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GEOTHERMAL WELL LOGGING: GEOLOGICAL WIRELINE LOGS AND FRACTURE IMAGING

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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 for example, (1) to study the well, its geometry and completion, (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 points 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 logs of temperature and pressure, which the geothermal industry utilizes extensively, but also geological logging tools and logs that are used to study the construction and condition of the well. The present paper gives a brief description of geological wireline logs applied in geothermal exploration in Iceland as well as logs that create an image of the borehole walls. The latter (televviewer log) produces an acoustic “picture” of the wall of the well, where fractures can be easily mapped and their strike and dip determined and other properties of the fractures, whether they are permeable or not, can be studied and their slope and orientations can be determined. The geological wireline logs discussed are the electrical resistivity log of normal configuration, neutron-neutron porosity log and the natural gamma ray log. These logs give valuable information on the lithological section of the wells, the boundaries and thicknesses of the rock units and complement the drill cutting analyses.

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 physical properties of the rock formation surrounding the well, as well as the temperature and pressure within the well. This family of measurements recorded along the well is commonly called well logs or wireline logs to distinguish them from various other drilling logs. This is a very heterogeneous group of measurements that have the only thing in common that they are carried out within a well. The purpose of the logs is often divided into three categories. The first type contains logs that relate to the well itself i.e. the well design, geometry and completion. The second category contains logs which are used to study the rock formations outside the well and the fractures intersected by the well and finally there are logs that

measure the temperature in the well at the time of measurement, fluid pressures and location of the feed zones intersected by the well.

Well logging in geothermal wells has been highly focused on temperature, pressure and spinner logs but the purpose of this paper is to look at wireline logs that informs on the geological formations intersected by the well and the fractures dissecting the formations. Geological wireline logging and fracture imaging consists of a very important technology in the oil well drilling and development where sophisticated (and expensive) well logging tools and interpretation methodology is applied to evaluate the geological structure around the oil wells, map permeable fractures and to determine the water, oil and gas content in the oil bearing formations. Application of these logs 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 drillsite and one or two logging engineers are standby to carry out logging operations. As the drilling proceeds several logs are done in the well. The logs most relevant for the drilling operations are temperature, caliper and CBL logs, but several geological wireline logs are also done to study the rock formations of the well and with pressure, the permeability (or transmissivity) of the well is determined through pressure transient tests.

The geological wireline logs are usually run “open hole” for each cased section of the well and when the production part of the well is completed and final depth is reached. The standard logging suit consists of:

- Temperature log to locate feed zones and feed points and to evaluate the heating up rate (heat recovery) 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 logs (normal 16” and 64”), neutron-neutron logs (porosity), and natural gamma ray logs to evaluate the geological formations.

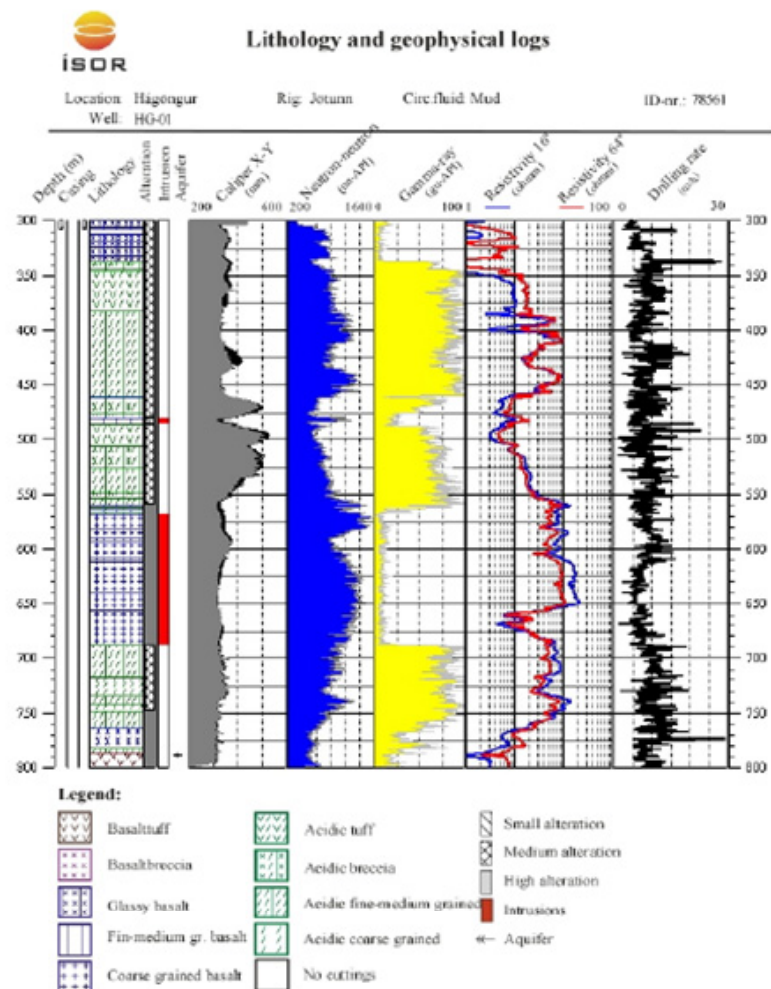


FIGURE 1: Examples of composite logs in a high temperature well in Iceland

An example of a suit of geological wireline logs from an Icelandic well is shown in Figure 1. The logs are plotted with and correlated to the lithology determined by the well site geologist through studies of drill cuttings. The locations of feed zones based on analyses of the temperature logs and circulation losses during drilling are marked on the lithology section and

correlated to the formations. The feed zones/points are in most cases connected to active permeable fractures. For further evaluation of these fractures ISOR acquired few years back a “borehole televiewer” a fracture imaging acoustic tool developed in the oil industry some 40 years ago.

In the following sections a short description will be given of the geological wireline logs applied in Iceland i.e. the resistivity, gamma ray and neutron-neutron logs and the borehole televiewer fracture imaging tool. The discussion will be limited to the basic principles and the logging equipments. Examples of logs will be given and their applications discussed.

2. THE NORMAL RESISTIVITY LOG

2.1 Formation resistivity

The knowledge of the resistivity of the rocks is of great importance in geothermal exploration. The geothermal activity influences the formation resistivity through hydrothermal alteration of the rocks where the alteration minerals have different resistivities. Conductive minerals i.e. smectites and mixed layer clays formed at reservoir temperatures of 50-230°C. Minerals (e.g. chlorite, epidote) which are formed at higher reservoir temperatures have on the other hand higher resistivity. This explains why surface electromagnetic soundings (TEM and MT) are the main methods of geophysical surface exploration of geothermal fields. The low resistivity anomalies outline the top and the boundaries of the geothermal reservoir where the medium temperature alteration conductive minerals have been formed. The high resistivity zone inside the resistivity low, maps the inner part, the core, of the geothermal reservoir where temperatures exceeding 230°C have formed resistive alteration minerals.

The specific electric resistivity of the reservoir formations is the result of two different factors; the resistivity of the rock matrix and the formation fluid. The electric resistivity of rock formations will therefore vary with the rock type, the water content, the salinity of the water and the temperature. The most common rock types in geothermal reservoirs are of volcanic origin but sedimentary reservoir rock formations are also found. An igneous rock matrix is generally a poor electric conductor with specific resistivity values of 10^4 - 10^6 Ωm , whereas the resistivity in a sedimentary rock matrix is few orders of magnitude lower. The matrix resistivity can, however, be considerable lower, if it has undergone medium temperature hydrothermal alteration. The geothermal fluids, even of low salinity, are generally much more conductive (<10 Ωm) than the rock matrix and therefore the fluid resistivity will define the resistivity of the reservoir formations, except in very low porosity ($<<1\%$) rocks or very conductive rocks.

The formation resistivity value depends therefore in general on the porosity (water content) as well as temperature and water salinity. Observations of various rock types, leads to an empirical law of the form: $R_o = F \cdot R_w$; where F is called the *formation factor* and R_o and R_w are the formation resistivity, and the pore fluid resistivity, respectively. Several empirical relations between the formation factor F and the porosity have been suggested. The most famous is the Archie's formula:

$$F = a \cdot \Phi^{-m}$$

where, a is a constant; Φ is the porosity and m is a constant called *cementation factor*.

The constants a and m are found to be approximately fixed numbers for rocks of similar type and of similar intergranular and intercrystalline porosity. For sandstone, which is the common rock type in oil reservoirs, the typical values for a and m based on measurements of core samples, resistivity logs and empirical studies are $a \sim 1$ and $m \sim 2$. Fractured igneous rocks are, however the most common rock type in geothermal reservoirs. Resistivity-porosity relations have been determined for fractured basaltic formations in Iceland. A cementation factor, $m \sim 1$ has been found in most cases. A cementation factor of 2 has, however, been found for sedimentary interbeds in the basaltic lava pile.

(Stefansson et al., 1982). The constant a , seems, however, to be variable in igneous rock formations and values ranging from 1 to 15 have been reported (Stefansson et al., 1982 and Stefansson and Steingrímsson, 1980).

2.2 Resistivity logs

There are several measuring techniques used today to measure the resistivity of the formations intersected in wells. The set-up, which we have been using in Iceland, is what is called “the normal resistivity logging tool”. This is a four-electrode array with two electrodes fixed on the logging probe. The third electrode is placed at surface (mud pit), and the armour of the logging cable is used as the fourth electrode. The cablehead and the first 20-25 m of the cable are electrically insulated to distance the armour electrode from the electrodes on the probe. This arrangement of the electrodes is shown in Figure 2. During logging, a constant electric current I is driven between the electrode A on the probe and the armour of the cable and the voltage between electrode M on the probe and the surface electrode N (mud pit) measured. For the normal electrode array the specific resistivity of an infinite homogeneous medium is given by an Ohm’s law relation with a geometric constant:

$$\rho = 4\pi * AM * V/I$$

where ρ is the specific resistivity of the infinite homogeneous medium (in ohm metres)
 AM is the distance between the two electrodes A and M on the logging probe.
 I is the electric current flowing between electrodes A and B
 V is the voltage measured between electrodes M and N.

For the normal logging probe it is common to have two M electrodes on the probe, one at a distance of 16” from current electrode A and the other at 64” distance.

The medium surrounding a logging probe in a well is neither infinite nor homogeneous. The well is filled with and the formations change every few metres in the well. The relation above is therefore not fully valid and the resistivity obtained using the relation will be a kind of average resistivity value within the radius of investigation of the resistivity tool. This value is called an apparent resistivity and the normal resistivity log will show apparent resistivity variations not true formation resistivity. To obtain the true resistivity one must correct the apparent values for well effects (fluid resistivity and well size/diameter) and limited bed thickness of the adjacent lithological units. The apparent resistivity logs obtained for two spacings i.e. 16” and 64” show relatively different well effects. The 64” log has a larger radius of investigation and will be less influenced by the fluid in the well than the 16” log, which on the other hand will have better resolution for thin formation layers.

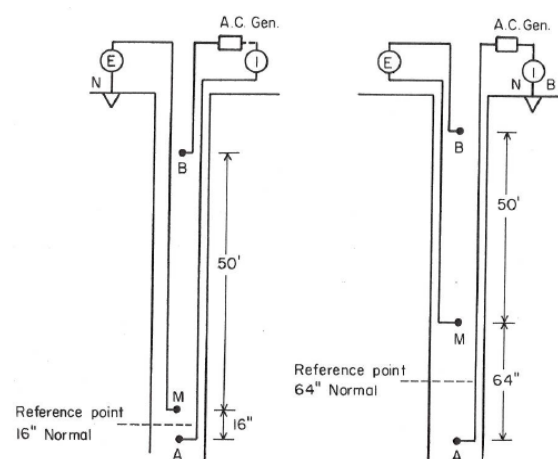


FIGURE 2: The configuration for the normal resistivity log (from Stefansson and Steingrímsson, 1980)

2.3 Applications of resistivity logs

Analyses and applications of resistivity logs can be divided into steps. The first step includes a qualitative observation of the data and comparison with other logging and geological information. For this purpose the log is plotted in parallel with other geological wireline logs, caliper and the geological section obtained through the drill cutting analysis (Figure 1). The logging data are used to define and locate accurately the contact between the various layers, to determine bed thicknesses and the results

help in depth correlation of the drill cutting analysis and compliment the geological section. The apparent resistivity values are compared to the geological description based on the drill cuttings and evaluated whether the geological analysis (the rock types) are correct. A notable resistivity contrast is for example observed between volcanic lavas and intrusive units, which will help the geologist in differentiating between these types.

Further and more quantitative evaluation of the resistivity logs is to eliminate well effects to determine the true formation resistivity and then through the Archie's equation calculate porosity values for the various formation units.

Finally the general resistivity structure on a larger depth scale is compared to the results of surface resistivity soundings (TEM and MT), and correlated to their resistivity depth models

The discussion on resistivity logs has only been on the normal electric log. This log has been applied for close to one hundred years in oil development and in groundwater and geothermal exploration. Several other electric logs have been developed. Tools like the Laterolog, where the electric current is focused into the formation by specific arrangement of electrodes. This is done to minimize well effects which can dominate the normal log when the well fluid is very conductive. On the other hand the Laterolog obtains a larger radius of investigation into the formation as the focused electric current penetrates deeper into the formations around the well. Example of another electric tool is the Microlog, a tool with several pads, which are pushed against the wall of the well. Each pad is equipped with electrodes for individual resistivity logging and will measure the resistivity in the nearest layer under the pad. The Microlog has a very short penetration depth (depth of investigation) but very high resolution of the formation resistivity, not only in the depth direction but also on the circular surface of the well. Micrologs are used to measure the resistivity in the invasion zone of the drilling mud but they also reveal fractures intersected by the well. These tools are mainly used in the oil industry but the Microlog could be a very useful tool in geothermal investigations for studying fractures in the future.

3. THE NATURAL GAMMA RAY LOGS

3.1 Natural radioactivity of rocks

Rock formations and minerals contain radioactive isotopes that decay continuously emitting radioactive particles and radiation into the surroundings. These are; α - and β -particles and electromagnetic γ -radiations. The radioactive isotopes that are mainly found in the Earth's crust are potassium (^{40}K) and those involved in the decay series of uranium and thorium. The ^{40}K isotope emits gamma rays of an energy of 1.46 MeV through an single decay process whereas uranium and thorium decay in series emitting α -and β -particles and electromagnetic γ -rays in different proportions and with different energies in each step of the series. The γ -ray energy spectrum for all the isotopes is shown in Figure 3.

The radioactive isotopes are only found in very small quantities in rock formations and sediments. Their concentrations vary, however, widely in crustal rocks over several orders of magnitude (Hearst and Nelson, 1985). In igneous rocks the concentrations of all three radioactive isotopes are ten times greater in acidic rocks than in ultra

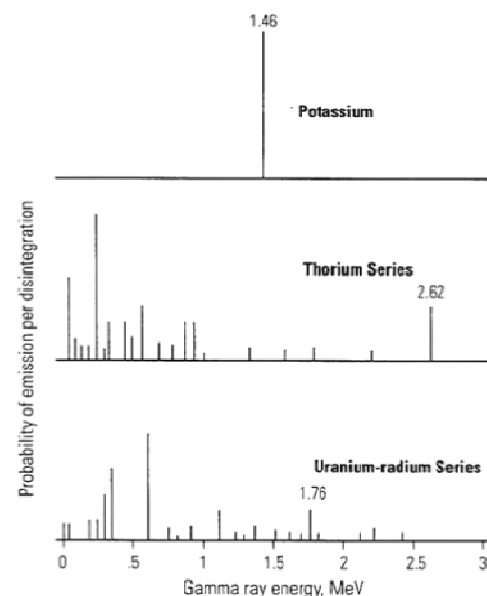


FIGURE 3: The distribution of gamma ray energy from the three naturally occurring radioactive isotopes (from Ellis and Singer 2007)

basic rocks and the concentration of each isotope is generally proportional to the SiO₂ concentrations. In sedimentary rocks the relative concentrations of the three elements is variable but the total concentrations of the radioactive isotopes are different for different sediments and therefore also the radioactivity.

3.2 Gamma ray logging

Although the concentration of radioactive isotopes is very low, the γ -radioactivity of rock formations is easily detectable. The α - and β -particles have, however, a short penetration length in fluid and solid materials and this type of radioactivity can generally not be detected within wells. The measurement of γ -radiation in wells is called the natural gamma ray log and was first introduced in the 1930's in the oil well logging and was the first non electric geological log. The gamma ray log is a passive measurement, where a detector is lowered into the well to register the natural radiation from the surrounding geological formations. The detectors used are either Geiger-Muller tubes or scintillation counters. The GM-counter measures the total gamma intensity, but the scintillations counter can either measure the total intensity or the energy spectrum of gamma radiations. The log of the total radioactivity is the gamma ray log but when the energy spectrum is measured the log is called the spectral gamma ray log. In Iceland we have only been using the gamma ray logs in geothermal well.

As the efficiency of counters is different and can change in time for the same counter, it is necessary to calibrate the gamma ray tools regularly in order to compare gamma logs done with different counters or at different times with the same counter in order to obtain the true radioactive intensity of the formations. The American Petroleum Institute has established such industrial standard, an API γ -ray unit. It is defined as 0.5% of the difference in count rate registered between zones of low and high radioactivity in a test pit situated at the University of Houston (Texas, USA). The radioactivity of the concrete in the pit corresponds to about 200 API gamma units and contains about 4% K, 24 ppm Th and 12 ppm of U. (Stefansson and Steingrímsson, 1980).

3.3 Applications of gamma ray logs in Iceland

The application of gamma ray logs rely on the fact that the concentrations of radioactive isotopes varies from one rock type to another and that acidic rocks are more radioactive than the basaltic rocks. The analyses of gamma logs as carried out in Iceland can be divided into steps similar to other logs. The main steps are the following:

- The logging data are reviewed, the count rate registered converted to API gamma ray units and depth scale correlated to other geological information from the well, before the log is stored in a database.
- The gamma ray log is plotted in parallel with other geological logs, caliper and the geological section obtained through investigation of the drill cuttings (Figure 1). Formation units showing elevated radioactivity are identified and the location of contact boundaries determined and the bed thickness. The units of elevated radioactivity should coincide with acidic (diorites, andesites, rhyolites) rock units in the geological section based on the drill cuttings but variations in radioactivity can also be related to higher concentrations of radioactive isotopes in sedimentary interbeds in the basaltic pile or in formation of intense hydrothermal alteration.
- The gamma ray log is corrected for well effects and the relations between radioactivity and the acidity of igneous rocks (Figure 4).
- The Icelandic crust is mainly of basaltic composition. Acidic formations are therefore relatively rare and most wells intersect only few acidic layers. This makes it possible to use the acidic layers observed in gamma ray logs as lithological markers and trace these units from one well to another. The gamma ray logs might even be more informative in other parts of the world, like Central America, where acidic formations dominate over basaltic ones and would therefore give a broader radioactivity spectrum than experienced in Iceland.

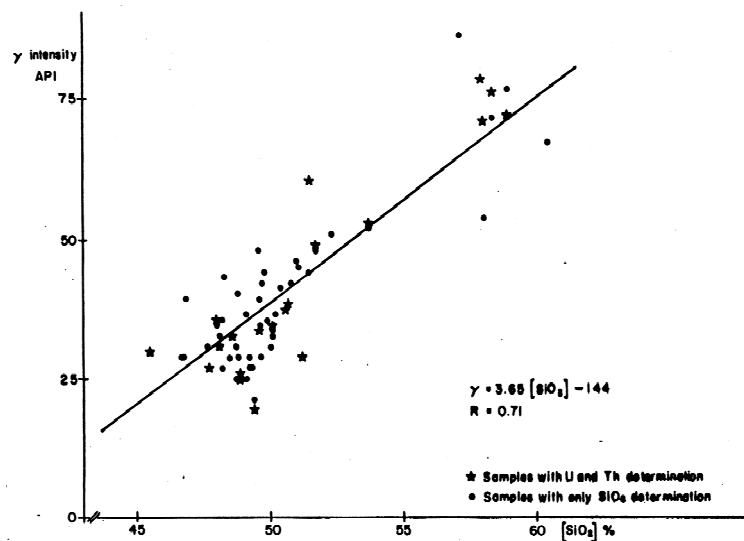


FIGURE 4: The relation between gamma ray intensity and SiO_2 in Icelandic rocks (from Stefansson et al., 1982)

4. NEUTRON-NEUTRON POROSITY LOGS

4.1 Scattering of neutrons in rock formations

The neutron is an electrically neutral elementary particle of approximately the same mass as a proton. The neutrons are found in the nucleus of the atomic elements but free (high energy) neutrons are generated in the decay of radioactive isotopes. The free neutrons are transient particles which interact with matter through elastic and inelastic collisions. The neutrons hit the nucleus of the matter and slow down to thermal velocities before being absorbed or captured by a nucleus, which in turn becomes radioactive and decays emitting a gamma radiation. The rate of which the fast neutrons are slowed down to thermal velocities depends on the chemical composition of the media they travel through.

In rock formation, the slowing down process is dominated by elastic (billiard) collisions between the neutrons and the nuclei in the surroundings, until thermal state is reached. It is well known from the collision theory that the incoming particle gives up more kinetic energy when colliding with a particle of similar mass. The nucleus in the surroundings with the mass closest to the mass of the neutron is the hydrogen nucleus which consists of a single proton. The hydrogen atoms in the formations are mainly found in the water molecules. The slowing down process of fast neutrons in rock formations is therefore primarily controlled by abundance of water in the surroundings either water in pores and fractures in the rock formations, or water bound in minerals i.e. geothermal alteration minerals in the case of geothermal. Hence the term “neutron porosity log” is not quite accurate more correct would be to refer to it as a log that measures the total hydrogen content of the formation as water by volume. This effect of formation water on the slowing down of fast neutrons, is the basic physical principle, which the logging technique to evaluate “porosity” of rock formations is based on.

4.2 Neutron porosity logging

A simple neutron porosity logging tool (Figure 5) consists of a neutron source emitting high energy neutrons and a detector (sometimes two), sensitive to thermal neutrons, located on the probe at an appropriate distance (~30-40 cm) from the neutron source. The double detector tool is called compensated neutron tool, where the far detector is some 60 cm from the source.

The neutron tool used in Iceland is a single detector tool, where the neutron source is a mixture of radioactive Americium and Beryllium (AM-BE). The radioactive Americium emits alpha particles which collide with the beryllium cores and cause them to emit high energy neutrons. The energy level of the neutrons is 4.5 MeV. This correlates to a neutron speed of some 30,000 km/s which will be reduced to some 500 km/s through the slowed down collisions when the neutrons become thermal and are detected counted by a ^3He -neutron detector. As for the gamma ray tool a standard calibration is used for neutron counters. It defines an API neutron unit as a part of the difference between two porous water saturated layers in a calibrations pit at the University of Texas in Houston, Texas.

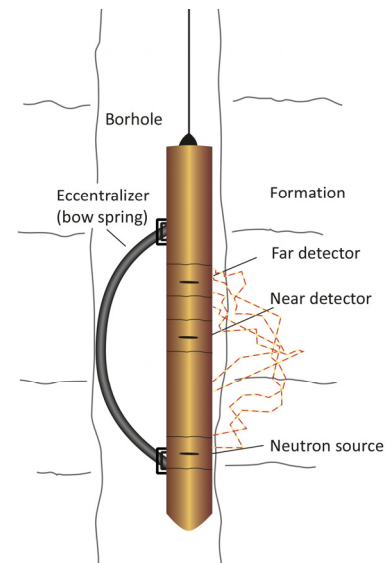


FIGURE 5: Neutron-neutron logging tool

4.3 Application of neutron logs in Iceland

Neutron porosity logs are primarily carried out in “open” holes but will work in cased sections with some attenuation of the signal.

The primary steps, in analysing the neutron logs, are similar to other logs. The logging data are calibrated and converted to API neutron units. The depth scale is correlated to other logs and stored in a database. The log is then plotted in parallel with other geological wireline logs from the same well (Figure 1) for determining the stratigraphy of the lithological section and comparison with other logs.

Further interpretation of the neutron log is an evaluation of well effects influencing the logging response. These are mainly effects caused by the water in the well. This effect must be subtracted from the log to obtain the “true” formation signal which in turn can be converted to formation “porosity”. Calibration curves relating neutron logs and porosity have been developed in the oil industry based on porosity measurement on cores and neutron logs as well as resistivity log. They define what is called “limestone porosity” and are fairly accurate for sedimentary (limestone) oil reservoirs. Example of such curves is shown on Figure 6. These curves have been used in Iceland for many years to estimate porosity of rock formation from neutron logs. The Icelandic formations are, however, igneous rocks and it is therefore not obvious that the “limestone calibrations” are fully valid for igneous rock where the bound water contribution to the

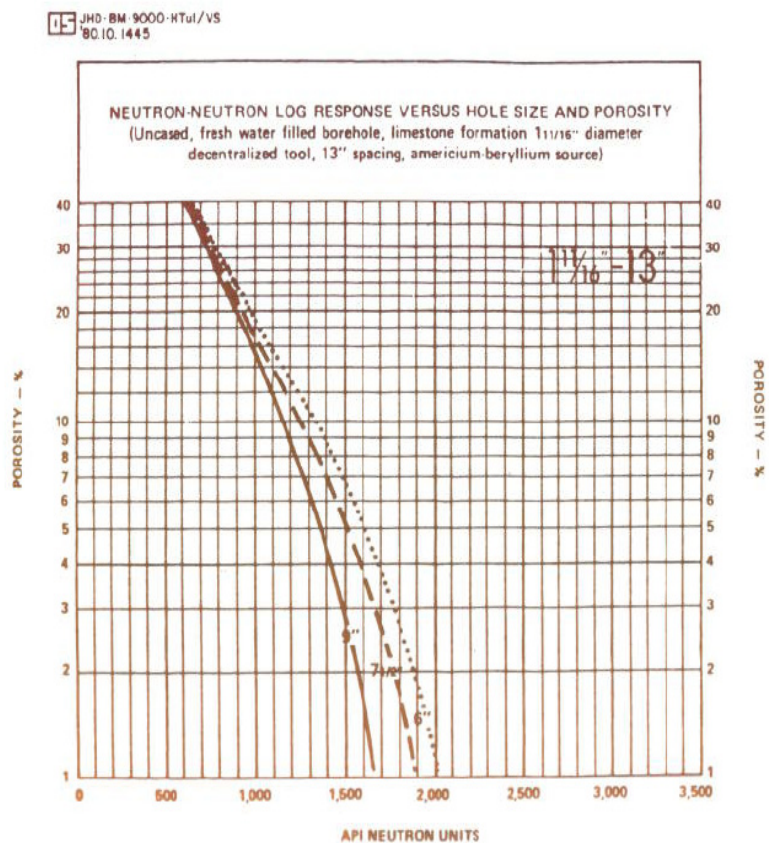


FIGURE 6: Limestone porosity and neutron-neutron logs. Example of calibration curves for 6”, 7.5” and 9” diameter wells. (Stefansson and Tulinius, 1983)

“porosity” might be quite different. Comparison neutron logs in limestone and igneous rocks indicate, however, that the difference between limestone porosity and igneous rock porosity should not be more than 3% (Czubek, 1981).

5. BOREHOLE TELEVIEWER LOGS

The permeability of igneous rocks in geothermal reservoirs is dominated by fracture permeability opposite to many sedimentary reservoirs, where matrix permeability dominates. Mapping of permeable fractures in the geothermal reservoirs is therefore very important. Several logging tools have been developed in order to study fractures intersected by wells. These tools create an image, a kind of a “picture”, of the wall of wells revealing the fractures and various features of the geology visible on the “picture”. A tool of this type is the borehole televiewer, an acoustic tool, that was developed in the oil industry in 1970 and we have used successfully in Iceland for a few years with the main objective to map permeable fractures in geothermal wells.

5.1 Borehole televiewer

The borehole televiewer is a logging tool that produces an acoustic “picture” of the borehole (well) wall. The tool consists of (1) an acoustic transducer which acts both as a transmitter and a receiver of a signal, that is sent from the tool directly to the wall of the well and reflects from the wall back to the transducer; (2) a motor which turns the transducer so a reflected signal is obtained from the circumference of the well (the tool is centralized in the well) and (3) a magnetometer (compass) to provide information on the orientation of the tool with respect to the Earth’s magnetic field and 3D accelerometers to determine deviation from vertical (see Figure 7). The signal from the transducer consists of 1500 very short acoustic pulses per second as the motor turns the transducer 3-7 revolutions per second while logging the well at a speed of 1-2 m/minute.

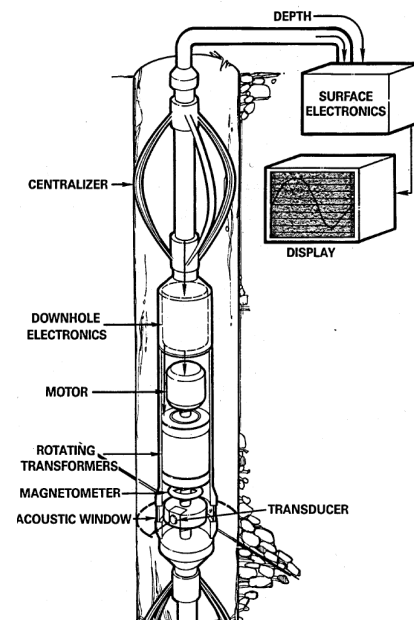


FIGURE 7: Acoustic Borehole Televiewer (from Heard and Bauman, 1983)

5.2 The acoustic picture and its applications

The acoustic picture obtained by the televiewer will depend on several factors including reflectance of the well wall which is higher for hard rock than soft rocks, roughness of the wall and the geometry of the well i.e. deviations from a circular form. The well fluid also affects the quality of the “picture”. Muddy water will cause dispersion of the acoustic signal and result in a foggy “picture” although the acoustic wave is not as sensitive to dispersion as photographs, due to the longer acoustic wavelength compared to wavelengths of light.

Figure 8 shows a part of a televiewer log from a low temperature geothermal well in Iceland. The log is viewed in two ways on the figure, in a core view and as an unwrapped picture of the wall of the well. The log shows an open fracture at 1324-1325 m depth. The fracture appears as a dark line but it has been traced with a green line on the log. The log suggests a fracture opening of some 20 cm and shows NE-SW strike and a fracture dip of 7 degrees from vertical. This fracture was quite permeable and produced 60 l/s of 75°C hot water during a pump test.

Figure 8 demonstrates the main application of televiewer logs but there are other uses some of which are listed below:

- The televiewer log is viewed and analysed in order to detect fractures visible on the log. The orientation of the fractures is determined, both the dip angle and the strike direction. Fractures that coincide with known feed zones in the well are of special interest.
- Detection of hard and soft formations intersected by the well and the determinations of the contacts layers between beddings.
- Geometrical information regarding the shape of the well (distance to the wall,) and the roughness of the wall.
- Detection of key seat forming of the well due to drill string erosion of the formation
- Detection of break-outs visible in the logs give information on stress conditions in the formation

6. CONCLUSIONS

The geophysical logs, resistivity, gamma ray and neutron-neutron log, discussed in this paper have the main purpose to study the lithological units intersected by a well, locate contacts of adjacent beds and determine the thickness of the units. The knowledge on the geological sections in geothermal wells is primarily obtained by studies of drill cuttings. The cuttings are formed at the well bottom and then flushed to the surface with the circulating fluid. The analyses of the drill cuttings must therefore take into account the time it takes to bring them to the surface and also the unavoidable different travel time for cuttings of different size and mixing of the cuttings as they are flushed to the surface. The three logs discussed have been used in Iceland since 1976 and have proven to be an important addition to the analysis of the drill cuttings for dividing the lithological column into different layers. In the case of blind drilling, i.e. drilling with total loss of circulation, these geological wireline logs and drilling penetrations rates (rock hardness) give the only geological information available for the blind sections, especially in order to define geological environment of the permeable formations.

The gamma ray log determines, in addition to rock stratification, the radioactive intensity of the rocks, which relates to the acidity of the rocks and somewhat to its hydrothermal alteration. The gamma ray log can therefore distinguish between acidic and basaltic formations and empirical relationship between the gamma ray logs and SiO_2 concentrations has been established for igneous rocks. The resistivity and the neutron logs have been found to be useful in pointing out hard, low porous formations (intrusions) and in general to estimate the porosity of the formations through empirical relations obtained through studies of drill cores and by comparison to logs in cored wells.

The permeability of the geothermal reservoirs is dominated by fracture permeability. Studies of permeable fractures are therefore very important in geothermal exploration. Several logging tools have been developed for fracture imaging. The tool that we use in Iceland is the borehole televiewer. We have used it in several wells during the past years and gained very valuable information for defining the inclination and direction of fractures intersected by the wells, knowledge very valuable for future targeting of wells.

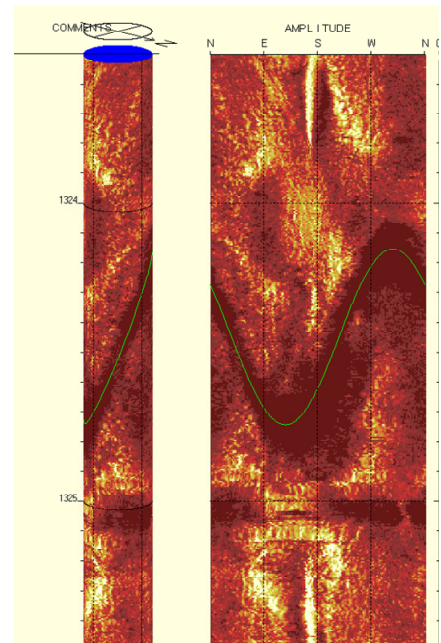


FIGURE 8: Televiewer log showing an open permeable fracture

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