

Servicing Geothermal Wells during Completion and Follow-up Monitoring

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ABSTRACT

Servicing geothermal production, injection and exploration wells at Iceland GeoSurvey begins with well siting and design. Siting and design are based on geophysical and geological investigations and measurements. To successfully drill and complete a geothermal well several factors have to be taken into account. Initially the contractor and the client (C&C) have to agree on what the criteria of success are and how to achieve them. After deciding on well design C&C have to select a fitting completion program for logging purposes. The geophysical logging implemented is chosen from a more or less standardized set of measuring programs with only slight variations as to what part of the well is to be logged during drilling. More than 20 specialists in the technical department and roughly 15 geologists, 6 logging trucks and some 60 tools are subject to careful planning as Iceland GeoSurvey undertakes 24-hour manning on drill-site, according to long-term schedules.

Monitoring measurements are not subject to the same strict manning schedule but in order to meet client requests swift and efficiently, slick-line trucks and manpower are also included in the aforementioned long-term schedules.

1. INTRODUCTION

Both geothermal drilling and geothermal logging have developed from the petroleum industry, Stefánsson and Steingrímsson (1980). However, there are major differences between these two types of logging concerning objectives, operation and interpretation. The main objective in geothermal logging is to locate fractures whereas in petroleum logging determination of porosity and hydrocarbon saturation are the main objectives. Therefore the petroleum logging know-how cannot be applied directly to the geothermal logging. Assessment of reservoir lithology and permeability is a common denominator for both types of logging, but basic differences exist since the geological settings for the majority of petroleum reservoirs are sedimentary rocks, whereas this is true for very few high temperature (HT) geothermal reservoirs.

Standard well logging instrumentation in the petroleum industry is capable of working at temperatures up to 150-180°C, which is too low for most geothermal logging. In Iceland temperatures up to 386°C have been recorded. Up until present this problem has been addressed by cooling the well bore but the process is costly and induces undesirable thermal stress on casings. In later years an increasing number of tools and cables have been developed for high temperature logging. One future development might be that the standard logging program is moved into HT logging only after the drill rig has left the well. Another scenario is that the logging tools are moved into the drill

string as it has been done in the oil and gas industry. In the last few years focus on cooling the production part of the geothermal wells has been increasing since alternating cooling and heating opens fractures thus improving well output but ongoing research seems to indicate fracture close-up with rising temperatures after cooling, Krístjánsson and Gunnarsson (2009).

Interpretation methods are relatively sophisticated in the petroleum industry. Developing and refining interpretation of logs from geothermal fields is still work in progress and in the latest years more interpretation programs have been developed but clearly the need for standardization is as great as ever and much can still be learned from the petroleum industry, Rider (1991).

The technical staff at Iceland GeoSurvey is very apt in dealing with special tasks and unforeseen problems during the drilling phase. With the introduction of directional (deviated) drilling an increase has been seen in cases of stuck drill string. The almost exponential increase in drilled wells per year, seen in the last decade (**Figure 1**), has meant a similar increase in logging, personnel, equipment and also a slight increase in tools lost in-hole (LIH) which can be accounted for mostly as a result of the increased activity.

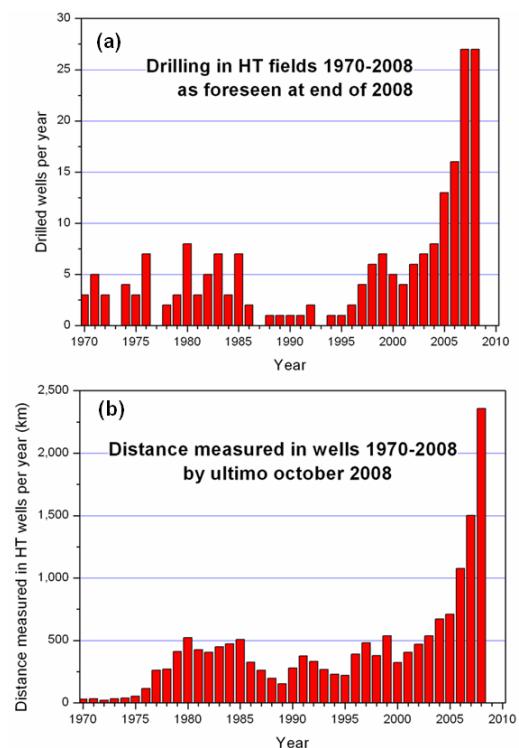


Figure 1: a) Number of drilled wells per year, from 1970 to 2008. b) Distance measured in wells under both low- and high-temperature conditions, for the same period. All data is from the Iceland GeoSurvey database.

2. PLANNING AND DESIGN

After initial geophysical and geological surface investigations and measurements are completed well siting can be localized and in the process the well design will be finalized suiting/complying with the chosen target.

2.1 Planning and Contracting

Once results from surface investigations are available and the site and target has been established the next step is to design the well to comply with the contractor's wishes and agree on a logging and completion program for the well. It is not the aim of this paper to cover the many details in planning contracts between C&C's. Thus the following table (**Table 1**) gives a very simplified overview. The actual programs are much more detailed and also include specific information on well diameter, casing sizes and material to be used, e.g. steel, cement or mud.

Table 1: Simplified completion and logging program.

| Stage | Drilling company | Iceland GeoSurvey – logging | Reports |
|-----------------------------|--|--|---|
| 1. Safety casing | Drilling and casing installation | Temperature, caliper, CBL, *neutron-neutron, natural gamma, resistivity | Daily progress, casing and cementing |
| 2. Production casing | Drilling, casing installation and main valve | Temperature, caliper, neutron-neutron, natural gamma, resistivity, CBL, #gyro | Daily progress, casing, cementing and #kick-off |
| 3. Production part | Drilling and liner installation | Temperature, caliper, neutron-neutron, natural gamma, resistivity, #gyro, pressure | Daily progress, #well path and liner |

*As a rule the lithological program is left out in the first stage, when overall knowledge of the field is abundant. Applies only when the well is deviated.

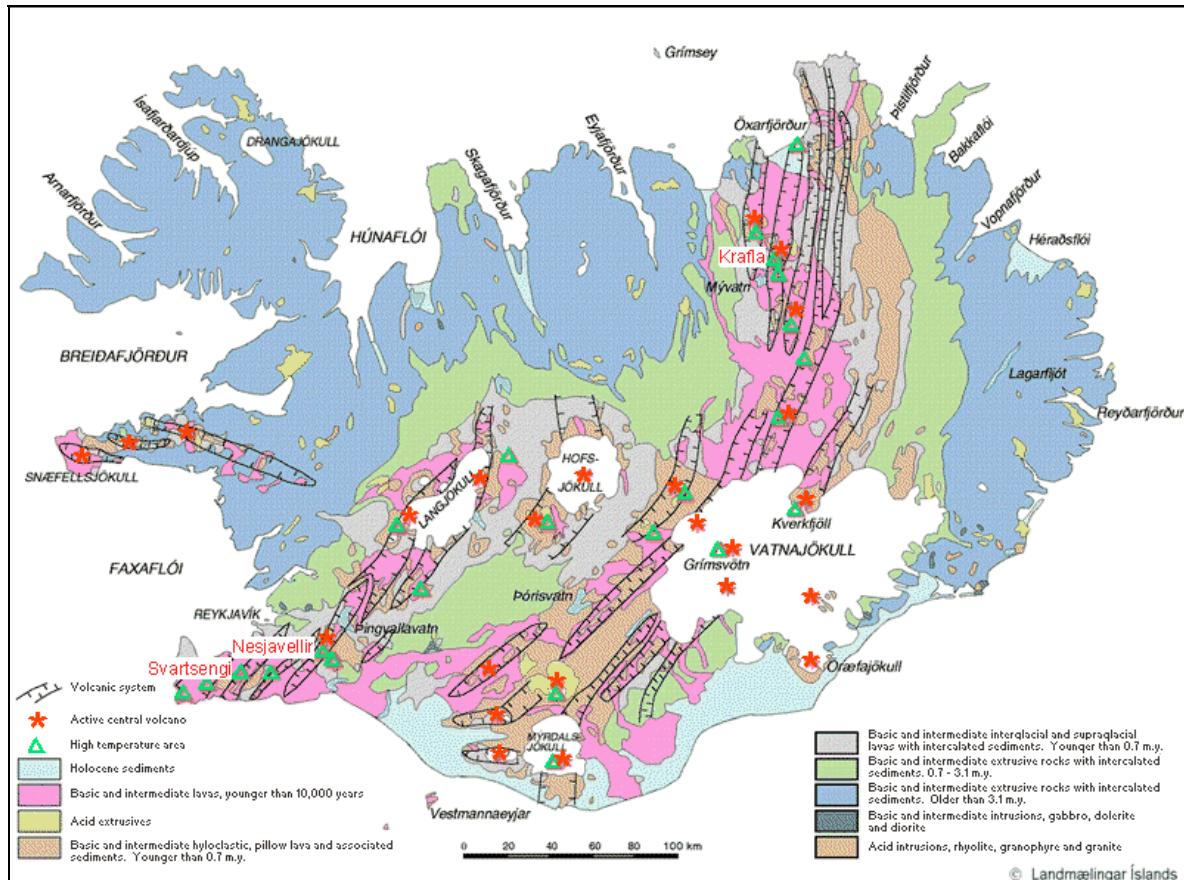


Figure 2: Map of Iceland showing Nesjavellir, Svartsengi and Krafla geothermal fields, located in the active volcanic zones.

2.2 Well Design

Designing HT geothermal wells has been standardized to a large extent during the last decades and two main designs are implemented in Iceland. The so-called "wide" program is completed in a 12-1/4" diameter section with a 9-5/8" liner. The wide program is mainly used for production wells in the fields owned by Reykjavik Energy (RE) and HS Orka (formerly Hitaveita Suðurnesja). These fields are situated in the South-Western corner of Iceland (**Figure 2**) where Nesjavellir and Svartsengi, respectively, are the fields with the longest production history. The so-called "slim" program is completed in a 10-3/4" diameter section with a 7-3/8" liner. The slim program is used by RE for exploration wells and as production wells by the Landsvirkjun company (LV). Situated in the North (**Figure 2**) Krafla is the field with the longest production history, exploited by LV.

3. LOGGING SERVICES WHILE DRILLING

The logging teams from Iceland GeoSurvey are on standby at all hours and man the logging trucks on a weekly basis, divided into 12 hour day and night shifts. This means that logging can continue non-stop and ensure that the contractor gets results and consultancy on a steady basis from trained experts. Last but not least it succeeds in saving the contractor costly rig time since the logging service package as a whole costs only a mere fraction of what it costs to pay the rig rate during idle time, Danielsen (2008).

During logging, quality and efficiency is of great importance. The head of the technical department together with the assistant head sees to the overall logistics in order to manage and supervise technicians, tools and trucks. On drill site it is the loggers on call that ensure that all regulations, safety rules and quality standards are followed. One illustrative example is that zero depth on a drill site is referenced to the rig floor. Since the drillers use rig floor as zero depth concerning geology (i.e. drill cuttings) and the real time drilling information (i.e. depth, torque, pump rate, circulations losses, hours of drilling etc.) everyone refers to the rig floor as zero depth and to minimize the possibility of misunderstandings. Loggers also uses rig floor as zero reference while logging during drilling. This procedure has been standardized and simplified with the introduction of the Warrior logging system from Scientific Data Systems (SDS), some two and a half years ago, since the system has built-in zero for each application. In the final well reports and subsequent HT monitoring logging, zero is moved down to ground level and all prior measurements and data thus corrected according to ground zero.

During the exploratory drilling phase determining borehole geology supported by geophysical well logging are the main tasks, which together with results from well testing make the basis for a revised geological and hydrological model of the reservoir, Mortensen and Flovenz (2008), and preliminary interpretation of logs and measurements on-site is needed. A brief reading of the different logs allows results to be interpreted on-site through collaboration between technicians, geologist and geophysicist. An explanation can be found in the following sub-sections, with the main emphasis on what Iceland GeoSurvey strives to comply with as a quality minded logging service company.

3.1 Temperature Logging

The temperature log (**Table 1**) is the most common log to run in any given well because it suits diverse purposes. The temperature log is mainly used to locate aquifers. Information on aquifers is very useful not only when locating the main in-flow for production purposes but also when the drilling company is cementing for casing purposes especially for very deep production casings where loss of circulation and powerful aquifers have to be known in order to ensure successful cementing for the whole length of the casing. The temperature log is also very important for the drillers as it makes it possible to monitor the maximum temperature at the bottom hole assembly (BHA). For instance while running a gyro in the drill string it is necessary to make sure neither bit, motor, MWD (measurement while drilling) nor any other part of the BHA exceeds temperature of maximum tolerance. Since most tools used in lithological logging today have considerably lower temperature tolerance than the temperature tools, the temperature log also gives the logging team important information as to what depth it is safe to run the various lithological tools which as a rule follow completion of each

drilling stage. The temperature log is run with a casing collar locator (CCL) sensor, and though the CCL log is used primarily for a practical application (counting connections in casing or drill string), it can also be a valuable addition to the lithological interpretation since it facilitates a relative estimate of the magnetic properties of the side rock.

3.2 Caliper Logging

Subsequent to the temperature log a caliper log is usually run (**Table 1**). On the basis of the measured width of the borehole from the caliper (diameter and cavities), drillers prepare for the cementing job (in the case of the two first stages only). As a rule of thumb twice the amount of cement will be available on-site, based on calculations from the caliper log. The drillers will have ample time to make all preparations while the remaining logs, such as the lithological logs, are run in the well. Besides using the caliper log for cement calculation purposes it is often applied when larger cavities or key-holes are troubling drilling progress in order to assist the drillers. Furthermore the log itself can be a useful addition to the lithological logs when interpretation of the geology for the final well report is being compiled.

3.3 Lithological Logging

All neutron-neutron (NN) and natural gamma tools (NG) run in Iceland (**Table 1**) are combined tools, acquiring two or three (dual neutron) log outputs. The neutron sensors measure the water content of the rock because H^+ atoms deflect neutron particles emitted from the radioactive source on the tool. Thus the porosity can be indirectly determined because high water content is indicated by high count rates and consequently relatively low porosity. The NN log furthermore gives an indication of the alteration stage of the minerals in the side rock. As a rule low NN API values indicates high alteration of basaltic rocks. The NG count originating from the side rock essentially reflects emission from the radioactive isotopes Potassium (K+), Thorium (Th) and Uranium (U). Emissions (K+) originates mainly from feldspar minerals in rhyolitic rock in Iceland but since Iceland is comprised overwhelmingly of volcanic rocks of basaltic composition, high NG counts are most likely indicators of rocks of rhyolitic composition, thus these are often used as stratigraphic markers in correlation between wells, Mostagel (1999). Thorium is common to most rocks and soils (average 12 ppm).

Since normal resistivity (NR) logging tools easily endure much higher temperatures than most neutron-neutron and natural gamma tools, they are usually run as the final log in the lithological logging program. The basic setup of a NR tool is three sensors; 16", 64" and SP (Self Potential) sensors where high resistivity generally indicates low porosity. The difference between the conductivity of the 16" and 64" sensors can be used quantitatively to estimate whether the formation is permeable or not, Johannessen (1972). It is essential for interpretation whether water based mud is used, as is the case only when drilling the first two stages of a geothermal well in Iceland, or only water, which is used in the production part, to avoid sealing of potential feed zones and lowering well output. The resistivity log also gives an indication of the alteration stage of the minerals in the side rock. As a general rule low resistivity will indicate low temperature minerals, such as smectite, zeolites and clays, whereas high resistivity will indicate high temperature alteration minerals, such as chlorite and epidote, Franzson et al. (2001).

As a later addition to lithological logging, the conductivity tool has been added. In a few fields in Iceland very low resistivity values are found which are close to or below the detection limit of the NR tool. The conductivity tool on the other hand has no problems with very low resistivity and has therefore been used with great success in these areas. The NR tool is still superior when it comes to HT tolerance.

3.4 Cement Bond Logging

With the completion of the lithological logging program the drillers will prepare installation and cementing of the casing as described in the above. In the case of the two first stages a Cement Bond Log (CBL) will then be run in the well to estimate the bond to the casing and the hardening of the cement (**Table 1**). When the cementing job is successful, a CBL is run to verify whether bonding of cement on the casing has begun and more importantly whether cement is present between casings, Rouillac (1994). If doubts arise as to the quality of the cement job more logs will be run and then it is also possible to estimate qualitatively how much hardening is progressing. The bonding to casing will deteriorate as soon as work on setting up the Christmas tree along with further drilling is done. Experiments done by Icelandic GeoSurvey has shown that it is still possible to get a relatively good estimate of the hardening after drilling and completion of the production part with the CBL as long as at least two CBLs has been done.

3.5 Directional Surveying

Directional drilling, hence directional surveying, has been an increasing element in geothermal exploration in Iceland during the last decade. Since Icelandic GeoSurvey undertook directional logging services three years ago, more than 80 wells has been logged successfully (**Table 1**). Two types of tools are in operation at present, one being a multi-shot true-north seeking tool from Stockholm Precision Tools (SPT), which is possible to run either as a wire-line SRO (surface read-out) application or in memory mode on a slick-line. The SPT tool is mainly used as a multi-shot tool, by Iceland GeoSurvey, for kick-off at the beginning of stage two and steering while completing build-up in the second stage, since it is easily and quickly deployed down-hole with very little preparation time. The German company System Entwicklungs GmbH (SEG) has developed the Target Inertial Navigation System tool (Target INS), which is also a true-north seeking tool. In early 2008 Flexit took over SEG and the tools are now marketed as Flexit Target INS. The SEG tool measures continuously while running in and out of the well and thus gives an on screen three dimensional survey. The SEG tool is mainly used in Iceland to survey the final well path. It takes longer time to deploy the SEG tool compared to the SPT tool, due to a lengthy calibration process but on the other hand the SEG tool has superior resolution and accuracy to the SPT tool. Since the SEG measures continuously while logging, it is actually faster to log deep wells (i.e. at depths below at least 1000 meters) than the SPT tool, since each measured point at depth needs a 1-3 minutes stop.

3.6 Pressure Logging

As seen in (**Table 1**) pressure is usually only logged after the well has been drilled to planned final depth. Transient injection step tests are then performed to estimate the injectivity index of the well. The injectivity index gives a rough idea of the corresponding productivity in megawatts (MW). Thus the result from the step-tests are used not only to decide whether to drill deeper in order to reach a more

permeable formation, but also give the contractor a rough idea of the MW output for use in further planning, Steingrimsson and Gudmundsson (2006).

3.7 Additional Logging

Besides the more or less standardized programs described in the above and shown in **Table 1**, Iceland GeoSurvey has also undertaken televue (TW), sonic and video logging in the resent years.

TW logs have proved to be very useful in locating fractures and shifts in lithology. Compared to other tools run in the lithological program, TW logs are time consuming and expensive. In Iceland however much if not all fluid flow in geothermal wells can be directly related to fractures and thus making the TW log a most useful addition to the ordinary lithological logs. The Sonic log can be used in estimating cement bond and hardening, much in the same way as the regular CBL tools but the main reason for adding the tool to the ordinary lithological program is to measure the bulk density of the side rock. Since the bulk density is a function of the porosity and matrix, it is then possible to calculate the porosity of the side rock assuming that fluid density and matrix density are known along the well bore. The tool has yet to be fully implemented in Iceland. The latest addition to Iceland GeoSurvey logging services is a borehole video camera. The camera features a lens with a vertical view and a lens with a 360° view perpendicular to the side-wall. The high quality and resolution enables close inspection of the casing, allowing estimation of precipitation rates or damage to the casing itself.

3.8 Special Case Scenarios

When endeavors are made to reach and tap the geothermal reservoir not everything always goes according to plan. Several well-known scenarios can occur while drilling, which has to be dealt with accordingly. If HT steam or high pressurized gases enters the well while drilling the risk of blow-out is great. The risk for underground blow-out is addressed by the drillers having fitted the well-head with the relevant blow-out preventers (BOP's) but on occasion careful interpretation of temperature logs might enable the loggers on-site to give the drillers an early warning.

Extreme acidic fluids have been encountered in Krafla field, where wells are drilled in close vicinity to the underlying magma and in the Reykjanes field, where mixing of meteoric water with a seawater component, makes the geothermal fluid extremely corrosive to most known metals and alloys used in drilling and logging applications (**Table 2**). It is obviously not feasible to change the fluid composition and thus measures have to be taken to deal with the problem of very corrosive geothermal fluids, Vaughn and Chaung (1981). These measures are still a work in progress.

An increase in stuck drill pipe has been seen with an increase of deviated wells being drilled and more pressure on drillers to deliver completed wells in less time. The problem usually arises when the well collapses on the drill string. In other words, a sudden pressure drop in the well makes the drill cuttings in suspension settle very quickly around the drill string. To deal with the issue when the drillers has been giving two to three days (as stipulated in the C&C contract) the normal procedure for Iceland GeoSurvey is to run a combined temperature and CCL tool. It is in itself a very simple but effective way to locate the fish but it also gives information to the loggers as to where

joints are situated and thus it can be decided where to place explosives (C4) if there's no other option than to back-off. More advanced tools such as the Free Point tool (FPT) exist and will most likely be added to Iceland GeoSurvey logging services in the near future. The basic idea of the FPT is to measure the torque or stretch on the drill string and thus enabling the logger to establish the deepest point of where the string is not stuck. Another well known problem often arises when drilling away from vertical (deviated) and that is a so-called key-hole. What can happen is that the well bore becomes increasingly ellipsoid (rather than circular) if the drill string starts to rub against the well bore. In some extreme cases this means that the drill string gets stuck when the drillers are trying to POOH (pull out of hole).

Table 2: Concentrations in steam from Krafla and Reykjanes geothermal fields

| Steam concentration | CL | CO ₂ | H ₂ S | pH | Max. recorded T (°C) |
|---------------------|---------------------|-----------------|------------------|-----|----------------------|
| Reykjanes* (mg/L) | 18000 - 20000 | 1000-2000 | 20-60 | 4.6 | 340 |
| Krafla** (mg/kg) | 1,6-250 | 3557 | 587 | 4.3 | 386 |

*Reykjanes: based on analyses from some 20 high-temperature wells.

**Krafla: based on analysis from one well but more wells are known to be of similar chemical composition. This particular environment becomes very corrosive when HCl begins to condensate from the steam.

Eventually the increase in logging also means increased risk of LIH. If the loggers do not succeed themselves in fishing the lost tool the drillers will go in with a suitable fishing tool on the drill string, trying to hook the logging tool. When everything fails and the fish is deemed lost for good the drillers will go down with milling equipment and remove the fish. When metal shards stop appearing in the drill cuttings, the normal routine of drilling can continue.

In the last years experiments have been made with stimulating wells while the drill rig is still on-site and thus using very powerful pumps and vast amounts of water, Steingrimsson and Gudmundsson (2006). As a rule, the stimulation is proceeded by a short step-test prior to the "real" transient step-test program. That way it is possible to evaluate improvement of injection, if any. In many cases an increase in the injectivity index has been seen but the data is not conclusive and more studies need to be done on the validity of spending valuable rig time on stimulation. Presently one contractor (RE) in Iceland is using coiled tubing to stimulate the well after the rig has been moved, saving a lot of money and seemingly getting much the same stimulation results.

When a well has been completed all measurements and activities surrounding the drilling and logging are collected in a number of final reports, usually one for each drilling stage. Here all relevant information concerning a given well in a certain stage of drilling are tied together, and the interpretation of the lithology is especially elaborated on. This means correction of data and, as mentioned in the above, adjusting depth zero to ground level.

4. WELL MONITORING AND TESTING

During drilling, mud and cold water are used for circulation and cooling and therefore temperature in the well at the end of drilling is much lower than that of the surrounding reservoir. Due to heat conduction the temperature begins to rise as soon as pumping is stopped. The warm-up period for a given well to reach equilibrium can be as long as several months. During this time measurements of water table and well head pressure are monitored. Furthermore down-hole temperature and pressure measurements are done by using HT Dewar flask electronic memory temperature and pressure tools. The standard at Iceland GeoSurvey for decades has been the mechanical tools from either Amerada or Kuster but recently data quality and resolution has increased immensely with the addition of the K10 Geothermal tool from Kuster Co., Danielsen (2008), to our HT logging tool services.

During recovery the water in the well expands as it warms up, indicated by increased well head pressure. Logging down-hole temperature provides data to estimate the true formation temperature as a function of depth. The down-hole pressure log will indicate where the well is best connected to the reservoir (pivot point), Steingrimsson and Gudmundsson (2006).

When recovery has been reached it is necessary to perform discharge or flow tests to determine the well characteristics and the chemistry of the fluid discharged from the well. Testing of flowing wells is in principle very similar to testing when injecting cold water. Three steps are usually taken controlled by either closing the main valve in small steps or opening it, depending on well performance.

Not all wells are production wells and a major issue is to re-inject into the geothermal reservoir both in order to replenish the reservoir but also for environmental reasons. Preliminary results (not yet published) from tests done in two injection wells owned by RE indicate that the injectivity index is highly influenced by the temperature of the injected fluid. Early results indicate a nearly linear relation between temperature and injectivity index, Krístjánsson and Gunnarsson (2009).

5. LONG-TERM PLANNING

As previously mentioned, the need for standardization is as great as ever and part of the effort needed in establishing this is a rigorous evaluation program where long term planning and re-assessment of applied tools, techniques, appliances and procedures, plays a critical role.

6. CONCLUSIONS

Abundant work is already at hand, for example Franzson et al. (2001), Mostagel (1999) and Waagestein et al. (2003) as referred to in this paper as well as many others, but the need for work on standardized interpretation and correlation of lithological logs of volcanic rocks in geothermal settings as Rider (1991) has done on sedimentary rocks for the oil industry, is pressing.

In case of exploring for low temperature fields heat flow measurements are also important as well as geophysical methods to detect water-bearing fractures. The exploratory work leads to a conceptual model of the geothermal field to be tested by exploratory drilling, Mortensen and Florenz (2008).

REFERENCES

- Danielsen, P.E.: High Temperature Geothermal Logging for Temperature and Pressure, Conference, ARGeo C-2, Entebbe, Uganda (2008).
- Franzson, H., Guðlaugsson, S.P. and Friðleifsson, G.Ó.: Petrophysical Properties of Icelandic Rocks, Proceedings of the 6th Nordic Symposium on Petrophysics, NTNU, Trondheim, Norway (2001).
- Johannesen, J.H.: Borhullslogging, Compendium, University of Bergen, p. 126 (1972).
- Krístjánsson, B.R. and Gunnarsson, G.: Re-injection of waste fluid from Hellisheiði Geothermal Power Plant, Report in Icelandic, Orkuveita Reykjavíkur, 2009-24 (2009).
- Mortensen, A.K. and Florenz, O.G.: The geo-scientific role in the harnessing of high temperature geothermal fields in Iceland, Conference, 33rd IGC, Oslo, Norway (2008).
- Mostagel, B.: Processing and Interpretation of Geophysical Well Logs from Well KJ-32, Krafla Geothermal Field, NE-Iceland, Report Nr. 8, United Nations University, Geothermal Training Programme, p. 193-219 (1999).
- Rider, M. H.: The Geological Interpretation of Well Logs, revised edition, Whittles Publishing, Caithness, England, p. 175 (1991).
- Rouillac, D.: Cement Evaluation Logging Handbook, p. 155 (1994).
- Stefánsson, V. and Steingrímsson, B.: Geothermal Logging I, An Introduction to techniques and interpretation, Report, OS80017/JHD09, p. 117 (1980).
- Steingrímsson, B. and Gudmundsson, Á.: Geothermal Borehole Investigations during and after Drilling, Presentation, Workshop for Decision Makers on Geothermal Projects in Central America, San Salvador, El Salvador (2006).
- Waagstein, R., Boldreel, L.O. and Andersen, C.: An integrated petrophysical approach to the sub-basalt imaging problem using well logging data to link measurements from cores and seismic surface experiments. Geophysical Research Abstracts 5(09388), SEIFABA (2003).
- Waughn, G.L., and Chaung, H-E.: Wireline materials for sour services. The International Corrosion Forum, April 6-10, paper nr. 182, Toronto, Ontario, Canada (1981)