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Well Site Selection Based on Acoustic Borehole Image Logs: A Case History from Hoffell Low-Temperature Geothermal Field in Southeast Iceland

Sigurveig Árnadóttir[1)], Þorsteinn Egilson[1)], Anett Blischke[1)], Halldór Ö. Stefánsson[2)], Friðgeir Pétursson[2)], Haraldur Jónasson[2)], Magnús Ólafsson[2)], Ólafur G. Flóvenz[2)], Árni Hjartarson[2)] and Sigurður G. Kristinsson[2)]

[1)] Iceland GeoSurvey (ISOR), Rangárvellir, P.O. Box 30, IS-602, Akureyri, Iceland

[2)] Iceland GeoSurvey (ISOR), Grensásvegur 9, IS-108, Reykjavík, Iceland

E-mail address: sigurveig.arnadottir@isor.is

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ABSTRACT

Geothermal prospecting in the Hoffell area in Southeast Iceland commenced in 1992, as potentials for a heating utility in the main town of the region were estimated. The research included drilling of 33 shallow exploration wells and resulted in a model of a workable low-temperature geothermal system with two predominant fracture trends, ENE-WSW and approximately N-S. Prior to siting a deep exploration well in 2012, acoustic borehole image logs (Televiewer) were performed in seven of the existing wells in the purpose of identifying orientations of permeable fractures. Results of these measurements demonstrate a quite complex sub-surface fracture system with fractures which arguably have formed during different geological periods. Focus was set on large, permeable fractures, which were clearly observed in Televiewer images from two of the deepest wells. The trends of these fractures, calculated from Televiewer data, support the two previously mapped predominant fracture trends. Final determination of a site for the deep exploration well was based on the orientation of one of these feed zones, namely ENE-WSW strike and ~73° dip towards SSE. The well was drilled more than 200 m away from the peak of the geothermal gradient anomaly and was anticipated to intersect fracture planes which are connected to this feed zone, only at greater depths, where estimated temperature was 80°C. The well intersects several feed zones and one of these, trending ENE-WSW and dipping 83° towards SE at 1340 m depth, is believed to be related to the intended fracture planes. The well yields ~25 l/s of 73°C hot water, which is found to be successful. The acoustic borehole image logging is in its early phase in Iceland and well siting on grounds of such measurements has proven to be a helpful addition to the conventional method of siting wells on the base of geothermal gradient data, usually drilling at or near the temperature geothermal-gradient maximum.

1. INTRODUCTION

The Hoffell low-temperature geothermal field is located in the region of Austur-Skaftafellssýsla in Southeast Iceland, in the upper Hornafjörður region. Bedrock in the area is mostly composed of basalt plateau lavas with thin sediment layers intermittently and intrusions widely intercalated, although layers of felsic rocks and sedimentary agglomerate are also found. The volcanic pile is of Tertiary age and was deeply eroded by glaciers during the Pleistocene. The area is at the edge of a monoclinal flexure which runs from Breiðamerkurjökull in the Southwest, along the Vatnajökull ice-sheet cone some 250 km north to Vopnafjörður. Intercalated with the lava pile is an extinct Tertiary central volcano, named the Geitafell volcano (Friðleifsson, 1983), which is exposed because of deep glacial erosion (Figure 1). The volcano was formed within a rift zone in central Iceland, and was active for about 1 m.y., between 5 and 6 Ma (Friðleifsson, 1983), slightly predating the SE-Icelandic flexure zone. According to studies of infilling sequences of mineral veins and amygdales and their associated wall-rock alteration (Friðleifsson, 1983), the Geitafell volcano has experienced three major structural events, (i) uplift of the central region, (ii) caldera subsidence, and (iii) regional flexuring. In addition, twelve intrusive phases were distinguished on the base of these studies. Following the emplacement of central gabbros belonging to the second intrusive phase, a high-temperature hydrothermal system was established at shallow levels (Friðleifsson, 1983). Prior to the emplacement of these central gabbros, cold groundwaters percolated through the volcanic strata and slowly became heated, presumably by dykes that intruded the volcano during the earliest intrusive phase (Friðleifsson, 1983). After the emplacement of the central gabbros, the previous low-temperature hydrothermal system then changed abruptly to an active high-temperature system (Friðleifsson, 1983). With time the hydrothermal system cooled and adjusted to hydrostatic values, until a second thermal boost accompanied the emplacement of the 10^{th} intrusive phase, comprising intrusion of marginal gabbros, local cone-sheets and NE-SW trending dykes, which maintained the high-temperature hydrothermal activity for some length of time, after cooling had begun, proceeding downwards with time (Friðleifsson, 1983). It is concluded that the flexure zone was formed during the cooling history of the Geitafell volcano hydrothermal system, and its formation may possibly have induced cooling by extensive fracturing (Friðleifsson, 1983). Both the flexure and the volcano subsequently became buried by younger lava flows erupted to the northwest, and later eroded during Pleistocene glaciation (Friðleifsson, 1983). Heat is still preserved in the crust at the Hoffell low-temperature field, which has been explored discontinuously over the last two decades or so in the purpose of finding hot water for a heating utility in Höfn, the main town of the region some 20 km away.

Geothermal prospecting commenced in the region of Austur-Skaftafellssýsla in 1992 with the drilling of shallow research wells which were employed to accomplish a survey of geothermal gradient (Stapi – Jarðfræðistofa, 1993). An anomaly was soon detected in the geothermal gradient data near the farms at Hoffell ("Hoffell" and "Midfell" in Figure 1), which are located at the periphery of the Geitafell volcano, and this area accordingly became the main focus of interest. Drilling was hence continued in the Hoffell field (Stapi – Jarðfræðistofa, 1992; 1993; 1994; 2002; 2005; 2006), totaling in 33 vertical research wells, most of them less than 60 m deep. Highest measured temperature was 61.1°C at 505 m depth in the deepest well in the area (ASK-86). Based on the geothermal gradient data, combined with further research, a model was constructed of the geothermal system which exhibited two predominant fracture trends, ENE-WSW and approximately N-S, which appeared to be related to the geothermal gradient maximum (Sæmundsson, 1995; 1996; Stapi – Jarðfræðistofa, 1992; 1993; 1994; 2002; 2005; 2006).

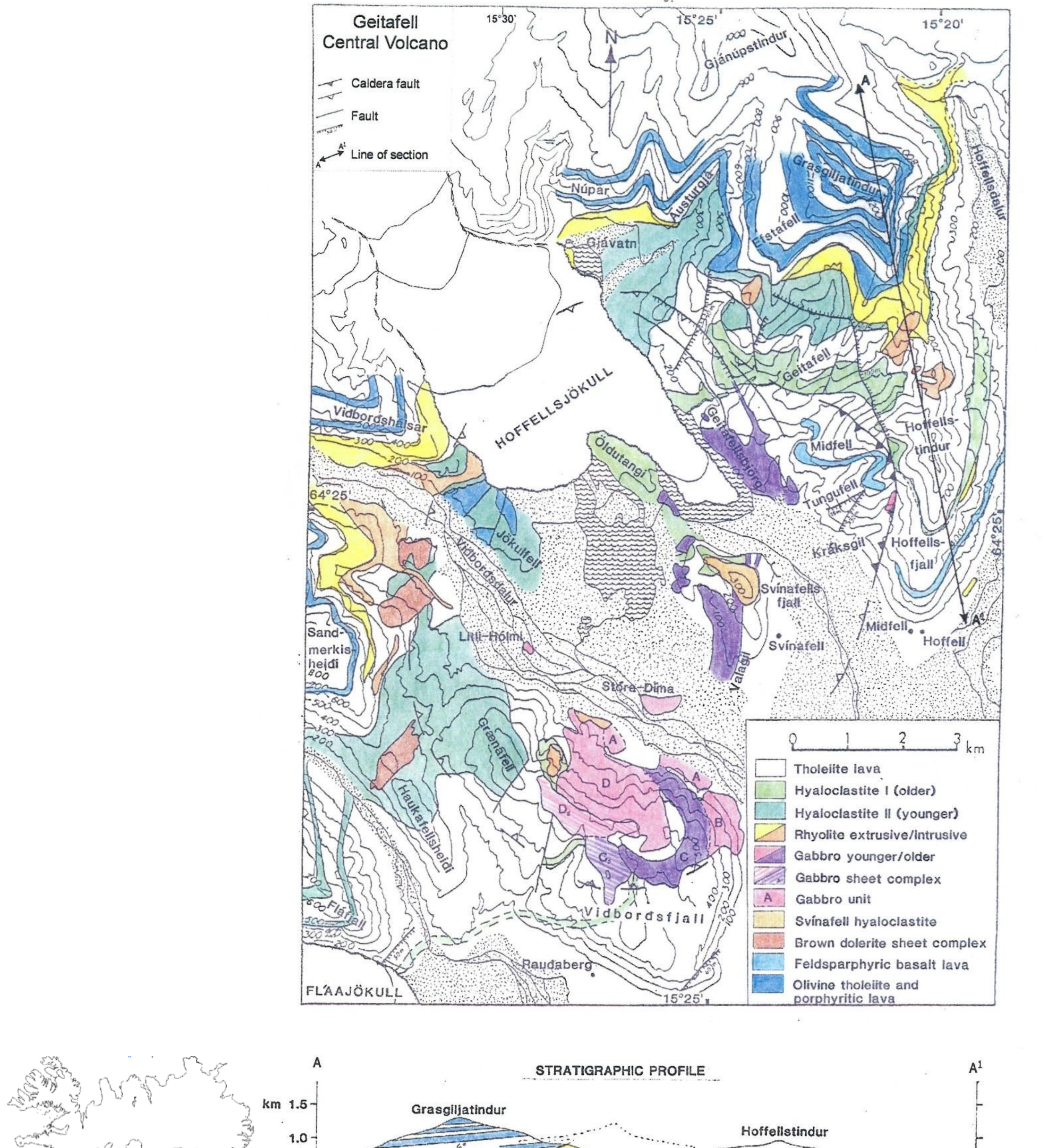

Figure 1. Friðleifsson's (2004) geological map of the Geitafell volcano. Location of the mapped area is shown to the left.

In terms of the model of the geothermal system it was recommended that further research would involve drilling of an approximately 1000-1200 m deep exploration well (Stapi – Jarðfræðistofa, 2006; Árni Hjartarson et al., 2012), which originally was intended to intersect the ~N-S trending fracture below 800 m depth. The dip of the fracture had been estimated by surmising which feed zones in different boreholes pertain to it and calculating the dip of a plane that fits best to these feed zones plus the trend of the geothermal gradient maximum, presuming that the wells are vertical and location of the fracture at surface is correct (Stapi – Jarðfræðistofa, 2006; Árni Hjartarson et al., 2012). After completing these calculations - which concluded in 75°-95° dip towards east - considerable uncertainty still remained in the dip of possible fracture planes (Árni Hjartarson et al., 2012), and accordingly it was decided that prior to drilling the deep exploration well, acoustic borehole image logs (Televiewer) would be performed in some of the existing wells in the purpose of identifying both trends and dips of permeable fractures.

2. TELEVIEWER LOGGING IN SEVEN WELLS IN HOFFELL, SEPTEMBER 2012

Acoustic borehole image logs (Televiewer) were carried out in seven wells in the Hoffell field (Table 1 and Figure 2) in September 2012, with the aim of obtaining better understanding of the fracture system and suggesting a location for a deep exploration well (Árnadóttir et al., 2013). The logging equipment was of ABI-43 type and data interpretation and processing were performed by use of the WellCad program. Features identified in the image logs were categorized by type into the groups presented in Figure 3.

Prior to interpreting the Televiewer images, quality of tilt and azimuth logs was reviewed, as these data were included in calculations of orientations of the identified features. It appeared that the azimuth logs, which record tool azimuth from magnetic north, were greatly disturbed by magnetization of basalt lava beds and dykes. This is a known issue in Televiewer logging in Iceland, as the bedrock is for the most part composed of basalt lavas and basalt intrusions which are often strongly magnetized. A fair solution to this problem would be to perform north seeking directional surveys (gyro logs) to acquire reliable azimuth measurements, but such was considered meaningless in this case as these are not significant in wells tilting less than 5° from vertical, and the wells in discussion were reputed to be vertical. Most of the wells however turned out to tilt 5° or more, and azimuth logs were thus required to calculate correctly orientations of identified features. To work this out, corrections were made on the troubled azimuth logs, thus disturbed parts were cut out and corrected in regards to undisturbed parts. Proper corrections for magnetic declination (11,8°W) were also applied. The outcome of Televiewer measurements from one well (ASK-84) were excluded from this study, as uncertainty in calculated trends of the interpreted structures was considered to be unacceptably large due to an extremely troubled azimuth measurement, in addition to poor image resolution. Some uncertainty, which should be noted, exists in calculated trends of interpreted features in the other wells due to uncertainties in the corrections made on the troubled azimuth logs.

Table 1. Logged wells; location, casing, year of drilling and depth: (*References: Stapi – Jarðfræðistofa, 1992; 1993; 1994; 2002; 2005; 2006.*)

Borehole name	East (m) (ÍSNET93)	North (m) (ÍSNET93)	Casing depth (m)	Casing caliper (")	Year of drilling	Depth (m)
ASK-29	676293	437462	2	3	1992	137
ASK-50	676333	437559	6	3	1993	100
ASK-57	676336	437533	3,4	6 ⅝	1993	206
			9,7	5	2002	306
			341	3	2005	364
					2006	465
ASK-82	676265	437506	12	7	2002	182
(ASK-84)	(676307)	(437623)	(12)	(7)	(2002)	(117)
					(2004)	(428)
ASK-85	676339	437213	42	8 ⅝	2003	102
ASK-86	676319	437377	11	8 ⅝	2003	102
			364	3	2004	365
					2006	505

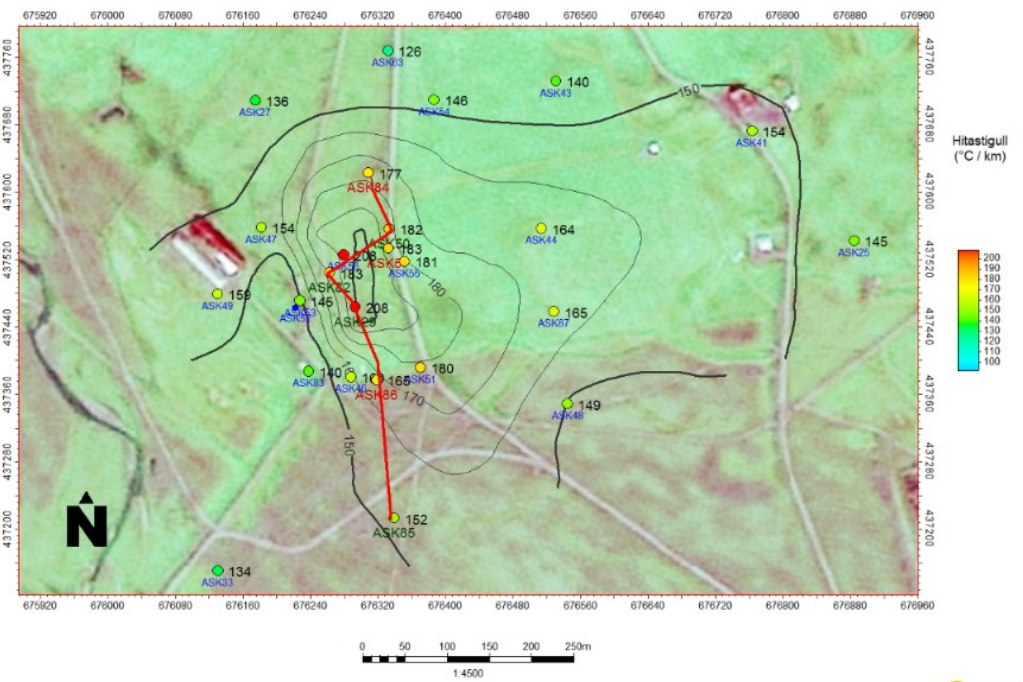

Figure 2. Location of wells in Hoffell. Temperature gradient of the boreholes is signified with colors (see color legend to the right). A cross-section through the seven logged wells (from south to north: ASK-85, ASK-86, ASK-29, ASK-82, ASK-57, ASK-50, and ASK-84) is marked with a red line. On figures presented in this text, Televiewer data from the wells are arranged according to the cross-section (well ASK-84 is excluded, see text).

	Broken zone: Broken/greatly fractured zone or rubble. Can be difficult to measure accurately.
	Large open fracture: Large fracture which obviously is open. Usually related to feed zones and detectable on temperature and caliper logs.
	Small open fracture: A fracture which obviously is open but cannot be considered to be large. Sometimes related to feed zones.
	Partially open fracture: Narrow and/or discontinuous fracture, or partially filled with alteration minerals.
	Filled fracture: Fracture filled with alteration minerals.
	Interfaces: Bedding, strata boundaries and intrusion contacts.
	Undefined: Structures which could not be categorized, usually because of obscure image.
	Joints/interfaces in granophyre.

Figure 3. Features identified in Televiewer images were categorized by type into the groups presented above. Color legend for the groups is shown to the left.

In all wells, filled joints are the most common fracture type, and these are seen striking and dipping variously, although trends on the range from NNW-SSE to ENE-WSW appear to be prominent, with dips either towards ~W or ~E (Figure 4). Regarding open and partially open fractures, approximately N-S trending fractures are pronounced. In wells ASK-29, ASK-82, ASK-57 and ASK-50, NNE-SSV trending open/partially open fractures are prominent, either dipping towards ESE or WNW. Open fractures in the southernmost well (ASK-85) are NNW-SSE trending and dipping towards WSW. Open and partially open fractures dipping towards south become more prominent below 70 m depth (Figure 5).

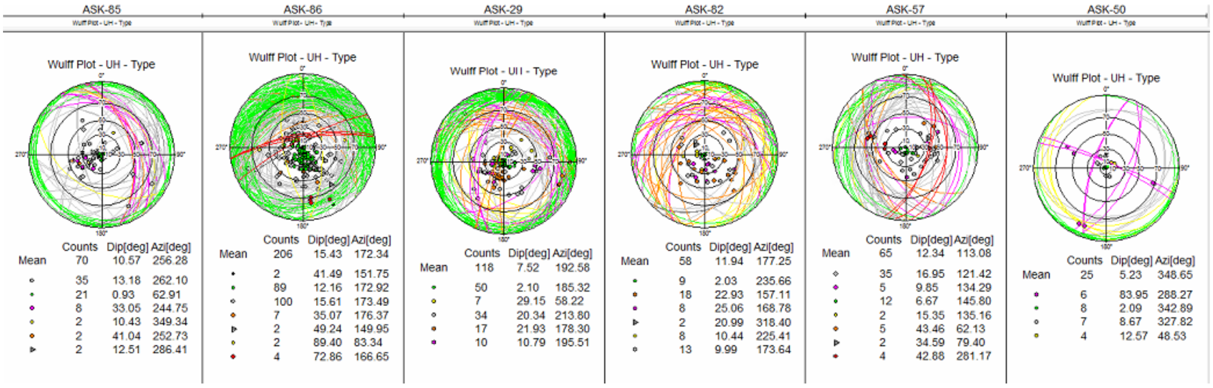

Figure 4. Planes of features interpreted in Televiewer images from shallow wells in Hoffell, presented on Wulff plots (upper hemisphere). Color legend is shown in Figure 3. Underneath each plot is the mean of dip from horizontal ("Dip") and dip azimuth ("Azi"). The cross-section through the wells is presented in Figure 2.

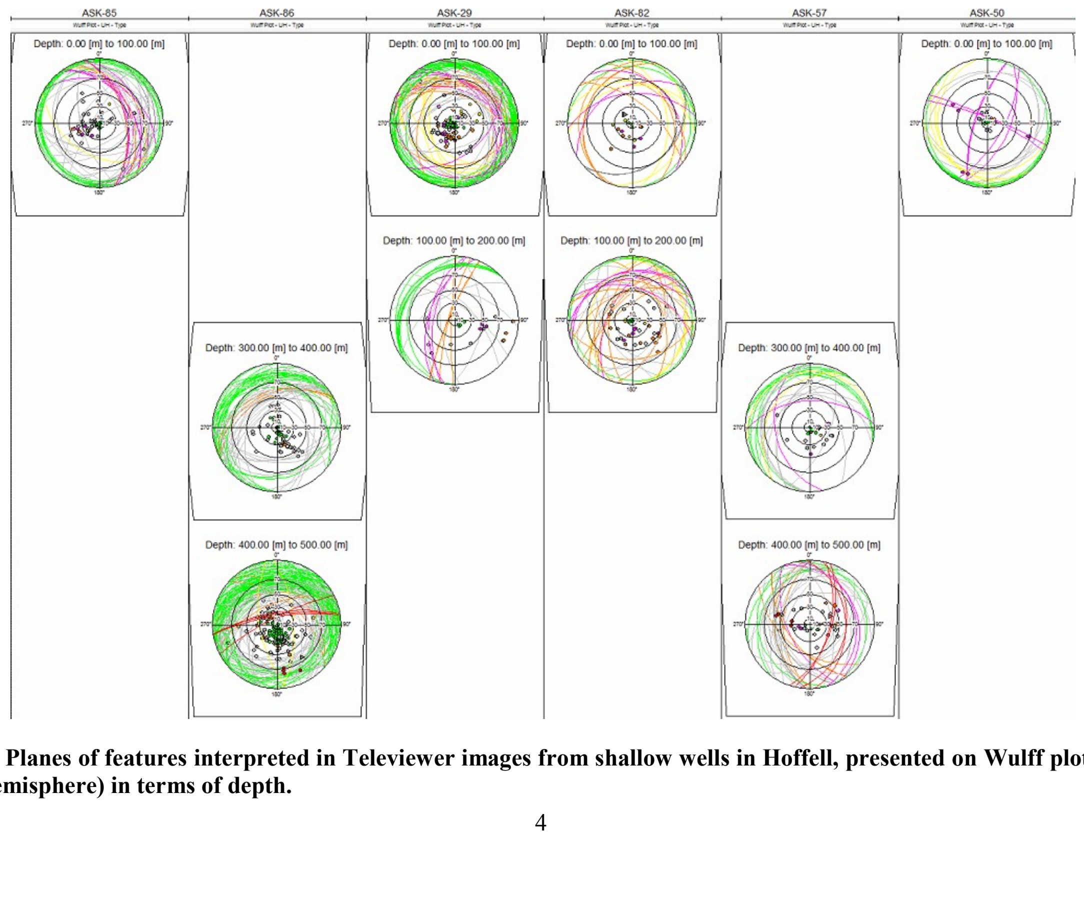

Figure 5. Planes of features interpreted in Televiewer images from shallow wells in Hoffell, presented on Wulff plots (upper hemisphere) in terms of depth.

3. SITING AND DRILLING A DEEP EXPLORATION WELL (HF-1)

Results from analysis of the Televiewer data described above were used to site a deep exploration well (HF-1). Requirements had been made that drilling should be vertical, the well would intersect ~80°C hot water at 800-1200 m depth, and that casing would reach deep enough to prevent inflow of cold water. Focus was set on large open fractures related to feed zones. Such fractures are clearly visible in Televiewer images at the bottom of two of the deepest wells, ASK-57 and ASK-86. The strikes of these fractures, calculated from Televiewer data (NNE-SSW trend with ~43° dip towards WNW in ASK-57 and ENE-WSW trend with ~73° dip towards SSE in ASK-86, see Figure 6), support the two previously mapped predominant fracture trends (Stapi – Jarðfræðistofa, 2006). Azimuth logs at these depth intervals are in both cases only slightly disturbed, and calculations of the fracture trends are therefore considered fairly sound.

Final determination of a site for the deep exploration well (Table 2) was based on the orientation of a feed zone at the bottom of well ASK-86, which is the deepest well and with the highest measured temperature, and the aim was to intersect fracture planes related to this feed zone. The deep exploration well was sited ~100 m southeast of well ASK-86, where it was considered most expectable to intersect the intended fracture planes at 800-1200 m depth. The extrapolated depth was modelled upon vertical drilling and its uncertainty was known to be substantial, due to shortage of azimuth and dip data from the uppermost part of well ASK-86. The well was originally proposed to be 1200 m deep, with possible deepening down to 1400 m (RARIK, 2012; Þórhallsson, 2012). Due to successful drilling and progressive volume of water with depth, a decision was made, when the well was 1400 m deep, to deepen it further, resulting in a final depth of 1608 m (Kristinsson et al., 2013).

Table 2. Well HF-1; location, casing, year of drilling and depth: (*References: Níelsson and Stefánsson, 2012; Kristinsson et al., 2013*)

Borehole name	East (m) (ÍSNET93)	North (m) (ÍSNET93)	Casing depth (m)	Casing caliper (")	Year of drilling	Depth (m)
HF-1	676380	437315	3,9/23,8/400	20/14/10¾	2012-2013	1608

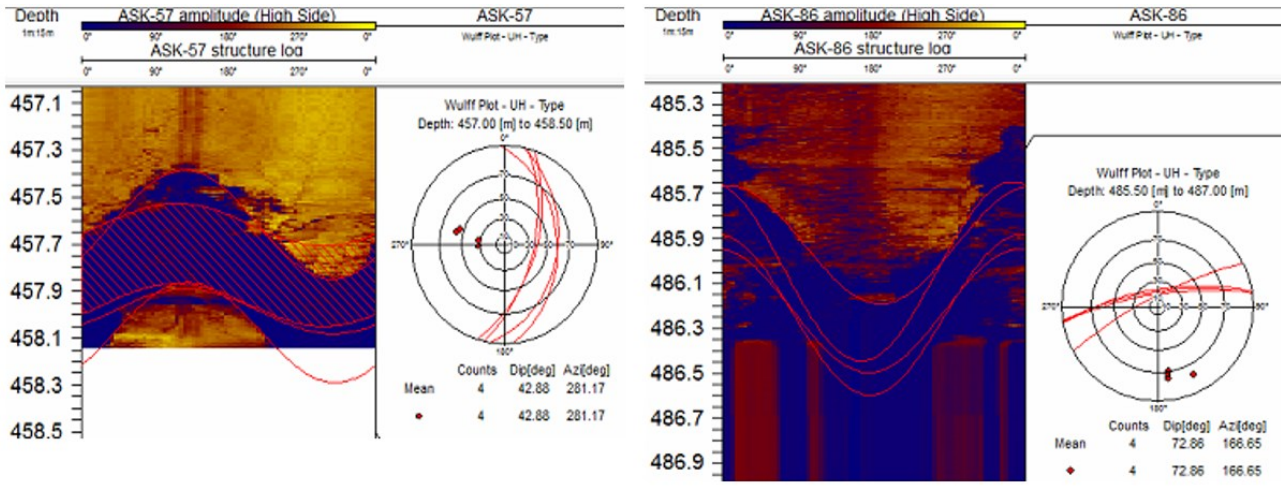

Figure 6. Amplitude images of large, permeable fractures at the bottom of wells ASK-57 and ASK-86. To the right of each amplitude image is a Wulff plot (upper hemisphere) presenting the interpreted fracture planes. Average of dips from horizontal ("Dip") and dip azimuths ("Azi") is given below each Wulff plot. Please note that the images are oriented to the borehole high side.

3.1. Televiewer logging in well HF-1

After drilling of well HF-1 was completed, a Televiewer log was run below casing, from 406 to 1605 m depth. As the well proved to dip up to ~8° (from vertical) in the lowermost part, a north seeking directional survey (gyro log) could be performed. The gyro log was included in calculations of orientations of the interpreted features, which accordingly are considered to be fairly reliable. Broadly speaking, structures most often strike on the range from N-S to ENE-WSW, dipping either towards E/SE or ~NW (Figure 7). Interfaces observed in the Televiewer images most often represent lithological boundaries and are most prominent in the uppermost 760 m of the Televiewer image. Such interfaces predominantly trend on the range from N-S to ENE-WSW and dip ~14° on average towards W/NW/NNW. One of these interfaces, observed at 1052 m (striking NE-SW and dipping 71° towards NW), is considered to represent a boundary between a dyke and the adjacent rock, as it is observed in the vicinity of such boundary with regard to drill cutting analysis. Well HF-1 intersects a granophyre intrusion from 1100 m depth to the bottom. Televiewer images of the granophyre show prominent features which appear as joints or interfaces between dissimilar image fabrics. These features, which are particularly pronounced at 1150-1260 m depth and mostly dip ~30-40° towards SE, with trends ranging from N-S to ENE-WSW, are considered to be notable for further studies.

Results of Televiewer data analysis from well HF-1 can roughly be described in terms of depth as follows (Figure 8). From casing to 650 m depth, open and partially open fractures striking approximately N-S (on the range from NNW-SSE to NNE-SSW) and dipping steeply eastward are most prominent. Few fractures are detected from 650 m to 800 m depth and below that, filled joints are most prominent down to 1000 m depht, mostly dipping towards NW. NW-dipping, NE-SW trending filled joints continue to be prominent from 1000 m to 1150 m depth, with an addition of partially open and minor open fractures, and the NE-SW trend becomes more decisive at that depth than above. At 1150-1260 m depth, the above-mentioned joints or interfaces in granophyre are the most prominent features, predominantly trending on the range from N-S to ENE-WSW and dipping ~30° on average towards SE. Below that and down to ca. 1350 m depth, filled and partially open fractures trending and dipping similar to the permeable fractures at the bottom of well ASK-86 (ENE-WSW trend and ~60-80° dip towards SSE), are seen. Underneath 1350 m, down to the bottom of the well, ~NE-SW trending filled, partially filled and open fractures are seen again, dipping ~60-70° towards ~NW.

Well HF-1 intersects several feed zones and one of these, at 1342 m depth, is in terms of Televiewer data considered to be connected to the intended permeable fracture planes observed at the bottom of well ASK-86. The feed zone is presumably related to a partially open fracture, observed in Televiewer image at 1340 m depth, trending ENE-WSW and dipping 83° (from horizontal) towards SE. As mentioned before, uncertainty in the extrapolated depth was, at the time when the well was sited, known to be substantial due to shortage of azimuth and dip data from the uppermost part of well ASK-86. This, combined with the fact that well HF-1 dips up to ~8° in the lowermost part, may arguably explain why these fracture planes were intersected at greater depths than intended.

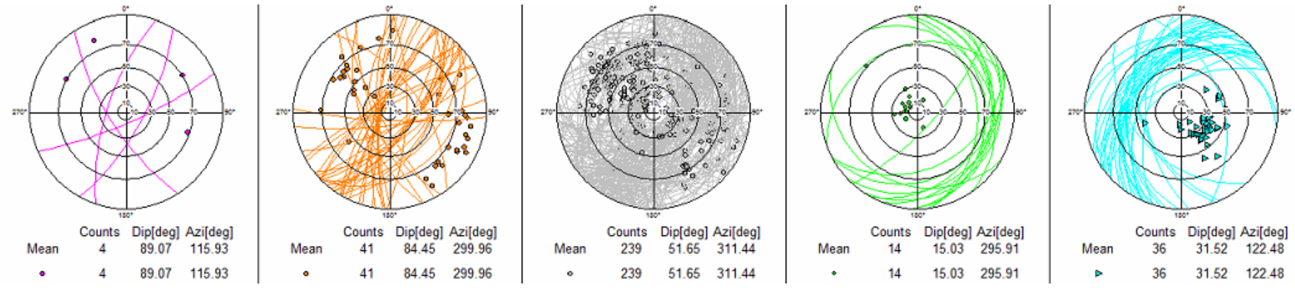

Figure 7. Wulff plots (upper hemisphere) presenting interpreted features in HF-1. Average of dips from horizontal ("Dip") and dip azimuths ("Azi") is given below each Wulff plot.

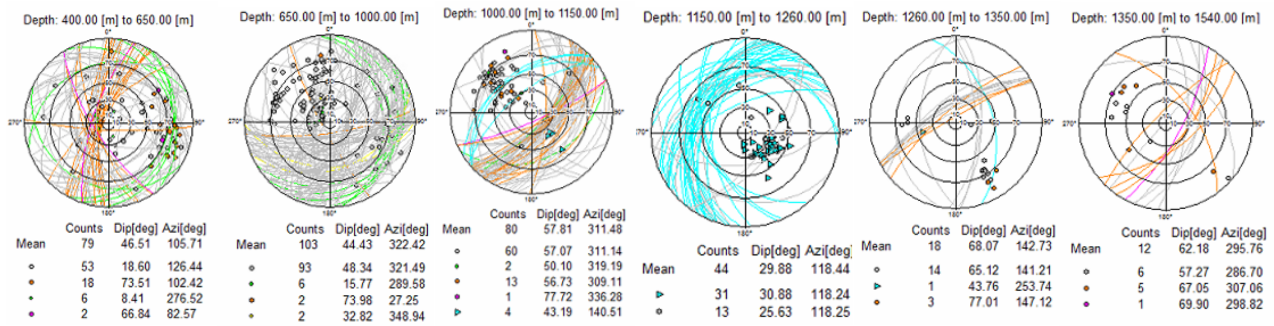

Figure 8. Wulff plots (upper hemisphere) presenting interpreted features in HF-1, shown in terms of depth.

4. CONCLUSIONS

The acoustic borehole image logging is in its early phase in Iceland and well siting on grounds of such measurements has proven to be a helpful addition to the conventional method of siting wells on the base of geothermal gradient data, usually drilling at or near the temperature geothermal-gradient maximum. Results of Televiewer logs performed in the Hoffell low-temperature geothermal field in September 2012 reveal a quite complex sub-surface fracture system with variously trending and dipping fractures. Open and partially open fractures can be observed in Televiewer images crosscutting older fractures which are filled with alteration minerals, demonstrating that these fractures have formed during different geological periods. The diverse fracture orientations can be assumed to reflect different geological conditions, stress fields and events that during time have generated different fracture zones which are partially filled with intrusions. Two predominant trends are however detected, ~N-S and ENE-WSW, supporting previous detection, with dips towards various directions. On the base of these results, a deep exploration well was sited where it was expected to intersect ENE-WSW trending, SSE dipping permeable fractures at more than 800 m depth. The well, which was drilled more than 200 m away from the peak of the geothermal gradient anomaly, is considered in terms of Televiewer data to intersect the intended fracture planes at 1340 m depth. The well yields ~25 l/s of 73°C hot water, which is found to be successful.

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