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Exploration Drilling in the Theistareykir High-Temperature Field, NE-Iceland: Stratigraphy, Alteration and Its Relationship to Temperature Structure

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ABSTRACT

The Theistareykir high temperature geothermal area is located some 25 km north of Lake Mývatn in North-East Iceland. This remote geothermal area has been the subject of surface exploration off and on for almost 40 years with the utilization of geothermal energy for electricity production as a long term goal.

Exploration drilling started in 2002 with the completion of well ThG-01, a vertical well reaching 1953 m below the surface. Since then 5 more wells have been completed including three wells using directional drilling. In addition one production section was abandoned and a new production section drilled from wellhead ThG-5, providing data from a total of 7 transects in the potential production zone.

In the top ~1 km the stratigraphy is characterized by sub glacial eruption products. These hyaloclastites are typically formed of pillow basalts, breccias and tuffs. The hyaloclastites are emplaced upon a succession of basalt-flows separated by relatively thick breccias and tuffs. The pile is sporadically cut by thin basaltic dikes. Alteration of the bedrock is extensive and minerals indicating high temperatures are found high up in the stratigraphic column. A narrow zone of overpressure is encountered in some wells between ~100 m and ~300 m depth.

Bedrock temperatures are among the highest recorded thus far in Iceland and the chemistry of the fluid is amenable to electrical production.

1. INTRODUCTION

The Theistareykir geothermal field is located in the north central highlands of Iceland (Figure 1). It takes its name from the locality where surface expressions of geothermal activity are most prominent (reykir = smoky). There, an abandoned farm site is nestled under the hyalocastite mound Bæjarfjall (Homestead-mountain) and partially sheltered to the east by the hyaloclastite ridge Ketilfjall (Kettle-mountain). The abandoned farm-stead is adjacent to a field of boiling mud-pools, fumaroles and gas-seeps. Farming in the area was abandoned near the end of the 19^{th} century.

The Theistareykir volcanic system stretches from Mývatn in the southwest to Öxarfjördur in the north (Figure 2). Volcanic productivity has been greatest near the center of the system where siliceous rocks are found, but a true caldera structure has not developed. The surface expression of the geothermal activity is located near eastern edge of the system while siliceous rocks are exposed near the western edge of the system (e.g. Mælifell).

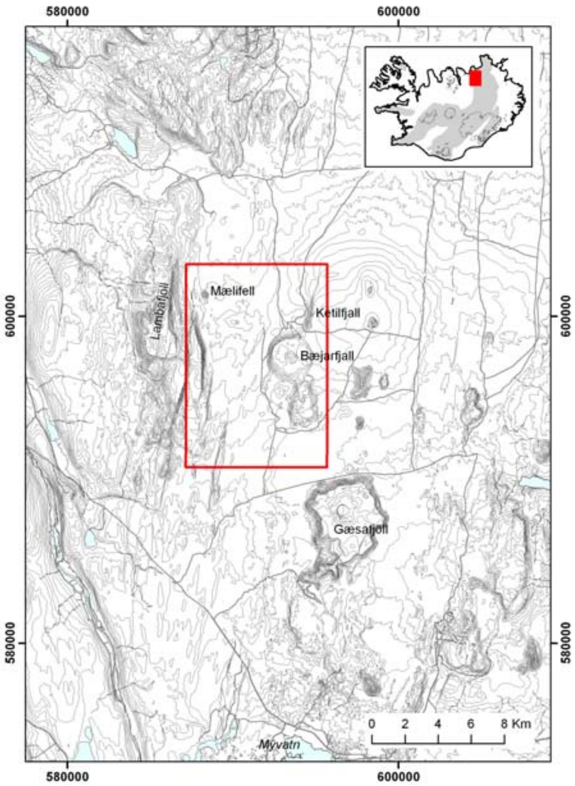

Figure 1: Map showing the location of the Theistareykir high-temperature field on the western periphery of the Northern volcanic zone in Iceland.

Volcanic activity in the area has been sparse in the last 10 ky. Most of the large lava flows in the area are form the end quaternary period. However in spite of the apparent lack of volcanic activity, it is still thought that relatively recent intrusive activity is dominant heat source for the geothermal system.

This paper presents a brief summary of the first stage of exploration drilling in the area. It draws on data and observations from the drilling reports by: Blishcke et al. (2007); Guðmundsson et al. (2002, 2004); Richter et al. (2007); Þórarinsson et al. (2006) and also from a collaborative effort resulting in a conceptual model for the Theistareykir field (Guðmundsson et al., 2008). After a very brief summary of the surface exploration in the area the drilling phase is discussed briefly. It is followed by a summary of the stratigraphy and alteration of the volcanic pile as observed to date. Finally some general conclusions are drawn.

2. SURFACE EXPLORATION

Surface exploration started in the nineteen-seventies and continued intermittently to the mid nineteen-eighties

(Gislason et al., 1984). In the late nineteen-nineties interest in the field increased again and the first deep exploratory well was drilled in the summer of 2002 (Table 1). Concomitant with exploratory drilling additional field surveys were undertaken including TEM (Karlsdóttir et al., 2006) and MT (Yu et al., 2008) resistivity surveys (Guðmundsson et al., 2008). In addition geological mapping in greater detail led to a much improved understanding of the age relationships of late quaternary and recent formations (Sæmundsson, 2007).

Mapping of fumaroles, mud-pools and gas-seeps and monitoring of gas and fluids in terms of abundances and isotopic constitution has been an ongoing effort for the last three to four decades (e.g. Ármannsson et al., 2000; Ármannsson, 2004; and Darling and Armannsson, 1989). On the basis of the chemical and isotopic data the geothermal field was subdivided in to five distinct subfields of which three were considered suitable for exploitation. The oxygen and hydrogen isotopic composition of steam condensates suggested that the fluid is recharged from further inland with a contribution from local precipitation (Darling and Armannsson, 1989).

3. DRILLING

Prior to drilling the deep exploration wells a number of shallow wells were drilled to obtain information on groundwater flow and to find a suitable source of cold water for drilling the deep (~2 km) exploration wells. To date a total of 8 such wells have been drilled. They are typically 100 m to 200 m deep. In addition to these a medium range exploration coring well (ThK-7), was drilled in 2007 (Table 1).

The first six deep wells have been aimed at exploring the deep temperature structure of the field, identifying producing zones and determining the composition of the hydrothermal fluid. In addition the goal is to map the subsurface stratigraphy and alteration of the volcanic successions and if possible relate the findings to the results of surface exploration campaigns. In this manner an integrated conceptual model of the field may be built.

The drilling of the wells has a times been a very trying endeavor. The first platform, from which three wells (1, 4 and 5) have been drilled, is located in an area of over pressure at relatively shallow depths (< 300 m). ThG-1 and ThG-4 were particularly difficult. In both wells over-pressured aquifers at roughly 200 m depth proved very difficult to handle.

Well ThG-5 however did not intersect over-pressured aquifers in the top 300 m possibly because they had been sealed by repeated cement jobs in wells 1 and 4 from the same platform. Well ThG-3 also displayed signs of over pressure but it proved fairly straightforward to handle. These difficulties were reflected in the number of days it took to complete the wells (Table 1).

Table 1: Exploration wells in Theistareykir, year of completion (YOC) is given along with days to complete (DTC), measured depth (MD) and true vertical depth (TVD) in meters.

Well	YOC	DTC	MD (m)	TVD (m)
ThG-1	2002	75	1953	1953
ThG-2	2003	74	1723	1723
ThG-3	2004	55	2659	2659
ThG-4	2004	53	2240	~1895
ThG-5a	2007	39	1910	~1640
ThG-5b	2008	54	2499	~2390
ThG-6	2008	53	2798	~2460
ThK-7	2007	31	458	458

3.1 Vertical Wells

The first three wells are all vertical wells. The casing program is of each well is quite typical for geothermal wells in Iceland (Table 2). The surface casing is 18 ⅝" and the section is drilled with a 22" bit. The anchor casing is typically 13 ⅜" and the section is drilled with a 17 ½" bit. The production casing section is drilled with a 12 ¼" bit and cased with a 9 ⅝"casing. Finally the production section is drilled with a 8 ½" bit and lined with a 7" liner.

Figure 2: Oblique photograph of the Theistareykir area looking south towards Bæjarfjall. Bæjarfjall is the prominent circular mountain close to the center of the photograph. The hyaloclastite ridge Ketilfjall is a N-S trending ridge extending northwards (towards the reader) from Bæjarfjall. Kvíhólafjöll are directly south of and adjacent to Bæjarfjall. On the right hand side (West) is the most recent lava (Theistareykjahraun) flow (dark) in the area and further west Lambafjöll, a prominent hyaloclastite ridge, may be seen.

Table 2: Typical casing plan and casing depths, as built (AB), for three vertical exploration wells in Theistareykir. Depths in meters relative to surface.

	Well	ThG-1	ThG-2	ThG-3
Casing	Casing plan	AB	AB	AB
Surface	50-100	69	109	74
Anchor	250-300	195	280	256
Production	600-800	617	617	756
Liner	1600-2400	1953	1723	2639

3.2 Inclined Wells

Wells ThG-4, ThG-5 and ThG-6 have been directionally drilled. The casing plans for the directionally drilled wells called for production sections that deviate about 30° from the vertical. Track b in well ThG-5, however, aimed for a 20° deviation from the vertical. Kick-off points are typically near the end of the anchor casing and the rate of build up is kept below about 2°/30 m, so that build up is completed near the end of the production casing.

4. STRUCTURE OF THE FIELD

4.1 Geology

The regional geology has been described in detail by Sæmundsson (2007) who added to, and expanded on, the work of Torfason (Gíslason, et al., 1984). The local geology is summarized in Figure 3 (from Sæmundsson, 2007). The oldest hyaloclastite formations in the region are exposed in the west in Lambafjöll (Figures. 1, 2 and 3). In the vicinity of the geothermal center at Theistareykir, Ketilfjall is the oldest hyaloclastite formation. It formed in a fissure eruption underneath the Quaternary ice-sheet on a 4 km long fissure. Bæjarfjall and Kvíhólafjöll are younger tuyas or table-mountains formed by eruptions on short fissures or single volcanic vents.

The highland between the hyaloclastite mounds and ridges are covered by basaltic lava-flows. The flows in the area are surprisingly old in that only one of flows considered to be less than 10 ky old. This is Theistareykjahraun which is considered to be a ~2500 years old (Sæmundsson, 2007). The lava flows have partially buried the sub-glacial table-mountains and ridges so their “roots” are hidden (Figure 2).

Table 3: First occurrence (elevation m.a.s.l.) of selected index minerals in drill cuttings from the wells in Theistareykir. Elevation of well head (m.a.s.l.) is given in parentheses under the well-number. Minerals were identified in cuttings using the binocular microscope, except for amphibole in ThG-1, identified in thin section.

ThG-	1	2	3	4	5	6
(masl)	*(352)*	*(330)*	*(400)*	*(352)*	*(352)*	*(400)*
Quartz	304	152	326	268	232	330
Wairak	158	144	306	192	202	186
Prehnite	134	110	194	140	106	-163
Epidote	90	-	58	122	94	-180
Wollast	-376	-	-412	-418	-443	-421
Amphib	-838	-	-1326	-614	-590	-902

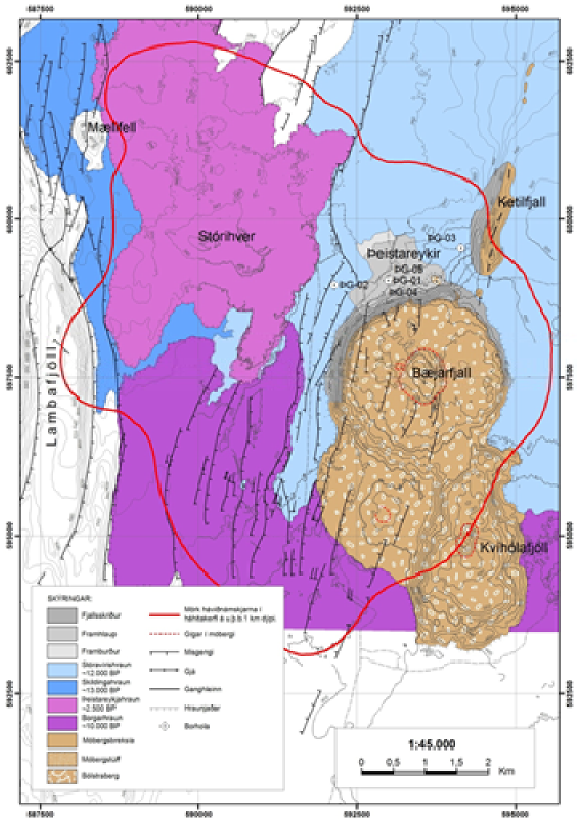

Figure 3: Geological map of the Theistareykir area. Red line encompasses the high resistivity core at ~1 km depth. It presumably delineates the alteration associated with the system. Oldest hyaloclastites, Lambafjöll (not colored) younger hyaloclastites in brown colors. Younger lava flows in blues and purple including Theistareykjahraun light purple (Sæmundsson, 2007).

The absence of younger volcanic products is intriguing when considering potential heat sources for the geothermal activity. Presumably intrusions at depth are providing the heat to drive the hydrothermal system (Sæmundsson, 2007).

4.2 Stratigraphy

The following description provides a simplified stratigraphy based on analysis of drill-cuttings and well–logging from the six exploratory wells that have been drilled thus far. In addition to these wells several shallow wells were drilled to obtain cold water for drilling the deeper exploratory wells and a medium range well was drilled in the western part of the area to obtain core.

Two of the drilling platforms and thereby five of the wells are situated adjacent to the hyaloclastite mounds. The top 1 km in these wells is characterized by sub-glacial rock formations namely pillow-basalts, breccias and tuffs. The uppermost section is characterized by breccias and tuffs that are often very well altered particularly below ~100 m depth. Further down the pile is made up of alternating pillow basalts breccias and tuffs. These hyaloclastites are typical sub-glacial eruption products.

The hyaloclastite sequence is emplaced upon a sequence of basaltic lavas intercalated with relatively thick tuffs and breccias. The pile is cut by relatively fresh basaltic dikes. These are believed to be vertical or sub-vertical intrusions. The abundance of intrusive rocks increases with increasing depth. However the proportion of intrusive rocks in the column is low compared to other geothermal areas such as Krafla.

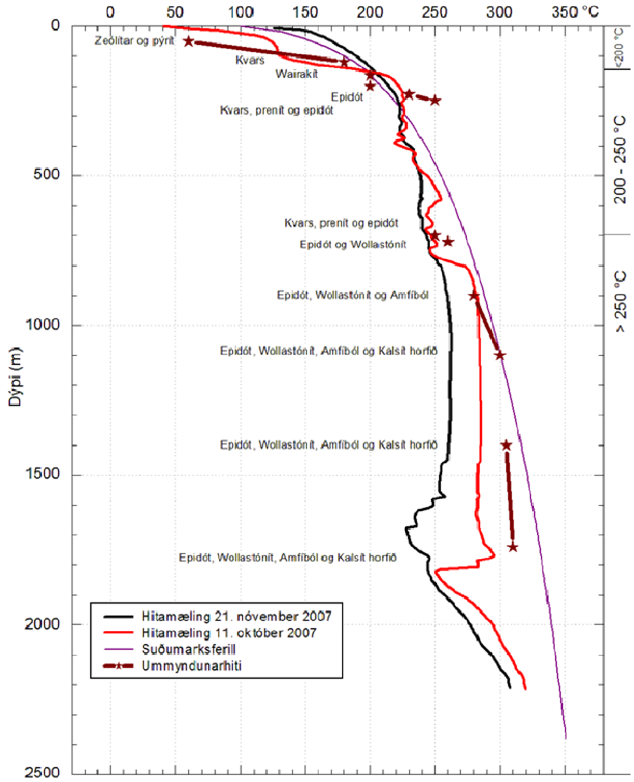

Figure 4: Relationship between measured temperature (black and red curves) and model temperature based on index minerals (stars) in well ThG-4. Boiling point curve (pink) show for reference. On the far right are shown temperature intervals based on clay minerals as identified by XRD (see also Figure 5).

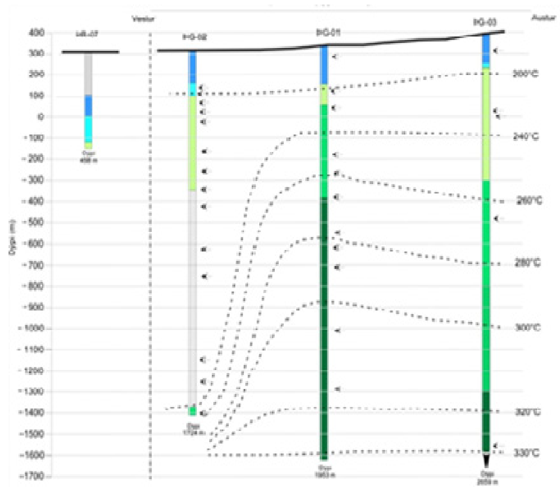

Figure 5: Graphical presentation of model bedrock temperatures from analysis of secondary minerals and temperatures from well logging. Grey are fresh rocks, blue is the smectite-zeolite zone (< 200°C), light blue is mixed layered clays (200-230°C), light green is th chlorite zone (230-250°C), green is chlorite-epidote (250-280°C) and dark green is the epidote-actinolite zone (>280°C) (from Guðmundsson et al., 2008).

4.3 Alteration and Temperature

Alteration of the bedrock is extensive and minerals indicating high temperatures are found high up in the stratigraphic column (Table 3). A narrow zone of over pressure is encountered in some wells between ~100 m and ~300 m depth. The first occurrence of selected index minerals in the deep exploration wells is presented as elevation relative to sea-level in Table 3. The elevation of the respective well-heads is also given.

Using well ThG-4 as an example of the wells immediately north of Bæjarfjall (Table 1 and Figure 4) it is apparent that the temperature suggested by the alteration minerals agrees reasonably well with the bedrock temperature estimated form temperature logs. In addition temperatures in the depth range exceed the boiling point curve providing an explanation for the overpressure encountered in this depth range in wells ThG-1 and ThG-4.

Selected samples from the wells have been subjected to XRD analysis to differentiate between different types of clays. Results for three vertical wells are shown graphically in Figure 5. Also for comparison is shown the shallow exploration well (ThK-7) located in the western part of the volcanic system (Lacasse et al., 2007; Guðmundsson et al., 2008). Furthermore bedrock isotherms based on temperature logging in the wells are also displayed.

Apparently there is good correlation between alteration and bedrock temperature and alteration in well ThG-1 whereas bedrock temperatures seem to be considerably higher in well ThG-3 than is indicated by the alteration. This may be an indication that temperatures are increasing in the eastern part of the area and that alteration has not yet re-equilibrated to the new temperature condition. Another possibility is that re-equilibration is hampered by sluggish kinetics due to relatively low permeability. Cuttings were not retrieved to any significant extent below 300 m depth in well ThG-2, however temperature measurements show much lower temperatures than on the other wells suggesting localized down-welling of relatively cold fluid.

Analysis of fluids extracted from the wells confirms to a large extent the findings from the exploration phase. The high enthalpy fluid in the system, which contains less than 1% (wt.) of gas and low Total Dissolved Solids TDS (~1000 ppm), is suitable for electrical production by conventional means.

5. CONCLUSIONS

A total of seven production sections have been drilled from a total of six well-heads in the Theistareykir area. They provide data from a ~4 to 5 km^3 volume of the geothermal reservoir. In general the volcanic pile is highly altered and there is reasonable agreement between alteration and bedrock temperatures, in what is apparently a key up-flow area immediately north of Bæjarfjall. An area of potential recharge appears to be associated with the faults and fractures immediately to the west of Bæjarfjall.

To date the highest bedrock temperatures recorded in the area are close to 380°C in well ThG-3. This is among the highest temperatures recorded in a potential production well in Iceland so far.

The first phase of exploration drilling in the Theistareykir area has confirmed that the area has great potential for electrical production using conventional methods.

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