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INTRODUCTION TO GEOPHYSICAL WELL LOGGING AND FLOW TESTING

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ABSTRACT

Well logging is the practice of making a detailed record of the geologic formations penetrated by the well. The log may be either geological logs or geophysical logs. In geothermal, geophysical logging is done to identify location of fractures, the lithology and record the physical parameters like temperature and pressure. Important logs include temperature, pressure, gamma, neutron, cement bond log, calliper log, resistivity and directional surveying.

When the well has recovered sufficiently, a flow test is conducted by flowing the well to evaluate the total flow rate, enthalpy and chemical characteristics of the discharged fluids. A common method used in flow testing is the lip pressure method (Grant et al., 1982). The well is discharged under different throttle conditions to get the characteristic curve to be used in selecting operating conditions for the turbines in the power plant.

1. INTRODUCTION

Logging generally means to “make a record” of something. Well logging, also known as borehole logging is therefore, the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a well. The log may be based either on visual inspection of samples brought to the surface (*geological* logs e.g. cuttings logs, core-logging or petro-physical logging) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Geophysical well logging was first developed for petroleum industry by Marcel and Conrad Schlumberger in 1927 (Schlumberger, 2000). They developed a resistivity tool to detect differences in the porosity of sandstones of oilfield at Merwiller-Pechelbronn in France. Since then, geophysical well logging has developed to become a key technology in petroleum, geotechnical, mineral, groundwater and geothermal industries. While geophysical logging in petroleum is done to determine porosity and hydrocarbon saturation, in geothermal, the main emphasis is on location of fractures and recording of physical parameters e.g. temperature and pressure. Well logging is done during all phases of geothermal development; drilling, completion, production and abandonment.

When the well has recovered from the effects of cooling during drilling, it is flow tested to evaluate its mass flow, enthalpy and chemical characteristics. This paper will attempt to give a short description of the more routine geophysical well logging methods used in the geothermal development as well as the method commonly used in flow testing of the geothermal wells.

2. GEOPHYSICAL WELL LOGGING

Knowledge of the subsurface comes primarily from drilling which is a very expensive process. Therefore, the number of holes to be drilled for studying the subsurface is limited. Geophysical logging offers an opportunity to determine the composition, variability and physical properties of the rocks around the well thereby enabling a proper understanding of the subsurface at a cheaper cost. The following are the common geophysical logging methods used in geothermal applications.

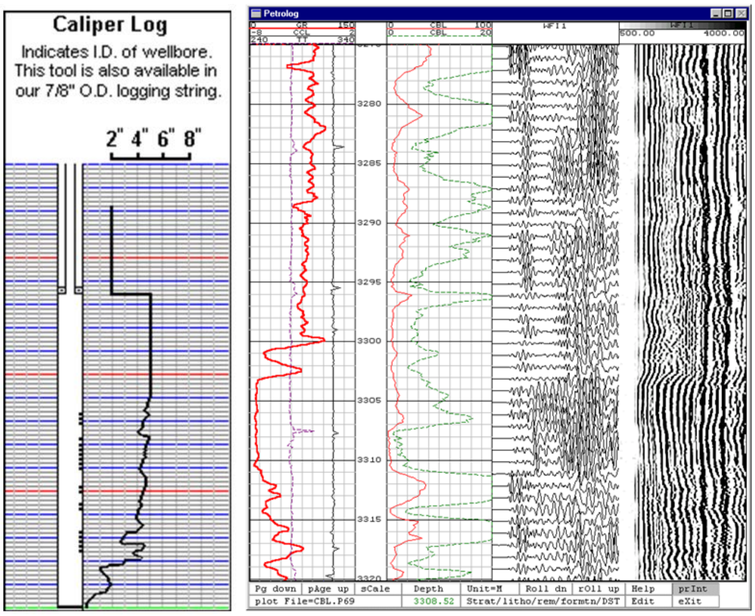
2.1 Caliper logging

A caliper tool is used to measure the diameter of a well and how it changes with depth. It works by using one or more spring loaded arms which are pressed against the well bore wall as the tool is raised from the bottom of the well. The arms move in and out from the bore wall and the motion is recorded electrically and transmitted to the surface recording equipment. Multi-arm tool gives a better resolution of the bore shape than a single arm tool.

The results of the caliper logs can be used by the drillers to calculate amount of cement to be used for cementing job if it is run in the open hole prior to cementing to identify the large cavities (Figure 1). Caliper logs are also used in addition to lithological logs when interpreting the well geology.

2.2 Cement bond logging

Cement Bond Logs (CBL) use sonic tools that work by transmitting a sound wave through the casing, cemented annulus into the rocks of the borehole wall. A basic sonic tool consists of two parts. One contains the transmitter and the other contains two or more receivers. The two parts are normally separated by a rubber connector to reduce direct transmission of acoustic energy along the tool from the transmitter to the receiver.



Indicates I.D. of wellbore. This tool is also available in our 7/8" O.D. logging string.

FIGURE 1: A Caliper and CBL log display (they are for different wells)

The transmitter injects a sinusoidal wave-train of acoustic energy into the formation. The detectors receive the signals whose arrival time will depend on the density of the media the signal has traversed. CBL is used for:

- Determining cement bond quality between cement and casing and also between cement and formation for zone isolation.
- Correlating open hole logs to cased hole logs using the Casing Collar Locator (CCL) and Gamma Ray tool.
- Indication of cement compressive strength. These tools can also measure casing thickness, micro annulus and cement channeling but do not measure cement bond to formation as well as the CBL.

Once a well has been determined to be productive, casing is run in the open hole and cement is pumped to the outside of the casing to seal the casing to the borehole wall. A Cement Bond Log (CBL) is then run to inspect the integrity of the cement sealing to the casing and to the formation. This will ensure that undesired formation fluids will not flow into the well when on production or up or down the outside of the casing.

2.3 Lithological logging

Common lithological logging tools use either radioactive or resistivity methods. Principal radioactive emissions of interest in borehole geophysics are gamma rays and neutrons. Other radioactive products such as alpha particles and beta particles have low penetration capabilities and so are not useful for logging.

2.3.1 Natural gamma logging

This is the simplest geophysical well logging. These logging tools record the level of naturally occurring gamma ray emissions from rocks around the borehole. The signals comprise gamma ray emissions at different energy levels from the radioactive isotopes of Potassium (^{40}K), Thorium (^{232}Th) and Uranium (^{238}U) and their daughter products of the decay series. Distribution of K, Th and U varies widely in the crust and as a result, logging of the gamma ray signals emanating from the rocks around the borehole can provide considerable information about the geology of the borehole (Figure 2).

2.3.2 Neutron

Neutron-neutron and gamma ray tools are normally combined and run together. The neutron sensors measure the water content of the rock because the hydrogen atoms deflect neutron particles emitted from the tool. Porosity is a function of rock type and slow neutron count.

2.3.3 Resistivity logs

Resistance is impedance to flow of current and is a function of geometry and intrinsic resistivity of the material. Resistivity is the inverse of conductivity. Current flow in porous rock is mainly through the fluid filling the pore space and is affected by pore volume, pore connectivity and pore fluid composition, degree of alteration and mineralogy and temperature. Pore space character varies from formation to formation and for this reason, resistivity logs are often useful for exploring lithological units (Figure 2).

2.3.4 Self potential (SP) logs

SP method was developed by Schlumberger and measure small potential differences between the downhole movable electrode and the surface earth connection. The potentials arise from electrochemical and electrokinetic processes and are typically in the range of a few mV to a few tens of mV.

2.3.5 Induced polarisation (IP) logs

IP uses a transmitter loop to charge the ground with a high current. The transmitter loop is then turned off and the change in voltage with time is monitored using a secondary loop. In a well, the primary loop induces current flow in the rocks beyond the bore wall and the current leads to a charge build-up on conductive particles. The time dependent dissipation of this charge is then reflected as a decaying voltage. The IP can be used in detection of alteration zones.

2.4 Temperature logging

Temperature logs are the most important in geothermal applications. They are used to show how hot the well is and to locate aquifers (Figure 3). The information on aquifers is very useful in identifying the main inflow into the well for production purposes and also for cementing purposes where powerful aquifers have to be known so as to ensure good cementing jobs. Lithological tools and other electrical tools are very sensitive to temperature and so before running these tools, a temperature log would indicate whether it is safe.

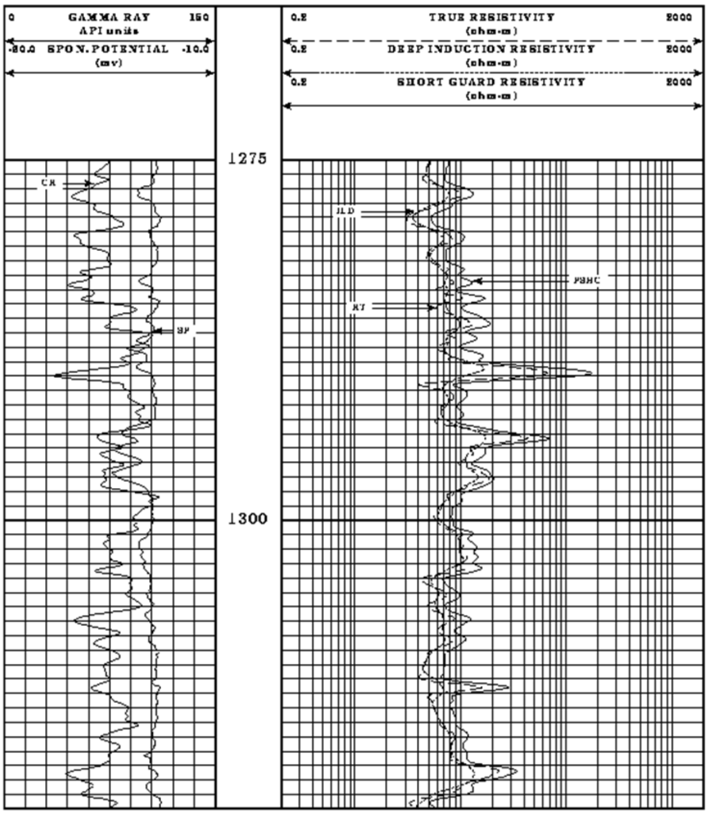


FIGURE 2: Gamma ray and resistivity logs

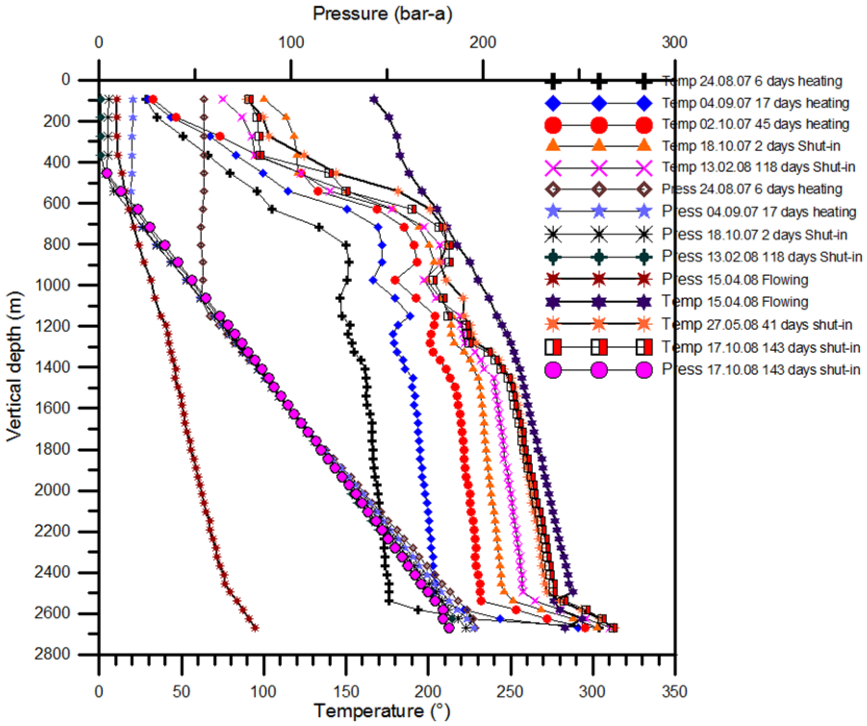


FIGURE 3: Pressure and temperature logs from one of the wells in Olkaria

2.5 Pressure logging

In most cases, pressure logs are done when the well has been drilled to the final depth. Transient pressure tests are done to estimate well injectivity index and hydraulic properties of the prominent aquifers. The injectivity index gives an idea of the well productivity. Pressure logs also indicate the type of fluids contained in the reservoir whether liquid or gas/steam as well as where the well is best connected to the reservoir.

2.6 Directional surveying

Directional drilling has gained importance in geothermal drilling in the recent past. To this effect, tools that can indicate the direction of the well profile as well as depth and azimuth are now available. Two types of directional tools are in operation i.e single-shot and multi-shot magnetic or gyro tool. Magnetic Single-Shot records one measurement, usually near the bottom of the well. It is comprised of a precision floating compass, a device to superimpose concentric circles (calibrated in degrees) with a plumb-bob type indicator, and a camera that photographs the plumb-bob and compass face to record both drift and direction. It cannot record compass directions inside regular drill collars or casing because steel pipe blanks off the Earth’s magnetic lines of force. Thus, it is used only in open hole or inside non-magnetic drill collars. Magnetic Multi-Shot records multiple measurements of borehole drift and azimuth on a single run into the hole. It consists of a modified magnetic single-shot instrument with the single frame camera replaced by a multi-frame camera (Figure 4). It also has incorporated timing devices, including a motion sensor, and is used for multi-depth drift and direction measurements. Like the single-shot, it must be in an open hole or inside non-magnetic drill collars to measure compass directions.

Gyroscopes are impervious to magnetic interference and can be used to survey in cased wells or orient directional equipment for re-entry wells. The photographic gyroscope is used primarily to survey wellbores that have already been cased. This instrument can run in casing, tubing or drillstring, using a wireline.

The latest high precision tool is multi-shot true north seeking tool by Stockholm Precision Tools (SPT). The SPT system uses the gyro-compassing method to find direction. As it is a north-seeking gyro, all measurements are in reference to geographic north. Unlike other downhole survey or magnetic tools, the GyroTracer is not affected by magnetic interference. It can be run inside casing, tubing, drill pipe and magnetically disturbed ground. It can be run either as wire-line SRO (surface read out) or in memory mode via slickline.

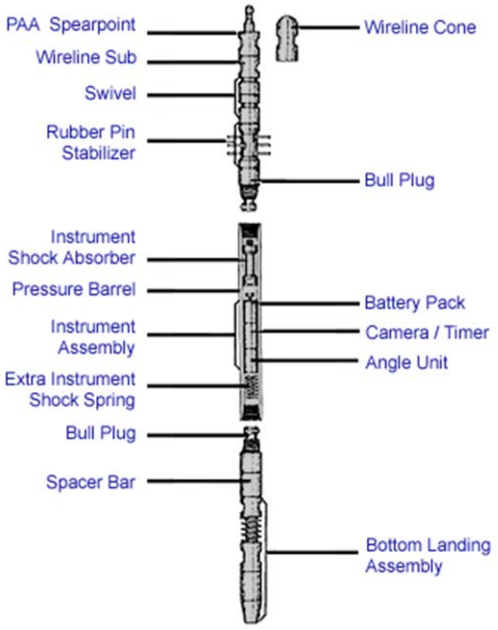


FIGURE 4: Multi-shot magnetic tool

3. FLOW TESTING

During recovery or warm up period, the water level in the well gradually rises and if there is boiling or accumulation of gas, the well will eventually build wellhead pressure above atmospheric for artesian flow. If not, the discharge can be initiated by compression, gas lift or swabbing. When the well has built up sufficient wellhead pressure and the well has recovered sufficiently, a flow test is then conducted by flowing the well through an orifice. Measurements are taken to evaluate the total flow rate, enthalpy and chemical characteristics of the discharged fluids. The lip pressure method (Grant et al., 1982; Figure 5) or a separator can be used to determine the total flow rate and enthalpy with a simple weir being used to measure separated water flow. By repeating the flow tests with different sized orifices, the well productivity as a function of wellhead pressure can be determined. This is the characteristic curve for the well that can be used in selecting operating conditions for the turbines in the power plant (Figure 6).

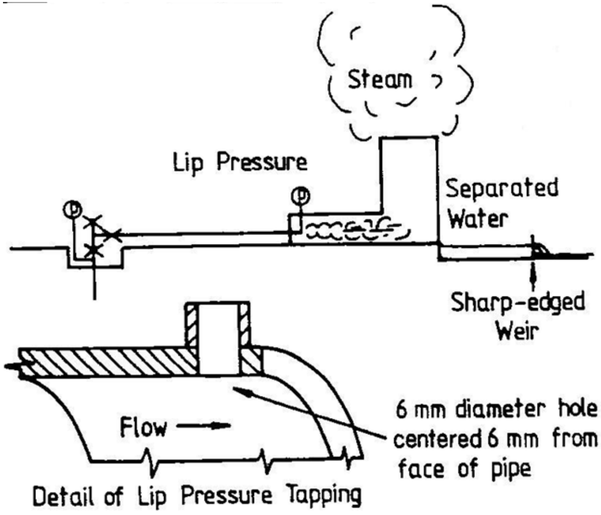


FIGURE 5: Schematic of Lip pressure method

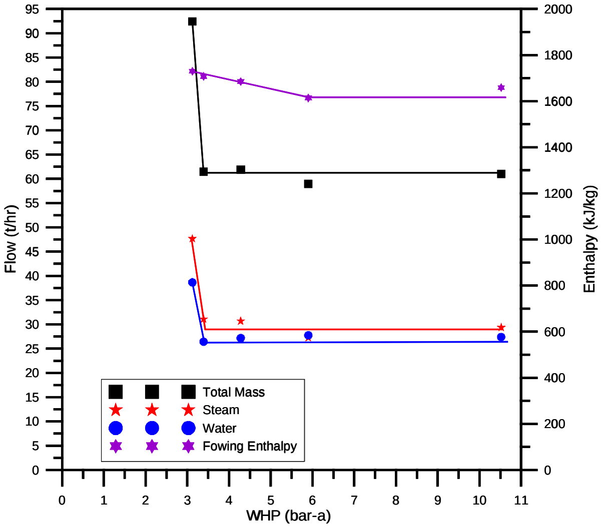


FIGURE 6: Characteristic curves of one of the Olkaria wells

REFERENCES

Grant M.A., Donaldson I. G. and Bixley P. F., 1982: *Geothermal reservoir engineering.* Academic Press, NY.

Batini F., Bertini R., Ciulli B., Fiordelisi A., and Valenti P., 2002: Geophysical well logging – A contribution to the fractures characterization. *Proceedings of the 27th Workshop on Geothermal Reservoir Engineering, Stanford, California.*