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Geothermal Data Collection and Consultancy at Drill Site

Ásgrímur Gudmundsson

Iceland GeoSurvey, Grensásveg 9, 108 Reykjavík, Iceland

asg@isor.is

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ABSTRACT

The history of geothermal investigations in high temperature areas spans over 50 years and involves projects in Iceland and abroad. Initially surface exploration is carried out by mapping the research area employing several methods based on geology, geochemistry and geophysics. The results are generally presented as a preliminary conceptual model of the area. The next phase in the research program is to drill exploration wells. Carrying out the exploration program requires geothermal knowledge both of the drilling crew and the research team. The design program for the wells has been rather consistent through the years as well as the research program, but even so progressively developed. The standard procedure for drill site investigations has for the last decades comprised a team of geologists and geophysicists as geothermal consultants. The main task of the geologist is to analyse the drill cuttings to provide information about the geological formation drilled into, prepare lithological logs and map the distribution of the alteration minerals. Furthermore, the geologist also gathers all data concerning the drilling procedure, including measurements of the circulation fluid, technical parameters such as weight on the bit, penetration rate, rotation of the bit and the torque. The geophysicist and the logging engineer run all necessary downhole logs, mostly temperature logs during drilling. A standard program is performed prior to casing consisting of temperature-, resistivity-, neutron-neutron-, natural gamma- and calliper logs is carried out. After cementing a casing a CBL (cement bond log) is a standard procedure to confirm a job successfully done. The completion program at the end of drilling includes the aforementioned logging program as well as an injection test and stimulation if required. The geologist and the geophysics evaluate all the data concerning the drilling project as a team in collaboration with the drilling engineer and a company representative. The intensive geothermal drilling in the last three decades in Iceland has led to significant innovation in drilling technology, exploration strategy and geothermal research.

1. INTRODUCTION

The Icelandic legislation on national resources has been developed in recent decades and has among other things emphasized the importance of a comprehensive central geological database. Orkustofnun (The National Energy Authority) fulfils various obligations to keep the database in proper order. Concerning drilling, the following is quoted from the legislation "If Orkustofnun insists, the drilling companies are obligated to deliver copy of their daily reports. Furthermore Orkustofnun can also demand that drill cores and cuttings should be preserved."

In the past, drill cuttings were only collected every two meters in the wells if specifically demanded by Orkustofnun, but over the years it has become a standard practice to sample the cuttings that way. A Geolograph was used in deep drilling projects to monitor drilling rate, weight on bit and pressure of the pumps and other parameters recorded regularly like pressure of the pumps, pump rate of circulation water, circulation losses, temperature of the circulation water and others if necessary. In other drilling projects the drilling rate was calculated for every hour as well as maximum and minimum values for other parameters. In recent years such recording has mostly been computerized and visualised continuously on monitors.

Geothermal drilling activity increased enormously as a consequence of the oil crises in the early nineteen seventies. The Icelandic government decided to place emphasis on domestic resources especially geothermal energy to lower the cost of imported fuel for space heating and related energy consumption. Drilling was started in explored geothermal fields and an exploration program for other areas was established. Comprehensive geological and geophysical surveys were carried out. The potential was great and by the end of the last century 87% of domestic space was heated by geothermal energy and electricity production from geothermal resources had been increased significantly (Fig. 1) (Ragnarsson et 2004).

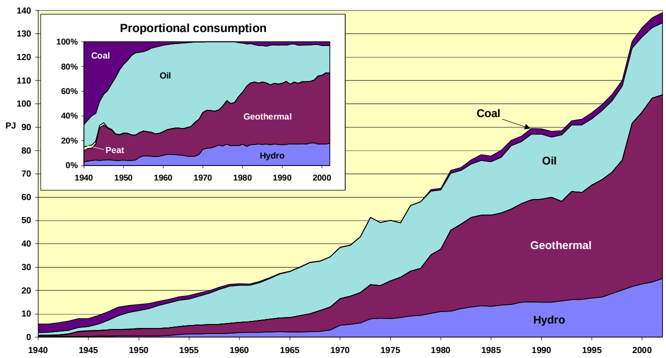

Figure 1: Primary energy consumption in Iceland 1940-2002.

The longest accumulated drilling per year was around 40 km (Fig. 2). It is equivalent to 20 thousand samples to analyze and obtain related data for interpretation. Several borehole geologists and geophysicists were trained to carry out (1) the analysis, mainly to prepare composite logs of the wells and create conceptual models of the geothermal areas and (2) consultancy at drill site. Apart from the analysis of the drill cuttings several downhole logs were run in the wells sometimes with different purposes. Temperature- and pressure logs were most common. In the late seventies some lithological log instruments were purchased to improve the interpretation of borehole geological data and it became a standard procedure to run caliper, neutron-neutron, gamma-ray and 16" and 64" resistivity logs. Furthermore the CBL-technique was adopted to confirm successful cementing and to locate cement behind a casing if perforation of a casing is needed.

The consultancy at drill site demands a good general knowledge of geothermal exploration and understanding of geothermal practices and experience in the analysis of the data collected.

This paper covers the methods used by a drill site geologist/geophysicist to evaluate the data collected.

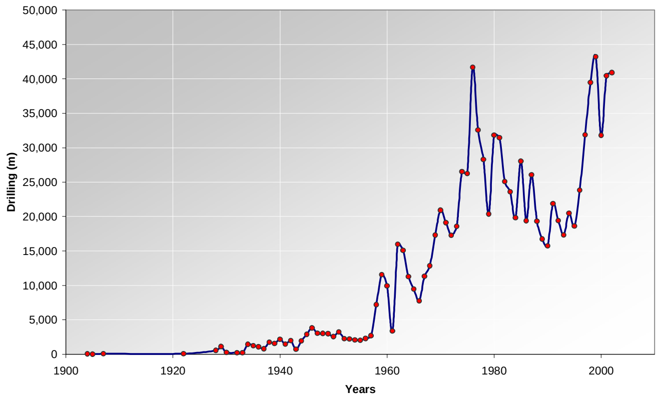

Figure 2: Drilled meters per year in the 20th century.

2. ANALYSIS OF DRILL CUTTINGS

The work procedure has been gradually changing during the last decades, but the basic method is to analyse the cuttings and prepare lithologcal and alteration logs. The instrument used for analysis of cuttings at drill site is a binocular microscope, but if the situation requires, XRD-analyses can be performed within 24 hours. Beyond the main purpose of cutting analysis there are other things pertinent at the drill site, such as an identification of a possible collapse in a well, metal fragment contamination in the cuttings to trace malfunction in the drillstring, the structure of the fragments to assess the condition of the bit. However the main purpose is to analyse the strata, which are penetrated and identify the secondary minerals. During drilling in high-temperature areas it is important to evaluate simultaneously the formation temperature by identifying some index minerals. Specific secondary temperature dependent minerals known as index minerals are listed in Table 1, but the list is not exhaustive. The temperature values are mostly based on geothermal empirical work in Iceland from 1970 up to the present (Kristmannsdottir 1979, Franzson 1998). The minerals anomalies where low- or medium temperature minerals appear with others, which are stable at high temperatures, are sometimes observed in mineral assemblages. This can be evidence of cooling in the geothermal reservoir either transient or long term. Overprinting of calcite is the most common indication of a cooling event. On the other hand if calcite disappears it is evidence of temperatures close to the boiling point depth curve. The relative high quantity of fracture fillings is a good indicator of past or present permeability. A high abundance of the secondary mineral pyrite is good evidence of good permeability. Pyrite is more abundant in the uppermost 1000 m where the variance in temperature is from 100–300 °C, but relative abundance where temperature is above 300 °C shows as well a good correlation with aquifers (Gudmundsson 1993). The appearance of certain secondary minerals is due to their temperature stability in the reservoir often the main criterion in deciding casing and final depths of wells.

The secondary minerals in Table 1 can be identified with good confidence either by recognizing crystal structure or determinant colors. The appearance of the minerals can vary form perfect formed crystal structure to almost amorphous mass. Some crystals like calcite can show many variances like platy calcite, “dog tooth” and Icelandic spar. However it can always be identified by the use of hydrochloric acid.

Table 1. Some temperature dependant minerals in high temperature areas in Iceland.

Minerals	Min. temp. °C	Max. temp. °C
zeolites	40	120
*laumontite	120	180
quartz	180	>300
*wairakite	200	
smectite		<200
**MLC	200	230
chlorite	230	>300
calcite	50-100	280-300
prehnite	240	>300
epidote	230-250	>300
wollastonite	260	>300
actinolite	280	>300

*Belong to the zeolite group.
**Mixed layer clay.

Mapping the subsurface stratigraphy is a direct continuation of surface geology mapping. The first exploration well shows the main formation penetrated to some depth and extends the first model into the geothermal reservoir; including porosity, permeable zones and chemical composition of the rock. The first wells are located to confirm the geological and geochemical interpretation of the surface exploration. Furthermore drill cuttings together with geophysical logs (Fig. 3) allow extrapolation with more confidence of tectonic features to some depth and evaluation of the intensity of intrusions.

Observations in Icelandic geothermal systems have revealed fractures and intrusions to be the main conductors of the geothermal fluid but generally the matrix permeability is low, but on the other hand the porosity appears to be high (5-30%). The actual design of the first well in a geothermal field is continuously under consideration during drilling. Information about the formations appears consistently and decisions on how to proceed need to be based on analysis of cuttings together with permeability (measured circulation losses). The first step is drilling for the surface casing, which prevents collapse of loose material from the surface layers into the well. A common depth for this step is 60–100 m. The second step is drilling for the anchor casing and the third one is for the production casing typically down to 200-400 m and 700-1100 m depth respectively. In each of these steps it is essential to locate the casing shoe in a solid formation. The alteration temperature along with the anticipated pressure drawdown and the expected pressure in the deepest aquifers are the main criteria for the length of the production casing.

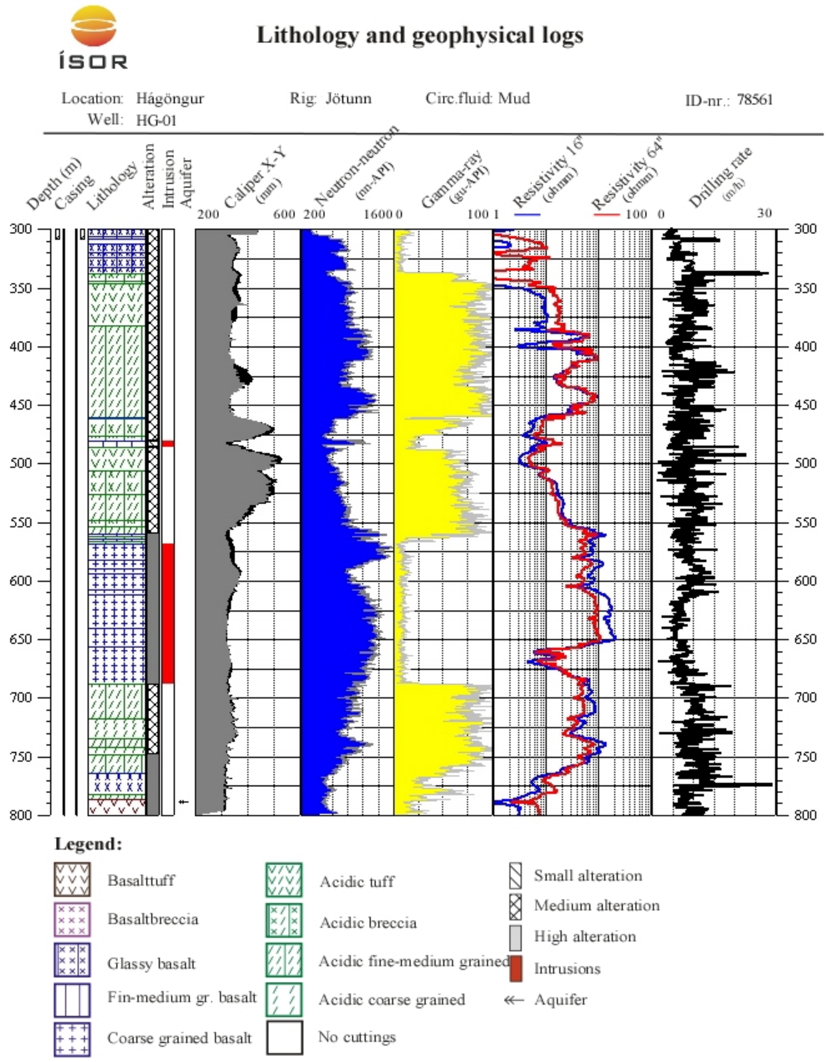

Figure 3: Example of composite logs in high temperature well in Iceland.

3. MONITORING OF DRILLING DATA

The main goal in geothermal production drilling is to locate permeable zones with desirable physical characteristics to utilize. In some cases information on the reservoir is limited to a predicted temperature from geothermometry but in others there are some more definite targets. Monitoring the drilling data serves the main purpose in gather together all possible information during the drilling operation. Beyond the analysis of the cuttings and the penetration rate significant information can been attained from the circulation fluid and related drilling data. Parameters that are presently recorded continuously versus time are: depth, total weight of the drill string, weight on the bit, rotation of the bit (rotary and motor if used), penetration rate, torque of the drill string, height of the elevator (top drive), pressure of the pumps, pump rate of the circulation fluid, fluid temperature down, fluid temperature up and the fluid differential temperature. Besides, there are some other technical parameters for the rig. The geothermal data collection has been divided into four main categories:

- ♣ Measuring the gain or loss of the circulation fluid.
- ♣ Measuring the temperature of the circulation fluid up and down.
- ♣ Measuring the amount of the circulation fluid pumped down and the pressure of the pumps.
- ♣ To measure the temperature close to the bit while drilling (MWD).

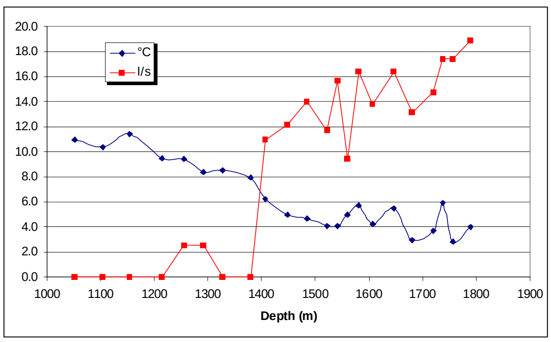

Figure 4: Circulation loss and differential temperature of the circulation fluid.

The last one is obviously related to the MWD-tools. Furthermore the circulation loss, which is one of the basic parameters, is still found by direct measurements and so far no reliable continuous recording technique has been applicable. These are done at least once every four hours by the drillers.

Two independent parameters observed during the drilling of the production part of well 34 in the Krafla high temperature geothermal area are shown in Fig. 5. The slow gradual decline in the differential temperature is an indication of some permeability. But the sharp decrease at the same depth interval where the first significant circulation loss is observed confirms that a good aquifer was crossed, due to the increased need of cold water into the circulation system. Continuous lowering of the differential temperature verifies permeability but does not imply anything about the formation temperature, which in this case is close to the boiling point curve as was measured later during the warming up period.

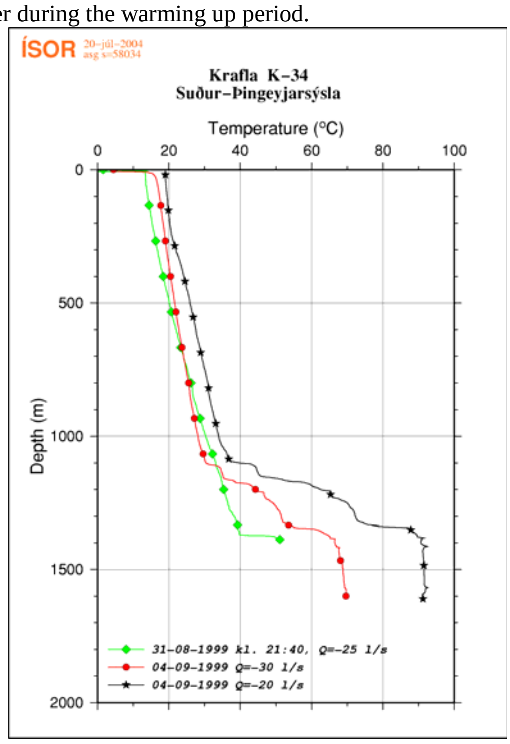

Figure 5: Temperature logs during drilling of the production part in well 34 in Krafla.

Fig. 5 shows temperature logs during short intermissions in the drilling of this particular well. The well is cooled during each run of 25, 30 and 20 l/s respectively by injecting cold water through the annulus. These temperature logs indicate a temporarily chilled reservoir and very strong evidence of the location of feed points, even many points of inflow of aquifers into the well and down towards the major bottom aquifer. Temperature logs during the warming-up period after drilling were closer to formation temperatures (~300°C) predicted from the alteration mineral assemblage.

An opportunity arose to monitor MWD-temperature close to the drill bit along with the others parameters mentioned above during drilling of the production part of well 29 in Krafla. The temperature readings did have a low resolution but under these circumstances were adequate. The shape of the curve showed steady temperature readings until in the deepest part of the well, below 1900 m depth (Fig. 6), where a gradual increase was seen. Based on this information it was predicted that the MWD-data provided valuable information about permeability in the section the drill bit penetrated. The results of temperature logging during the completion of the well confirmed this prediction. Comparison of these two data sets showed roughly the same character, i.e. an impermeable section below 1900 m depth, while data on the circulation loss and differential temperature of the fluid down and up might on the other hand be interpreted to indicate continuous permeability to the bottom of the well. The readings from the MTW-equipment were obtained during drilling by signals through the drilling fluid and was stored in a memory tool in the BHA as well.

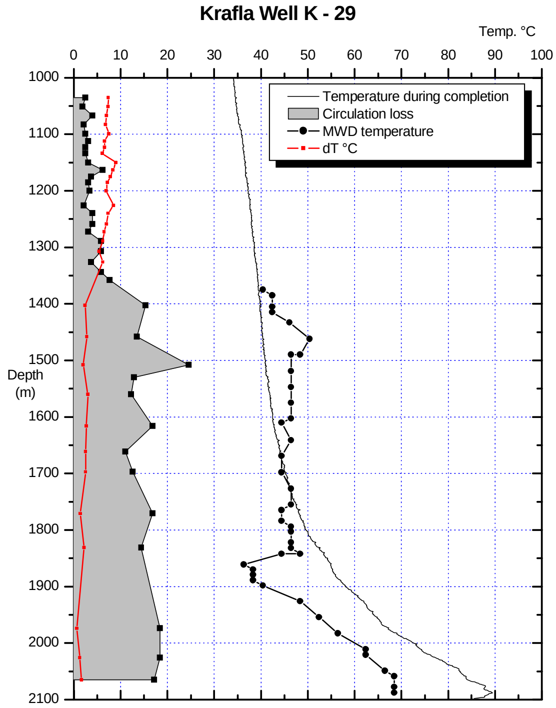

Figure 6: Data achieved from the drilling of the production part of well 29 in Krafla.

Pressure on the pumps is a valuable parameter to monitor during the drilling operation. If the pressure drops without any change in water flow in the pumping circuit, it can mean (1) a transient circulation loss (2) a total circulation loss (3) a hole or some other damage in the drillstring. The first consideration is the drillstring and if it is found to be in a proper condition then the second is to locate the permeable zone, which was penetrated.

However it is common to drill several hundreds meters with total circulation loss (blind drilling). In such cases the most reliable parameter to monitor is the water flowrate and the pressure on the pumps. Any variation in pressure with constant water flow implies changes in the well conditions. If the pressure drops and continues thus it can be a significant indication of a new aquifer penetrated by the bit. The graph in Fig. 7 demonstrates the pump-pressure and the flow rate from a continuous recording system during total circulation loss drilling in well HE-12 at Hellisheidi at 30 m depth intervals below 1730 m. Polymers reduce drastically the resistance in the circulation fluid circuit as can be seen in the graph., If drilling is with total circulation loss polymer pills are pumped in periodically, to minimise the risk of the operation. The 9.5 bar pressure drop at 1736 m depth, at approximately constant flow rate, is an indication of an aquifer which was penetrated. The observation of a lower pump-pressure further down at the same or even a higher pumping rate supports this interpretation. Another pressure drop seen at 1756 m depth although of a smaller magnitude is also an indication of a new aquifer or reopening of another above. In both cases the first response was to confirm if the drill string was in order.

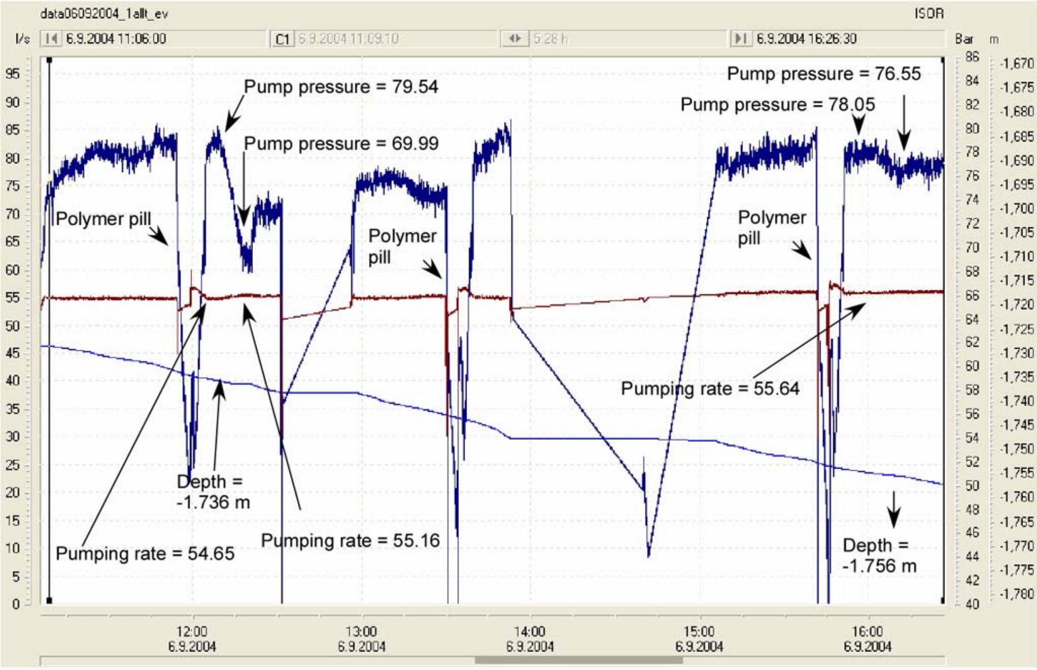

Figure 7: Monitoring flow rate and pressure on the drilling pumps in blind drilling, while aquifer were intersected.

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4. WIRE LINE LOGGING DURING DRILLING

In the high temperature drilling program in Iceland it is always anticipated that the well be logged on most occasions to obtain as much information as possible on the condition of the well and the reservoir. Generally the logging-truck is at drill site and available 24 hours of the day. If the drilling stops for some reason and the drill string is pulled out of the well a temperature log is run to locate the aquifers, particularly the deepest one. It is done partly to look for cross flow, rate of heating and information about the permeability in the reservoir and how deep cooling through the annulus will reach, before a new bit is operated (Fig. 5). In other cases, it may be useful to run a pressure log to detect the water level or for step-pressure injection tests to estimate the transmissivity. Other concurrent logs may be required. Inclination and direction surveys of wells have been carried out more or less as a routine for the last 25 years. Gyro-surveys have been a standard procedure in all directional wells, as normal MWD equipments in the drillstring are not considered adequately reliable in the highly magnetic environment of the volcanic strata.

A logging program is performed in every part of the open well before casings. The program consists of a temperature log, a caliper log, 16” and 64” resistivity logs, neutron-neutron and gamma ray logs. The last four are known as geophysical logs. A composite well log is prepared by combining the geophysical logs and the results of the analysis of the cuttings. Most of the well logs have been adopted from the oil industry and adjusted to the volcanological environment in Iceland. Some methods to interpret geophysical logs have been developed in Iceland like translating gamma-ray values into percentage of SiO_2 (Stefánsson et.al. 2000) and neutron-neutron units into porosity (Jónsson & Stefánsson. 1982, Stefánsson et. al. 1997 and Stefánsson 1998)

5. DRILLING COMPLETION.

It has been a standard procedure during the drilling completion to run selected logs as described above. During that process it is estimated whether the characteristics of the well suggest that it is sufficiently productive or if it needs to be stimulated. The stimulation process causes an increase in the permeability by periodically warming up the well and cooling it down to create thermal cracks. On many occasions an increase in the permeability up to a factor of four has been obtained. The reference value for success is measured in l/s per bar. It may take several days up to week to improve a well. Therefore it is important to remember that the main purpose of the drilling is to create a good producer but not only a hole in the ground.

6. STORAGE OF DATA AND PUBLICATION

Drillsite geologist is not only working as researcher and geothermal consultant. One of the responsibilities are daily reports to the client and the project team. The communication processes have changed during the years from phone calls, e-mails and finally to the internet. Access to the internet is one of the required needs at drillsite and every morning a daily report is placed on the website for everyone who has access to read. Furthermore the drillsite geologist is responsible for preliminary reports about the whole drilling operation, containing all data gathered during the drilling and description of the project.

7. CONCLUSIONS.

This paper places emphasis on how important it is to use available knowledge to achieve the best result from each drilling project. An integrated professional team has appeared to be a good solution to the success of drilling projects. Members of such a team have included a spokesman for the client, representatives of the drilling company, geologists, geophysicists and a drilling engineer.

The value of seeking for know-how and ways of applying it should never be underestimated.

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