ON GEOPHYSICAL LOGGING OF GEOTHERMAL WELLS WITH EXAMPLES FROM WELL KJ-13 IN THE KRAFLA GEOTHERMAL FIELD, N. ICELAND

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ABSTRACT

This report describes the stratigraphic sequence and the alteration in drillhole SG-9 in the Svartsengi high temperature field, SW-Iceland. The stratigraphic column consists of three series, a 442 m thick olivine tholeiite lava series, a 216 m thick hyaloclastite unit, and a 242 m thick tholeiite lava series. Correlation of the stratigraphy of SG-9 with other drillholes in Svartsengi suggests the existence of a buried fault in the area. The upper aquifer (441 m) conicides with a basalt/ hyaloclastite boundary, whereas the lower one (907 m) conicides either with a basalt/hyaloclastite boundary or a vertical fracture. The alteration minerals are arranged in three zones: 1) smectite-zeolites, 2) mixed-layer clay minerals, and 3) chlorite-epidote. The alteration mineral of dolomite, which has not been reported before in an active thermal area in Iceland, occurs between the depths of 250 and 420 m. The correlation of the hydrothermal alteration between SG-9 and SG-8 implies that the alteration zones occur at deeper levels towards the west.

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PROLOGUE

The full stream development of the indigenous geothermal resources in the Philippines necessitate skilled technical men to carry out the main objectives of the ongoing exploration in the country. In 1979, two geologists of the PNOC-EDC attended the first UNU Geothermal Training Programme in Iceland, to avail of the technology transfer program offered by the host country and UNU. In 1980, the author was also awarded a UNU Fellowship in the second year of the programme. After about four weeks of introductory lecture course in general geothermics (geology, geohydrology, surface geophysical techniques, geochemistry, reservoir engineeering, utilization, economics, drilling and mineral alteration etc.) the author received specialized training in borehole geophysics. It included actual execution of well logging comprising temperature and pressure measurements in low and high temperature wells, nuclear logging, electrical logging and other miscellaneous logs (3 weeks), theoretical aspects and interpretation of these logs held in tutorial type instructions (3 weeks).

Moreover, two weeks were spent by all UNU Fellows visiting most of the thermal fields in Iceland, receiving lectures and seminars in each respective area (i.e. on geological exploration, geophysical prospecting, geochemical research and the stages of development of the geothermal projects).

This report represents the outcome of a research project carried out mainly during the last 10 weeks of specialized training. The emphasis of this report is on the various well logging techniques commonly used in the petroleum industry, but which are still at an experimental stage in geothermal studies. In the Philippines only the conventional temperature and pressure measurements/analyses are being applied in well logging, but the possibility of utilizing the more advanced technology is foreseen. In view of this the author was encouraged to concentrate on this field, where the Philippines lack experience, through the support of the Geothermal Division of NEA in Iceland who are conducting experiments and research in this field.

Part I is a review of the principles in geophysical logging with special emphasis on geothermal logging. The second part deals with the interpretation of several logs measured in Well KJ-13 at the Krafla high-temperature field in Iceland. In this part some of the interpretation methods are described and used to obtain correlation between several parameters of the reservoir rock.

Part I REVIEW OF PRINCIPLES IN GEOPHYSICAL LOGGING

1. INTRODUCTION

Geophysical logs can be defined as records of sequential data pertaining to some properties or characteristics of liquids and rocks traversed by the borehole (Keys and McCary, 1971). The geophysical logs commonly applied in the oil industry are temperature and pressure logs, porosity and density logs, resistivity, self potential and sonic logs. In geothermal investigations only the temperature and pressure logs are common, but application of the other logs has started in recent years.

The properties of the geothermal fluid as well as the properties of the reservoir rock are very important to understand the characteristics of a geothermal system. Interpretation of the above mentioned geophysical logs gives information on such petrophysical properties as density, porosity, permeability, thermal conductivity, natural radioactivity, electrical resistivity and sonic velocity. Several empirical relations have been found between these parameters which are valid in sedimentary rocks. In volcanic rocks much less experience is available in geophysical logging other than temperature and pressure logging. With proper calibration methods it is, however, possible to obtain as valuable information on volcanic formations as on sedimentary. In this review of the principles on geophysical logging, it is attempted to show the differences and limitations of each geophysical logging method to give the reader some background on the application of the techniques. First, the temperature and pressure logs are discussed then the nuclear logs which include natural gamma ray logs, gamma-gamma logs and neutron-neutron logs. Electrical logs, i.e. resistivity and self potential logs are thus described as well as other miscellaneous logs such as caliper logs, the casing collar locator, and sonic logs.

2. TEMPERATURE AND PRESSURE LOGS

2.1 Introduction

Temperature and pressure are the basic parameters being evaluated in geothermal studies. In this report, only some basic points regarding these parameters will be discussed. For more detailed discussion the reader is referred to Grant 1979, Kappelmeyer and Haenel 1974, Elder 1965, McNitt 1965, White 1973, and Stefansson and Steingrímsson 1980.

This chapter will first deal with the instrumentation applied in temperature and pressure logging in low and high temperature fields. Secondly it will deal with the application of these logs during the initial exploration and the development stages, in the modelling of geothermal fields.

2.2 Instrumentation

Instruments for continuous temperature logging in low temperature conditions (up to 180°C) are presently available from commercial logging companies. For high temperature fields, mechanical instruments like Amerada and Kuster gauges are commonly used and they can withstand temperatures up to 350°C.

Normal temperature logging probes primarily consists of a thermistor whose resistance changes in response to temperature. The sensor is a glass insulated semiconductor, which is enclosed by a very high thermal conductive material. Only small currents are fed to the thermistor to prevent self heating that would introduce an error. Electronics are designed in such a way that resistance effects will be negigible i.e. there should be no leakage in the circuits.

Since this instrument has an inherent response lag, the time constant and logging speed should be properly adjusted. Trial and error can determine the best logging conditions, but to overcome this problem correction factors characteristic for each instrument can also be calculated.

Mechanical thermometers commonly used at temperatures higher than 180°C are of bourdon tube type (Amerada and Kuster gauges) and register the temperature and pressure according to their corresponding deflection on a chart which is inside the instrument. The recording chart is moved by a clock over the stylus which records the temperature and pressure. These instruments are designed to withstand high temperature conditions for up to several days depending on the duration of the clocks.

Similarly there are now available high precision quartz pressure gauges which can monitor a continuous pressure profile in a well. It can even be run together with some other logs shown in the diagram below, Fig. 1. It should be remembered that unless the temperature is less than 180°C, presently designed continuous logging instruments cannot be used. Otherwise, high temperature instruments mentioned above have to be utlilized.

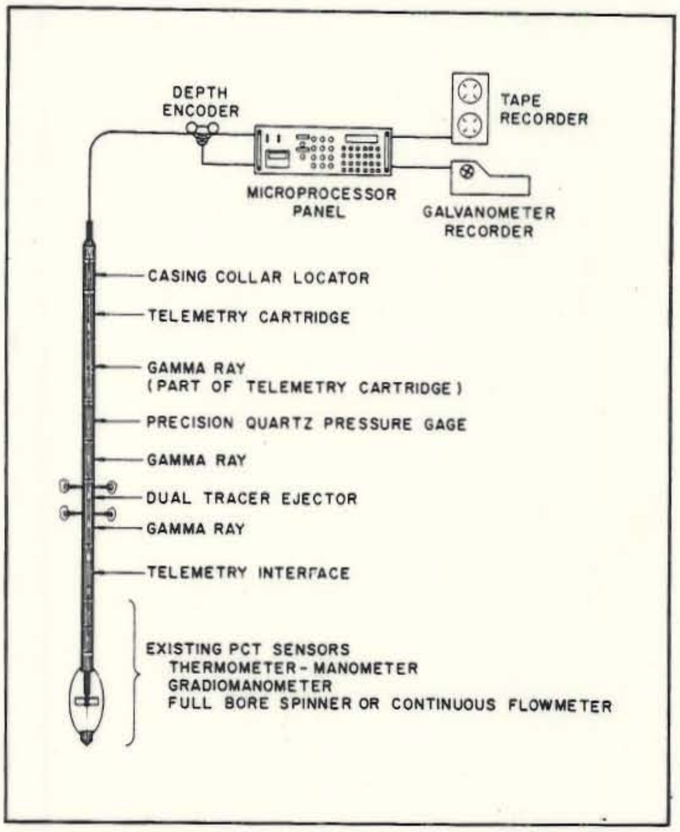


Fig. 1 Pressure gauge in a logging tool
(From Anderson et al., 1980)

2.3 Application

2.3.1 Initial exploration

After several types of reconnaissance surveys (including inventories of fumaroles and hot springs) shallow drillholes provide information about local temperature gradients and heat flow in a geothermal area. Heat flow data are often treated as an indicator of the magnitude of the heat source stored in the subsurface rocks, and is in many cases very valuable in identifying local hydrothermal systems (Yuhara, 1977). For example in Iceland regional heat flow values range from 80 mW/m^2 to 200 mW/m^2 in the active volcanic zone (Palmason et al., 1979).

If the heat flow is assumed only conductive the following equation is valid:

$$q = k \frac{\Delta T}{\Delta Z}$$

where:

q = heat flow, k = thermal conductivity, ΔT = differential temperature, ΔZ = differential depth

2.3.2 Development / exploration

A temperature log is one of the most important logs to describe the conditions in the well if the drilling is stopped for one reason or another. Equilibrium rock temperatures can be determined from measurements made at intervals in the drilling as shown by Albright (1975), Messer (1976), and others. Similarly temperature logs are of great importance in solving problems regarding the casing or aquifer conditions. Temperature logs during injection can provide location of aquifers and can outline the extent of permeable zones. As the well warms up, aquifers can usually be distinguished, and when interpreted along with the well head pressure, can give indication of the well at discharge. At this stage, some acquifers or producing zones can be observed even though they are masked during injection tests. It is important that throughout the life of the well, temperatures (like pressure) are monitored both before and after discharging.

2.3.3 Low and high temperature fields

In low temperature fields, static pressure does not play as great a role as temperature. Pressure exerted at any point in the well depends on the hydrostatic effect and therefore could be determined without actual measurement, if the temperature of the water column is known. However, after drilling completion, pressure testing aids reservoir engineers in determining permeability and productivity efficiency. In Iceland, pressure testing is done with simultaneous measurement of pressure while pumping, utilizing injection packers lowered to the desired test level (Tomasson and Thorsteinsson, 1978).

In high temperature fields static pressure in a well is a very important parameter as the pressure at the main production zone is equivalent to the reservoir pressure at this depth. The pressure profile of a well varies according to changes of temperature and liquid density in the well as it heats up. The constant pressure at a certain depth, known as the pivot point, represents the major production zone or aquifer and hence the reservoir pressure at this depth.

When wells are not flowing, water level changes reflect drawdown or recovery depending on the conditions in the field. When the well is used as a monitoring well it gives information on reservoir responses during exploitation of the field in question. Aside from this, several pressure tests, like pressure build up, pressure fall off, multirate flow tests, injectivity tests and others indicate permeability or transmissivity (kh), storage capacity, and skin effects etc., which like temperature are valuable tools for reservoir evaluation (Mathews & Russell, 1967, Earlougher, 1977).

2.3.4 Modelling and interpretation

Notice has to be taken of the principle regarding the saturation curve characteristics of water in the initial interpretation of temperature and pressure logs. At the surface, water boils at 100°C and following the established boiling point curve, we could superimpose it to the measured temperature in the well. In general any segment that intersects this curve is boiling, as the temperature is equal or higher than the saturation temperature of the measured pressure profile. If the temperature is higher than the corresponding saturation temperature, then it is superheated.

Actual determinations of pressure and temperature in geothermal reservoirs are essential starting values for all simulation work of geothermal systems (Jonsson, 1978, Pruess et al. 1979). In the early stages of exploration, models of the geothermal fields are introduced considering the areas of probable heat source and upwelling, temperature of reservoirs, the regional heat flow and geohydrology, the outflow zone and the extent of the geothermal activity. Fig. 2 shows a conceptual model of the Tongonan Geothermal Field in the Philippines made after 20 wells had been drilled.

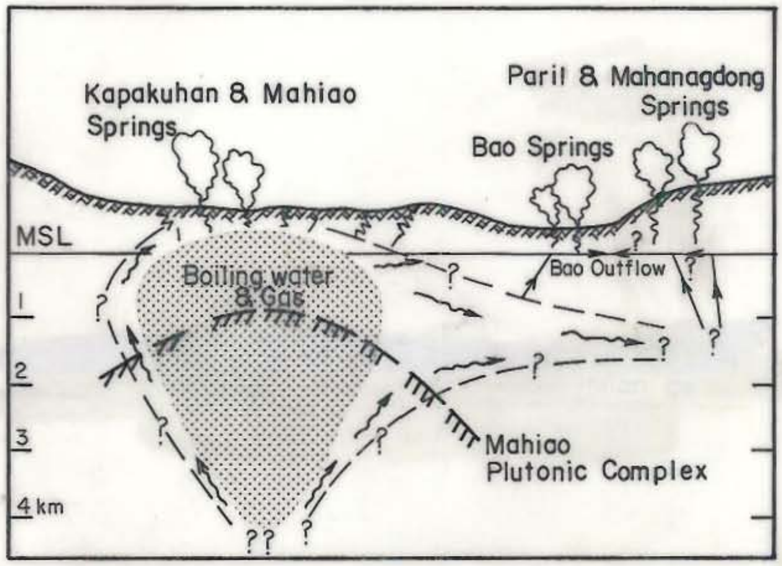


Fig. 2 Conceptual model of the Tongonan geothermal field (After Whittome and Shith, 1979)

3. NUCLEAR LOGGING

3.1 Principles

Nuclear logging as the term implies is related to the measurements of the intensity of the radioactivity of rocks or the scattering of nuclear radiation within the rocks. To understand the application of these methods it is necessary to review the main concepts and principles involved. It is known that an atom consists of the following particles:

a) neutrons-with the same mass as protons and with neutral electrical charges

b) protons - with positive electrical charges

c) electrons - each with a mass of $\frac{1}{1840}$ of a proton

Rutherford (see Dresser Atlas 1974) postulated that the nucleus of an atom was composed entirely of protons and their number z, but later Chadwick in 1932 resolved that there is another particle composing it, the neutrons (see Dresser Atlas 1974). Thus in a simplified form an isotope could be represented by $^{A}_{Z}E$

where: E = element symbol

Z = number of protons contained in nucleus

A = number of protons and neutrons in nucleus

For example $^{4}_{2}He$ describes the particular isotopic form of helium nucleus that contains 2 protons and 2 neutrons.

Number of protons in the nucleus is the same as the number of electrons in the surrounding electron cells. Isotopes are different states of an element where A changes but Z remains constant, i.e. the isotope of the natural uranium isotope with atomic weights of 234, 235 and 238 (see Keys and McCary, 1971). Each of the possible combinations of neutrons and protons identifies an isotope. Accordingly there are now 1400 recognized nuclides, of which 265 are in stable forms of naturally occurring elements while the remaining 1130 are unstable. Of the unstable group only 65 occur naturally.

Stable isotopes are those that do not change in time, whereas unstable isotopes are radioactive and spontaneously decay into other isotopes and emit radiation or particles. Natural radioactive isotopes are used in nuclear logging as the emitted radiation from the rocks can be detected in the well. The radiation is emitted as the isotope decays to other isotopes (called radioactive decay). The radiation consists of alpha particles, positive and negative beta particles, and gamma rays.

Of interest in well logging are the gamma rays which have the ability to penetrate high density materials. Neutrons produced by an artificial source, such as used in well logging, have the ability to penetrate dense materials though they are slowed (thermalized) by hydrogenous materials.

Gamma rays possess the characteristics of both particles and waves and hence are called photons. The energy of the gamma rays is characteristic of the particular nuclear decay in question. Identification of the gamma ray energy can thus give information on the element giving the particular radiation.

3.2 Statistical variation and detection

The statistical nature of radioactive emissions has to be considered in interpretation of nuclear logs. The emissions occur randomly as shown in Fig. 3. This has the consequence that better accuracy is obtained in the intensity determination if the observation time is longer. Averages of measurements are made in such a way that the effects of the whole system are considered (i.e. from pulse detection to pen travel). Longer time constant reduces the statistical fluctuations but too long time with respect to logging speed can cause the pen not to record the true radiation intensity of the approaching unit that has a different intensity. Usually as basis of checking, a statistical check is made of a certain level for several minutes with the instrument stationed at a certain depth in the well.

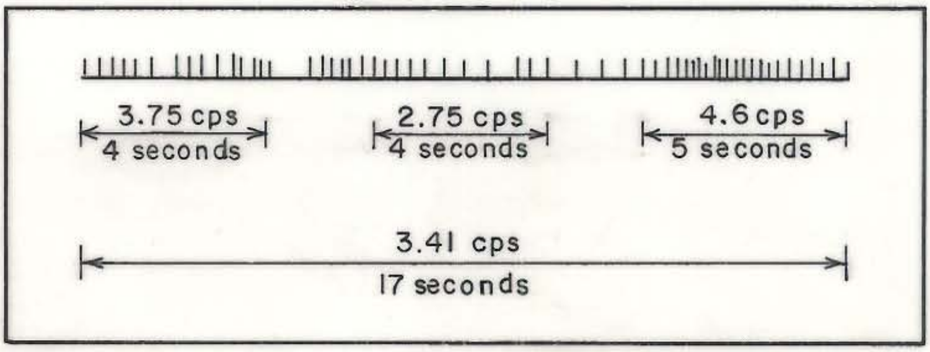


Fig. 3 Statistical variation in nuclear logs

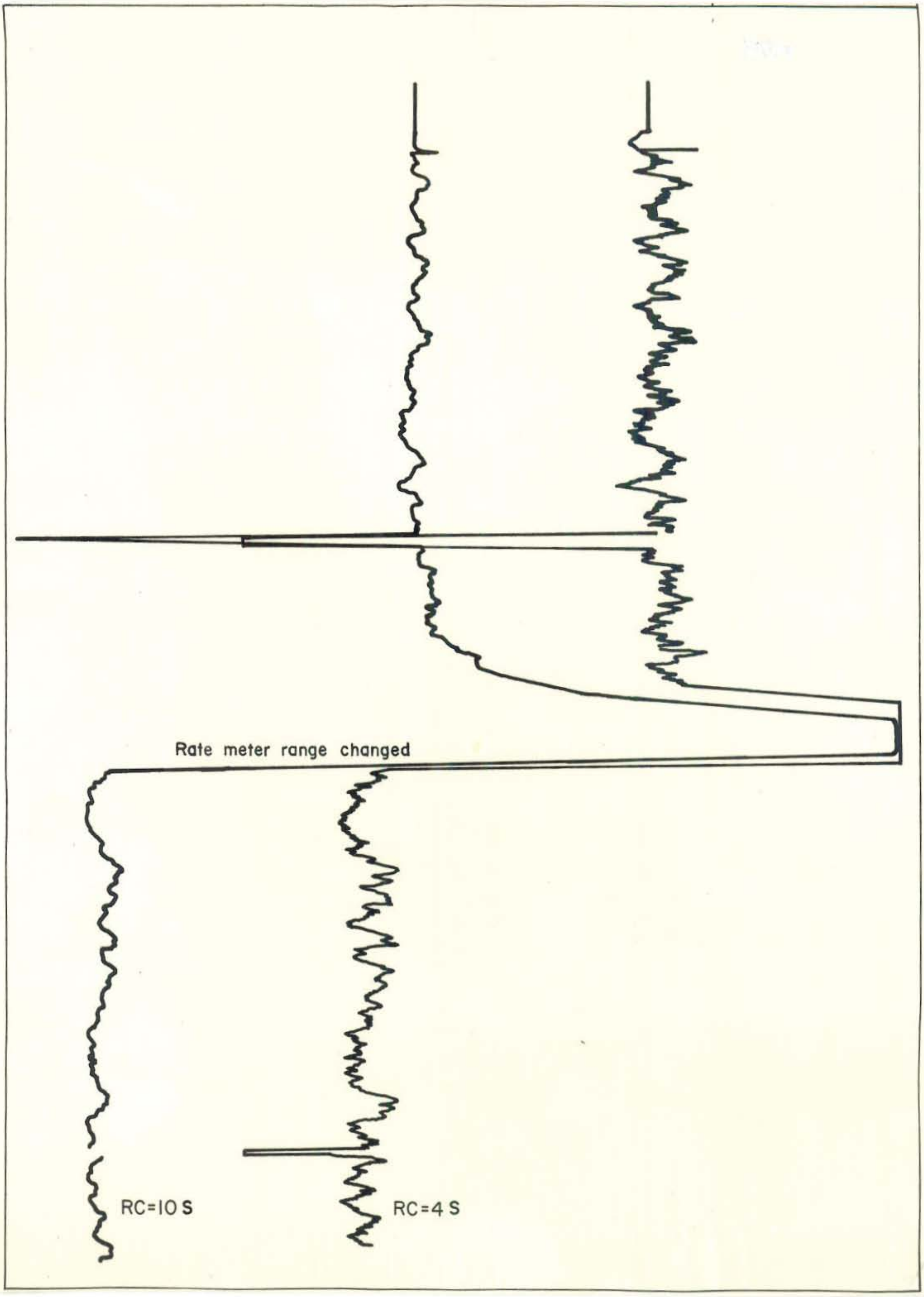


Fig. 4 Log responses at two different time constants (RC) and constant logging speed

Fig. 4 shows a comparison of the response of a natural gamma ray log made with different time constants. It is obvious that with a small RC (herein referred to as time constant), statistical fluctuations are unsmooth relative to longer intervals. Fig. 5 shows the difference in the same logs obtained with two time constants and two logging speeds.

Aside from the time constant and the logging speed, the effect of the instrument function is also an important parameter to be considered The dead time or the resolving time of the instrument causes only one pulse to be recorded even if two pulses occur in a time interval smaller than the resolving time of the equipment. Keys and McCary (1971) show a correction equation $N = \frac{n}{1-nt}$, where N = corrected counting rate, n is the observed counting rate and t is the dead time of the instrument in seconds.

3.3 Selection of logging parameters

Before proceeding with a logging operation the logging engineer has to choose the proper conditions wherein the desirable results can be gained. Time constants and detection efficiencies vary among logging equipments and there is therefore no standard logging speed and time constant applicable to all conditions. Usually these parameters are determined on the basis of trial and error taking into account the statistical fluctuations that can be tolerated and the thickness of the bed that is desired to be measured. Standard deviation of 5% is usually adequate.

In Table 1 Czubek (1978) has listed the values of $\frac{H}{vRC}$ and the dynamic distortion Δ (%), where H = minimum thickness of a layer, v = logging speed, RC is the time constant and Δ(%)=dynamic distortion in %. We find that for Δ = 5%, the value of $\frac{H}{vRC} = 3$ which means that the probe should be at least 3 time constants (RC) inside the layer to record the maximum dynamic anomaly. For qualitative measurements, we set the values $\frac{H}{vRC}$ between 2 and 3, that is $.5\ H_{min} \geq vRC \geq .3$ and for quantitative measurements, $\frac{H}{vRC} \geq 4$. Thus for an instrument with an intensity of 10 cps, RC = 20 seconds, $H_{min} = 1$ meter; for qualitative measurement,

$$.5\ H_{min} = v.RC$$

$$v = \frac{15}{20}$$

$$v = 1.5 \text{ m/minute}$$

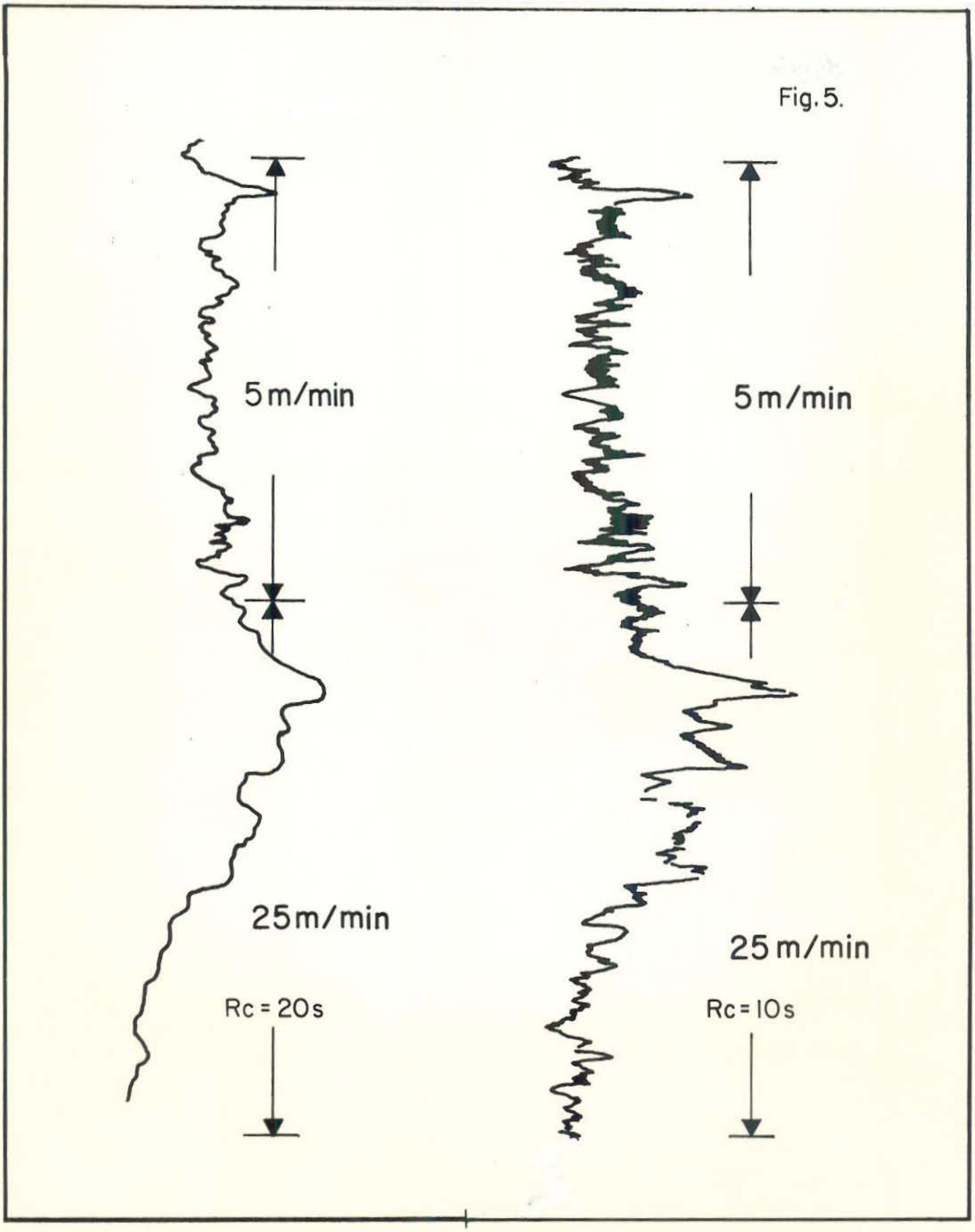


Fig. 5 Log responses at two different time constants and two logging speeds

Table 1 Deviation (Δ) and dimensionless value ($\frac{H}{v.RC}$) for qualitative and quantitative interpretation of nuclear logs (From Czubek, 1978).

$\frac{H}{v.RC}$	1	2	3	4	5
Δ (%)	36.79	13.53	4.98	1.83	.67

4. TYPES OF NUCLEAR LOGS

4.1 Natural gamma ray logs

It was discussedin a previous section that gamma rays are of particular interest in borehole logging. Among the 65 unstable isotopes known, the only ones that are in significant abundances in nature are of ^{40}K (in the amount between 0-6 % in igneous rocks) and the radioactive decays of the uranium series and the thorium series. Uranium and thorium occur naturally in the concentration range of 0-30 ppm, with the Th/U ratio usually about 3. In volcanic rocks the uranium and thorium content increases from basic to acidic rocks. In sedimentary formations the gamma ray intensity mormally reflects the shale content of the formation. Gamma rays are thus useful in lithologic units both in sedimentary and igneous rocks.

Acidic rocks, which are mostly composed of quartz, feldspar, micas and some accessory minerals contain large fractions of thorium, uranium and potassium. Feldspars and micas contain a large share of the K fraction. This mineral group decomposes at a relatively rapid rate into clay minerals due to its small individual particle size and open lattice structure. The radioactive elements may be leached from rocks by hydrothermal fluids and subsequently absorbed in the lattices of the clay minerals. Thus the natural gamma intensity will increase with increasing clay content and shale,whose principal constituent is clay will generally be relatively highly radioactive (Dresser Atlas, 1974).

On the other hand fresh formations tend to possess very low levels of radioactivity except if the rock is highly acid in composition (e.g. rhyolite or granite). In igneous formation, as in Iceland, the natural gamma rays are observed to be high in rocks like rhyolite, granophyre,andesite, docite and diorite relative to basaltic lavas and hyaloclastites (see Part II of this report). Stefansson and Emmerman (1980) relate the concentration of U, Th and K as following the degree of magmatic differentiation of rocks in such a way that U, Th and K tend to be enriched in the more acid phases of magmatic differentiation.

4.1.1 Gamma ray characteristics

Gamma rays are the products of the bursting of high energy electromagnetic waves which are massless quanta. To explain their atomic interaction, they are viewed as particles. Gamma rays and X-rays are in this sense the same and they are composed of oscillating electromagnetic fields. The former are emitted from excited nuclei, whereas the x-rays originate from the excitation of electrons outside the nucleus. Of the three natural radioactive isotopes, ^{40}K, ^{238}U and ^{232}Th, one gram of ^{40}K emitts an average of 3.4 photons/s. at a fixed 1.46 MeV energy, whereas the equivalent weight of either U and Th emitts 12,000-26,000 gamma rays/s with a complex energy spectrum (Dresser Atlas, 1974). Note also Fig. 6.

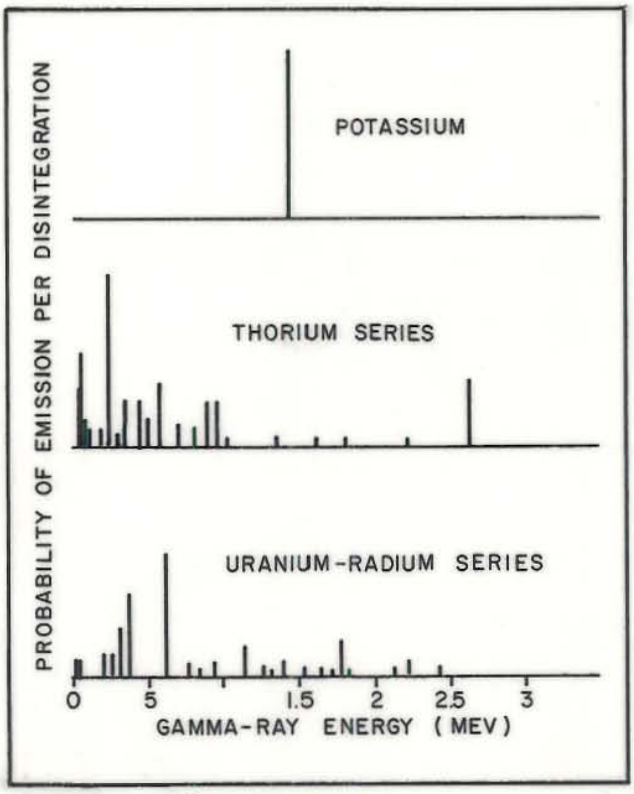


Fig. 6 Gamma ray emission spectra of radioactive minerals (From Tittman, 1956)

4.1.2 Instrumentation

The nuclear logging equipment used so far in the investigation of geothermal resources originate from the petroleum industry. The various types of equipment have different detection efficiencies, but basically only 3 types of detectors are used for natural gamma rays:

(a) Ionization chambers: the ionization chamber is a simple device with a gas filled chamber consisting of an insulated rod in the center which is maintained at 100 volts positive with respect to the case. As a gamma ray enters, it reacts with the wall material and the gas and emits an electron. This electron moves very fast within a space of about an inch or so in the gas, gradually slowing down as it collides with atoms in the gas. In this process, ionization takes place and additional negatively charged electrons are attracted towards a wire within the gas chamber constituting a minute flow of current in the chamber. One gamma ray produces only a small current, but the gamma rays flowing in the borehole are in sufficient quantities to produce approximately 10^{-13} amperes, which is measurable. The series of incoming radiation produce current pulses and electrical signals are obtained by measuring the average flow of current through the external circuit.

(b) Geiger Mueller counter/ Proportional counter. The assembly of the GM counter is same as the ionization chamber with the difference of having higher operational voltage and a lower pressure within the chamber. The gamma ray ionizes electrons from the gas and secondary electrons are formed during the slow down of the primary electrons because there is a high voltage between the wire and the outer wall. This process is known as ionization by collision (Pirson 1963). Due to gas multiplication, each interacting gamma ray gives rise to a pulse of few volts at the counter terminal. The signal is also measured as the average current flowing to the external circuit.

(c) Scintillation counters are a rather complex assembly consisting of:

(1) transparent crystals that give off minute bursts of light when struck by gamma rays

(2) a photomultiplier tube which produces an electric impulse when

the burst of light impinges on them. A series of electron multiplications follows. These are secondary emitting electrons, which have the property of giving off additional 3 electrons for every one impinging on it. It continues for about 12 stages until the internal current multiplies to about one million. The final avalanche of electrons produces a small pulse which is amplified within the recorder and transmitted to the surface.

Among the three types, the scintillation counter is the most efficient. The instrument is short in comparison with the other types and this enables it to resolve relatively thin formations (about 1 meter). GM counters produce large pulses which are easily detectable. However to give high counting rates the instrument has to be fairly long. Ionization chambers are simple and are used at low voltages. Its main disadvantages is that its detection limit is at a current of 10^{-13}A.

4.1.3 Calibration

Measured quantities are correlated with calibration pit for the petroleum industry at the University of Texas in Houston. A section of the pit for gamma ray calibration is shown schematically in Fig. 7.

The unit used is the API gamma ray unit, which is defined by means of a special concrete slab containing about 24 ppm Th, 12 ppm U and 4% K, which roughly speaking corresponds to the Mid Continental Shale of the USA. The difference in the counting rate of a given logging tool between the radioactive concrete and the low activity concrete slab in the facility is defined as 200 API gamma ray units.

Everytime a gamma ray log is conducted, a calibration run is first made on the surface without any radioactive source to detect the background radiation caused by cosmic rays, and then subsequently with a radioactive source at a given distance from the probe.

True field calibration is then obtained by subtracting the background anomaly value from that of the radioactive source. At about 20 m depth, the background radiation from the cosmic rays is negligible.

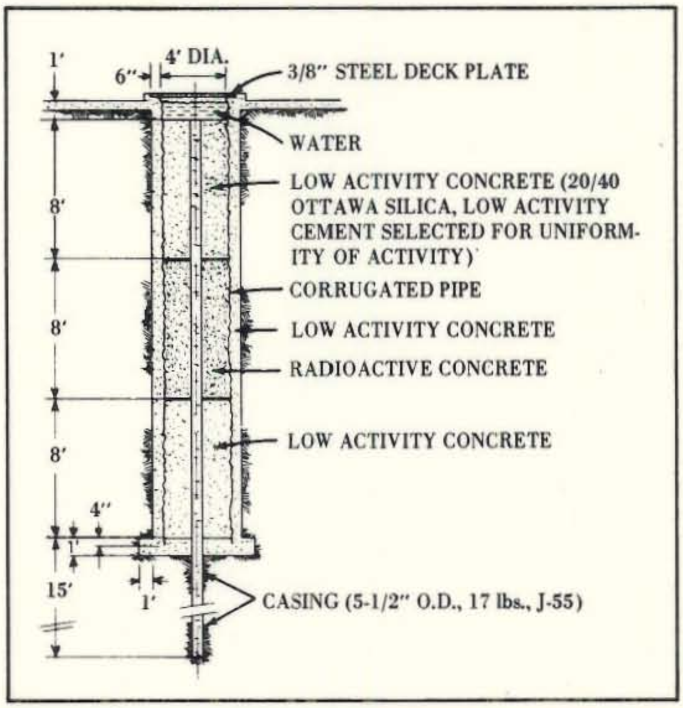


Fig. 7 The API gamma ray calibration pit (From Dresser Atlas, 1974)

4.1.4 Parameters affecting the response of the log

Shifts in the gamma ray logs may be caused by changes in the borehole media (air, water, mud) casing, hole diameter, gravel packs, cement behind casing and other factors associated with the well that are not necessarily related to changes in rock types.

Czubek (1978) showed that when a borehole is filled with water or drilling fluid, the recorded intensity, I_1, should be corrected by a factor CF depending on the size of the well in order to obtain the undisturbed value I_∞

$$I_\infty = CF \cdot I_1$$

The correction factor CF depends on the following parameters: R = radius of well, R_s = radius of the instrument, ρ = density of drilling fluid, μ_p = effective mass absorption coefficient for the drilling fluid which in the case of natural radioactivity of rocks is taken as $\mu_p = .03\rho$ ε = off axial position of the tool in the borehole ($\varepsilon = o$ for central position, $\varepsilon = 1$ for a tool completely decentralized).

Therefore the values of the so called absorption factor $Ap(\mu_p R)$ is related to CF by

$$CF = \frac{1}{1 - Ap(\mu_p R)}$$

Fig 8 shows the graph for some values of $Ap(\mu_p R)$

Different correction factors with graphs are supplied by different logging companies supplying the equipment. This subject is dealt with in detail by Pirson (1963), Dresser Atlas (1974), and Schlumberger (1972).

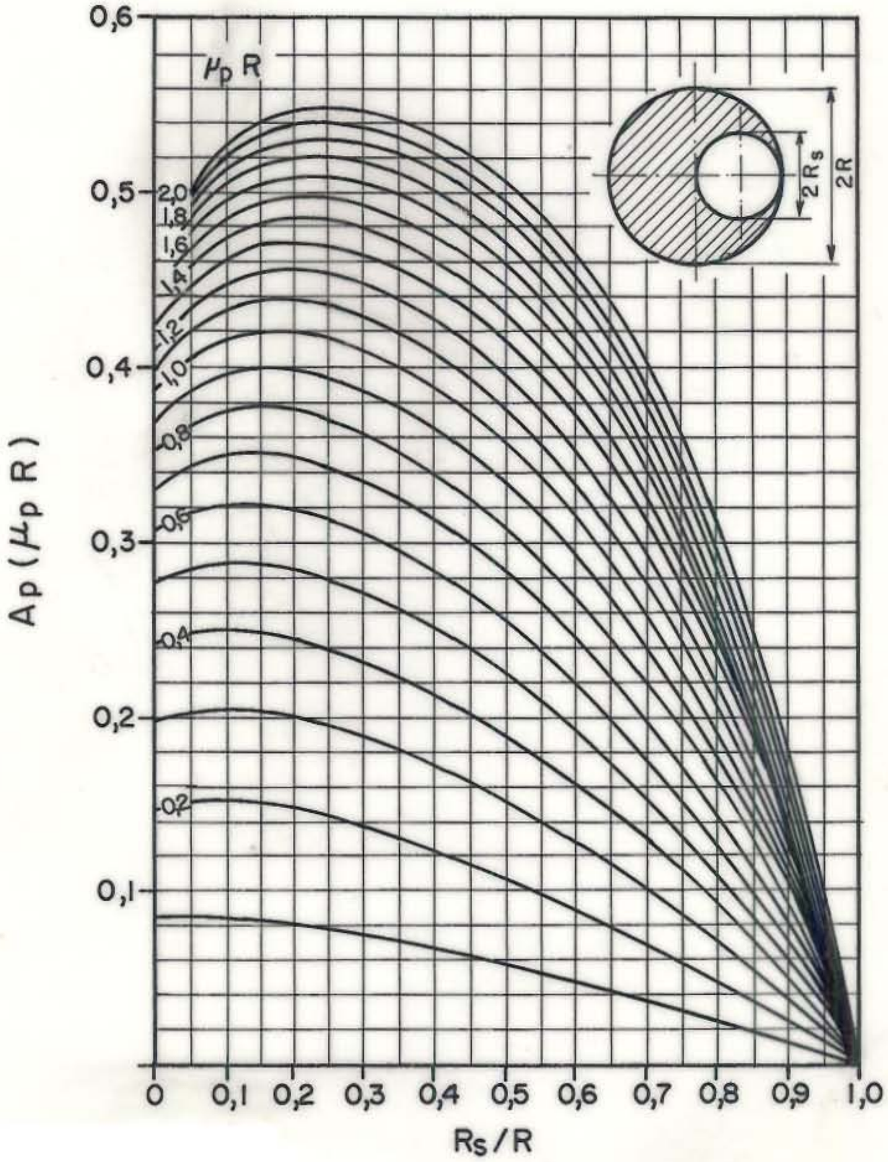


Fig. 8 Absorption function A_p (μ_p R) of the borehole fluid (From Czubek, 1978)

4.1.5 Common applications

One of the advantages of gamma ray logging is that it can be applied both in open and cased holes. Logging of gamma rays is commonly applied:

a) in sedimentary formation to define shale beds

b) for detection and evaluation of radioactive minerals (i.e. potash and uranium ore)

c) for delineating non-radioactive minerals, like coal beds

d) in radioactive tracer operations with e.g. injection in one well and detection in another well

e) to locate aquifers which are characterized by secondary minerals with either high or low radioactivity

f) to define acid and basic units and the general type of lithologic units.

4.2 Gamma-gamma logging

Gamma-gamma logs were first used to determine the density of rocks and were in the beginning intended to supplement gravimetric surveys. Later this logging method was developed to evaluate the bulk density and the associated porosity of the formations.

4.2.1 Principles

When the probe is lowered into the borehole the radioactive source emits gamma rays and irradiates the formations. The rays interact with the electrons of the media and loose energy in every collision according to the Compton scattering. This loss of energy is the main parameter recorded by the logging instrument. Other less important factors are the photoelectric processes and the pair production. Compton scattering contributes to the overall response recorded by the densilog counter by varying not only the number, but also the energy photons reaching the detector. The photoelectric effect causes a photon to loose all its energy in one process, resulting in no trace to the detector.

In the pair production process, when a high energy photon (larger than 1 Mev) interacts in the field vicinity of the atomic nucleus, the energy of the photon is converted into a negatron and positron pair, each having .51 Mev energy (Dresser Atlas, 1974). The positron which almost immediately combines with an electron to form positroneum has a mean life of 10^{-10} seconds. The positroneum is mutually annihilated and again they are converted into energy of two .51 Mev photons. It is this annihilation that can also be counted as scattered gamma in the detector.

From the above, it can be said that the reactions which contribute to the density measurements depend on the collision of individual gamma rays with electrons. It follows that the decrease in energy in the constant gamma ray flux is proportional to the electron density of the media passed, which is also proportional to the bulk density at least for most low atomic elements (Dresser Atlas,1974).

4.2.2 Instrumentation and Calibration

Fig. 9 shows a typical density logging equipment from Lane Wells Company. They use a source of ^{60}Co while Dresser Atlas uses ^{137}Ce. Both manufacturers use either Geiger Mueller counters or scintillation counters as detectors. The spring and the slides are allocated in the design so that the instrument will always be in contact with the walls of the well. The radius of investigation extends on 3-6 inches into the rock formation. Spacing between them may cause a partially reversed log response due to increased back scattering effects.

For calibration, test pits with material of different densities for cased and uncased conditions are needed. As an example for calibration of the density logs from the continuously cored IRDP drill hole in eastern Iceland three test pits

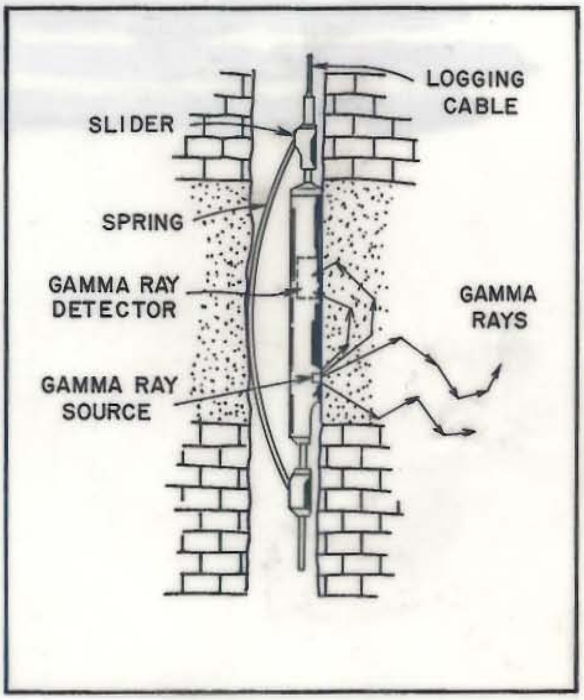


Fig. 9 Density logging tool from Lane wells company

with a hole diameter of 7.5 cm were made with different densities of $3.41 \times 10^3 kg/m^3$, $2.7 \times 10^3 kg/m^3$ and $2.47 \times 10^3 kg/m^3$. (Jonsson and Stefansson, 1980)

4.2.3 Other considerations in the application

The radius of influence for a gamma-gamma response is about 6-15 cm, hence all the materials within the vicinity of the probe influence the log. The influence of the well fluid and the size of the well must also be acounted for. Gamma-gamma intensities are higher above water level than below, and higher in open holes than in cased holes. It has been observed that the main cause of misinterpretation of density logs in Iceland is due to an accumulation of cuttings or other low density material in cavities of the walls of the wells which give false indications of porosity layers. Variation in borehole diameters and cavities can cause loss of contact of the probe within the walls of the well.

Gamma-gamma logs should be run at relatively slow logging speeds to overcome the small penetration capacity of the instrument. In the IRDP drill hole, several logging measurements were carried out and analyses were compared with laboratory results on the core. Basaltic rocks have higher bulk densities than intermediate and acid units (Jonsson and Stefansson, 1980).

Sethi and Fertl (1980) using a commercial compensated densilog proposed that a densilog appears to be less useful in igneous and metamorphic rocks than in sedimentary formations. The densities are usually so high in the intrusive rocks and so low in volcanic tuffs that the values may be outside the calibration range of the probe. This obstacle can be circumvented by using proper calibration methods rather than using the calibration procedure suggested by the service company.

4.3 Neutron-neutron logging

Neutrons are electrically neutral particles having a mass equal to the hydrogen present in the formation, i.e. more of the neutrons kinetic energy is transferred if they collide with a nucleus of hydrogen. Thus formations filled with water can be identified.

4.3.1 Principles

The scattering of neutrons can be detected either as gamma rays caused by inelastic scattering of neutrons or radioactive capture of thermal neutrons, or by the detection of thermal or epithermal neutrons.

The scattering of neutrons causes an energy transfer from neutrons to the surrounding material. The average distance which the neutron travels depends on the number of collisions and the energy transfer in its collission. When the neutrons have only the same kinetic energy as the surrounding particles, they are called thermal.

Table 2 shows the difference in energy transfer when neutrons collide with different nuclei.

Table 2 Neutron energy losses during thermalization (From Dresser Atlas 1974)

Element	Average no. Collission	Max. Energy Loss/Collission	Atomic Weights	Atomic No.
Calcium	371	8%	40.1	20
Chlorine	316	10%	35.5	17
Silicon	261	12%	28.1	14
Oxygen	150	21%	16.0	18
Carbon	115	28%	12.0	6
Hydrogen	18	100%	1.0	1

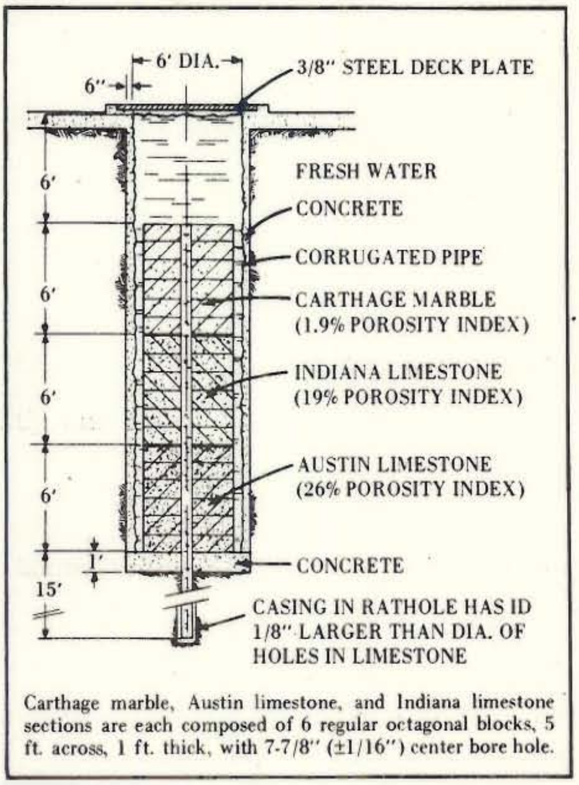
4.3.2 Nature of responses

As mentioned previously, the response of a neutron log is sensitive to the hydrogen nucleus concentrations. This means that there is no distinction as to where the response originated, (i.e. from formation water or bound water). Bound water is that which is trapped within the rock matrix itselt. In this case, say in igneous rocks, porosity values might be found slightly higher than usual porosity values analysed in the lab. Jonsson and Stefansson (1980) proposed that secondary minerals affect the porosity values as most secondary minerals like zeolites contain bound water.

4.3.3 Calibration

The calibration unit of the neutron-neutron measurement is the API neutron unit. It is related to the response obtained in a 19.7 cm diameter test pit at the University of Texas. By definition, 1000 API neutron units correspond to a change in the counting rate obtained between those measured in Indiana limestone blocks (19% porosity index) and Carthage marble (1.9% porosity index). See Fig. 10.

Neutron tools delivered with calibration curves allow the conversion of tool response in cps into API neutron units. It should be noted that calibration made in this pit cannot be used directly for absolute units of porosity due to possible differences in matrix density. However, for qualitative comparison, these values are relatively good. Thus in a study of igneous rocks in Iceland, an apparent limestone porosity has been found to give reasonable estimates of the total porosity (Jonsson and Stefansson, 1980).



Carthage marble, Austin limestone, and Indiana limestone sections are each composed of 6 regular octagonal blocks, 5 ft. across, 1 ft. thick, with 7-7/8" (±1/16") center bore hole.

Fig. 10 API neutron calibration pit (From: Dresser Atlas, 1974)

In field practice, calibration of instrument response between zero radiation and that from a source is always done and is a part of the heading of the log transscript. Neutron sources with small half life like polonium (half life 140 days) need recalibration frequently, whereas sources like Ra-Be and Pl-Be with half lives of 1670 years and 24.300 years respectively, require no recalibration.

4.3.4 Borehole effects

(a) The attenuation of the counting rate in nuclear logs increases with increasing hole diameter. The attenuation depends on the presence of liquid near the probe.

Anomalously high enlargement structures (i.e. cavities and fractures) give false high porosity values. Qantitative interpretation at such a portion of a well should be avoided.

(b) The presence of casing decreases the counting rates and the porosity resolution of the tools. Hence, logs in cased holes should only be used for qualitative correlation.

(c) A mud cake keeps the logging tool away from the walls of the well and introduces a substance of high porosity and low density between the tool and the formation. However, when drilling is carried out with water these effects can be neglected. Cuttings sometimes tend to accumulate in the walls, and may give rise to false signals.

5. ELECTRIC LOGS

5.1 Resistivity logging

Resistivity of the formation is its capacity to impede the flow of electrical current through it. A medium, like water and mud, is needed to allow the current to flow between the electrodes and the formation. In empty holes or gas filled holes, this log can't be performed.

Dry rock has very poor electrical conductivity. Values associated with rock are therefore attributed to the resistivity of the conducting fluid. The resistivity depends on the temperature and salinity the fluid. Knowing these parameters, investigation of a reservoir rock can be complemented and correlated with other logs.

5.1.1 Principles

Resistivity of a substance is the ability to impede flows of electric current passing through it. In a homogenous isotropic medium, electrodes placed apart will produce a radial flow of current in its surroundings as spheres as shown in Fig. 11.

Fig. 11 shows a schematic picture of the probe with "normal" spacing. The derivation of its resistivity is governed by the following expression,

$$V = IR$$

where V = voltage in volts

I = current in amperes

R = resistance in ohms

R is dependent on the geometrical configuration of the current distribution and follows the relation:

$$R = \rho \frac{L}{A}$$

where ρ = specific resistivity

L = length between electrodes

A = surface area of the **material** surrounding the probe in question

Therefore $V = \frac{I\rho L}{A}$

Referring to Fig. 11, the voltage that could be measured on an equipotential sphere M is $dV = \frac{I\rho}{A} dr$ where $A = \pi 4 r^2$

The summation of equipotential spheres from r to any distance, say A-N, is found by integrating the voltage over this distance. N is regarded to be at infinity, hence

$$dV = \int_{16"}^{\infty} \frac{I\rho dr}{4\pi r^2}$$

$$dV = \frac{I\rho}{4\pi} \int_{16"}^{\infty} \frac{dr}{r^2}$$

$$V = \frac{I\rho}{4\pi} \left\{-\frac{1}{r}\right\}_{16"}^{\infty}$$

$$= \frac{I\rho}{4\pi} \left\{-\frac{1}{\infty} + \frac{1}{16"}\right\}$$

$$V = \frac{1\rho}{4\pi} \frac{1}{16"}$$

or $\frac{I\rho 1}{4\pi "AM"}$ where

AM = distance between current electrode and voltage electrode and

$V = \frac{I\rho 1}{4\pi 64"}$ for long normal device.

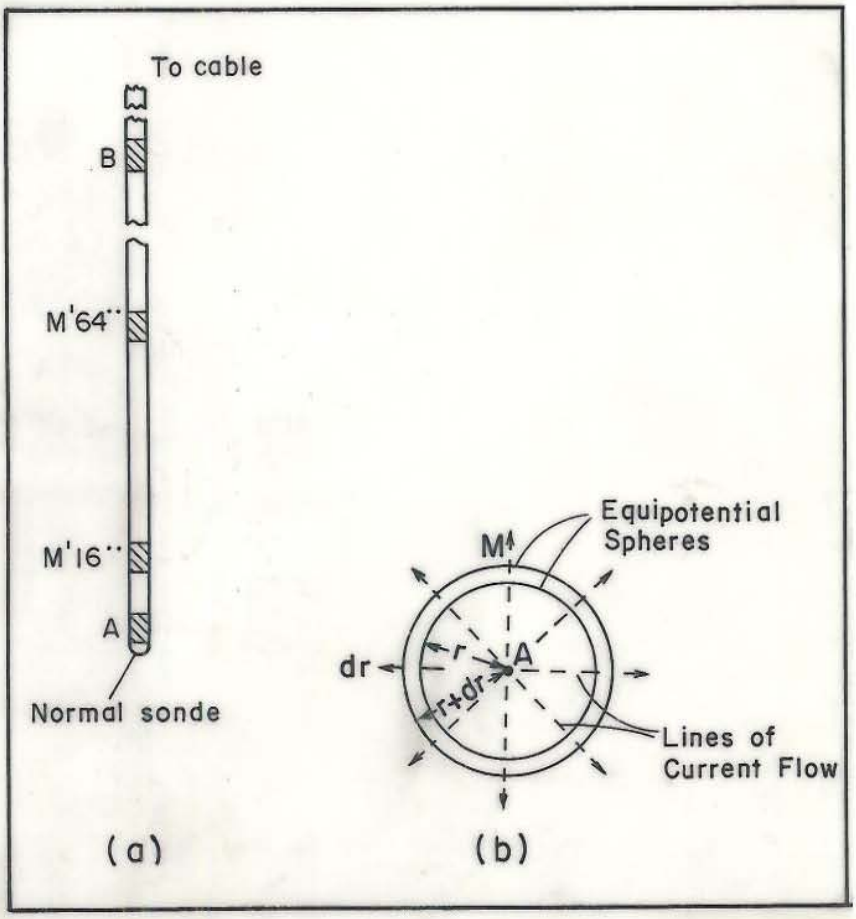


Fig. 11 Resistivity normal device and geometry of current flow (From Keys and McCary, 1971)

5.1.2 Instrumentation and operation

Normal resistivity logs employ two current and two voltage electrodes. A constant current is supplied to energize the formation and the voltage across the potential electrode is measured in terms of resistance.

As shown in Fig. 11 a, the 16" and the 64" electrodes are the potential electrodes corresponding to their distance to A which are used to pick up voltage changes. The armored cable is used as a current electrode B and the lower end is insulated with rubber sleeve at least 30 meters above it. The voltage reference electrode N is a lead on the end of a rubber covered wire and is placed in a mud pit at the surface. It is also ground reference for the self potential, which is measured simultaneously with the resistivity.

In field practice, electrode N should be placed in a wet ground, but should be far away from electrical installations. Poor results can easily be observed when the mud pit does not give good electrical contact with the ground.

One difference of this log as compared with the nuclear logs is that resistivity logging can be carried out at a relatively fast logging speed with a short time constant. In all practical measurements alternating currents are applied to avoid polarization effects and interference with existing d.c. potential. A low frequency, not exceeding few hundred Hz, is used to minimize inductance and capacitive resistance effects making the measurement practically to be true resistance.

The calibration of resistivity tools is made directly within a suitable calibration box supplied by the manufacturer.

5.1.3 Interpretation and correlation

It is known that the resistivity measured in a borehole depends on several parameters, i.e. salinity of the liquid, the temperature and the resistivity of the formations. Commonly it holds that the more saline the liquid the higher the temperature, and the more porous the formation is the less resistivity .

One of the formulae derived from these parameters is Archie's equation expressed as

$$F = a\phi^{-m}$$

where F = formation resistivity factor

m = cementation factor

a = empirically determined constant

ϕ = porosity of the rock

Accordingly a and m are related to the petrophysical properties of rock, like turtuosity, degree of cementation, type of pore system, permeability etc. (Sethi, 1979).
As an example for sands, satisfactory results for the porosity are obtained from

$F = \frac{.81}{\phi^2}$, so knowing the formation resistivity factor which is obtained from

$$F = \frac{R_o}{R_w}$$ where R_o = resistivity of the medium, R_w = resistivity of the

formation fluid, porosity values can be obtained by using both equations.

In geothermal investigations, there has been only one well where a relation between these two parameters is obtained. This was determined from Kilauean rocks in Hawaii by Keller et al.(1974) as $F = 18 \cdot Q^{-1.05}$.

5.2 Self potential logging

Self potential or spontaneous potential corresponds to the voltage measured between a fixed point (electrode) in the mud pit and the movable electrode in the borehole. In Fig. 11 values are taken at mid point of a 16" electrode. Self potential logs have been used in sedimentary rocks to identify permeable beds, but does, however, not give a quantitative measurement of permeability. Normally it is described as having a shale base line, which is a more or less straight line having a peak to the left. In sedimentary formations the base line frequently has been stated to correspond to impervious beds while the peaks are usually found to correspond to permeable horizons (Doll, 1971). In igneous rocks the SP-log behaves quite differently from that in the sedimentary rocks and no "rule of thumb" has been established.

The electrical potential is measured with reference to an arbitrary point, hence absolute zero has no meaning in this log (see Appendix I and II of this report). The surface electrode N (Fig. 11) is used as a reference electrode, such that if its potential does not change and assuming no other factors the values recorded in the log can only be attributed to the formation.

5.2.1 Principles

There are two phenomenas associated with the self potential which are assumed to be responsible for the changes of the voltage, i.e. electrochemical and electrokinetic or electrofiltrations. The former has the same principle as the common wet cell battery, where two unlike formations in contact with each other act as the poles and a part of the well fluid acts as the electrolyte. Electrofiltration on the other hand arises when electrolytes move in the formation. In groundwater wells, streaming potential like this is observed in zones gaining or losing water (Keys and McCary, 1971). If the well is giving up fluid to the formation, the potential contributed is a negative potential, but a positive potential results if fluids flow from the formation into the well. However, this occurrence is a function of formation pressure. If there is no flow into or out from the well only the electrochemical phenomena are expected to be observed.

6. MISCELLANEOUS LOGS

6.1 Caliper logs

A caliper log is a continuous record of borehole size diameter and plays an important role in borehole geophysics. It provides a basis for correction for borehole size effects as well as being useful in distinguishing one rock from the other. High density rocks and consolidated rocks in volcanic units tend to have smooth walls, whereas unconsolidated and fractured rocks exhibit rugged and irregular walls. This is clearly demonstrated by the caliper log.

6.1.1 Principles, applications and instrumentations

Caliper probes have one or several arms that stretch out to the walls of the hole, and thus measure the well diameter which the tool traverses Fig. 12 shows schematic diagram of a 3 arm caliper tool from Gearhart Owen Co.

In Tongonan, Philippines, where no caliper tools are available, a rude way of checking borehole diameter is by running a fabricated go-devil tool. It is found to be a useful substitute for determining scaling and deposition, although it cannot provide the exact diameter of the hole.

Changes in the hole diameter are caused by a combination of factors governed by drilling techniques and the lithology. A few factors can be named such as the bit load and straightness of the drill stems, mud fluids, pressure and volume associated with the degree of cementation of the rocks, the density, the porosity and the fracture orientations.

An open hole with a diameter less than the bit size suggests a mud cake or cuttings to be accumulated whereas for cased holes, a decrease in the hole diameter indicates deposition or scaling. Cavities and fractures are obviously recorded as having larger diameter than the bit size .

The radius of influence of the caliper is the point where the arms touch the wall.

The calibration of caliper logs is made on the surface before and after running the logs. The arms are calibrated utilizing a metal sheet to a pre-desired size.

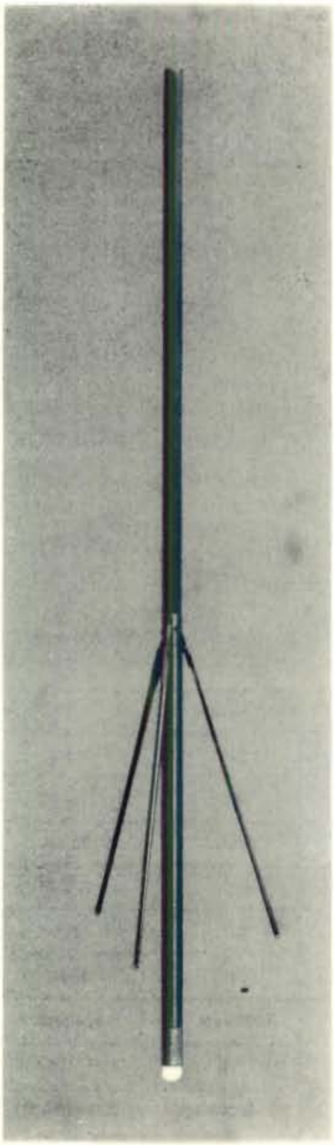


Fig. 12 Three arm caliper tool (From Gearhart Owen, 1980)

6.2 Acoustic logs

Acoustic logs measure the transit time required for a compressional sound wave to traverse the distance from a wave transmitter to a receiver. Transit time depends on the type and porosity of the rocks. In intrusive rocks, it is quite short and in hydrothermally altered and fractured rocks it is long (Keys, 1979). When the amplitude of the first arrival is registered, the log is called sonic bond log. This type is mainly used to investigate the quality of cementing in cased wells.

6.2.1 Principles and application

There are two parameters that are measured by the sonic or acoustic logs:

(a) The interval transit time, which is the reciprocal of the velocity of the compressional sound wave.

(b) The amplitude, which is the reciprocal of the attenuation of the sonic wave.

The interval transit time is used to determine porosity values in rocks if the velocity of the signal in the fluid and the rock matrix are known. The amplitude log has been found useful in locating fractures and for investigating the quality of cement behind casing.

Fig. 13 shows a schematic diagram of the probe. It consists of a transmitter which converts electrical energy to acoustic energy.

The sound wave that arrives first to the receiver is the compressional sound wave. Notice that the speed of sound has to be faster in the formation than in the probe or the drilling fluid.

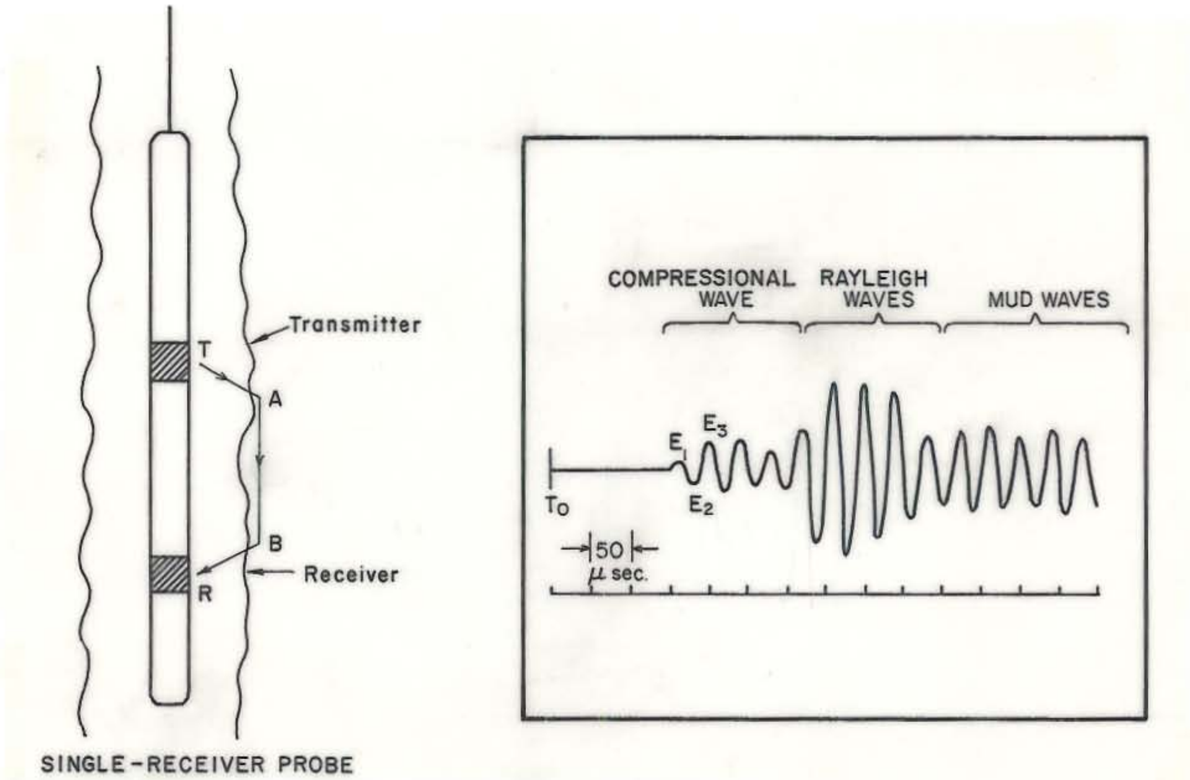


Fig. 13 Sonic probe and acoustic wave patterns (From Schlumberger, 1972)

Several relations have been established in the oil industry regarding the porosity and the interval transit time. Wyllie et al. (1958) proposed the following empirical relation to determine the porosity,

$$\phi = \frac{t - t_{ma}}{t_f - t_{ma}}$$

where t_f = transit time in pore fluid

t_{ma} = " " " rock matrix

t = interval transit time

However this is only good for clean, compacted formations of intergranular porosity containing liquids. In igneous rocks, very little experience has been gained in order to compare this formula with reality.

6.2.2 Instrumentation

Most transmitters and receivers used are composed of a magnetostructure alloy wrapped with a coil of wire. Piezoelectric crystals are also inside the coil and the crystals oscillate due to contraction and expansion when current pulses are introduced through the coil wire. The vibrated energy is transmitted from the probe to the formation and back again to the receiver.

Oscilloscopes are very useful in this kind of logs as they provide means of selecting the proper point for first arrival. These also allow observation and photography of the wave form. Circuits average the transit time and convert them into a d.c. voltage which is recorded.

6.2.3 Calibration

Interval transit time can be expressed in microseconds per meter and can be read directly from the calibrated oscilloscope. The simplest method of correlation of porosity values is to compare the logs with core samples analyzed in a laboratory. However, to simulate the borehole conditions is rather difficult. Core samples should be undisturbed when analyzed and should be saturated with native fluids (Keys and McCary, 1971).

There are several extraneous effects that can be observed in the sonic logs. The borehole size, the tilting of the instrument, as well as fractures and cavities often caused spurious observations. The use of a centralizer is necessary to obtain good results. Cycle skipping, which is caused by non-detection of first arrival, happens frequently. The receiver will be triggered by later arrivals which have larger transit times. If this occurs, the curve will show sudden jumps and the amplitude of the registered first arrival shows a small value.

6.3 Casing collar locator (CCL) og

Iron content or magnetic properties of the material through which the tool passes is what causes the responses in the CCL log. It is very useful in locating casing and collar joints. This log provides detailed information on the actual construction of pipes in a hole. Errors in the counting and arrangement of various length of pipes can be checked with this log.

The simplest type of CCL probe consists of a permanent magnet wrapped with a coil of wire. Changes in the magnetic properties surrounding the probe provide a small direct current in the coil. This current gives a deflection to the pen in the recorder.

Collars and casing joints are reflected by sudden and big deflections. This log is commonly run simultaneously with other logs to give reference to casing depth. Fig. 14 shows a typical CCL log.

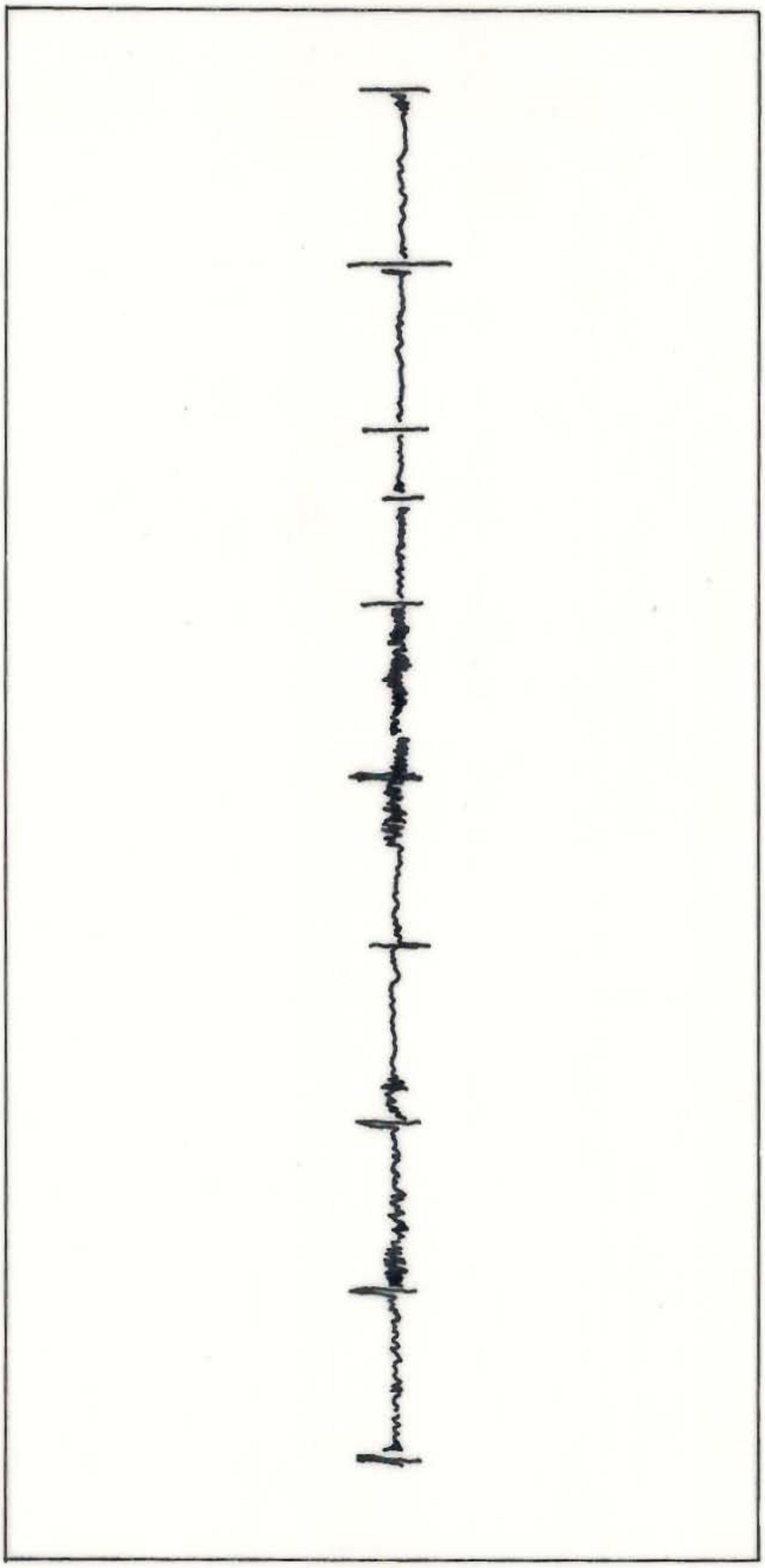


Fig. 14 Typical CCL log

7. LITHOLOGICAL INTERPRETATION OF GEOPHYSICAL LOGS

Lithological interpretation in geothermal logging is considered in its infancy stage. Very few reports deal with the subject in the literature. Peculiar problems are associated with the interpretation, such as the rock matrix response, unfamiliar lithology and effects hydrothermal alteration and fracture systems (Sanyal, et al., 1979). Similarly lack of standard calibration with each type of lithology hinders reliable quantitative calculations.

The different geophysical logs measure different parameters of the same formations and one type of log may support or contradict conclusions drawn from other logs (Keys & McCary, 1971). However, by accounting results of many parameters rather than only one or two, good results can be obtained.

Initially visual correlation of logs is made to see conspicuous peaks and lows. The logs are matched together to observe patterns or characteristics that can give some description. Each one is check after the other and after considering borehole effects, influence of the lithology is studied. This is an approach for preliminary qualitative correlation.

One of the best concepts of log interpretations that originates from the petroleum industry, is the multiple cross plotting of logs. Locations of the measured values in the plots determine the lithology. For example sandstone, limestone and shale are usually determined through their positions in the crossplots. On the other hand, in geothermal investigations this is still being studied. Common logs suited for crossplotting are the neutron-neutron, porosity, gamma-gamma, density, acoustic time, resistivity and natural gamma ray logs. From the first three parameters, another crossplot was found to be useful in sedimentary rocks. By plotting neutron versus density and acoustic versus density, and taking the slopes of both, an M and N plot could be obtained. Here, N refers to the slope of the former and M for the slope of the latter. Fertl (1978) discussed and showed examples of this plot.

Another approach is the plotting of frequency versus parameters values of identical responses. By hand, this is very laborious, but present technique of digitizing log responses helps in minimizing the difficulties. High speed digital computers can do this job in a faster time, subsequently eliminating human factors. Points are sampled at certain intervals, most preferably at small intervals (for example 0.1 m intervals).

PART II INTERPRETATION OF GEOPHYSICAL LOGS IN WELL KJ-13, KRAFLA GEOTHERMAL FIELD, N.- ICELAND

8. INTRODUCTION

8.1 General aspects of the Krafla geothermal field

The main geothermal field is situated within the Krafla caldera and measures an area of about 7 km^2 according to the 10 Ωm contour line resistivity measurements (Fig. 15). The Krafla caldera is presently covered with volcanic materials from recent eruptions and the rim of the caldera is not prominent in the landscape. Additionally the drilling area is situated east of the main fissure swarm intersecting the caldera (Fig. 16). The main field is elongated in a NW-SE direction. Series of explosion craters are found along a gulley called Hveragil. This location has been found to be the upwelling zone of the geothermal system.

Since 1975, a rifting episode has been active in the Krafla caldera area causing magmatic activity and rapid ground movements both horizontal and vertical (Fig. 16). Intense earthquakes and widespread ground deformation plus magmatism are affecting an 80 km long segment of the plate boundary in this part of Iceland (Bjornsson et al., 1979). It has been demonstrated that at 3 km depth there is a magma chamber and that dykes are formed laterally from the magma chamber (Fig. 17). The inflow of magma into the chamber under the caldera is estimated to have been at the rate of 5 m^3 per second in average during the last five years. Several wells have been affected by the volcanic activity with volcanic gases turning the pH of well fluid from 8 to as low as 1.8 and with a gas content of the fluid increasing by a factor of 100.

There have been drilled 14 wells in the Krafla field with depths ranging from 1110-2250 meters. Installed power capacity is 30 MW with the second unit on standby, awaiting further drilling operation. Since January 1979 the plant is operating at 7-8 MW supplied by 5 wells with a total yield of 25 kg/s of high pressure steam.

8.2 Subsurface geology

The rock units in the production area have been classified into three main lithological units (Fig. 18) I Hyaloclastite formation, II Lava formation, III Intrusive formation (Kristmannsdottir, 1979).

Hyaloclastites are the products of subaquatic eruptions. They appear to be glassy and highly brecciated. The term hyaloclastite formation as used in Krafla includes pillow lavas, pillow breccias and palagonite tuffs. The basaltic lavas within the shallow hyaloclastite formation consist of individual fine grained lava flows, but the lowest 100 m or so consists of coarser grained lavas that might be a part of a shield volcano.

The lava formation consists mainly of fine grained altered basaltic lavas, interbedded with scoriaceous material.

The intrusive formation has similar geochemical composition as the lavas and hyaloclastites. The difference is mainly in the structure and texture. A granophyre intrusion has been identified in the deeper part of the formation. This appears to be thick in the northern part of the drilling area (i.e. KG-10 and KG-4) where it is approximately 60 m thick but thinning towards the south. At the granophyre margins, aquifers have been observed. The boundary between the lava formation and the intrusive formation fits well with the division of the two geothermal systems observed in this field (Stefansson, 1980).

The lavas and hyaloclastites have a composition near to that of saturated tholeiite basalt, varying from olivine tholeiite to quartz tholeiite. The intrusions are of the same chemical composition with the exception of the granophyre.

8.3 A simplified model of the Krafla geothermal field

The geothermal system of the field has been modelled (Stefansson, 1980) as having two separate convection systems, the shallower one extending down to 1100 meters depth and the second one below that level down to at least 2.2 km depth . The upper zone is a single phase water dominated system whereas the lower zone is a two phase boiling system (Fig. 19).

Temperature in the upper zone is measured to range from 205-215°C (Stefansson, 1980). The relatively low temperature in the upper zone encourages calcite deposition, however, casing of this zone prevents difficulties with depositions. The lower zone is characterized by a high gas content and high discharge enthalpy with temperature in an undisturbed state close to saturation 300-350°C. Partial gas pressure was estimated to be 5-6 bars owing to a high concentration of CO_2 (3-5%) by mass (Jonsson, 1978). Permeability thickness values are found to be $10 \times 10^{-12} m^3$ (Stefansson, 1980). Jonsson (1978) used values of 10-60 md and 1-40 md respectively for the upper and lower zone for simulation calculations.

During production, the water fraction is observed to diminish with constant steam yield. After a certain period, wells produce dry steam with additional heat obtained from the rocks as well as from the evaporated phase. (See for example a description of the Olkaria Field, Björnsson, 1978).

The geothermal model of Krafla geothermal field is shown in Fig. 19 and is described in detail by Stefansson (1980).

8.4 Geochemistry

As mentioned above, the heat source is a magma chamber at the depth interval between 3-7 km depth. The magma apparently heats the meteoric water coming from the recharge area which is outside the magmatically affected channel (Armannsson et al., in press). The lower part of the system is the upflow channel carrying steam and water from great depth to surface. Moreover, it is suggested that the upper part of the system is a run-off of the upflow channel.

Armannsson et al. (in press) have divided the wells into 3 groups according to the discharge composition. Group I comprises the relatively shallow wells drawing pure water at depths above 1000 meters. Silica temperatures correspond to the measured temperature and the discharge enthalpy of the fluid. Gas content is small and diminishes westward from Hveragil.

Groups IIa and IIb comprise the deep wells, the inflow of which consists of a steam and water mixture at 300-340°C. Silica temperatures assuming single water phase and adiabatic flow do not correspond to measured temperatures and discharge enthalpy. Fluids at IIa are magmatically influenced and rich in gas. Iron and silica deposits have been formed occasionally and the fluid has in some cases caused serious corrosion problems. Group IIb represents wells where the fluid has little magmatic influence with minimal production problems.

8.5 Surface geophysics

Geophysical invesigations in the Krafla area include airborne and surface magnetic measurements, gravity measurements, Schlumberger resistivity and quadripole-quadripole roving dipole. The main features of the aeromagnetic map are the magnetic low anomalies over Námafjall and the Krafla field, the latter having a NNW-SSE trend in the Krafla caldera .

Gravity measurements were carried out in order to determine changes due to exploitation but the volcanic activities and eruption which are continuously going on since 1975 cause greater variation in gravity than is caused by the exploitation. A Bouguer gravity map reveals an anomaly following the caldera rim, and irregularities within the caldera confine a NNW-SSE geological continuity.

Fig. 15 shows the resistivity contours at 600 meter depth which coincides with the assumed upper geothermal system. Similar discontinuities are observed in the resistivity of the area, as seen in gravity and magnetic surveys (Karlsdottir et al., 1978).

9. WELL KJ-13 IN THE KRAFLA GEOTHERMAL FIELD

9.1 Location

Well KJ-13 is the 13th well drilled in the Krafla area and is situated in the eastern part of the caldera near Hveragil where the upflow zone is postulated. Southeast of the well (approximately 150 m) is well KJ-12 that exhibits almost the same output and geological characteristics as well KJ-13. In the vicinity are wells no. 3 and no. 9, which had been observed to be good producers. Well KJ-13 is 2050 m deep and is cased off to 1060 meter depth with a 9 5/8" casing and a slotted liner from that level to the bottom of the well.

9.2 Injection and recovery period

Fig. 20 shows temperature and pressure profiles of the well during injection and recovery period. Several circulation losses are encountered below 1100 meters and at the depth 1700-1800 meters, the circulation loss was approximately 4 barrels per minute (11 l/s).

Temperature profile T_1 shows a remarkable outflow of injected water at the depth 1700-1800 m, though part of the injected water descends at 2050 m. The significant feature appearing in the recovery measurements is a major heating effect at depth 1700-1800 m. Above and below it, the temperature rises more slowly.

Subsequent pressure measurements show a rather unusual profile. A segment of similar pressures appeared at 1200-1400 meters in the two runs, but varies as the distance increases away. Water level stood at 200 m in the first profile with boiling at 1700 m. In the second run (18-DS) the well was on bleed. Prior to this stage maximum temperature had been recorded as 327°C at 1700 m depth. The well then continued to boil and the temperature decreased (18-DS, extreme right curve). It appears that there has been no change in pressure at 1200-1400 meters.

Closer investigation of the primary logging data reveals that the well condition was changed during the measurement of the latter profile (18-DS, pressure). This change took place at the same time the probe was lowered through the 1200-1400 meter depth. Initially, the well head pressure was

32.5 bars, but when the probe was lowered down at this depth, the well head pressure was 30 bars.

Pressure profiles can be interpreted in two different ways. Using the description applied by Grant (1979), the same pressure observed at 1200-1400 meter depth indicates that the well has two feed zones, one at 1700-1800 meters and the other at depth 1200-1400 meters. The pivot point is then moving during discharge between the two zones. However, it should be noted that in the model described by Grant (1979), the inflow at the two feed points is predominantly in the water phase and this fact caused that the two zones are alternatively dominating each other. If this is the case, a similar effect is observed as in wells 105 and 401 in the Tongonan Geothermal Field in the Philippines (Smith, 1979, Menzies, 1979, and Abejo and Sarmiento 1980), although no segment with similar pressure is observed in these wells. As shown in the next section, well KJ-13 developed into a stage where it discharged dry steam. This indicates that the conditions in well KJ-13 are different from those wells.

Another point of view in interpreting these pressure profiles is to recognize that in a two phase reservoir there must be an intersection between pressure profiles measured in a water filled well and that in flowing condition. This intersection of pressure curves will depend on the wellhead condition when the well is flowing. In this case it could be interpreted that this segment is only accidental, that it is only caused by the change in the bleeding pressure, which subsequently alters the pressure condition in the well (see Stefansson and Steingrímsson 1980).

9.3 Discharge tests

Discharge tests show that this well developes into a stage where it discharges dry steam (Fig. 21). The total mass flow is calculated as 6 kg/s with a discharge enthalpy of 2658 kJ/kg after 30 days at a wellhead pressure of .7MPa. As discussed in the model, this well exhibits a good example of the effect of exploitation in a two phase boiling reservoir.

9.4 Types of logs performed

Aside from what is shown in Appendix I and II, gamma-gamma log, differential temperature and absolute temperature log, CCL, sonic bond log, and flow meter logs were carried out. These are done in three stages during the drilling, actually just before the 13", 9 5/8" and 7 5/8" casings were placed in the well.

All these logs are recorded on paper on a scale 1:500. All instruments are manufactured by Gearhart-Owen Industries Inc. Double runs are insured by logging in descending and ascending direction.

9.5 Logging devices

The logging cable 7 mm in diameter, is a four conductor cable with tefzel insulation from Rochester, Virginia. For the neutron neutron log, the detector used is a 2.5x15 cm ^{3}He detector, the neutron source is a 3 Cu ^{241}Am-Be source and the distance between source and detector is 33 cm. The tool was calibrated by a special neutron calibrator provided by Gearhart-Owen. The gamma-gamma density tool has a Geiger-Mueller tube as a detector and an overall diameter of 4.2 cm. The gamma ray source used was a 125m Cu, ^{137}Cs source. The resistivity tool was locally fabricated and resembles that shown in Fig. 11.

9.6 Methods of investigation

For the time being, except in the IRDP drillhole, interpretation and correlation of structural and lithological studies in well logs are carried out in Iceland by manual manipulation of logs by geophysicists and geologists. Present logging instruments do not have the capability of onsite logging computers which could record and digitize data while logging. Due to these cirsumstances, interpretation is quite limited, and sometimes prejudiced by the log analyst. The author concentrated his studies in well KJ-13 to the intervals at 1800-2000 meters and at 400-800 meters. However, remarkable portions,elsewhere in the well,are also considered.

Davis (1973) discussed methods of cross correlation of two different logs (i.e. two resistivity logs) by composing similarities occurring in sequences. Noble and Abril (1978) were able to construct the perpendicular cross section through the Cerro Prieto geothermal field by visual log matching which was in conformity with the results obtained by an auto correlation program. Since this work in well KJ-13 is only an initial interpretation, auto cross correlation was no attempted. In the following sections the results of each logging technique will be discussed.

9.6.1 Resistivity histograms

Of the 13 wells drilled in Krafla, only KJ-12 and KJ-13 have been logged completely. In some other wells resistivity and self potential logs have been carried out as well as the conventional pressure and temperature logs. For this reason resistivity histograms were worked out so that more correlation among wells could be obtained.

A pattern of increasing resistivity with depth is very common in Krafla wells (Stefansson, personal comm.). Self potential is particularly difficult to interpret and in this well, no apparent correlation is observed. Keys (1979) and Heflin (1979) show that self potential is useful especially in locating zones of water influx that produce streaming potential. In well No-9 in Svartsengi this also proved useful (Zuniga,1980).

Fig. 22 is a resistivity histogram of the hyaloclastite units from 540-800 meters. Resistivity values are taken every meter and the distribution is computed. The resistivity is also compared with the geological description of the cuttings. The peak in the figure corresponds mainly to the hyaloclastite at depths 610-670 meters (Appendix I). The high resistivity values are from those units that are impregnated between basaltic lavas. Without careful examination, this could be interpreted as two different units (bimodal distribution) as lavas in this zone exhibit 30-50 Ω meter also.

In the intrusive formation, where the geology is described to be complex, (for example, the alternating sequence of lavas, breccias, dolerites, altered and fresh rocks), ambiguous responses are observed. The fact that responses of the resistivity log are dependent on the porosity, types of fluid in the pore space, fractures, hydrothermally altered minerals and other petrophysical parameters make it difficult to use resistivity alone for unit identification. However, in the intrusive formation below 1100 meters, cavities or changes in rock types are commonly recognized. The depth interval 1200-1500 meters is composed mainly of basaltic lavas and dolerite intrusions. It is obvious that the resistivity is high (150-170 Ωm) in these formations. Basaltic breccias are recognized by the marked change in resistivity associated with them. In this well, acid units tend to have relatively higher resistivity than basic units, but in some cases similar values are observed (for example at 1970-1990 and 1890-1905 m).

9.6.2 Density - Porosity Crossplot

Fig. 25 is a bulk density - porosity cross plot of rocks penetrated at 1800-2000 meter depth. The values are taken from Fig. 23 . Identification of the units are based on analyses of the geological cuttings (A. Gudmundsson, pers. comm.), but corrections are made of the boundaries of units by using the natural gamma ray log (Appendix II). In this way the basalt unit was adjusted to 1955 and 1990 meters and the thickness of the dacite unit reduced to 35 m.

The calibration of bulk density is obtained by following the approach suggested by Jonsson and Stefansson (1980), in the IRDP drill hole. The dense part was chosen to have the density of 3.1 g/cm^3 and a parallel calibration curve was drawn as shown in Fig. 24. The porosity values are obtained from the API neutron units and its relation to limestone porosity as described in the Formation Evaluation Data Book of Gearhart-Owen (1975).

In the cross plot, the position of the dacite unit is very distinguishable and appears in a unicluster on the diagram. Basaltic lavas occur in a wide scatter, similar to what is observed in the IRDP drillhole. Jonsson and Stefansson (1980) suggested that the presence of zeolites and other secondary minerals in the IRDP well caused the great scattering observed in the porosity relations of individual units.

Basaltic breccias (which can also be referred to as hyaloclastites) are recognized as occupying the lowest density portion in the crossplot. A check on the caliper and natural gamma confirms this position, at the depth 1912-1917 meters. The cluster of points below the dacite plot are identified as dolerite (1885-1895 m) according to the analyses of the geological cuttings (A. Gudmundsson, pers. comm.). Its position in the cross plot is not in agreement with the geological description even considering possible errors caused by variation of the well diameter. The log suggests a rock of lower density than dolerite. The apparent limestone porosity value is observed to be high (about 24%) near the contact of dacite and basalt in the crossplot (Fig. 25).

9.6.3 Silica content of the rocks

Stefansson and Emmerman (1980) have established a relationship between the silica content and the gamma intensities in volcanic rocks of Iceland. Similarly, the radioactive elements can also be determined based on their work. They described that the radioactivity of rocks follows the degree of magmatic differentation and that this pattern is of general nature and is observed to hold true in most rocks traversed in numerous wells in Iceland.

From the analyses of cores obtained in the IRDP drillhole, it is found that the correlation between the gamma intensity and the concentration of radioactive elements cannot be described by a single linear equation such as

$$Y = a_0 + a_1\{U\} + a_2\{Th\} + a_3\{K\}$$

because the concentration of U, Th and K are not independent variables in this context (Stefansson and Emmerman, 1980)

However, SiO_2 can be used as a chemical variable that can link the gamma ray intensity to the chemical composition of the rocks. Plots of gamma ray intensities and SiO_2 concentration give the simple correlation

$$Y = 3.65\{SiO_2\} - 144$$

where Y = gamma ray intensity in API unit

SiO_2 = silica concentration in per cent

The correlation coefficient is .71.

Stefansson and Emmerman (1980) also determined empirically the relation between the silica content and the concentration of U, Th and K. They found

$$\{K_2O\} = .169\{SiO_2\} - 7.79$$

$R = .78$

$$\{Th\} = .323\{SiO_2\} - 14.6$$

$R = .93$

$$\{U\} = .114\{SiO_2\} - 5.05$$

$R = .91$

where: { } = concentration in % for K_2O and SiO_2 and in ppm for U and Th.

R = correlation coefficient.

If these relations are used, the expected chemical composition of some of the geological units in well KJ-13 are shown in Table 3.

Table 3 Estimated chemical compostition of rocks traversed in well KJ-13

Depth (m)	Rock type	Corrected intensity API g.u.	SiO_2 %	K_2O %	Th ppm	U ppm
1945-1950	Dolerite	23.8	45.9	-	.23	.18
1825-1830	Tholeiite Basalt	41.7	50.9	.79	1.9	.75
1975	Dacite	83.3	62.2	2.72	5.5	2.04
965-970	Diorite	61.88	56.4	1.7	3.6	1.4
650	Hyaloclastite	47.6	52.4	1.1	2.3	.92
1190-1200	Felsite	64.5	57.1	1.9	3.9	1.49

These values appear to be very close to the typical values of the formations quoted especially the silica content. This method can therefore be very useful in identifying the doubtful units. In the absence of any cuttings, this is an indispensable tool.

9.7 Correlation of the lithology and the geohysical logs

In general, good correlation is obtained between the logs and the lithology as observed from microscopic studies of cuttings at the depth intervals under study: 470-480 m, 540-670 m, 1190-1200 m and 1955-1995 meters.

A sudden increase in porosity and a decrease in resistivity show very well the boundary between the basaltic lavas and the hyaloclastites at 540 m. A similar boundary is recognized at 670 meters. At 800 m the transition from the hyaloclastite formation into the basaltic lava formation is clearly demonstrated by the marked increase in resistivity. Beginning at this depth, resistivity, neutron-neutron and caliper logs become less useful in the identification of each unit.

The caliper log shows that at 1730-1740 meters a cavity is located at the contact of a hyaloclastite and a dolerite intrusion. Keys (1979) and Sethi and Fertl (1980) showed that radioactive minerals are commonly formed and precipitated along pores and fractures where fluid flows. A relatively small peak in the natural gamma ray intensity is recorded at this depth, which may indicate slightly radioactive secondary minerals. Another cavity at 925 meters was observed to have the same phenomena.

10. CONCLUSIONS

1. The experience and calibration obtained in the IRDP drill hole (Jonsson and Stefansson, 1980) was successfully applied in well KJ-13. Analyses matched very well with available geological results.

2. The natural gamma ray log appears to be very useful in identification of units. Silica composition can be determined using the SiO_2 and gamma ray correlation. In cases where total circulation losses are encountered, this is immensely valuable.

3. Cavities were detected by the caliper log and in two cases high gamma ray intensity was observed in the cavities indicating accumulation of radioactive minerals.

4. Resistivity logs show clear responses with hyaloclastite and basaltic lavas in the depth interval 540-800 meters. Furthermore within a high resistivity formation, hyaloclastite and basalt breccia units are recognizable.

5. There is a general increase in resistivity values with depth.

6. The main production zone at 1730-1740 m is characterized by a rapid heating during the temperature recovery. It is also related to a cavity detected in the caliper log and coincides with a small peak in the gamma ray intensity.

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