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Experimenting with Deflagration for Stimulating Geothermal Wells

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ABSTRACT

The Reykjanes high enthalpy geothermal system is located at the tip of the Reykjanes peninsula were the mid-Atlantic Ridge comes ashore in southwest Iceland. Its geothermal fluid has seawater salinity and originates from seawater source underneath the peninsula. The first research drillings were made in 1956 and limited (50 kg/s) production was from the system in the 1980s for a chemical plant. During that episode a total of nine wells were drilled. In 1998 research and preparation for 100 MW generating power plant started and the plant came on line in May 2006. The number of drilled wells for steam supply went up to 28 while the old wells were abandoned. In recent years five more wells have been drilled.

At least three of the recently drilled wells are step-out wells and they have not found as good permeabilities as the wells within the main well field. In order to recover the investment in those wells attempts have been made to stimulate them. Stimulation methods have been limited as equipment for hydraulic fracturing are not available in Iceland and in most cases too costly to import for single operation. Also acidification is generally not applicable for the basaltic rock formations. Therefore, introduction of propellant stimulation was a welcome addition. For the simpler configurations the propellant carrying tool is similar to other logging tools in weight and size. The operation is also simple and similar to a logging run into the well. The additional environmental impact on the operation has been negligible. The paper describes the first experiments with the propellant stimulation in Iceland and the results obtained in four wells at the Reykjanes field. At the end thoughts are given to improve the results in future trials that will take place.

1. INTRODUCTION

The Reykjanes high enthalpy geothermal system is located at the SW-tip of the Reykjanes peninsula where the mid-Atlantic Ridge comes ashore in southwest Iceland (Figure 1). As such the tip is the landward extension of the mid-Atlantic spreading ridge. In the last glacial period (12,000-100,000 years ago) the icecap covering Iceland extended far south along the mid-ocean ridge. At that time the geological formations were saturated with water of meteoric origin. As the icecap melted and retracted, seawater started to seep into the formations and replace the water. Evidence of the former water is now only found in crystalline inclusions. Land also started to rise and volcanic activity increased. The volcanic activity has been fracture intrusions and eruptions forming dike swarms, which have supplied the heat sources to form the Reykjanes geothermal system.

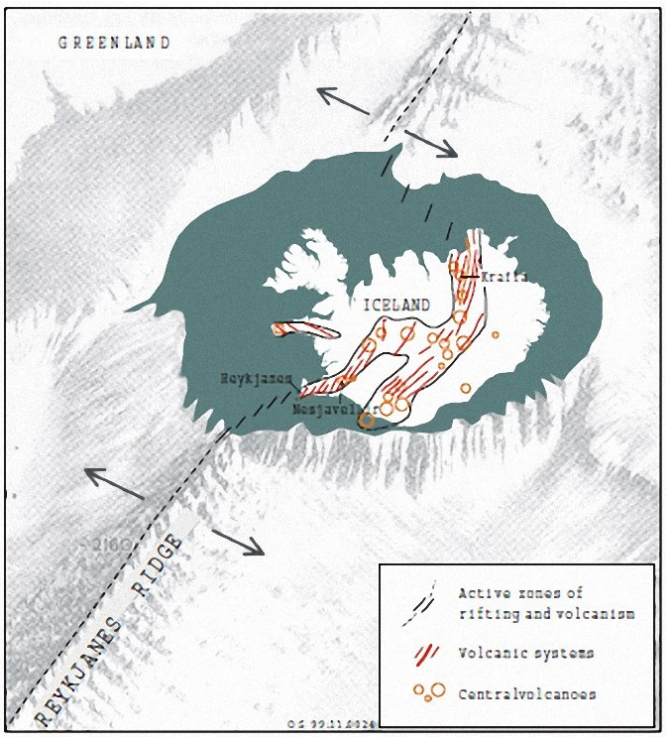

Figure 1: Iceland and its mid-ocean ridge. Location of Reykjanes shown.

The geology and surface distribution of the high-enthalpy geothermal system at Reykjanes is shown in Figure 2, and an aerial view in Figure 3. The surface is almost entirely covered by subaerial basalt lavas of Holocene age; whereas hyaloclastite ridges of late Pleistocene age poke the lava fields, with the same NE-SW strike as the volcanic crater rows, faults and fissures (Fridleifsson and Albertsson, 2000). Parts of the hyaloclastite ridges and the lava fields are hydrothermally altered, centered within manifestations of fumaroles, mud pools and hot springs. The youngest fissure eruption dates back to 1226 at the crater row Stampar on the NW-side of Reykjanes, while the 2nd youngest is about 2000 years old. In Holocene time, at least four volcanic eruptions have taken place within this fissure zone. An older eruptive fissure zone is on the SE-side of Reykjanes (the Skalafell fissure zone), mostly involving early-Holocene lava eruptions. The faults and fissures have moved frequently in historic times, reactivating the hydrothermal surface manifestations, which are mostly located in between these two eruption zones.

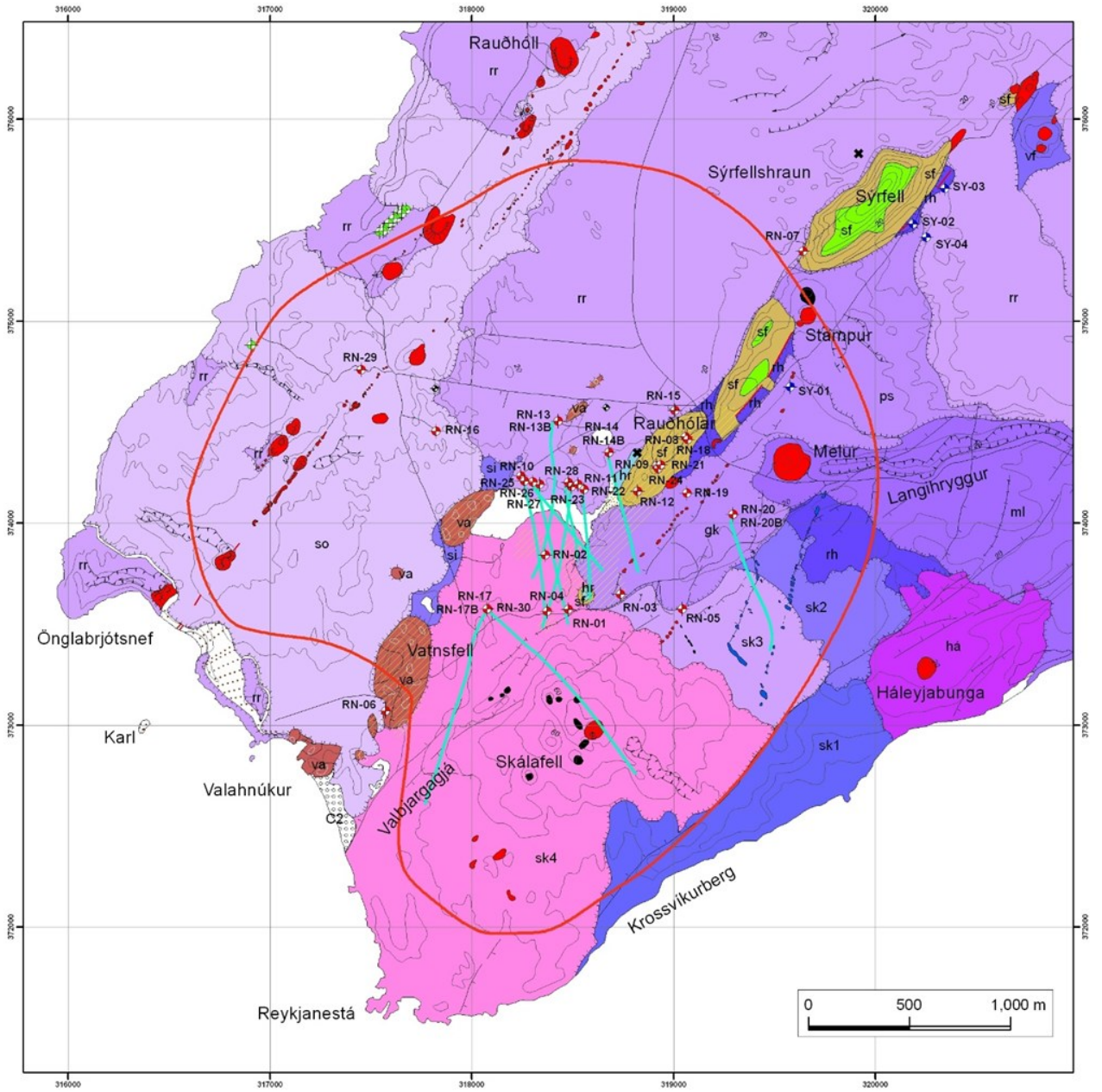

Figure 2: Geological map of Reykjanes showing most of the drill holes and their paths (light blue lines). Lavas from different eruptions are in violet to bluish color with darker color older to lighter color younger formations. Brownish color is hyaloclastite. Red circle represents 10 ohmm (TEM) at about 800 m depth roughly marking the outlines of the geothermal field while red dots are craters or eruptive fissures.

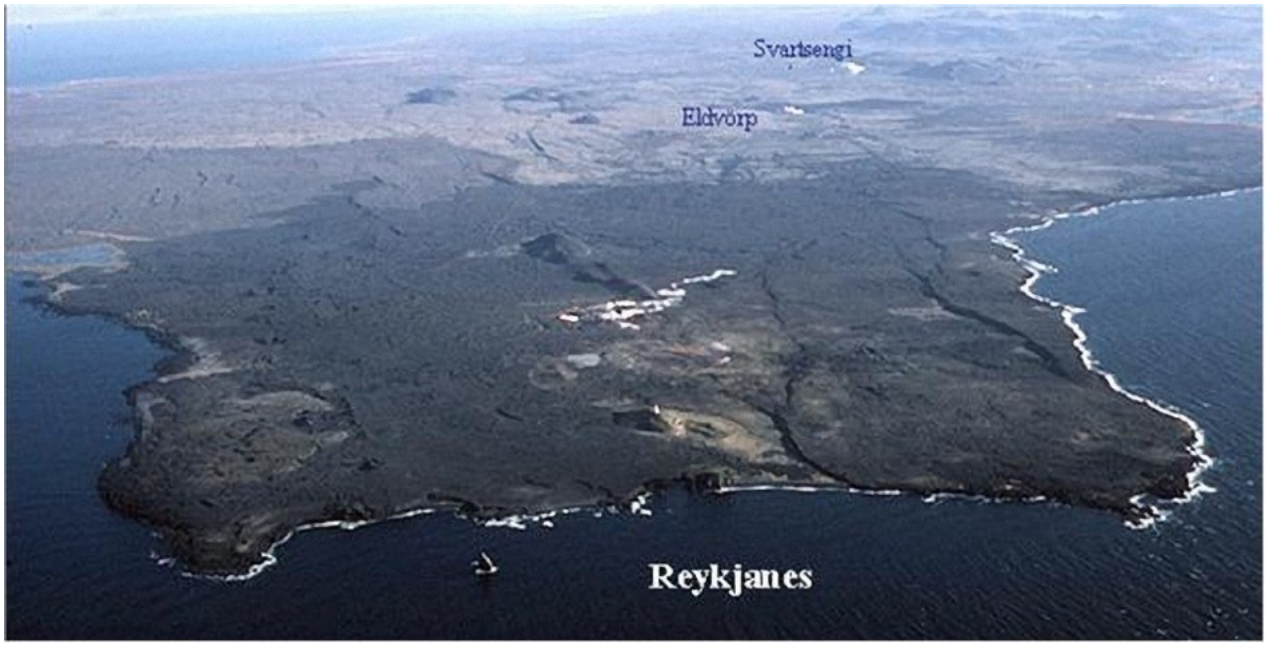

Figure 3: Reykjanes, the landward extension of the Reykjanes ridge. The fields Reykjanes in the foreground and Eldvorp and Svartsengi can be seen.

The exploration of the Reykjanes system dates back to 1956 when the first well was drilled to 162 m depth and encountered a temperature of 185°C. The well produced 3-4 kg/s of a steam-brine mixture for the next years, but was plugged in 1962. The chloride concentration of the brine was about 25% higher than that of ordinary seawater and no noticeable change was observed in its chemical composition during the production (Bjornsson et al., 1971). The fact that the fluid produced was brine of seawater origin, and not meteoric water as commonly found in Icelandic hydrothermal systems, affected the course of later exploration and developments.

Extensive investigation and drilling of additional seven wells was carried out in the years 1968-1970. Most of the wells were shallow, but three of them reached depth greater than 1000 m with well 8 reaching 1754 m. This effort was done in relation to plans for a sea-chemical plant for production of various types of salt, but it did not materialize until about 12 years later at relatively small scale. In relation to that, well 9 was drilled in 1983 and used along with well 8 for the sea-chemical production, but the plant was only in operation for few years.

In 1998 investigation started again with plans for electrical power generation and drilling of well 10. Drillings to obtain steam for a power plant was mostly carried out in the years 2002-2006 with wells 11 to 24 while the plant was constructed at the same time. The power plant came on line in May 2006 generating 100 MW_e from two 50 MW_e double flow turbines with seawater cooled condensers. Four more wells were drilled for the plant during the next two years. In recent years five additional wells have been drilled, two as make up wells but others as step-out wells for further exploration of the geothermal system.

The step-out wells have not encountered as good permeability as is experienced in the main well field. Therefore, these wells have been candidates for stimulation in an attempt to make them economical producers.

2. STIMULATION POSSIBILITIES

Icelandic geothermal fields in general as well as the Reykjanes field are situated in basaltic type formations with varying degree of alteration dependent on the reservoir temperature. The rock matrix has relatively low permeability so the transmissivity of a given geothermal well is controlled by fracture permeability which is often concentrated on a handful of feeding points intersected by the well. In some instances the permeability of these observed feeds is not enough to make the well a producer or injector. The potential of these feeds may be apparent so successful stimulation could shift the well to be economically usable.

There is a variety of stimulation methods available, but most of them fall into three categories; pressurization, chemical cleaning and thermally induced. In Icelandic basaltic formations the stimulation options are generally limited to methods that can change or affect the aperture of fractures that show indications to be active feed points. Acidification is normally out as few fractures in high enthalpy basaltic fields have calcite scaling in them. So left are pressurization or thermal shock methods.

Thermal shocking is commonly used in Icelandic high enthalpy fields as a stimulation attempt. The method is used both during completion of a well and after the drilling rig has been moved. The method basically involves that the well is allowed to warm-up for some time and then quickly cooled down again. As the fluid flow is mainly concentrated to few feed points the cooling affects those fractures and the rock around them most. The rock can contract during cooling while it expands during warm-up, but after repeated cycles the movement in the fracture may cause some repositioning that can affect the aperture leading to improved permeability. This method has proved very useful for many high enthalpy wells in Iceland. However, the improvement in permeability that can be expected from this method is generally observed in the first few cycles and in some cases it will not be enough to make the well economical. If that is the case only pressurization is left as a stimulation option.

Most commonly is pressurization applied to the rock formation by closing of portions of the wellbore with packers. In Iceland equipment for hydro-fracturing are not available and it would be very costly to import them from service companies for such operation. However, use of packers and pressure stimulation at relatively low pressures, generally well below the formation fracturing pressure have proven successful in many instances, mainly in low enthalpy fields in Iceland (Axelsson and Thorhallsson, 2009). Therefore, propellant deflagration with high energy gas flow (HEGF) is an appealing alternative method to put pressure on the rock formation at selected points.

For the trials with propellant stimulation carried out in Iceland, solid state fuel with two different energy content have been used. The solid state fuel units were 24" long x 2.4" diameter (61 cm x 6 cm) with energy content 14.2 MJ (3.4 Mcalories) and 27.5" long x 3.6" diameter (70 cm x 9 cm) with energy content 32.6 MJ (7.8 Mcalories). The carrying tools used can hold four fuel units and in all the described trials the tool was fully loaded. For the configuration used to control the burning time it was estimated that the burning time for the smaller units could be around 400 milliseconds and up to 600 milliseconds for the larger units. A schematic of the tool configuration is shown in Figure 4. The operation as has been applied in Iceland so far is straight forward. After the carrying canister has been loaded with the propellant fuel sticks it is brought to the work site. There or at the preparation site an inner tube with cuts along the tube for controlled weakening and loaded with detonating cord is placed through the center of the fuel sticks. Before lowering the tool to the wellbore on a wireline a shape charge holder is connected to the top of the canister. The carrying tool is then lowered to predefined depth and ignited. Basically no additional environmental impact is brought on the drilling operation by this method.

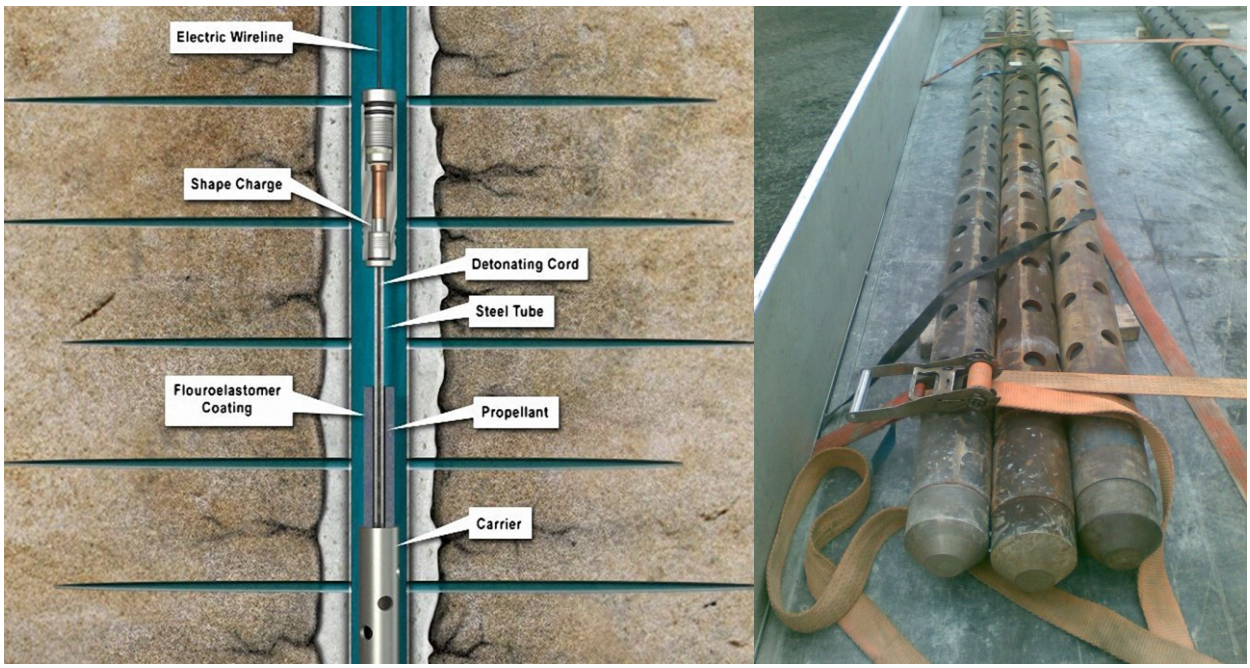

Figure 4: To the left is a cut away schematic of the propellant carrying tool showing the main components (courtesy of Precise Propellant Stimulation). To the right are 4.5" OD canisters on well side holding the larger diameter fuel units.

3. TRIAL WELLS

3.1 Well 29

Well 29 is located at the western outskirt of the Reykjanes field (Figure 5). It was drilled in between the eruptive fissures in the Stampar swarm that erupted last time in the 1220-1240's. The well was planned as a vertical well, but actually the well turned out more like a corkscrew where the inclination reaches a maximum of 5 degrees at 540 m before it drops down and brings the bottom of the well nearly in line with the top. The well was drilled to 2837 m depth and completed in June 2010 with 13-3/8" casing to 900 m and with 9-5/8" perforated liner to 2500 m depth and then barefoot to bottom. The nominal pipe length in the liner used at Reykjanes is about 12 m and it has about 100 perforations of 20 mm diameter per meter length, but about one meter at each joint is not perforated. The well had been drilled with aerated circulation water to reduce cutting losses to potential feed zones. At completion circulation loss was estimated around 80 L/s which for a static water level at about 300 m depth in cold conditions would correspond to an injectivity index about 2.7 L/s per bar. Short injection tests were carried out during the well completion that confirmed that the injectivity index was not higher than estimated from the circulation losses (Fig. 6). From experience and comparison with other wells in the field a short time step injectivity index estimate below 4 L/s per bar is an indication of a poor well. Therefore, preparation were made to attempt to stimulate well 29.

At that time the mother company had been introduced to propellant stimulation and had experienced positive and very promising results with it stimulating a well at Soda Lake in the U.S.A. in a sedimentary formations. It was foreseen that the necessary material for propellant stimulation could not be import to Iceland in time to be available at the time for well completion. Therefore, it was decided to spend some additional time to deepen the well while waiting on the material. Two short injection tests had been

made while the well was 2782 m deep after some extra cooling of the well, but as it was drilled with aerated circulation water it was warmer than if drilled with conventional circulation. One injection step on June 1 was over 5 hours in duration giving a good reference for the shorter steps. The drill bit put under for the deepening lasted only for 55 m so the final depth of the well was 2837 m. A short injection test was made after the drill string was out of the hole indicating similar conditions of the well. The well was then shut-in on June 8 for warm-up while waiting for the propellant material for the stimulation work. After two weeks of warm-up a temperature and pressure profiles were measured. Temperature was then over 210 °C in the depth interval where the main circulation losses were observed (1800-2400 m) and over 260 °C in the less permeable intervals.

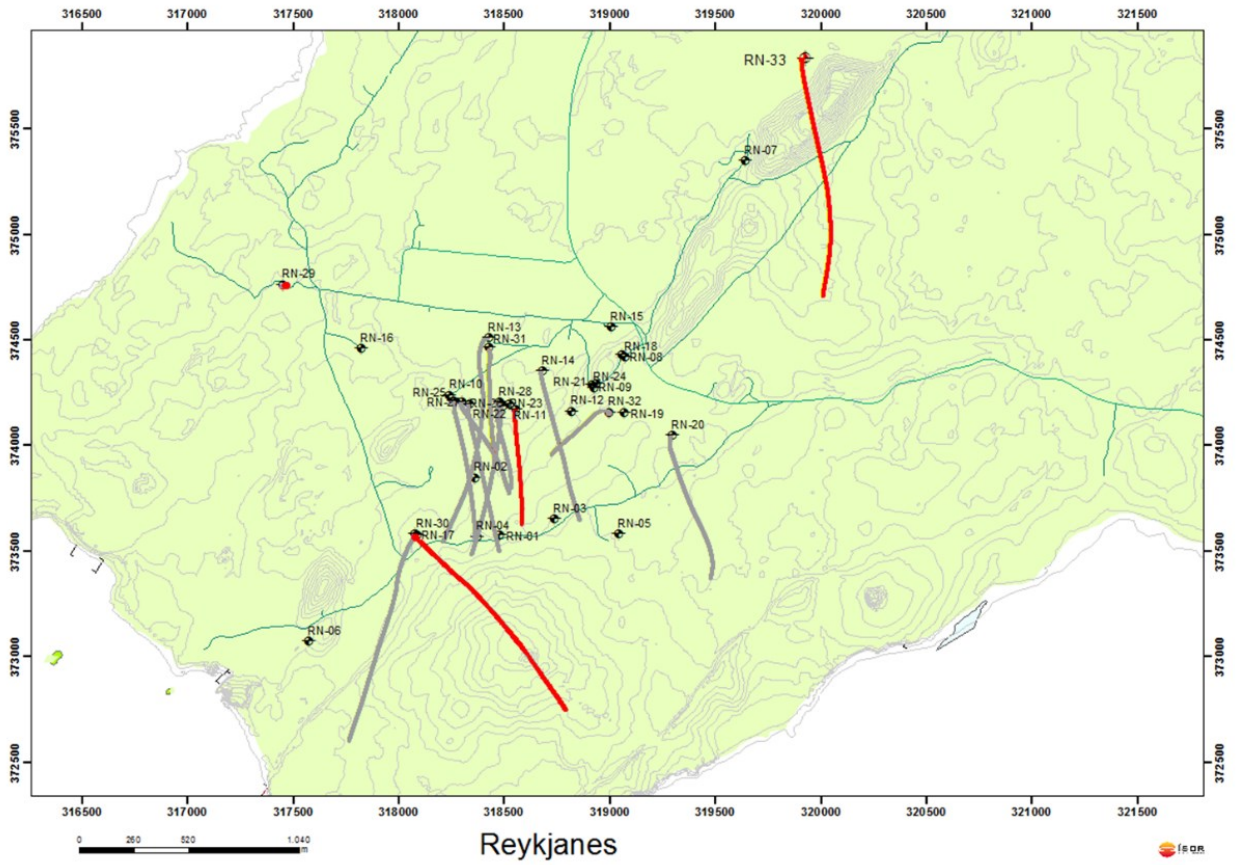

Figure 5: The well paths of the Reykjanes wells. In red are the well paths of wells 22, 30 and 33 while other well paths are in gray. Red dot to the WNW is well 29 and green lines are roads.

After the propellant material had arrived it was started to cool down the well on July 8. After the well had been cooled for five days while the perforated liner was set, a short injection test was carried out on July 13 for comparison and to see if the warm-up and cooling had increased the transmissivity of the well. The results are seen in Figure 6 where no marked changes in injectivity are observed. Propellant fuel units of the smaller diameter had been ordered. About six shooting locations had been selected in the well based on determination of potential feed zones from analysis of temperature profiles. The perforated liner was already in hole so CCL (casing collar locator) shooting tool was used to place the propellant carrying tool at the selected locations in the well and to avoid placing it near the liner joints. Three fully loaded canisters were deflagrated on July 13 at 2370 m and two times at 2130 m. A short injection test was carried out (Fig. 6) that did not show much improvement in injectivity, but was on the positive side. On July 14, two more canisters were deflagrated at 1960 m and 2040 m. An injection test was repeated that indicated that the injectivity had increased by at least 1 L/s per bar. The day after on July 15 three more canisters were deflagrated at 2270 m, 2160 m and 1780 m. With the last two runs a miniature data logger was located about 9 m above the deflagration canister taking readings at 1 second intervals. For the deflagration at 2160 m the logger indicated about 10 bar pressure drop in the well while it recorded some pressure and temperature increase during the deflagration. However, the injection test carried out afterwards did not support those changes and indicated that the injectivity was similar as the day before and had not increased more for these last shots.

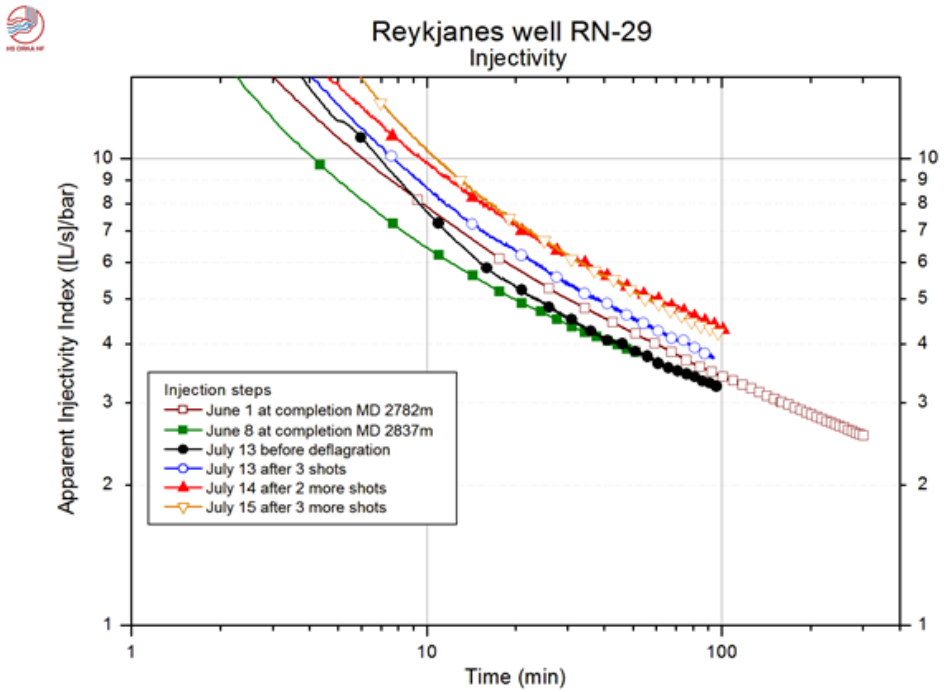

Figure 6: Change in injectivity at well 29 from drilling completion and during stimulation attempts.

The short time injectivity (1.5 hour reading) had increased by at least 1 L/s per bar from about 3.3 L/s per bar to about 4.3 L/s per bar while extrapolated longer term reading (5 hours) would give an injectivity index around 3.7 L/s per bar. The propellant stimulation had improved the transmissivity of well 29 beyond what was obtained by circulation cleaning and thermal shocking though the injectivity indicated the well to be marginal as economical producer.

3.2 Well 30

Well 30 is located in the southern part of the well field and was directionally drilled to 2869 m depth with an inclination up to 35 degrees towards SE. With that direction the well went slightly north of the center of the 3200 year old volcano Skalafell (Fig. 2). The well was completed in June 2011 with 13-3/8" casing to 1213 m depth and with 9-5/8" perforated liner to 2509 m depth. The well was first drilled to 2510 m depth and the liner set. Circulation losses were in the range 30-38 L/s which was not promising. A short injection test was performed, but the well filled up and the run off was not noticed so that test is not representative (Figure 7). After the liner was set three few meters long cores were taken down to 2532 m. The cores consisted of dolerite dikes and one fine-crystalline basalt dike. After the coring the well was deepened with 8-1/2" bit to total depth of 2869 m and that portion left barefoot. Circulation losses were about 30 L/s at end of drilling, but after overnight warm-up and then cooling the circulation losses went up to 60 L/s. Assuming a static water level around 300 m in cold conditions that loss indicated an injectivity around 2 L/s per bar so preparation were made for further stimulation attempts.

For this stimulation propellant fuel units of the larger diameter size had been ordered and were available at well completion. Three shooting locations were selected in the well for the first trial based on determination of potential feed zones from analysis of temperature profiles. The perforated liner was already in hole so CCL shooting tool was used to place the propellant carrying tool at the selected locations and to avoid placing it near the liner joints. Three fully loaded canisters were deflagrated on June 5 at depths 2495 m, 2086 m and 1933 m, but at 1933 m only half of the fuel in the canister burned due to damaged detonation cord. During the deflagration about 25 L/s were pumped in the well. A short injection test was carried out afterwards and as comparison allows with the earlier test there was little or no gain in injectivity after these shots. The apparent injectivity index read at short time (1.5 hour) was about 3.1 L/s per bar, but the test was far from stabilization so extrapolated reading (5 hours) would be around 1.9 L/s per bar (Figure 7).

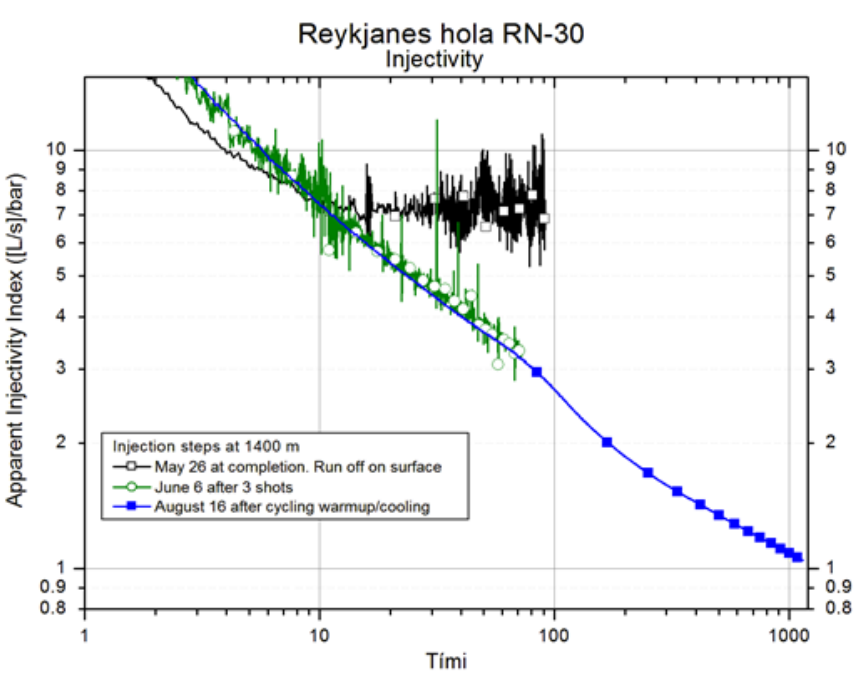

Figure 7: Change in injectivity at well 30 from drilling completion and during stimulation attempts.

Further stimulation of the well were attempted by allowing it to warm-up for about 9 days and cooling it for up to two weeks by injecting about 20 L/s on the top of the well. On August 15 the well was measured by lowering PT tool to 2070 m and let it sit there for about 19 hours while the well was cooled down. This gave a very long injection step (Fig. 7) which did not show signs of stabilization after such long time. Although the test is interfered with temperature changes it shows that several weeks of cycling warm-up and cooling had not improved the injectivity. It further indicated that the long term actual injectivity could be lower than 1 L/s per bar. On August 23 when the well had been cooled down propellant stimulation was repeated and a fully loaded canister deflagrated at 2488 m. A second canister located at 1936 m did not ignite due to malfunction with connection and when rerun into the well it got stuck inside the liner at 1713 m and broke of the cable. The carrying tool fell down and went below the liner. A third attempt was made on October 31 and two fully loaded canisters deflagrated at 1935 m and 1835 m. No injection test was made after those shots, but a miniature data logger was located about 5 m above the carrying tool that showed some pressure changes at 1935 m which could indicate some improvement for that shot. The injectivity index was still estimated to be low for well 30 or mostly about 2 L/s per bar. The propellant stimulation caused minimal improvement to the transmissivity at well 30.

3.3 Well 22

Well 22 is located in the central part of the main well field. The well was directionally drilled to 1680 m depth towards south and completed with 13-3/8" casing to 720 m and 9-5/8" perforated liner to 1647 m in January 2006. The well was a powerful producer in the beginning, but had declined considerably in 2009. The decline was thought to be related to scaling. A cleaning run was made in 2009 with drill bit down to the liner with the well discharging, but did not find any scaling inside the production casing. Another cleaning attempt was made in 2011. However, probing the well width with baskets (GO-devils) only indicated minor obstacles around 1518 m in the liner, but otherwise the liner appeared to be free of scaling inside. An experiment of trying to cool down the production casing slowly with cooling from below resulted in a kick clogging the string so the well had to be killed. Run with 8-1/2" drill bit through the liner did not encounter any scaling. As a final attempt to stimulate the well and possibly break scaling on outside of liner and on borehole wall three fully loaded canisters were deflagrated at 1575 m, 1167 m and 990 m. The larger diameter fuel units were used at 1575 m, but the smaller ones at the other depths. The conditions in the well were unstable so injection test was not performed and a short discharge test after this workover did not indicate much change in the well behavior. However, the test was inconclusive for evaluation of the propellant stimulation. The discharge rate was good, but the enthalpy lower than before making the wellhead pressure marginal for the collection system.

In 2013 an extensive workover, mostly for research purpose, was carried out on well 22. Interpretation of deep fluid sampling made early in the production history of the field predicted that sulfide scaling could be severe in the production wells. Surface sampling indicated the scaling to be less severe so a large discrepancy was between the chemical results. Different declining rates between wells had been attributed to this potential scaling so one of the goals for the workover was to get a better understanding of the scaling potential and behavior. Well 22 was killed for the workover which included pulling out the liner from the well, running in with initial bit size (12-1/4") and deepening it to 1822 m, under reaming most of the former production interval (960-1719 m), clean out cuttings from the reaming operation, propellant stimulation at 1578 m in open hole, and install new perforated liner to 1804 m.

Three short injection test were carried out during the workover that was completed in May 2013. The conditions in the well were unstable in the sense that there were inter zonal flow from shallower feed zones down to about 1200 m where most of the circulation water was also lost. Therefore, the deeper part of the well could be warming up or cooling depending on the circulation rate and depth of drill string. Temperature log made after the liner was set did not indicate changes in inter zonal flow or more cooling down to the shooting point. The results from the injection tests are shown in Figure 8. The first two tests are approaching

some stabilization but not the last one. All the test results in high injectivity, the lowest estimate from May 17 at about 15 L/s per bar. Extrapolated to longer times the results for all the test would be similar and around that estimate. When the well was newly drilled in 2006 its injectivity index was estimated about 13 L/s per bar so the tests indicate that the near well transmissivity is about the same as it was when the well was new.

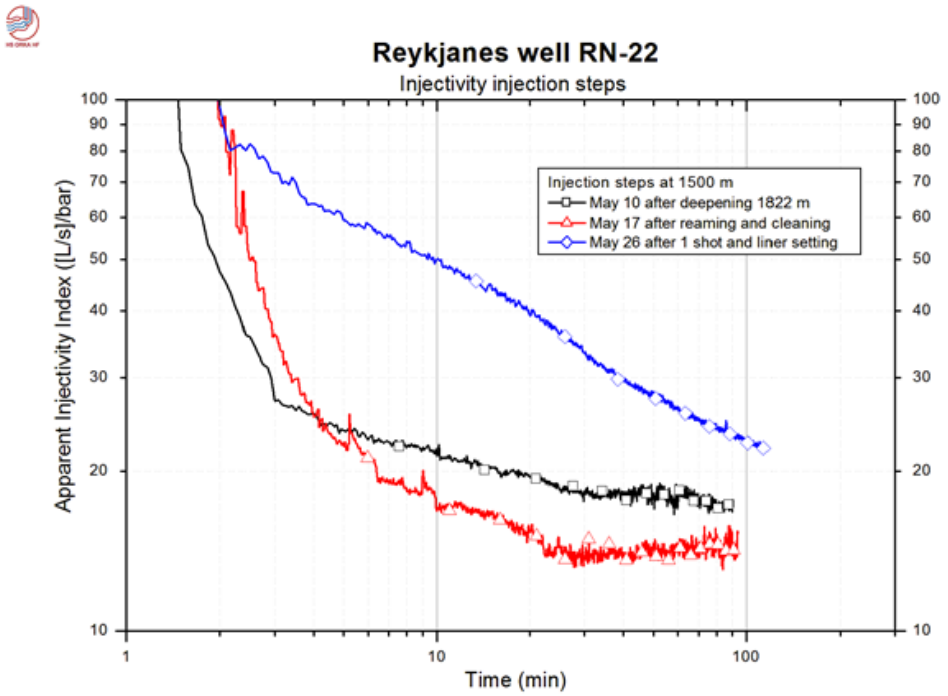

Figure 8: Change in injectivity at well 22 during workover operation in 2013. All tests made in unstable well conditions.

3.4 Well 33

Well 33 is located about 1.5 km NE of the main well field. It was directionally drilled with inclination up to 35 degrees towards just east of south to 2695 m depth and completed with 13-3/8" casing to 956 m and 9-5/8" perforated liner to 2645 m in November 2013. The well was drilled as an injection well. During drilling a total loss of circulation (> 70 L/s) occurred briefly at 1252 m depth, but when drilling was halted at 2530 m the circulation loss was only about 27 L/s which was not promising. The well was logged and a short injection test made that indicated that the injectivity was less than 0.8 L/s per bar (Figure 9). After a short warm-up and cooling cycle the circulation loss was up to 52 L/s. The well was filled with water and pressure applied by increasing the pump rate which gave an additional head of 56 bar. The wellhead pressure was monitored which still indicated low injectivity and after 6 hours it was about 0.7 L/s per bar. The circulation loss had increased to 56 L/s and after another warm-up cooling cycle it was up to 63 L/s when it was decided to deepen the well.

After the well had been drilled to final depth the circulation loss was around 35 L/s. The well was pressurized with oscillating pressure for pump rates between 60-110 L/s for nearly 20 hours. Indication were for some small increase in injectivity. Televiewer measurements were made over intervals with potential feed zones and locations of fractures selected for stimulation (Figures 10 and 11). Four fully loaded canister with propellant fuel of the larger diameter were deflagrated at 2248 m, 1909 m, 1556 m and 1239 m. The stimulation was made in an open hole and no collapse nor debris from it was observed in the hole. A local seismic network sensitive to M~0 did not pick up the shots and a geophone placed on top of the well did not pick out the shots from other noise. Afterwards cold circulation water was pumped in the well during the night and it was clear that the circulation loss was now more than the pumping capacity of 110 L/s. A short injection test was carried out before the liner was set which indicated injectivity over 2 L/s per bar (Fig. 9). After the liner was set an injection test with slightly longer steps confirmed that the injectivity was stabilizing around 2 L/s per bar or higher. The circulation loss for cold water was estimated at least about 130 L/s making the well useful as an injector.

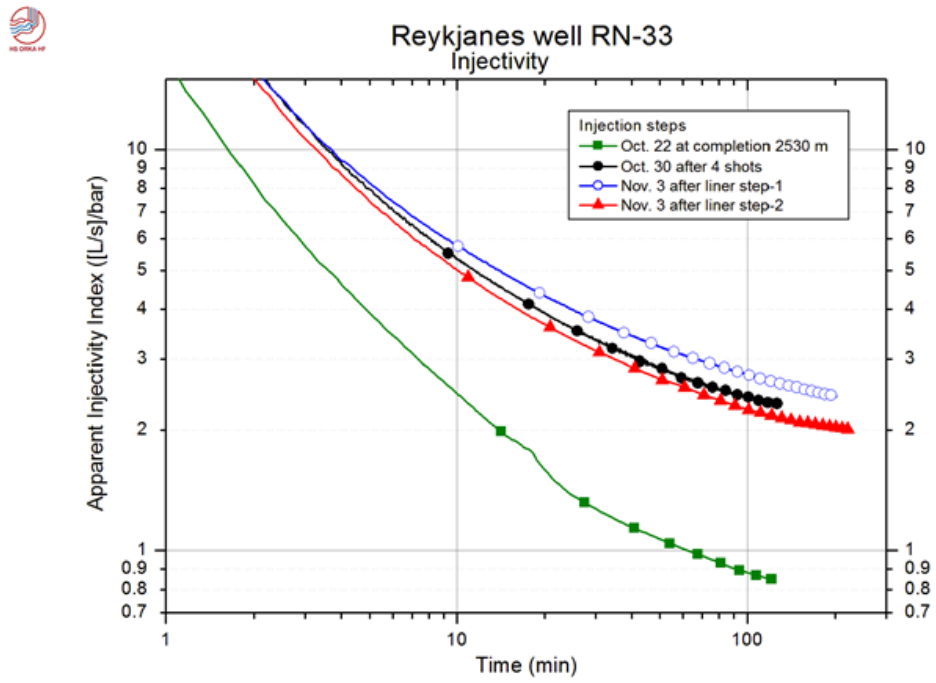

Figure 9: Change in injectivity at well 33 from completion and during stimulation attempts.

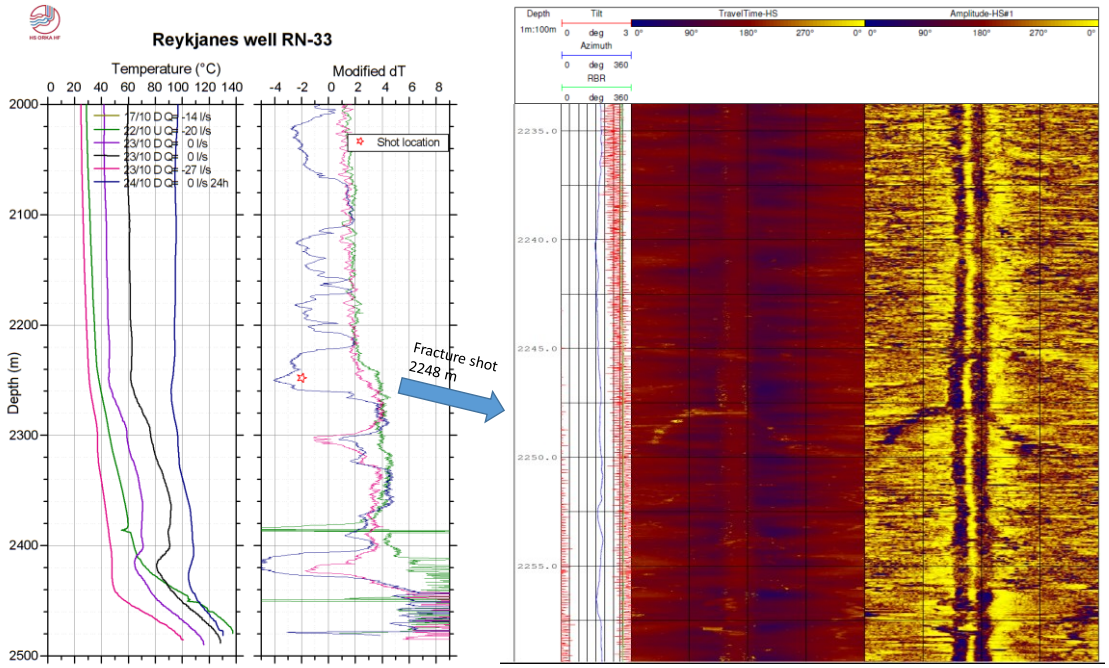

Figure 10: Sonic televiewer measurement over pre-assumed one of the better feed points in well 33 from interpretation of temperature logs. Selected temperature profiles and magnified temperature difference to the left.

4. DISCUSSION

Propellant stimulation has been applied at four wells at Reykjanes. Well 29 was drilled in between eruptive fractures at the Stampar swarm and the dikes in these fractures may cause restriction to the near well permeability. Use of the larger fuel units might have given slightly better results there. Well 30 appears to have been drilled into a low permeability region in the field. Temperature distribution in the field and recent work on subsidence with InSar images indicate less drainage from that part of the reservoir. It is therefore not clear if any type of stimulation would have improved that well much. Well 22 is a former production well and near well transmissivity appears to be similar as was earlier after the workover and stimulation operations. Therefore, there are other reservoir and operational factors that dictate its usefulness. Well 33 is planned as an injector and is outside the main reservoir. Fractured intervals are seen in sonic televiewer measurements made in the well, but many of them did not have much leakage. Therefore, the fractures could be blocked over some distance and near wellbore stimulation attempts would have limited effect in such instances.

For the configuration used the influenced interval affected by deflagrating the propellant fuel appears to be on the order of 2-3 times the length of the fuel sticks. In our case the carrying tools did hold four fuel units which for the larger diameter units equals to 2.75 m (9 ft.) in length. In the first three wells where the propellant stimulation was implemented the selected shooting locations were selected based on interpretation of temperature logs. Looking on Figure 11 one can see temperature logs and calculated magnified temperature difference. Several things can and do affect fluctuating locations of changes in temperature gradient, but clear and repeated observation of such change is generally interpreted as location of feed zone. Factors that influence such fluctuation between logging runs are; small errors in reference depth, different circulation rates that also affect cable tension, possibly slightly different activity of the feed zone (accumulation of cuttings) and possibly slightly changed interaction between feeds in the well. Pinpointing the feed zone location from such logs like in the figure can easily involve error on similar magnitude as the length of the propellant fuel. Therefore, the carrier tool may not have been located at the most effective location for the stimulation in all cases. Furthermore, the liner will likely have some damping effect on the pressure pulse that the formation feels. Looking at Figure 11 and comparing the temperature logs with the televiewer log it becomes much easier to determine the shooting location in the well.

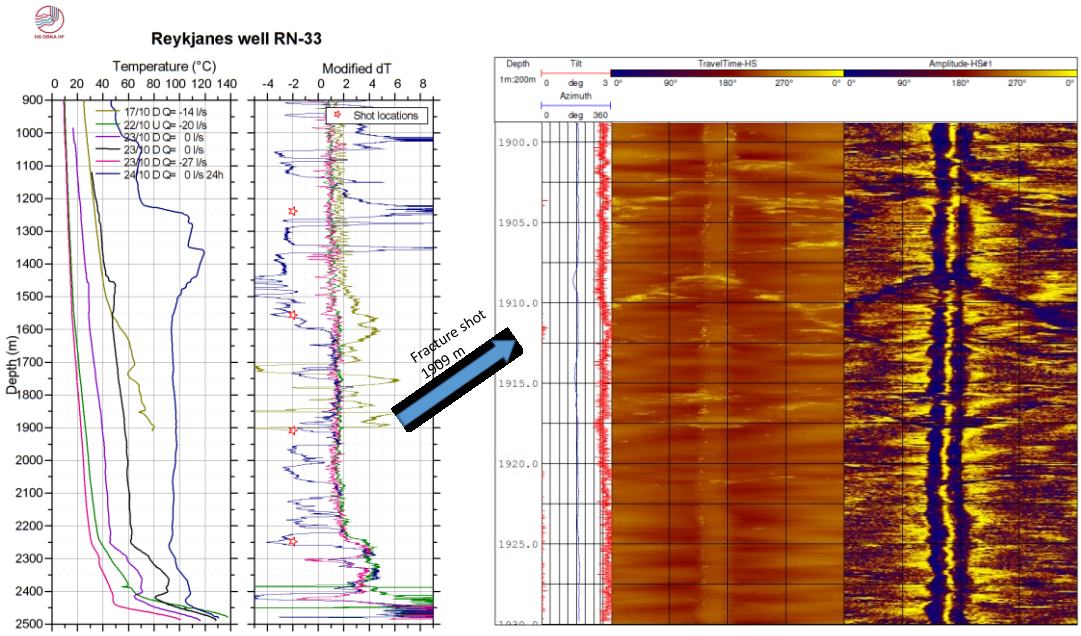

Figure 11: The sonic televiewer measurement shows at least three fractures over a short interval. Although the fracture at 1909 m is well defined it does not appear from the temperature logs to be much active for fluid flow.

As implied above stimulating a fracture which has some blockages further out that limit flow along it will have limited results. Where possible some form of hydraulic fracturing could help in such cases. Even though possibilities for hydraulic fracturing are limited in Iceland its effect has been kept in mind by applying high injection rates where possible after the stimulation. Furthermore, though the stimulated zone may not be much active after the stimulation, it may have created pathways that could possibly be stimulated further with warm-up and cooling cycles (thermal shocking).

5. CONCLUSIONS

It is clear in our mind from these experiments with the propellant stimulation that it has helped to increase the near well transmissivity. The increase in the above cases has not been as much as we had hoped for, but as mentioned other factors can have a role in that. The basaltic formations are fairly stiff where the main rock body has relatively low permeability (<1 mD) (Sigurdsson et al., 2000) and the main fluid flow is in fractures and micro fracture network or along weaknesses between layers. If the propellant fuel is placed against the rock body and even if it performs as expected when deflagrated the fractures it creates may not connect to the prevailing flow paths in the formation. Therefore, these experiments indicate that it is important for the success of the stimulation that the potential feed points can be determined and located accurately. Some evaluation of the potential feed points could help, but in the above cases it was not necessarily the predetermined strongest feeds that gave better results. The evaluation could take to conditions of formation i.e. type and alteration; type of feed, fracture or layer boundary; time open during drilling like could cuttings have collected into it.

In our case the results appeared to be improved when the potential feeds as selected from temperature logs were pinpointed by use of an imaging tool like televiewer. Furthermore, making the stimulation in open hole will use the full impact of it and it does not appear to decrease the stability of the borehole itself. After propellant stimulation it would be interesting to re-measure the stimulated interval with an imaging tool to see the change it has caused. That is something that we aim at were possible in our next trials.

The propellant stimulation method is most effective for the near wellbore permeability. Therefore, some follow up on it with some alternative stimulation when possible will maximize its results. In our cases we have applied circulation at high rate (>60 L/s) for

6-12 hours. Also thermal shocking by cycling warm-up and cooling of the well both with the drilling rig on the well and after it has been moved. It should also been considered to deflagrate more than once at a given location in the well.

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REFERENCES

Axelsson, G., and Thorhallsson, S., 2009: Review of Well Stimulation Operation in Iceland. *GRC Transaction*, Vol. 33, (2009), 795-800.

Bjornsson, S., Arnorsson, S., Tomasson, J., Olafsdottir, B., Jonsson, J., and Sigmundsson, S.G., 1971: Reykjanes – Heildarskýrsla um rannsókn jarðhitasvæðisins. (*Reykjanes – Final Report on Exploration*) (in Icelandic). Iceland Energy Authority, 122 p.

Fridleifsson, G.O. and Albertsson, A.L., 2000: Deep Geothermal Drilling on the Reykjanes Ridge Opportunity for International Collaboration. *Proceedings* World Geothermal Congress (2000), 3701-3706.

Sigurdsson, O., Gudmundsson, A., Fridleifsson, G.O., Franzson, H., Gudlaugsson, S.Th. and Stefansson, V., 2000: Database on Igneous Rock Properties in Icelandic Geothermal Systems. Status and Unexpected Results. *Proceedings* World Geothermal Congress (2000), 2881-2886.