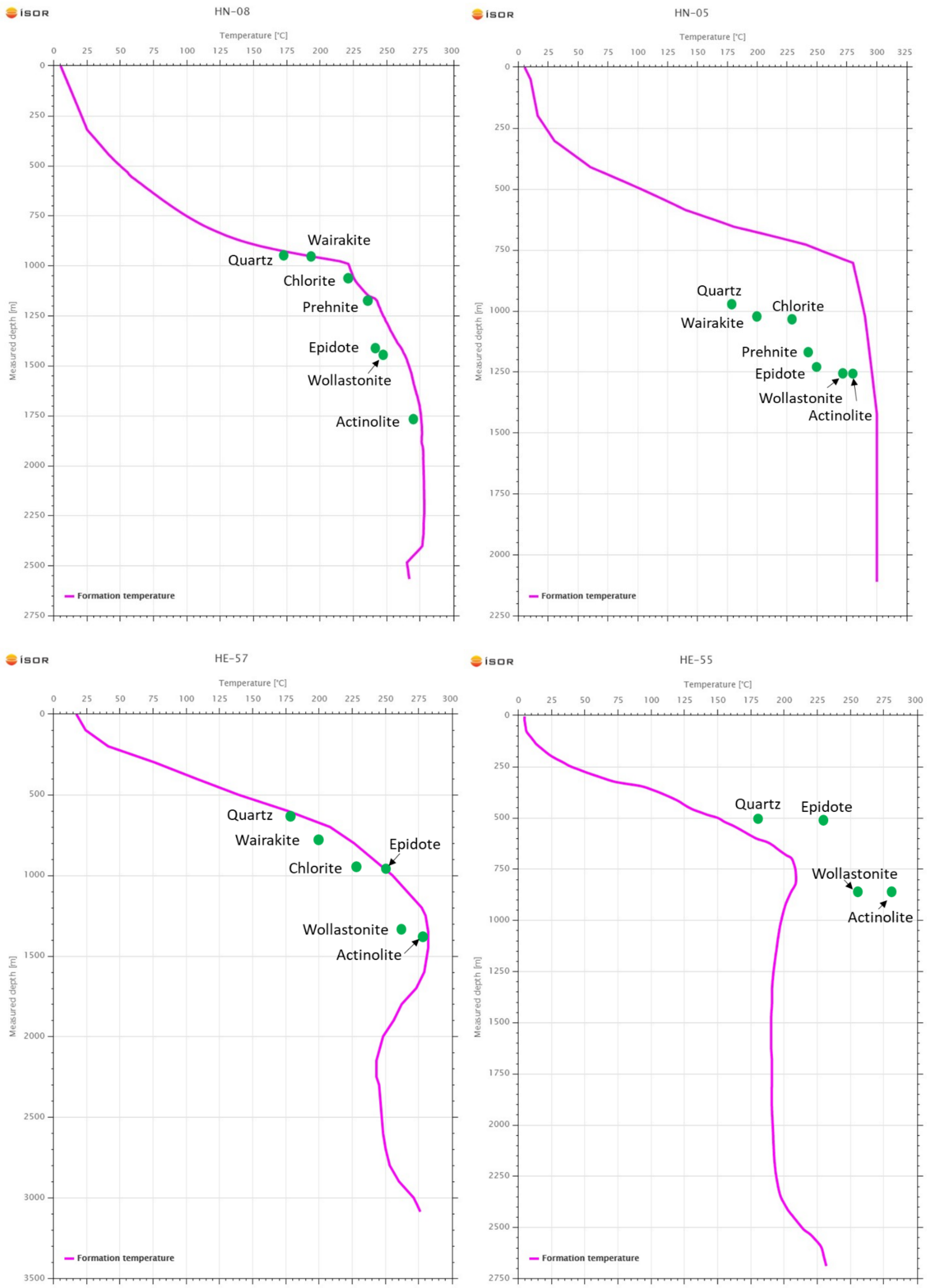

Figure 4. Formation temperature (pink line) compared to alteration temperature (green dots) in wells HN-8, HN-5, HE-57 and HE-55 (top left to bottom right).

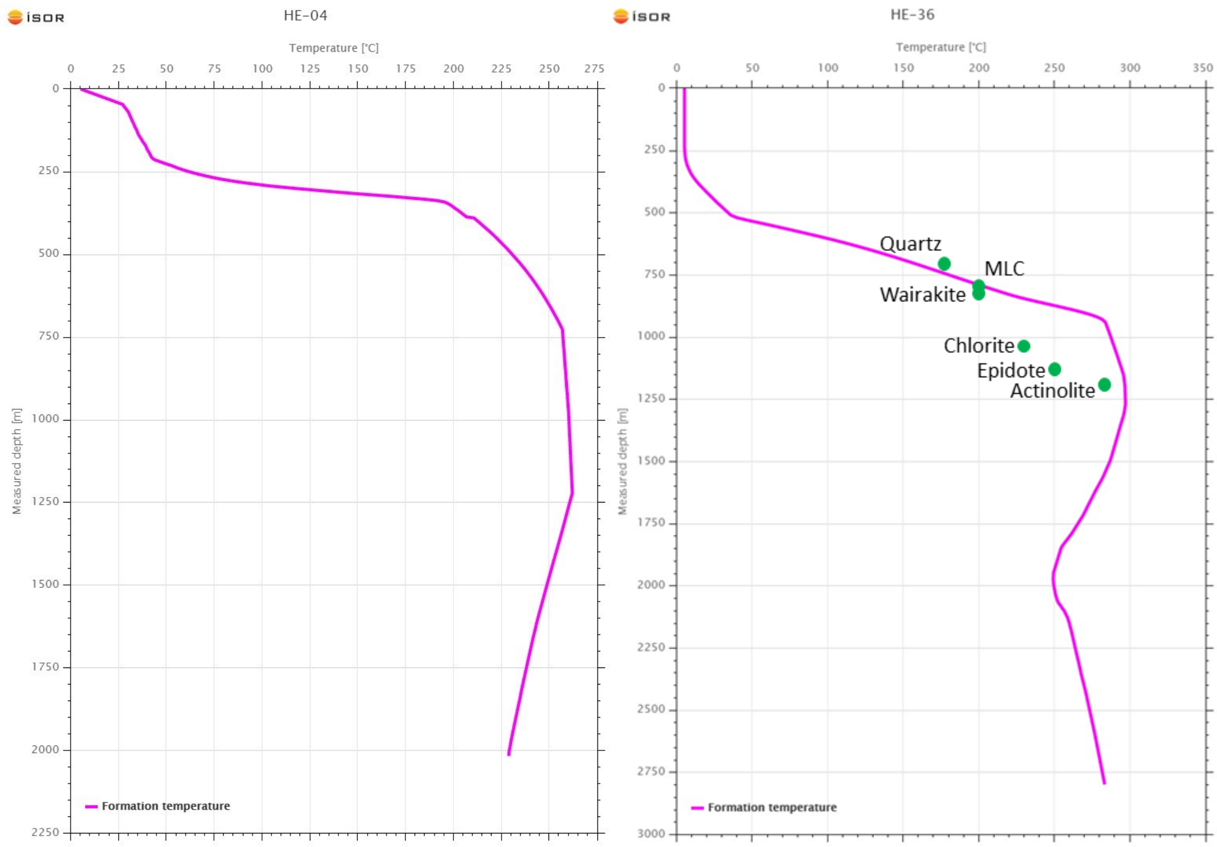

Figure 5. Formation temperature in HE-04 (to the left) and HE-36 (to the right, with alteration temperature).

5. DISCUSSION

Formation temperature in the Gráuhnúkar area, currently used for reinjection, suggests that the area is a promising production area. Comparison between the formation temperature and alteration temperature in wells that have already been drilled indicates that the upheating of the Gráuhnúkar area may be "recent". The temperature data just to the east of Gráuhnúkar indicate, however, that the temperature is not high enough for electricity production and alteration minerals in well HE-55 suggest that major cooling has occurred. Furthermore, there are signs of reversal in temperature in the northern part of the graben seemingly followed by the main "ridge" of the resistivity model, evidenced by well HE-36. It is not certain whether this is also true in the southern part of the graben, east and northeast of mount Litli-Meitill. There seem to be changes in the resistivity south of the NW-SE possible fracture just east of Stóri-Meitill (Figure 6).

The volcanic fissures (2000 and 5700 years of age) have been associated with cooling in the past. Wells HE-55 and HE-04 both go through the volcanic fissures (Figure 6) and have both revealed rather low temperatures. The bottom of well HE-04 reaches towards the shallowest part of the bottom of the low resistivity layer in the area. Furthermore, despite the high temperatures in the reinjection wells in Gráuhnúkar the bottom of the low resistivity layer is quite deep in that area. This suggests that the resistivity model in the northern part of the Gráuhnúkar-Meitlar area may not represent the current temperature regime.

6. CONCLUSION

Further work is preferable to improve the data used for well siting. Field work as well as careful studying of aerial photos is needed to analyse the nature of fractures in the area. In the end drilling will confirm the existence of an active producible geothermal system.

The area to the east and northeast of Litli-Meitill is regarded as a potential site for high temperature drilling. Figure 6 shows the Gráuhnúkar-Meitlar aerial photo with the fractures already discussed along with the resistivity model as well as the volcanic fissures. The comparing of the data has suggested two feasible targets for exploration drilling although further studies are recommended. These suggestions are also presented in Figure 6. The most feasible targets are, at this time, considered to be in the southern part of the area where the bottom of the low resistivity layer is closest to the surface and where fractures are expected to be penetrated (dark red circle in Figure 6). From an exploration point of view of it would be interesting to drill towards the area southeast of mount Stóri-Meitill where there seems to be a NW-SE trend in the resistivity "ridge" (blue circle in Figure 6). The high temperatures in the reinjection wells in Gráuhnúkar certainly suggest that the margins of the resistivity "ridges" in the area may be feasible drilling targets. It is not considered feasible to drill just east of Gráuhnúkar towards the northernmost area where the bottom of low resistivity is shallow because of the evidence of cooling. The volcanic fissures in the area should be avoided. Available data from drill holes suggest that the resistivity model may not correspond with the current temperature regime of the northern part of the Gráuhnúkar-Meitill area. The validity of the model in the southern part cannot be confirmed without drilling.

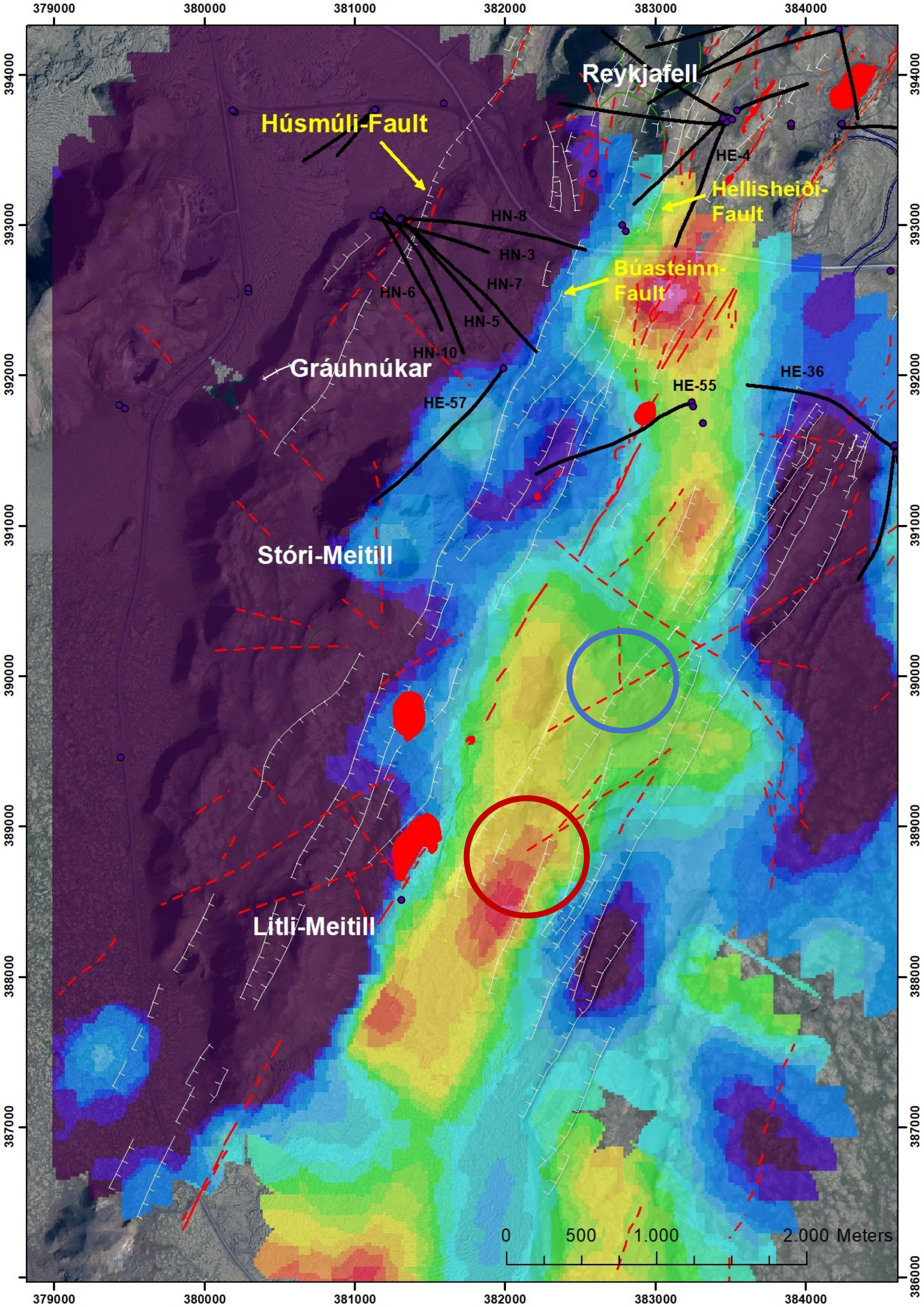

Figure 6. The resistivity data from Figure 2 on top of an aerial photograph of the Gráuhnúkar-Meitlar area along with fractures from Figure 1. Volcanic fissures and craters are marked with red. Suggested drilling target no. 1 is marked with a red circle and drilling target no. 2 is marked with a blue circle.

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