Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Well Locations Consideration of Purpose, Objectives and Achievement with Emphasis on Recent Drilling in the Krafla Geothermal Area

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Keywords: Krafla, geothermal field, well location, resources assessment

ABSTRACT

Landsvirkjun, the owner of the Krafla Power Plant, decided in 2006 to continue exploration drillings for further utilization. A comprehensive research program in NE-Iceland was initiated focusing on geothermal potential with the main purpose to generate electricity. The research program included surface investigations and exploration drilling within four geothermal areas. Several wells were drilled in Krafla, Bjarnarflag (Námafjall), Gjástykki and Þeistareykir to support existing conceptual models and geothermal assessments. The exploration and drilling activities in the Krafla geothermal area will be emphasized in this paper. The strategy was to expand previous drilling fields and identify new ones on the basis of a comprehensive TEM- and MT-resistivity survey as well as re-evaluation of previous research work.

In this paper emphasis is placed on the preparation and success of two wells in Krafla, KJ-36 and KT-40. The strategy was to focus on selected targets, according to surface observation, tectonics and CO_2 emissions, inside the resistivity anomaly close to one of the main up-flow zones of the geothermal fluid. The operations were successfully completed and permeable fracture zones located. Indications of this potential had been under discussion for some years. After completion of these drilling operations the knowledge of the interior of the geothermal reservoir increased as well as the learning experience.

Figure 1 demonstrates the distribution of wells in Krafla and their trajectories as well as revealing the tectonic outlines.

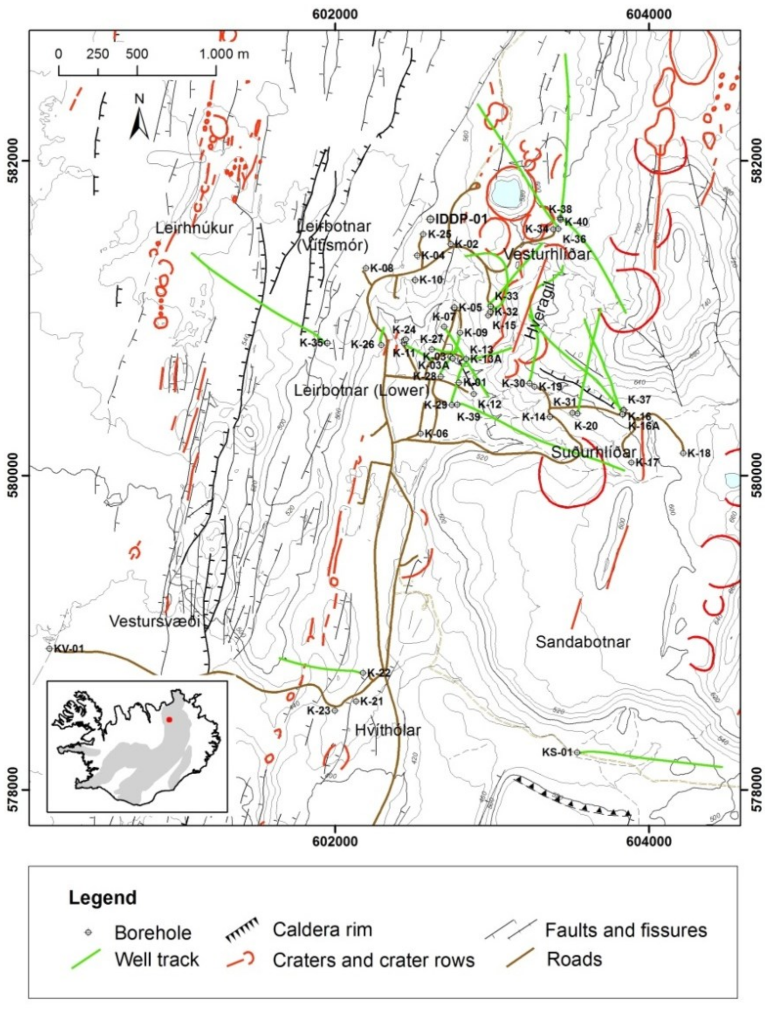

Figure 1: Distribution of wells in the Krafla geothermal area and the main tectonic outlines.

1. INTRODUCTION

The first comprehensive geothermal research program in the Krafla and Námafjall area was carried out during the years 1969-1973. Exploration drilling initiated in Krafla in the year 1974 with the drilling of two exploration wells close to 1200 m depth. Until 1978 twelve exploration / utilization wells were drilled, the deepest down to 2222 m depth. Well KG-12 was the first one where the deviation from vertical was carefully monitored and controlled by varying the weight on the bit. Unfortunately, a volcanic period started in the end of the year 1975 and lasted for nine years with serious consequences for the geothermal development. Invasion of volcanic gases contaminated the main geothermal reservoir and the drilling activities needed to be moved to new fields (Gíslason. et al. 1978). During the years 1980-1984, 11 wells were sunk in Sudurhlídar- and Hvíthólar field, as well as in the Leirbotnar field, which had been contaminated by volcanic gases. Two wells were directionally drilled; KJ-20 and KJ-22, and well KJ-13 rehabilitated by a new directionally drilled leg.

As a consequence of the volcanic gas invasion, it was more complicated than before to utilize the Krafla geothermal field and it was delayed for some time to install a second 30 MW_e unit in the power station. Three wells were sunk until 1996, when certain improvements in the reservoir were observed. Monitoring data from well KJ-15 revealed that since 1980 the volcanic gas concentration was in wane in the reservoir and by 1996 the gas concentration had decreased so much that the concentration was only slightly higher than before the volcanic period "Kröflueldar" (Gudmundsson, A. 2001). A decision was taken to continue drilling for steam in the year 1996, to supply the second turbine. This project turned out to be successful. Eight more wells were added and this drilling period lasted for three years and was completed by drilling well KJ-34 in the year 1999. Five of the wells were directionally drilled.

A new exploration program was commenced in 2006 for NE-Iceland, including continuation in the Krafla area with seven of eight wells directionally drilled. Iceland Deep Drilling Project commenced in 2008 where the IDDP-01 was drilled in Vítismór, which is the northern part of the Leirbotnar field.

A total of 44 wells have been drilled into the Krafla geothermal system (Fig. 1), but the wells range in depth from 985 – 2894 m. The main well field is located in the eastern part of the Krafla caldera and through drilling the volcanic structure at depth has been outlined as well as the physical conditions of the geothermal system, but the geothermal area is divided into four fields, Leirbotnar, Sudurhlídar, Vesturhlídar and Hvíthólar (Mortensen. et.al. 2009).

The purpose of this work is to review the outcome of the drilling activities based on the premises of well siting with examples from locations of wells KJ-36 and KT-40.

2. GEOLOGICAL OUTLINES

The Krafla central volcano is located within the neo-volcanic zone in NE-Iceland in the active rift zone, but volcanic activity related to Krafla volcano expands at least 200 thousand years (Sæmundsson, K. 1991). The volcano is approximately 20 km in diameter and within it is an eroded and partly filled caldera 8-10 km in diameter. A N5-15°E oriented and 90 km long rifting fissure swarm extends through Krafla volcano, while a prominent NW-SE elongated geothermal area covering ca. 10 km^2 is present within the caldera structure verified by Schlumberger resistivity measurements (Sæmundsson 1991). The NW-SE elongated geothermal area was also exposed as a magnetic anomaly, measured from air and surface (Karlsdóttir, R., et. al. 1978). The Krafla volcano is an active volcano with recurring volcanic episodes, which in the Holocene have predominantly been in the form of fissure eruptions. In the past 3000 years volcanic activity has been centred in the eastern part of the fissure swarm occurring with a frequency of 300-1000 years (Sæmundsson, 1991). The volcanic episodes affect the geothermal system in many ways and renew the heat supply, but they can also cause deterioration of the fluid source with excessive volcanic gas influx as was experienced in the deeper part of the Leirbotnar geothermal field during the Krafla Fires 1975-1984.

The geothermal area appears to be closely associated to an inferred underlying magma chamber, since seismic studies during the Krafla Fires 1975-84 indicated S-wave shadow delineating a NW-SE elongated magma domain at 3-7 km depth (Einarsson, 1978). The geothermal system in Krafla is estimated to be ~48 km^2 in size according to TEM- and MT-resistivity surveys (Árnason and Magnússon 2001) and over the past 40 years it has gradually been explored and developed. Currently a 60 MW_e geothermal power-plant is in operation.

The subsurface geology in Krafla is based on 44 wells. In general the stratigraphy in the Krafla area consists of basaltic lavas and hyaloclastite formations in the upper 1000-1350 m of the wells reflecting changing climatic conditions through time as the volcanic pile has accumulated as well as the formation of the caldera. The intrusion frequency is up to 90-100 % below 1000- 1300 depth, with thin intervals of lavas and hyaloclastites. Dolerite and diabase intrusions are dominant in the Leirbotnar field, and appear to be less altered below 1900-2000 m depth. In the northern part of Leirbotnar granophyre intrusions are abundant below 1900 m depth. East of Hveragil in Sudurhlídar field is a difference in stratigraphy, where a silica rich rock formation is dominant between approximately 900-1200 m depth, while gabbro intrusions appear below 1800-2000 m.

A prograde hydrothermal alteration assemblage is present and the epidote-actinolite zone (>280°C) is shallowest beneath Sudurhlídar well field where the geothermal fluid temperatures are controlled by the depth to boiling. In the Leirbotnar well field, where IDDP-1 was drilled, the geothermal system is divided into an upper reservoir that is sub-boiling (~190-220°C) and fluid-saturated, and a lower reservoir of high temperature (~280-340°C), but the two reservoirs are separated by a relatively impermeable zone. Fluid temperatures in the lower reservoir are generally controlled by depth to boiling, but superheated steam has been encountered in some wells below 2000 m depth.

The alteration pattern is complicated. It reveals prograde alteration from surface and down, but in the Leirbotnar field cooling is observed where calcite overprints epidote, prehnite and wollastonite. On the other hand, in the deeper part in same field, a superheated system exist and the secondary minerals are scarcely distributed and mostly as fracture fillings.

In the Hvíthólar field calcite disappeared around 300 m depth and was replaced by prehnite, which is in good correlation to the existing temperature. Slight overpressure was indicated there.

Figure 2 shows compiled data of lithology from selected wells, alteration- and temperature distribution in E-W cross-section, from Leirhnjúkur (KJ-35) through the main drilling fields, Leirbotnar and Sudurhlídar, to Hrafntinnuhryggur, which is an obsidian ridge east of well KJ-18. The figure demonstrates the separation of the geothermal system in Leirbotnar into two parts, upper (water dominated) and lower (vapor dominated). Different characteristic appears in the Southern-slopes of Mt. Krafla, east of the up-flow zone in Hveragil. The temperature decreases westward from Hveragil as is established in the upper aquifer of the Leirbotnar field.

In 2008 the conceptual model of the Krafla geothermal field was revisited by a large group of scientists from various disciplines where a range of new data was considered. The new conceptual model confirms the large scale understanding of the reservoir mechanism and provides a great increase in knowledge about the detailed structure of the reservoir. In connection with the development of the new conceptual model, geological, geochemical, and geophysical data from the Krafla geothermal field have been compiled and interpreted by using the PETREL software (Mortensen. et.al. 2009).

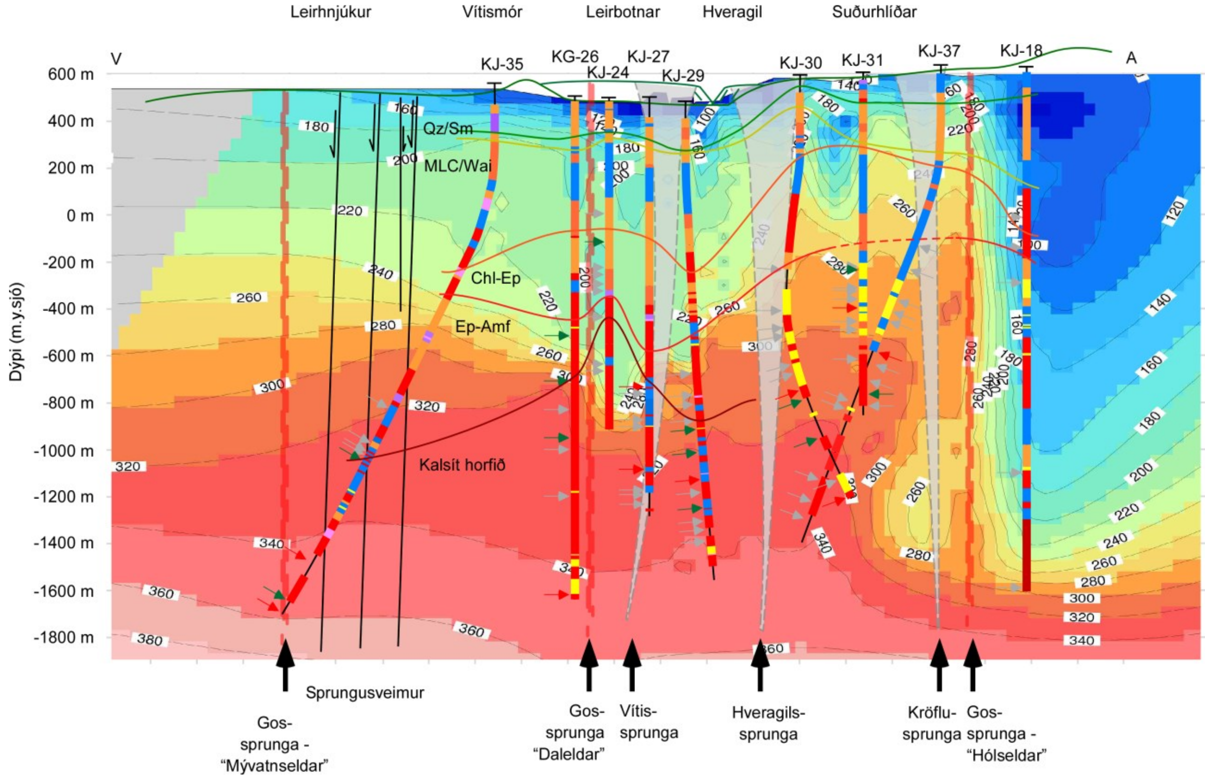

Figure 2: E-W cross-section through the drilling fields in Krafla, from Leirhnjúkur to Hrafntinnuhryggur.

3. CRITICAL ISSUES FOR WELL SITING

The Krafla high temperature area is structurally sophisticated as demonstrated on Fig. 2. Heterogeneity characterizes the geothermal system in respect to every geo-, fluid- and physical parameter. The dynamic of the volcanic system controls the flow patterns and composition of the geothermal fluid in the reservoir. Eventually it establishes some kind of balance between rifting episodes. The most important aspects, which are required to evaluate while siting a well are:

- formations (lithology and alteration minerals)
- temperature distribution
- pressures
- permeability
- composition of the geothermal fluid
- topography

When considering the well location and the well trajectory, all the above parameters need to be evaluate. The conceptual model is a dynamic one and is constantly under revision. It is essential to recognize the development of the research interpretation when well site is decided. Design of a borehole depends on exact location and the trajectory. The geothermal reservoir in Krafla is complicated as Figure 2 reveals. Each drilling field has its own characteristics. Therefore it is important to have drilling strategy with a clear focus, which intergrades above mentioned parameters. It is crucial to recognize different temperature conditions from one field to another while designing a well (Fig. 3). The character of the geothermal system has developed throughout the research period and at the early stages it indicated two main aquifer systems in Leirbotnar field (Ármannsson et. al., 1989). The upper zone consists of 180-220°C water dominated zone down to 1000-1700 m depth in the area west of the up-flow zone in Hveragil. The lower zone is characterized by vapor dominated aquifers. According to the same model a certain part of the reservoir was contaminated by volcanic gases which resulted in low pH aquifers (pH < 3) with highly corrosive fluid. Further drilling in the years 1997-2008 revealed this low pH zone underlying most of the reservoir (Fig. 4). The model was reconsidered when KJ-36 provided data indicating the existence of a superheated zone with high chloride content instead of low pH zone. During the research of the IDDP-01 well in Krafla the ideas of superheated zone were reviewed and suggested (Hauksson 2008).

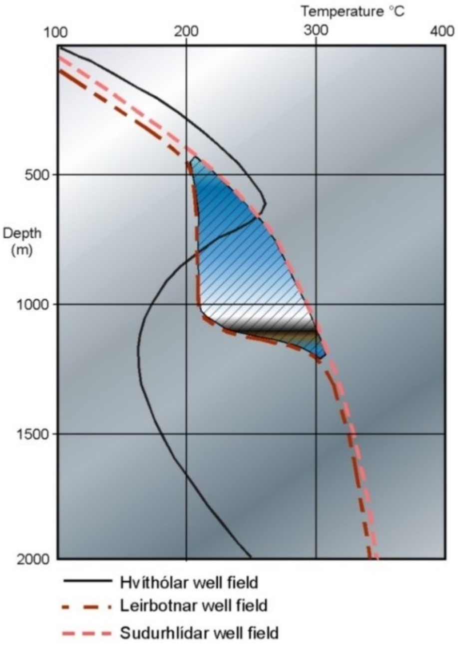

Figure 3: Characterizing temperature profiles for Hvíthólar-, Leirbotnar- and Sudurhlídar drilling fields.

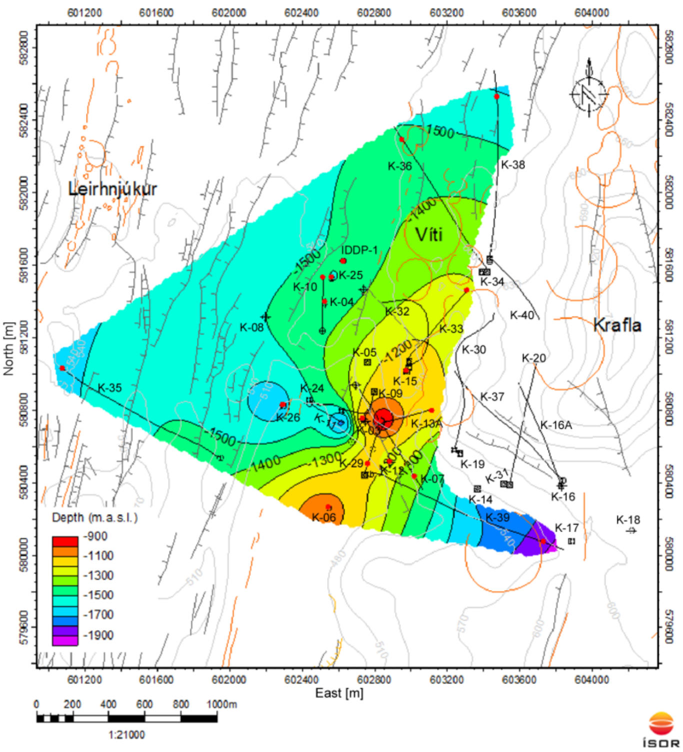

Figure 4: Map showing the inferred depth of superheated feeders in the Krafla geothermal reservoir (Mortensen et al., 2009).

4. SITING WELLS

4.1 Well KJ-36

It was considered to re-evaluate the conditions in the geothermal reservoir in the north part of the Leirbotnar field as to examine if the fluid properties had improved. The focus was particularly on the pH value in the deep aquifers, and discharging data from wells

KG-4, KG-10 and KG-25 over a 16 years period was re-evaluated. Furthermore it was necessary to compare the observations with fluid in other wells over the same time period. One important topic to examine was the reinjection into the deep aquifers, but since 2002 an average of 50 kg/s was reinjected into the deeper part of the Leirbotnar field. The reinjection was supposed to improve the quality of the fluid as a long term effect (Gudmundsson, A., 2001). Some seismic data indicated flow pattern from the injection well (well KJ-26) to northeast, i.e. into the low pH part of the reservoir (Tang et al. 2008).

According to the observations it was decided to drill a borehole in the Vítismór part of the Leirbotnar field since the influences of the volcanic gases were reducing. Therefore it was seen as an opportunity to review the logic behind locating well KJ-34, one of the most powerful well drilled in the Krafla area. The concept of the powerful up-flow of the geothermal fluid through the Hveragil gully acted as a valve for releasing the access of volcanic gases from the volcanism in Krafla Fires. The invasion of volcanic gases was believed to be the main reason for high gas concentration west of Hveragil in the deep aquifers of the Leirbotnar field compared to the east side of it in the southern and western slopes of Mt. Krafla. As a consequence of the high gas concentration the original production zone in the Leirbotnar field was unfit for production from the deeper part of the reservoir. KJ-34 was placed in the zone between the western slopes of Krafla and the northern part of Leirbotnar field. The fluid showed good quality which was an indication of improvement of the deeper aquifer. ÍSOR, the main geothermal consultant, recommended the location of well KJ-36.

Premises for location, trajectory and design of well KJ-36 were as follows:

- Location (ISNET93) X: 603420 Y: 581567 Z: 603 m a.s.l.
- KOP (kick of point) 300 m depth
- Dog leg (angle build up) 1,5°/30 m
- Deviation 30° from vertical
- Direction 325°
- Total length 2.500 m
- Real depth 2.258 m

The casing program, assumed to case off the upper (Leirbotnar) aquifers:

- Surface casing 70-90 m
- Anchor casing ~300 m
- Production casing ~1.100 m
- Slotted liner in the production part

Figure 5 reveals the trajectory of the well in correspondence to the main targets, the Víti fractures and Hóls fires fissure (2200-2500 years old). It was predicted to be highly permeable fracture system.

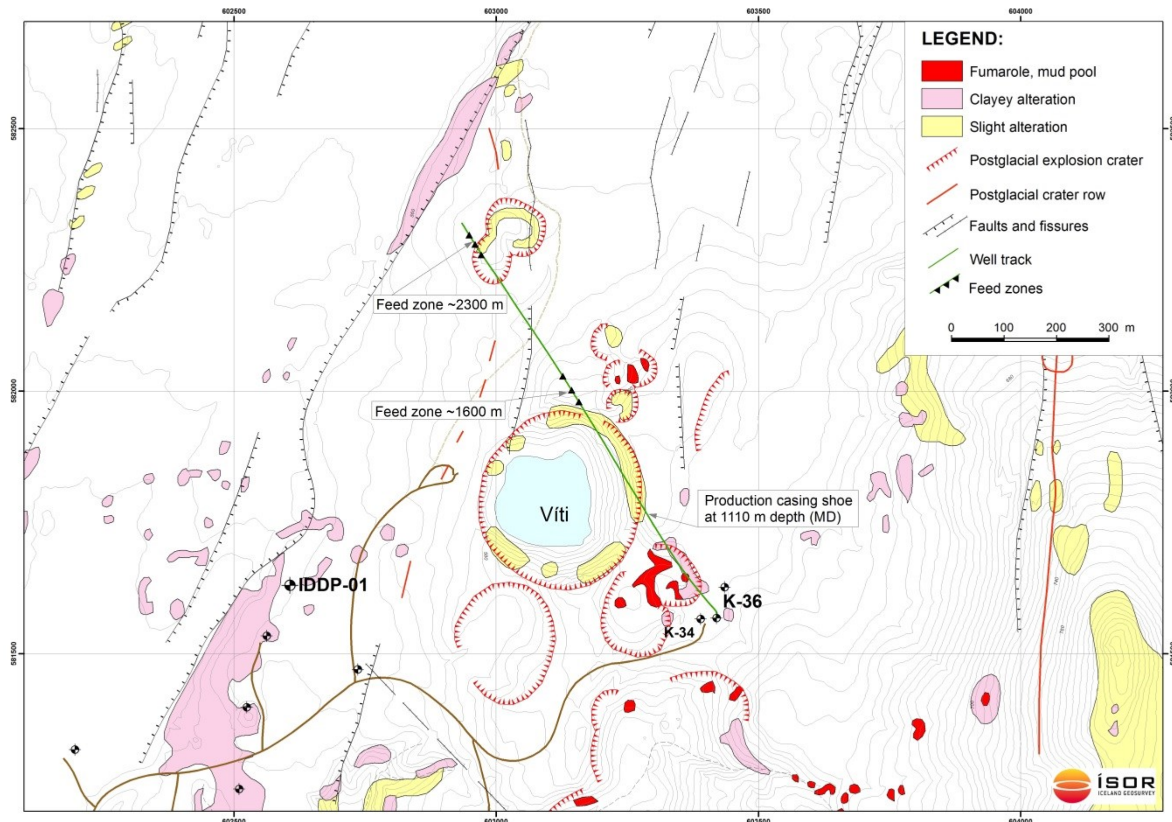

Figure 5: A geothermal/tectonic map revealing the NW trajectory of well KJ-36. It intersects the Holocene volcanic fissure of Víti (1724AD), the beginning of the Mývatns Fires (volcanic episode) and the older Hóls Fires fissure (2200–2500 yr old) just northwest of Víti, as well as several other faults.

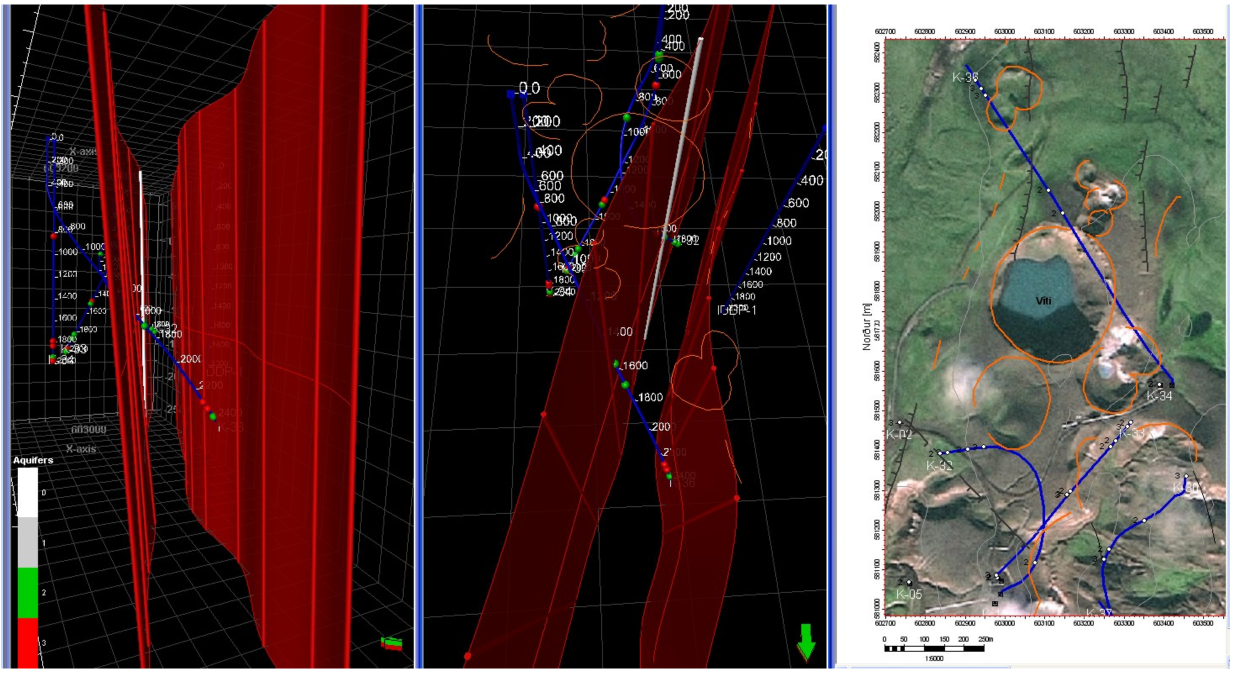

Figure 6: Different perspective of the trajectory of well KJ-36

All drilling parameters concerning permeability were monitored by the recording system of the rig during drilling of the production section and occasional well loggings. Most dependent parameters were circulation losses, standpipe pressures and differential temperatures. Important evidence of a permeable zone was detected at 1634 m depth. A circulation loss of 37 l/s was measured and later on it was verified in a temperature log (Fig. 7). At the depth interval 1560-1760 m the temperature was almost constant and therefore interpreted as a 120 m wide permeable fracture zone in the trajectory of the well. Furthermore it lined up with extrapolation from the Víti fracture. Another fracture was penetrated around 2300 m depth, which is believed to be the Hóls Fires fracture. The deepest aquifer was at 2400 m. The total displacement from vertical was 940 m (Gudmundsson. 2008). The trajectory of the well confirmed the fracture zones that was initially planned to cross. During the drilling completion the measured injection index was estimated to be 8-10 l/s/bar, which is twice over the average.

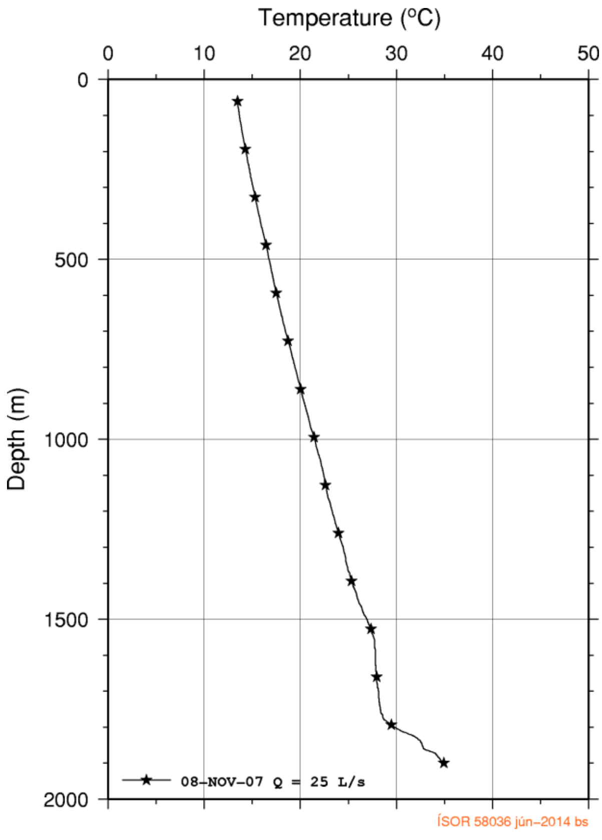

Figure 7: Temperature log while drilling. Indication of a fracture zone is seen at 1560-1760 m depth.

At this point one question was left to answer, namely the quality of the well fluid. The pressure built up at the wellhead was fast and it was only possible to run one P-T log of the three scheduled in the warming up period. The most likely explanation was interflow from the deepest aquifer into the Víti feed zone. The drilling operation was completed on the 18th of November 2007. The wellhead pressure increased quickly from 20 to 125 bars in less than three weeks. The discharge period commenced on the 12th of December. The well appeared to be extremely powerful and the high pressure steam was estimated to be 40-50 kg/s. Unfortunately, the fluid was erosive at the wellhead because of high velocity and also corrosive because of low pH. Furthermore, the steam was superheated as demonstrated on Fig. 7, which revealed a narrow transparent zone at the top of the silencer. It proved necessary to shut-in the well and fix the wellhead and after few flowing tests it was evident that the top manifestation on the well was too weak to utilize this power. To make the well productive it was decided to run a work-over rig to cement up and seal the deeper aquifers and keep the feed zone connected to the Víti fracture zone. This lowered the output to 10-11 kg/s. However, the operations left important knowledge even though this was well no. 36. Two distinctive permeable fracture zones were penetrated revealing the deeper part as superheated, not necessarily low in pH but obviously high in chloride gas. The chloride in the stage of gas is not corrosive in the superheated zone but in the case of mixing with some water droplets it will become highly corrosive as a concentrated sulfuric acid. This can happen in wells if both types mix in the same well.

Figure 8: Well KJ-36 discharging showing transparent steam at the top of the silencer.

4.2 Well KT-40

Well KT-40 is located on the same drilling platform as KJ-36 east of the explosion crater Víti (Mortensen and Gudmundsson 2008). The platform is at one of the main up-flow zones inside the Krafla geothermal system. There is a strong indication of a location of an up-flow zone between Víti and the explosion craters in the western slopes of Mt. Krafla, according to geothermal surface manifestations and resistivity measurements. Great potential of success may still be in this area further to the east. This potential has been confirmed by drilling a vertical well, KJ-34, and a directional one, KJ-30, but they are the most powerful wells in the Krafla area.

In the preparation phase of designing and drilling well KT-40, the focus was on the area east of the Víti-platform. Some interesting geological features are evident in the western-slopes of Krafla above the target zone. Beside the resistivity anomaly a cluster of explosive craters arranged on a NNE-SSW trending eruption fissure, evidence supported by abnormally high CO_2 gas emission through the warm altered (soil) mud covered surface indicate fractured formations underneath and eventually good permeability (Fridriksson 2009). In addition, the occurrence of permeable formations of silicic composition, characterizing the depth interval 1000-1500 m down under the southern slopes of Mt. Krafla, probably extends to the north.

ÍSOR, the main geothermal consultant, recommended the following location of well KT-40 and design program. Estimated length of the production section was 1000 m unless circulation losses were sufficient to complete the work. The main goal was to penetrate the target zone in the western slopes of Mt. Krafla, estimated at 1200-1500 m from the wellhead according to CO_2 emission anomaly on surface and silicic rich rock-formation. The interval 1500-2000 m from the wellhead was the second target, crossing the alleged fracture zone underneath the explosion craters (Fig. 9).

Premises for location, trajectory and design of well KT-40 were as follows:

- Location (ISNET93) X: 603450 Y: 581596 Z: 604 m a.s.l.
- KOP (kick of point) 315 m depth
- Dog leg (angle build up) 2°/30-3°/30 m

- Deviation 27° ± 3° from vertical
- Direction 135° ± 10°
- Total length 1.468 m
- Real depth 1.372 m

The casing program, assumed to case of the upper (Leirbotnar) aquifer:

- Surface casing 70-90 m
- Anchor casing ~300 m
- Production casing ~1.000
- Slotted liner in the production part

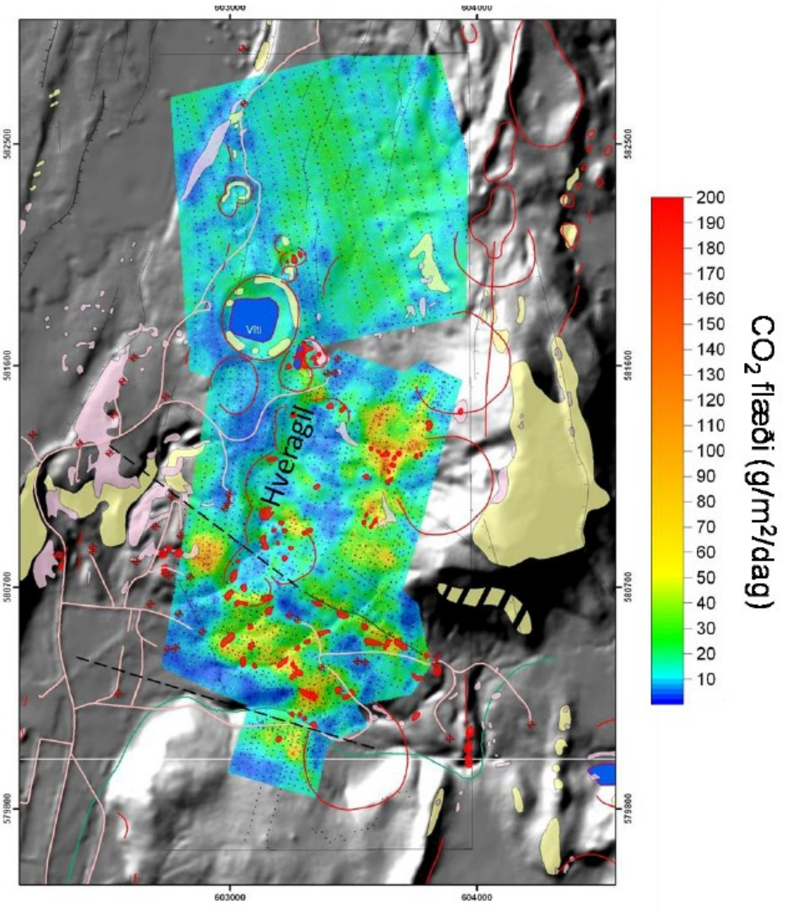

Figure 9: Emission of CO2 through the soil in the western slopes of Mt. Krafla.

KT-40 was drilled in two stages. The former one was drilled in the year 2008. The task was to deviate the well toward the targets and place the cemented casings down to 1000 m depth. A year later it was completed. Before drilling, a temperature log was run and valuable information were added as Fig. 10 reveals (Sigurgeirsson, et. all. 2009a, 2009b). The upper aquifer as seen in the Leirbotnar field still exists but is much shallower and extends only down to 700-800 m depth compare to 1200-1500 m depth west of Víti.

Shortly after the drilling of the production section started, the first circulation loss was detected at 1050 m depth. It continued to increase slowly down to 1207 m depth where it had reached 28 l/s. At 1233 m depth the bit penetrated a feed zone with total circulation loss. The drilling continued and the rotation of the string hesitated once in a while, probably because of fillings falling down on the BHA (bottom hole assemblage). It was decided to pull out when the depth was 1468 m. After pulling out two singles, the string was stuck. Several attempts were made during the following days. Three times, explosives were used to detach the string, without making progress. Finally, a backup was provided and 70 m of the BHA was left in the hole. Temperature logs and circulation losses indicated a permeable zone at the bottom of the well. At drilling completion, the injection test measured 16 l/s/bar, the highest so far in the Krafla wells (Mortensen. et. all. 2009a, 2009b).

The progress of the drilling operation was acceptable, even it did not fulfill initial schedule. The discharge test confirmed good quality of high enthalpy fluid (Ho~2700 kJ/kg). The flow reached balance roughly one year after the discharging started. The total flow was ~18 kg/s, equaling steam output which corresponds to 7,7 MW_e (2,3 kg/s per MW_e). This operation confirmed a high permeability zone in the western slopes of Mt. Krafla, which was indicated by CO_2 emission through the surface. On the other hand there may still be potential aquifers underneath the explosion craters, which were not reached during this operation.

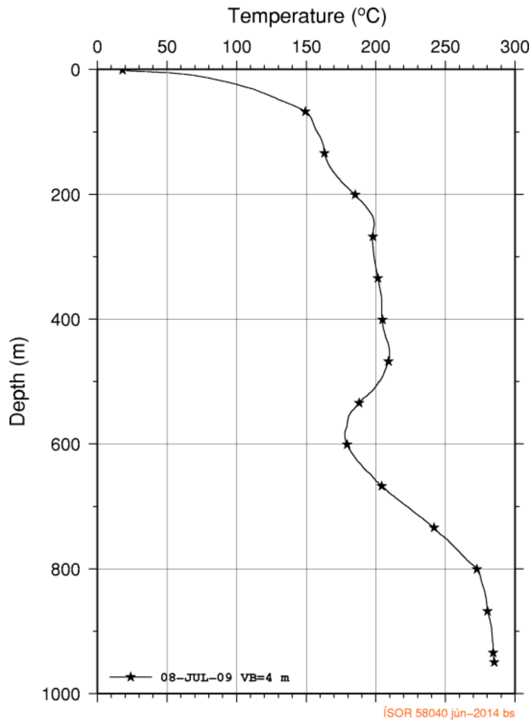

Figure 10: TP log of KT-40 before drilling the production section.

5. CONCLUSION

The high temperature area in Krafla has undergone comprehensive research programs. It has been attractive to diverse scientific groups. What makes it exceptional is probably parallel research programs of volcanism and geothermal. Magma chambers were discovered and located by a S-wave shadow at a shallow depth in the early days of the Krafla Fires. The magma and its derivative intrusions are the main heat source for the geothermal system and the driving force for the geothermal activities, as well as the dynamic in the crustal movements and tectonic patterns.

The high temperature system in Krafla is complicated and each drilling field possesses its own character. Well design programs need to be specific to each location. Well trajectories may intersect permeable zones with a different fluid quality, like is observed in well KJ-36. However, both aquifers may be utilized by drilling two wells, one for the Víti permeable zone and one to utilize the deeper superheated aquifers. Technology for utilizing superheated fluid is still in the research phase but in good progress has been made (Hauksson, T., and Markússon, S. H., 2014). The trajectories of both KJ-36 and KT-40 penetrate high permeability fracture zones characterized by vapor dominated fluid. In the future more fluid may be extracted from these fractures with more wells, particularly designed for these targets.

AKNOWLEDGEMENTS

The authors would like to thank Landsvirkjun (The National Power Company) for allowing and financially supporting the publication of this paper.

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