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GEOTHERMAL WELL LOGGING: CEMENT BOND AND CALIPER LOGS

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ABSTRACT

Well logging is a highly advanced technique where complex electronics and sensors are placed inside a logging probe which is lowered on a wireline into a well to carry out measurements continuously or at discrete depth intervals as the probe is moved down or up the well. The objective of the logging can be of various types, (1) to study the well, its geometry and competition, (2) to study the rock formation and fractures intersected by the borehole, (3) to determine the reservoir temperature and fluid pressures, and (4) to locate feed zones connecting the well to the geothermal reservoir.

Well logging has been used systematically in Iceland since 1976 to study and explore geothermal wells, not only the classical temperature and pressure logs of the geothermal industry but geological logging tools and also logs that are used to study the well itself. The present paper gives a description of two wireline logs of the last category, the Caliper log and the Cement Bond Log. The Caliper log is the measurement of the diameter of the well as function of depth using logging probe with arms placed symmetrically around it. The Cement Bond logging tool utilizes the attenuation of acoustic waves as it travels along the casing to determine the bond of the casing to cement in the annulus behind the casing.

1. INTRODUCTION

Drilling into the crust of the earth makes it possible for us to lower instruments into the boreholes and carry out in situ measurements in order to gain information on the rock formation surrounding the well, temperature and pressure within the well and other parameters. This family of measurements recorded along the well is commonly called well logs or wireline logs to distinguishing them from various drilling logs. This is a very heterogeneous family of measurements that have the only thing in common that they are carried out within a well. The purpose of the logs or the measurements is manifold but the objective is often divided into three types. The first type are logs that relate to the well itself i.e. it’s design, geometry and completion. Then there are logs to study the rock formations outside the well and the fracture intersected by the well and finally there are logs that determine the temperature of the well, fluid pressures and location of the feed zones intersected by the well.

Today, wire line well logging is highly sophisticated technique where complex packages of electronics and sensors are placed inside a logging probe which is the lowered on a wireline (cable or steel wire) into the well to carry out measurement continuously or at discrete depth intervals while the probe is moved down or up the wells. The measurements and the depth locations are sometimes stored in an electronic memory in the logging probe but most commonly they are transmitted through the cable to the surface and stored in a computer for later analysis and interpretation. Well logging is carried out in all kinds of wells but it is most advanced 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 wire line logging in geothermal exploration has been limited in most countries through the years in most to temperature and pressure logging.

In Iceland we have since 1976 used oil well logging techniques for a systematic investigation of 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, the main parameters measured are; temperature, well diameter and cement quality behind the casings as well as gyro surveying of directionally drilled wells. Logging probes measuring rock properties i.e electric resistivity and formation porosity are used for each section of the well to obtain information on the lithology units intersected by the well and a borehole televiewer is used to investigate fractures, their slopes and orientations. Pressure is measured at the end of each drilling and pressure transient tests are carried out to determine permeability and injectivity index for the well.

The well temperatures, measured during drilling, are usually very different from the true temperatures 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 logs after drilling are used to determine the heating up rate and estimate the formation temperatures.

In this paper we will discuss two types of logs. These are the Caliper log, where the geometry of the wells, their size and shape is measure and the Cement Bond log (CBL), where the quality of the cement placed in the annulus behind the casing is evaluated how its binds the casing to the formations outside the well.

2. THE CALIPER LOG

2.1 Introduction

Geothermal wells are drilled with a drill bit rotated into the ground. This action is expected to form a circular well of a diameter corresponding to the diameter of the drill bit. This is, however, not necessary the case. During the drilling, the drill cuttings created at the bottom are flushed to the surface through circulation of drilling mud and water. This sandy fluid will erode the formations as it flows up the hole, creating a larger hole than the drill bit size predicts and, as formations drilled through are of different hardness, the erosion will be greater in soft formations than in the harder formations. Some formations drilled into might even be unstable, formations such as sand, gravel or sediments, in which case caves will appear in the well. The Caliper log is the measurement of the diameter of wells to obtain information on their true sizes and shapes. Figure 1 shows a schematic picture of a geothermal well in Iceland comparing casing (bold lines) and drill bit soft straight lines) sizes to actual Caliper logs. The figure shows that the true diameter of this well was often much larger that

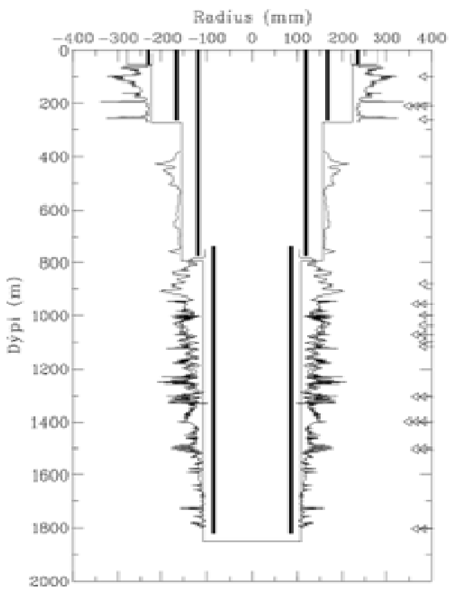

FIGURE 1: Schematic picture of a geothermal well; showing casing and drill bit sizes and caliper logs

the drill bit size would predict. The differences were greatest from 100-300 m depth in the drilling for the anchor casing and from 800 to 1500 m in the production part of the well. In both of these sections are found relatively soft hyaloclastite formations. At 400-800 m and below 1500 m the well was drilled into much more consolidated formations, basaltic lava flows and intrusions. The form of the wells can also be quite different from circular shape. Directionally drilled wells have for example often an elliptical shape.

2.2 The caliper tools

Many different types of Caliper logging probes are in use. Most of them are mechanical tools equipped with several arms which are operated through a small electric motor placed inside the logging probe to open or close the arms. In open position the arms are pushed against the wall of the well by springs. The position of the arms is registered to measure the diameter of the well. Commonly the tools can register diameters up to about 1 metre (30”), but extensions are available for wider holes. In a circular well a tool with one arm would be sufficient, but as the open section of wells is often oval in shape, most Caliper probes have several arms. Probes with 3, 4 or 6 arms are most common and in special cases i.e. inspection of casing wear or corrosion, probes with up to 60 arms are available. The arms in the 3 arm tool are all interconnected and only show an average diameter for the well where the arms in the 4 and the 6 arm probes are independent pairs and will reveal if the well is elliptical.

FIGURE 2: X-Y (4 arm) Caliper probe

Caliper logging starts as the tool is run into the hole with the arms closed. At bottom or the deepest logging point the tool is stopped and the arms are opened until the springs push them properly against the wall of the well. The tool is then run out of the well at a constant logging speed, typically 15-30 m/min while the diameter is registered at few centimetres interval.

FIGURE 3: Go devils

The electronic components in the Caliper logging probe as well as the logging cable used have a limited temperature tolerance. The most common tools have only a maximum temperature rating of 150-175°C. This is generally sufficient, even for very high temperature wells, during the drilling phase as the wells are cooled constantly during the drilling by cold water injection. High temperature tools are available for hot wells, mechanical clock driven tools with downhole registration, similar to the famous Kuster temperature and pressure gauges, but also tools conventional design but with high temperature electronic. These tools are, however, rather expensive and the same applies for the high temperature logging cables.

Go devils are frequently used in high temperature wells when cooling the well is not an option. They are in fact sinker bars of different fixed diameters, and therefore show only the maximum depth of each clearance in the well. The go devils give therefore a much cruder picture of the well diameter, than conventional Caliper tool. Go devils are mainly used to study scaling in wells and casing damages. Figure 3 shows typical go devil used in Iceland.

2.3 Applications of Caliper logs

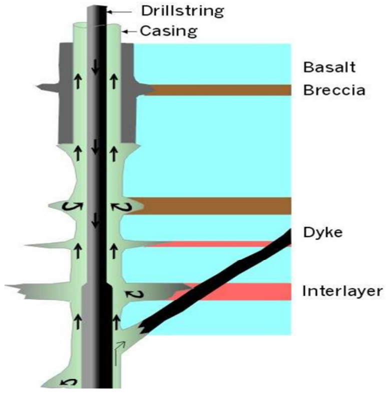

FIGURE 4: Forming of cavities, as water is circulated through the drill string during drilling

Caliper logs give information on the rock formations that wells intersect. Soft formation tend to wash out but stronger formation not. Cavities are seen were the well crosses sediments, sandy layer or fracture zones. Figure 4 demonstrates how cavities are formed in the soft formations and interlayers during drilling, as the circulating fluid, which carries the drill cuttings to the surface, erodes the formations. The cavities can become a problem for the drilling as the circulation fluid is slowed down when it flows through the cavity. At critical cave diameters the circulation fluid velocity will become too small to carry (lift) the drill cuttings up through the cave and the drill cuttings accumulates in the cavity. This will lead to insufficient cleaning of the well and the drillers will observe filling in the well, irregular torque in rotating the drill string and sticking of the drill string. If the drillers do not act on this they will sooner or later find the drill string stuck in the well. Running a Caliper log in the well will show the location of the cavities and their size. Large cavities can then be filled with cemented and when the cement has set the cement plug is drilled out leaving a cement shell filling the cavities. The success of the cementing of the cavities can then be checked by running a Caliper log. This is an example of application of Caliper logs.

In Iceland we routinely run Caliper logs in geothermal wells. Example of a Caliper log is shown on Figure 5. The Caliper logs are studied and evaluated for many purposes. The main applications are the following:

- Comparison of the Caliper logs with the lithology section of the well according to drill cuttings studies with respect to formation strength.
- Location of cavities, determination of their diameter and length.
- Evaluation of the success of cementing large cavities causing problems during drilling.
- Estimating the amount of cement needed to fill the annulus between the casing and the wall of the well.
- Finding location for a packer in hard formations where washout is minimal.
- Evaluate depositions in wells (calcite or silica scaling).
- Evaluate casing corrosion.
- Evaluate casing damages.
- Correction of other geological logs. The response of those logs is influenced by the amount of water surrounding the probe, which is determined by the size (diameter) of the well.

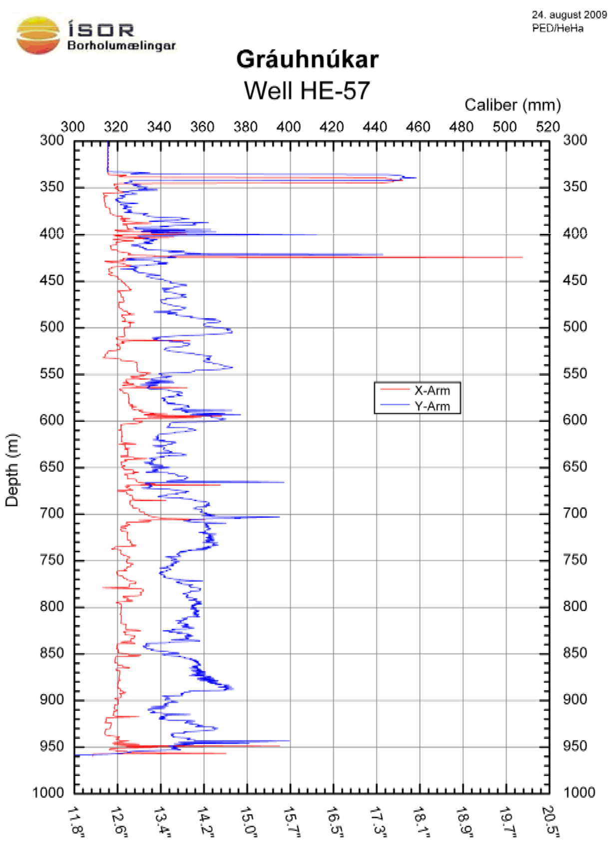

FIGURE 5: X-Y Caliper log. Notice the difference in X and Y, which shows an elliptic well. This is a directionally drilled well

Several examples of these applications will be shown in the presentation at the Short Course.

3. THE CEMENT BOND LOG

3.1 Introduction

The high wellhead pressures that can develop in high temperature wells make it necessary to place deep steel casings in the wells and cement them to anchor the casing to the formation. Typical depths for production casings in geothermal wells are of the order of 600-800 m but there are examples of casings which extend from surface to 2000 m depth. Cementing of such long casing is a difficult operation and problems due to poor cementing are far too common in geothermal wells.

The cementing of a casing in a well serves several purposes. It binds the casing to the formation and provides a seal that prevents fluid from flowing behind the casing from one feed zone to another. It also supports the casing and holds it tight and thus prevents free thermal expansion of the casing. This is extremely important in the case of a geothermal well as the casing is placed and cemented while relatively cold (typically less than 50°C) but will later heat-up to 200-300°C. The heating-up will put large thermal stress on the casing. If the top part of the casing is poorly cemented and the casing can expand freely the wellhead will be lifted as the casing expands. An uplift of the wellhead of the order og 50-100 cm has been observed but if the casing is properly cemented only 1-5 cm uplift is normal. (The thermal expansion coefficient for steel is approximately 12cm/100m/100°C).

Several logging techniques have been developed to evaluate the quality of cement behind a casing and it's binding both to the casing and to the formation. The most efficient logging tools for this are acoustic tools, Cement Bond Tools, but nuclear tools i.e. gamma-gamma density tools and neutron-neutron porosity tools can be used to determine whether cement, water or air/gas fills the annulus between the casing and the formation.

3.2 Cement Bond logging. Principle, tools and the acoustic signal

The acoustic Cement Bond logging tools are described widely in the logging literature. The physical principle in the CBL logging, common for all the CBL tools, is that an acoustic signal will propagate undisturbed in a free casing but it will attenuate fast if the casing is bonded to a solid material such as cement.

The basic instrumentation for cement bond logging is shown on Figure 6. The downhole probe, the CBL tool, is centralized in the well. It comprises an acoustic transmitter which generates recurrently a short high frequency (kHz) sound pulse, usually 15-20 pulses per second. A sound receiver (sometime two) is situated on the tool few feet below the transmitter. In Iceland we have been using tools with one receiver 3 feet below the transmitter but also tools with two receivers at 3 and 5 feet spacing. The transducers used are commonly radial piezoelectric crystals which convert electric signals to mechanical energy and vice versa.

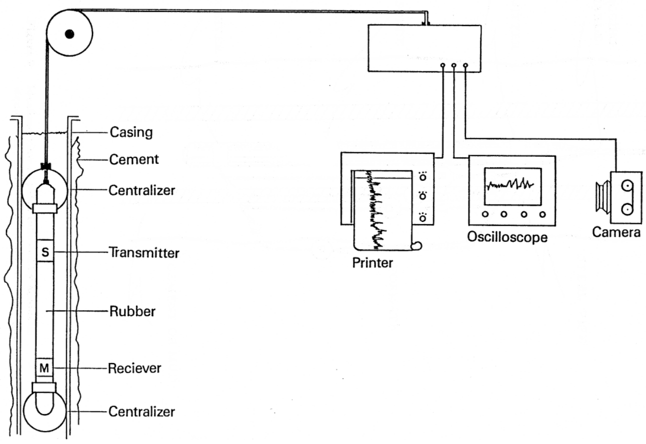

FIGURE 6: Analog Instrumentation for Cement Bond Logging. (In digital logging today, the printer and the camera has been replace by digital data logging computers (Steingrimsson, 1988)

The acoustic pulse from the transmitter spreads in all directions and a portion of it will eventually reach the receiver. The received signal is viewed on an oscilloscope triggered by the shot pulse 15-20 times per second which is seen as a continuous picture on the scope showing the shot pulse, the dead time until the first signal reaches the receiver and then the total wave (sound) train arriving at the receiver. The amplitude of the first arriving head wave (called first arrival) is registered but the total wave signal is displayed either as a full wave signal or as intensity modulated diagram. These three registration forms of the Cement Bond (CBL) log are called; pipe amplitude (PA), full-wave (FW) and variable density (VDL) logs.

In order to visualize the propagation of the acoustic signal from the transmitter to the receiver, we can assume that the acoustic propagation occurs through several separate and independent flow paths. Figure 7 shows a schematic drawing of a CBL probe centralized in a well and the it shows paths H, P, C and M for the acoustic signal. The shortest path for the signal to travel from the transmitter to the receiver is through the probe. This path is, however, not shown on the sketch because the CBL probes have a rubber coated section between the transmitter and the receiver so the sound will not flow through the probe to the receiver. The paths shown on Figure 7 are:

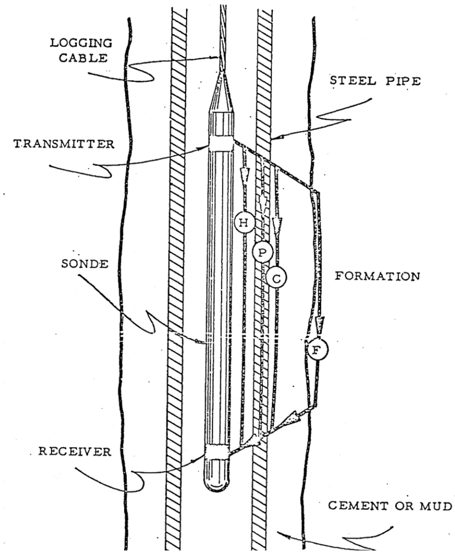

FIGURE 7: Schematic figure showing several propagation paths for the acoustic signal from transmitter to receiver

Path H: A portion of the transmitted signal will travel in the liquid (water) surrounding the probe. This is a compressional sound wave as transversal waves do not propagate in fluid.

Path P: Some of the signal will travel through the water and refract into the casing (compressional wave) and then propagate as compressional and transversal waves along the casing before re-entering (refract onto)) the fluid and travel as compressional wave to the receiver.

Path C: Some of the signal travel through the casing and propagates in the cement in annulus behind the casing before re-entering the casing and travel to the receiver.

Path F: Finally some of the sound signal will travel beyond the casing and the cemented annulus and refract into the rock formation and propagate in the rock along the borehole before re-entering the well on its way to the receiver.

The travel time of the acoustic signal along the flow paths will differ not only because they are of different length but mainly due to the fact that the velocity of the sound is different in the different media. The compressional velocity of sound in water is 1.5 km/s but is 5.3 km/s in steel (casing). The velocity of sound in cement depends on the compressional strength of the cement and can vary between 2.7 and 4.8 km/s where a value of 3 km/s is most common for casing cements. Transversal velocities are about the half of these compressional velocities. The velocity of sound in rock formations depends on many parameters i.e. rock type, porosity, temperature and pressure.

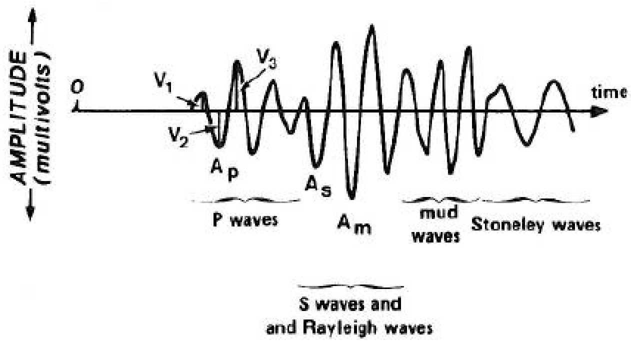

FIGURE 8: The full wave signal arriving at the receiver showing the arches usually used for amplitude measurement. Ap, As and Am for compressional, share and maximum amplitude, respective (Serra, 1984)

Typically the P-wave velocity for consolidate rocks is of the order of 3.5-6.5 km/s with the high values in hard porosities rocks. S-waves velocities are about half of the P-wave velocity.

The transit time of the acoustic signal along the different flow paths can be calculated assuming conventional well and casing diameters and transmitter-receiver spacing (3 ft). Applying the sound velocities given above the result of the calculation is that the signal which arrives first at the receiver will be the signal that travels along path P and travels directly to the casing and then along the casing until it is opposite to the receiver when it propagates directly through the water to the receiver. This signal will arrive long before the water and the cement signal (paths H and C). The casing signal will also arrive ahead of the formation signal (path F), except for extremely hard, high velocity formations. It is a good exercise to calculate the travel time for the acoustic signal for the different paths shown on Figure 7.

The wave train arriving at the receiver for each shot pulse will be a superposition of signals from travel paths (Figure 8). The first part of the signal is a superposition of the compressional pipe waves travelling through most of the way from transmitter to receiver, followed by the shear wave signals from the formation and then the signals travelling through the water will arrive at the receiver with later reflections (Stoneley waves).

3.3 Applications of Cement Bond logs

As stated earlier the casing signals, the first part of the signal (Figure 8) will attenuate fast if the casing is tightly bonded by cement. Strong casing signals indicate therefore free or poorly cemented pipe, whereas weak casing signals indicate a good cementing of the casing. The first analysis of the CBL signal is to study the first casing signal arriving at the receiver. The amplitude is measured using an electronic gate as shown on Figure 9. The amplitude of the first arrival for a free pipe in water is the reference and lower amplitudes tells, qualitatively, how good the cement bond. Further studies of the CBL signal include studies of the whole wave train. The signal is then either presented as full wave signal as function of depth or as intensity modulated amplitude signal, variable (VDL). A comparison of pipe amplitude, full-wave and VDL logs are displayed on Figure 10 for several hypothetical cement situations as shown on the borehole cross section to the left part of figure.

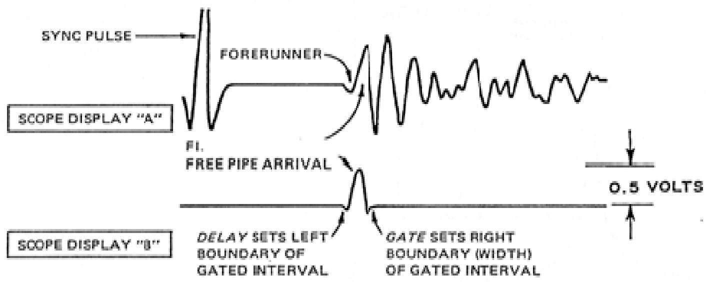

FIGURE 9: The CBL signal and the gate of the first arrival

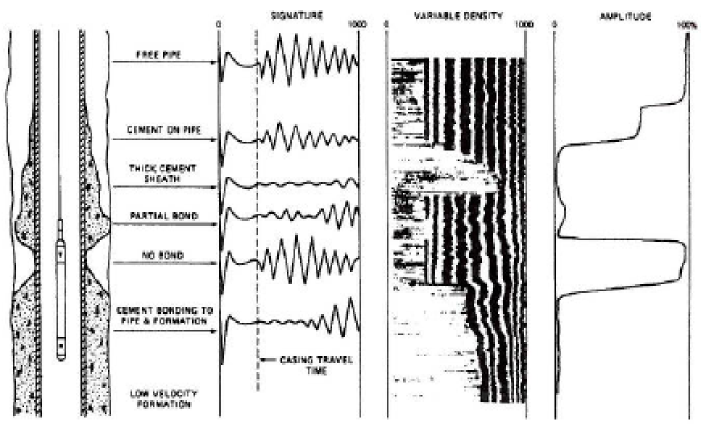

FIGURE 10: Full-wave, VDL and pipe amplitude cement bond logs for different cementing conditions (Rollman, no date)

The CBL log is usually run several hours after the cementing of a casing. The setting time of the cement is a function of temperature, the cement mixture and retarders added to the cement. In Iceland we have been using Portland and Haliburton G-cement. We add retarders to the cement for deep production casing but seldom for the shallower casings, partly because the cementing operation takes shorter time but also because of relatively lower near surface temperature than is the case for deeper casings. Our experience is that the wait upon the cement to set is of the order of 10 to 20 hours. We sometimes run a calibration log in the casing before cementing or early in the setting period. Comparison of this free pipe calibration with the actual log after the cement has set makes the evaluation and analysis of the log much accurate. It should be remembered that the CBL tool only works immersed in water. The casing has therefore to be filled up with water prior to the CBL logging.

CBL logs have been carried out routinely in geothermal wells in Iceland since 1978. Several examples of such CBL logs will be shown in the presentation at the Short Course. The main features in the CBL logs that gain most attention in the interpretations are the following, some of which can be observed on the CBL log on Figure 11:

A) *The rate at which the cement sets.* This will depend on the cement mixture, retarders and the temperature as mentioned before, but also on the width of the annulus. Cement in large cavities takes usually longer time to settle than the cement in sections where the well is narrower. The cement in the annulus between casings is also slower to set than in open-hole sections.

B) *Determination of "top of cement:"* Casings are usually cemented from bottom to top. Some of the cement is, however, lost into open fractures and feed zones intersected by the well. If these losses are excessive, no cement returns are obtained at the surface during the cementing operation. CBL logs are used to evaluate the quality of such cement jobs and determine the distance from the surface to the top of the cement in the annulus.

C) *Water pockets in the annulus:* The cement column is not necessary continuous in the annulus. There can be sections where the cement does only covers a part of the circumference of the casing and water covers the rest or there can even be sections of the annulus filled with water only, which is then bounded by cement from above and below. These water pockets will allow the casing to expand freely thermally in these sections, which might lead to collapsing of the casing if the section is long. Water pockets in between casings contain trapped water. When the well heats up this trapped water will tend to expand but with no space to expand pressure builds up in the water pocket and will eventually reach the collapse pressure of the inner casing.

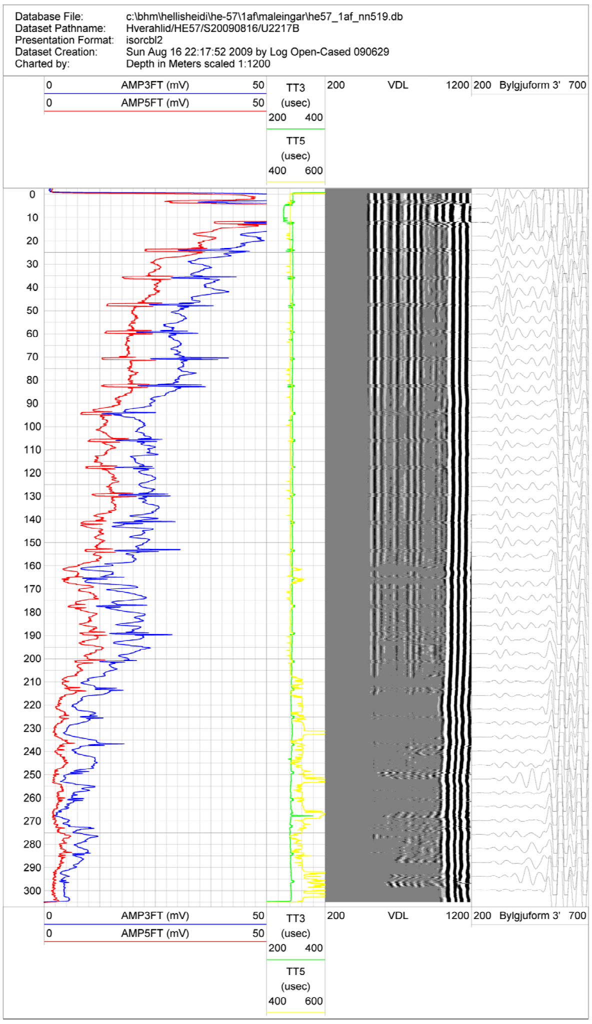

FIGURE 11: CBL log from well HE-57 at Hellisheidi, Iceland

4. CONCLUSIONS.

Geothermal logging has been used extensively to in Iceland since 1976 to study geothermal wells. This paper describes two logging methods used to study the size and the shape of wells and the cementing of casing in the wells. These are the Caliper log and the Cement Bond log.

The Caliper log gives information on the true size of the well. It relates to lithology as washout indicates the hardness of the formation and cavities are seen were drilled through soft sedimentary layers and sandy formations. The log will also show deposition in wells.

The Cement Bond log is run for quality control and assessment of cementing of casings in the wells. Incomplete cementing of casing in geothermal wells can lead to casing damages, when the well heat up. The CBL log are studied in order to locate "top of cement" if cement returns are not observed during the cementing, to locate water pockets in the cement column and the rate of the setting of the cement.

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