

GEOHERMAL BOREHOLE INVESTIGATIONS DURING AND AFTER DRILLING

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ABSTRACT

Investigations of geothermal resources are often divided into surface and sub-surface exploration. In the early investigations, the main emphasis is on the surface exploration but later subsurface exploration takes over when drilling into the geothermal system starts. First with shallow and deep exploratory wells and later with appraisal and production drilling. When the boreholes become available the observation point of the investigators is moved from the surface into the geothermal system where direct measurements can be carried out for various parameters. Samples of the geological formations drilled through are brought to surface and analysed and when a well starts to flow, fluid samples are collected and the fluid chemistry determined. The objective of the subsurface exploration is to determine the natural geothermal conditions in the geothermal system and its production characteristics prior to utilization. Production wells are the means to tap the energy from the geothermal system and bring it to the surface where it can be exploited. These wells also give information on the inner structure of the geothermal reservoir and last but not least they tell how the geothermal reservoir responds to utilization. Geothermal high temperature drilling has been carried out in Iceland for decades. This paper describes a general subsurface exploration programme that is carried out in all high temperature wells in Iceland independent of whether the well is drilled for exploratory purposes or for production. The objective of the programme is not only to obtain information on the geothermal system in the vicinity of the well but also to obtain information on the well, the geological units drilled through and the hydrological connection (permeability) between the well and the geothermal reservoir. Such information is often used in decision making during drilling, and is especially valuable when unexpected situations come up in the drilling.

1. INTRODUCTION

The first steps in exploring and developing geothermal resources consist of geological, geophysical and geochemical observations, mapping and measurements which are carried out on the surface to locate the geothermal system. The objective of the surface exploration is to obtain initial estimates on: (1) The geological structure of the system. (2) the fracture network that controls fluid flow within the system (3) The size of the system. (4) Subsurface temperatures. (5) Heat source and natural recharge to mention a few.

The results of the various investigations should converge in a preliminary conceptual model of the geothermal system and point out suitable sites for exploratory drilling into the system. When surface exploration of a geothermal system has been carried out, further exploration and evaluation of the geothermal system is mainly based on information gained from wells (exploratory and production wells) drilled into the reservoir. Geological samples (cores and drill cuttings) are obtained from the wells to determine the lithology and alteration of the rocks.

The wells make it possible to sink various measuring instruments right into the heart of the geothermal reservoir to carry out measurements and estimate reservoir parameters, of which the most important ones for geothermal purposes are reservoir temperature and pressure. Well tests are carried out to determine the hydrological parameters of the reservoir and the production and/or injection capacity of the wells. Fluid (water, steam and gas) is sampled during flow testing of the wells and analysed in order to determine the chemical characteristics of the geothermal fluid.

Some of the methodology of the geothermal research has been borrowed and adapted from groundwater and petroleum exploration, but most of the methods have been developed specially for the geothermal investigations, as geothermal systems are indeed, quite different in nature from petroleum and groundwater systems. The difference is not only the high temperature. The geology of the geothermal systems is more complex, many geothermal systems are found in highly fractured volcanic rocks with low permeability. The fluid is chemically different as the high temperature fluid interacts with the host rock. The geothermal fluid can also undergo phase changes from liquid to steam and vice versa through boiling. The geothermal systems are also dynamic in nature as there is a continuous flow of fluid and heat into the system (natural recharge), within the system (fluid convection) and out of the system towards surface manifestation (hot springs and fumaroles).

Investigations of geothermal boreholes have developed during the last decades. In Iceland, these investigations have been standardized for high temperature wells and a detailed exploration programme is carried out for each new well drilled. The programme describes what investigations are carried out during the drilling of the well, during warm-up after drilling, and during flow testing of the well and pressure recovery after the flow. The progress of the drilling of the well is described in daily reports published on a website and in a few progress reports where a preliminary interpretation of the collected data is published. The final phase of the programme is data analysis and joint interpretation of the results of the different investigations. This is published in a “final” report. It is our experience that this last phase is most difficult to complete, especially when high temperature drilling is carried out all year around as it has been in Iceland for the last five years and the relatively small group of specialists are busy just to keep up with the drilling.

This Icelandic investigation programme will be described in the following chapters.

2. INVESTIGATIONS DURING DRILLING

Geothermal specialists are stationed at the well site for longer or shorter periods of time throughout the drilling of the well, which typically takes 40-50 days from start to completion of a 2 km deep well. The specialist group consists of well site geologists, logging engineers, and reservoir and drilling engineers. Their duty is to monitor the progress of drilling, analyse drilling parameters, analyse the drill cuttings and to carry out well logging operations and well tests. They make the preliminary interpretation of the collected data, write the daily reports and the preliminary reports. An important part of their work is consultancy at the drill site to the client and the drilling contractor and participation in meetings regarding the work. Such consultancy demands a solid general knowledge of geothermal drilling and experience in analysing well data.

2.1 Analysis of drill cuttings.

The work procedure has gradually changed during the last decades, but the basic method is to analyse the drill cuttings and prepare lithological and alteration logs. Drill cuttings are collected at two meters intervals. The instrument used for analyses of cuttings at the drill site is a binocular microscope, but if the situation requires, XRD-analyses can be performed within 24 hours. In addition to lithological analyses of the cuttings, other analyses pertinent at the drill site are carried out, such as identification of a possible collapse in a well, metal fragment contamination in the cuttings to trace malfunction in the drillstring, and 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 to identify the secondary minerals. During

drilling in high-temperature areas it is important to evaluate simultaneously the formation temperature by identifying main index minerals (Table 1).

TABLE 1: Some temperature dependant minerals in high temperature areas in Iceland (Franzson, H.1998, Kristmannsdóttir, H. 1979)

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 geological mapping. The first exploration well shows the main formation penetrated to some depth and extends the first conceptual 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 interpretations of the surface exploration. Furthermore, drill cuttings together with geophysical logs (Figure 1) allow extrapolation with more confidence of tectonic features to some depth and the 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. On the other hand, the rock 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 the analyses of cuttings and 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 (Gudmundsson 2005).

2.2 Monitoring of drilling data

Monitoring of the performance of the drilling operation was previously done by a mechanical Geolograph, but has in recent years been replaced by various electronic sensors with the data computerized and displayed continuously on computer screens. The main parameters monitored are: well depth, penetration rate, weight on bit, rotation of bit, pump pressure, pump rate of the circulating fluid, fluid returns, circulation loss/gain, temperature of circulating fluid and fluid return. 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.
- Measurement of the temperature close to the bit while drilling (MWD).

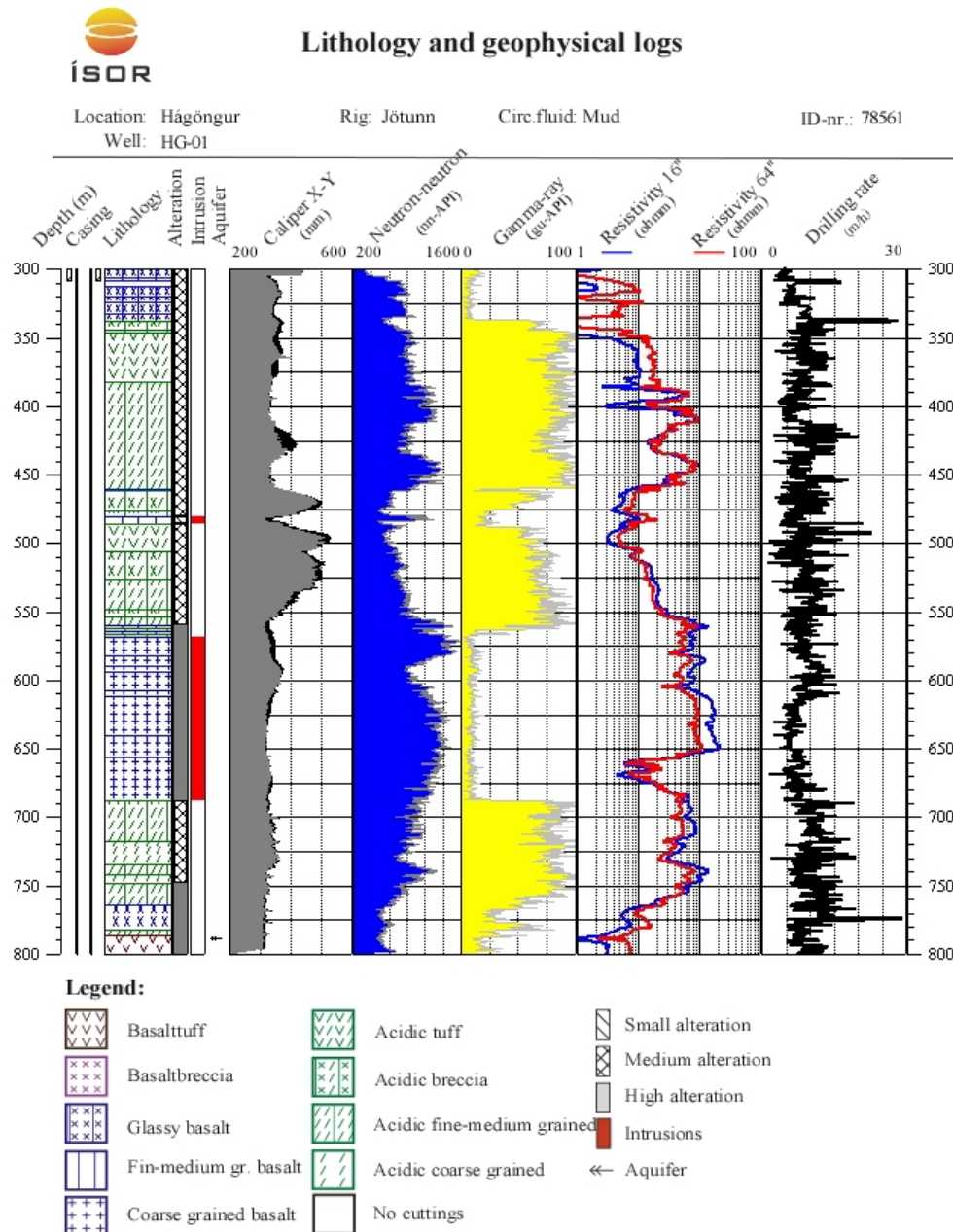


FIGURE 1: Example of composite logs in a high temperature well in Iceland

2.3 Well logging

Wire line well logging is a very important tool in oil well drilling where sophisticated (and expensive) well logging tools and interpretation methodology is applied to evaluate the geological structure around the oil wells and to determine the water, oil and gas content in the oil bearing formations.

Application of geophysical wire line logging is still relatively limited in geothermal exploration in most countries, except in Iceland where we have since 1976 used oil well logging techniques for a systematic investigation of the geothermal wells. A logging truck is stationed at the drill site during drilling and one or two logging engineers are on standby to carry out necessary logging operations. During the drilling, these are mainly temperature and caliper logs, and in deviated well also gyro surveys. Temperature logs are often run if drilling is stopped. The well temperature values measured are, however, usually very different from the true temperature in the formation outside the well. This is because of the cooling of the well caused by water or mud circulation in the well during drilling. Still the temperature logs give valuable information on well and reservoir conditions. The logs are analysed in order to locate feed zones and to look for internal flow between feed zones. Temperature log are also used to determine the heating up rate and to evaluate blow-out risks. The caliper log is a measurement of the diameter of the well and is useful to locate and evaluate zones of soft formations.

A standard suit of logs is preformed in “open hole” at each casing depth and when the final depth is reached. The standard logging suit consists of:

- Temperature log to locate feed zones and to evaluate the heating up rate of the well after circulation is stopped.
- Caliper log to locate washout zones and to estimate the volume of cement necessary to fill up the annulus between the casing and the formation.
- Resistivity (16” and 64”), neutron-neutron (porosity), and natural gamma ray logs to evaluate the geological formation.

After running the casing and cementing it, a cement bond log (CBL) is run to evaluate the cementing job.

An example of a suit of logs from an Icelandic well is shown in Figure 1.

2.4 Well completion, stimulation, well logging, and well testing.

A special well completion programme is executed when the drill rig reaches the final depth of a well. Earlier completion programme consisted of the following work tasks:

1. Circulation with drill string on bottom to clean the well and the feed zone in order to improve the transmissivity of the well.
2. Temperature logging inside the string to locate aquifers and to look for the tendency for internal flow.
3. Drill string pulled out of well
4. Open hole well logging suit as described above.
5. Running of a slotted liner into the well and hanged near the bottom of the production casing.
6. Execution of a pressure transient test to determine the hydrological connection between the well, and the reservoir to get a rough estimation on the production potential of the well.

During the last few years a large effort has been made to stimulate the wells in order to improve their production potential. The drill rig is often used in these stimulations and therefore they are carried out before the rig is moved off the well. The stimulation operations often start when the well has been circulated after drilling and the temperature log is completed. The first step is to lower a pressure gauge into the well and positioning it near the best feed zone in the well. Then the injectivity is determined by a short injection step test. A considerable experience has been collected on how injectivity in an cold well at the end of drilling corresponds to the productivity of the well when it has heated up after drilling and starts to flow. Based on this experience, a decision is made whether stimulation operations should be carried out or not. The most common stimulation technique includes: (1) Water circulation through the drill string. (2) Injection of cold water on wellhead using all available cold water supplies and the full pump capacity of the drill rig. (3) Alternate heating and cooling of the well by stopping the injection for several hours or even days and then start the pumps and inject at full force to cool the well as rapidly as possible in order to form thermal cracks. Lately, experiments have been carried out in letting the well produce for a few hours by airlifting the well and then start the cold water pump to cool the well.

The stimulation is carried out in steps, and the injectivity determined after each operation. Improved injectivity suggests that the stimulation should be repeated. But if the stimulation does not increase the injectivity a different stimulation can be tried or else the stimulation operation should be stopped. It is, however, the experience in Iceland that the injectivity index can be improved considerably by the stimulation methods mentioned above, typically by a factor of 2-3, and sometimes more.

3. INVESTIGATION DURING WARM UP AFTER DRILLING AND FLOW TESTING

Drilling mud or cold water is used for circulation during drilling in Iceland. During the completion programme cold water is injected into the well for several days. The temperature in the well at the end of drilling is therefore much lower than in the geothermal reservoir. When the coldwater injection is stopped, well temperatures start to rise due to heat conduction into the well and internal fluid flow between the feed zones of the well. The rate of the heat recovery depends on how much cooling the formations have experienced during the drilling and the intensity of the heat conduction and the internal flow. Typically, it takes several months for a well to reach stable thermal conditions after drilling.

Geothermal wells are monitored during the heat-up period by regular water level or wellhead pressure measurements. Temperature and pressure logs are carried out using mechanical tools (Amerada or Kuster) but in recent years high temperature electronic tools or heat shielded memory tools have become available (Kuster K-10 and other). Figure 2 shows an example of a temperature logs in a well during the recovery after drilling.

During the recovery after drilling, the water column in the well expands as it heats up. The rising water level which is observed in wells during warm-up is therefore an indication of the rate of heating up in the well. The objective of monitoring the down hole temperatures during warm-up is to use the data to determine (estimate) the true formation temperature as a function of depth at the well site. The pressure logs on the other hand reveal location of the best connection in the well and the reservoir (pivot point). An example of temperature logs during warm-up is shown in Figure 2.

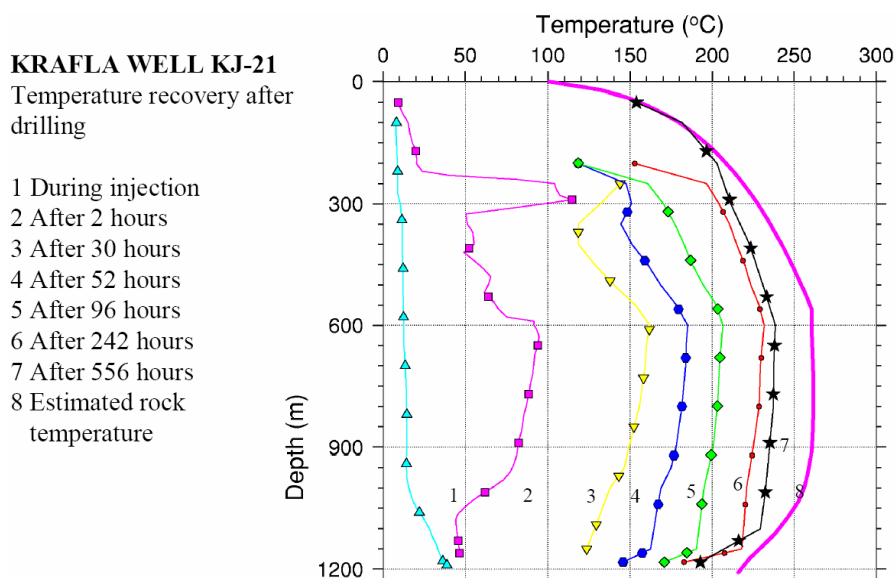


FIGURE 2: Temperature logs during warm-up after drilling

It takes high temperature wells often several months to heat up after drilling. When the recovery is complete the next thing is to start production from the well and determine the output characteristics of the well and the chemical properties of the fluid discharged from the well. The most important parameters are:

- Q = the total mass flow from the well (in kg/s).
- H = the discharge enthalpy (in kJ/kg).
- P_o = the well head pressure during discharge (in bar or Pascal). The curve showing the total mass flow versus the well head pressure is called the output curve of the well.
- The non-condensable gases in the steam.
- The dissolved solids in the reservoir fluid.
- Pressure drawdown in the well during discharge.

The duration of these flow tests is typically a few months or until the flow has fully stabilized and the fluid chemistry is no longer contaminated by the drilling fluids that entered the reservoir during drilling. Dynamic temperature logs are carried out in the well to determine the location of feed zones and inflow temperature. Dynamic pressure logs measure pressure drawdown. Pressure transients in the well, and used to determine productivity indices and the hydrological reservoir properties in the vicinity of the well. The final transient test is the pressure build-up after the well is shut-in when the flow test ends.

4. EVALUATION OF DATA. FINAL GEOTHERMAL WELL REPORT

All data collected during drilling, warm-up, and flow test are evaluated and incorporated into data bases and finally interpreted by a team of experts from the relevant fields of geology, geophysics, reservoir engineering and geochemistry. The main tasks in the interpretation are the following:

1. The geologists have thin sections made of samples from the drill cuttings and carry out XRD analysis and fluid inclusions studies on crystal samples from the drill cuttings. Based on the analysis, the lithological and alteration logs are reviewed, corrected and compared to the geophysical logs. This is done in co-operation with the logging experts. The geological information is also compared to previous knowledge of the field and the geological sections for wells in the vicinity.
2. The logging experts analyse the geophysical logs and calculate rock properties such as porosity and acidity and compare in co-operation with the geologist the geophysical logs with the geological logs.
3. All available information on the feed zones in the well is gathered (circulation losses during drilling, evidence in the drill cuttings and all the temperature logs) and analysed in order to determine a list of all the feed zones of the well.
4. Well test data, both injection and production data, are evaluated and interpreted to determine injectivity and productivity indices for the well and transmissivity, storativity and skin.
5. Temperature and pressure logs are analysed in order to estimate formation temperature profiles for the well and initial reservoir pressure. The formation pressure is compared to the secondary alteration minerals seen in the drill cuttings and fluid inclusion analysis in order to evaluate temperature history of the reservoir close to the well.
6. Flow test data is evaluated and the flow characteristic of the well determined.
7. The geochemists analyse the chemical fluid samples in order to determine the chemical composition of the reservoir fluid and its chemical properties for utilization (gas content, scaling potential and corrosion).

The interpretation work and conclusions on the properties of the well and the reservoir properties in the vicinity of the well are compared to previous work and existing conceptual models. All this work is described in a final report for the well, which forms the basis for further development of the reservoir.

5. WORK QUANTITY AND COST ESTIMATES FOR SUBSURFACE EXPLORATION PROGRAMME IN ONE HIGH TEMPERATURE WELL

The exploration programme described above has been applied for most high temperature wells drilled in Iceland during the last 30 years. The following table gives a summary on the work and a cost

estimate for the various phases of the subsurface exploration programme based on the experience for a 2 km deep well with anchor casing depth of about 300 m depth and production casing to about 800 m depth. Such a well is expected to be drilled in Iceland in 45 days including the time it takes to move the drilling rig to the drill site and to prepare it for the drilling. Two to three pairs of temperature and pressure logs are assumed measured during warm up and another pair during the flow test (dynamic logs).

TABLE 1: Work and cost estimates for geothermal exploration and services for a high temperature well in Iceland.

1) Exploration work during drilling.

	<i>Amount</i>	<i>Cost (USD)</i>
Project manager	80 hours	9,000
Well site geologists	40 days	50,000
Logging and reservoir engineers	60 days	65,000
Logging truck	35 days	20,000
Logging operations		50,000
Preliminary reports	3 x 40 hours	12,000
Transportation		6,000
Miscellaneous		8,000
	Total cost	220,000

2) Warm-up after drilling, flow test and pressure build-up after flow.

	<i>Amount</i>	<i>Cost (USD)</i>
Project manager	20 hours	2,500
Logging and reservoir engineers	10 days	10,000
Geochemists	3 days.	3,000
T+P logging	20,000 meters	20,000
Chemical analysis	3 total samples	6,000
Interpretation and reporting	80 hours	10,000
Miscellaneous		10,000
	Total cost	61,500

3) Interpretation and final well report.

	<i>Amount</i>	<i>Cost (USD)</i>
Project manager	50 hours	5,500
Geologist	300 hours	30,000
Well log analyst	100 hour	10,000
Reservoir engineer	100 hours	10,000
Thin sections and XRD	20 each	5,000
Miscellaneous		10,000
	Total cost	70,500

The total exploration cost for one high temperature well in Iceland is according to the values above of the order of 330,000 USD which is about 10% of the drilling cost of such a well in Iceland.

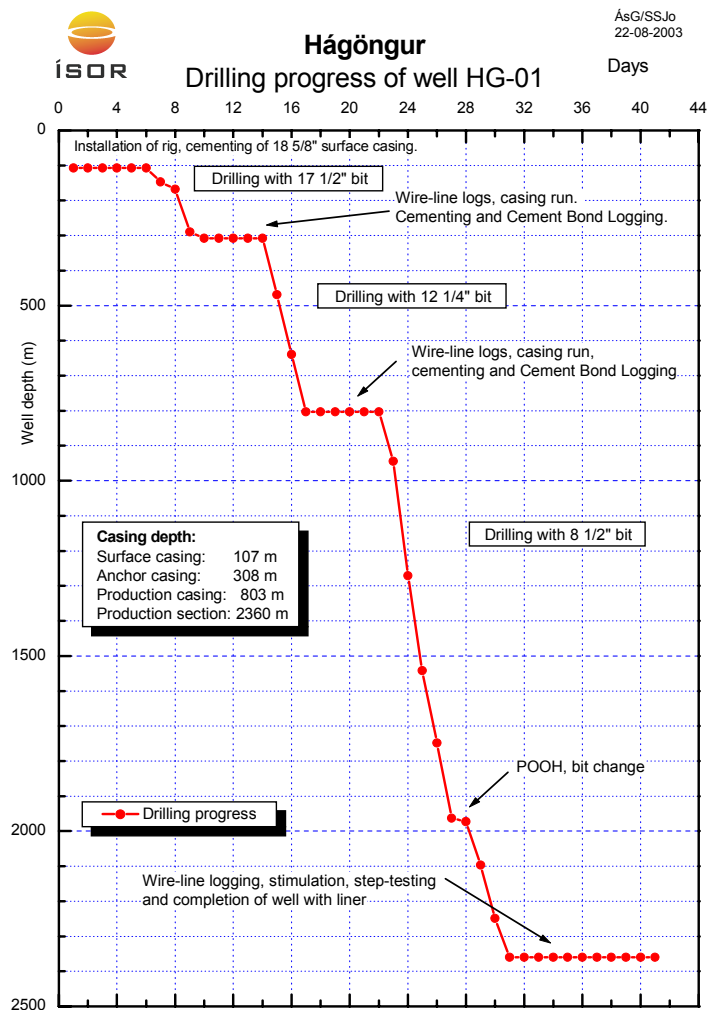


FIGURE 3: The progress and major events in the drilling of well HG-01

5. SUMMARY AND DISCUSSION

The surface exploration programme described above was initially developed during the production drilling in the Krafla field in northern Iceland in late 1970's. Since then, it has been applied and further developed during drilling and testing of some 100 high temperature wells in Iceland. The objectives of the programme are mainly:

- To monitor the progress of the drilling and gather relevant information and data regarding the drilling operation, the borehole and the reservoir.
- Use this information in decision making during the drilling.
- Analyse the drill cuttings to prepare lithological and alteration logs.
- Locate permeable zones and the hydrological parameters of the well.
- Estimate formation temperature profile for the well and the initial pressure in the reservoir.
- Determine the production (injection) capacity of the well, and the output curve.
- Determine the chemistry of the reservoir fluid and its production characteristics.
- Reporting of the findings in daily reports during drilling and preliminary reports for the different phases of the development.
- Interpretation of the data and final geothermal well report.

The programme discussed in this lecture is limited to the drilling, warm-up period and flow test of each well drilled into the geothermal field. The next phases of the subsurface exploration are:

- (1) Comparison of the information obtained from all wells drilled into the geothermal field.
- (2) Evaluation of the reservoir properties and development a conceptual model of the field
- (3) Reservoir modelling to assess the capacity of the reservoir for geothermal production, and
- (4) Monitoring of the response of the reservoir to production.

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