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PROCESSING AND INTERPRETATION OF GEOPHYSICAL WELL LOGS FROM WELL KJ-32, KRAFLA GEOTHERMAL FIELD, NE-ICELAND

Bijan Mostaghel
Department of Renewable Energy,
Office of Deputy Minister of Energy Affairs
Ministry of Energy,
Tehran
IRAN

ABSTRACT

The purpose of this study was to improve the understanding of the litho-stratigraphy of the geothermal reservoir rocks in the Leirbotnar field of the Krafla geothermal area. The geological structure of the reservoir has important bearing on the reservoir properties and the location of feed zones. Drilling in the Krafla geothermal area is proceeding northwards to the northern Leirbotnar field. KJ-32 was the first well to be drilled into this part of the reservoir. The well was drilled directionally using a mud motor and high drilling rates. This resulted in low depth resolution of the cuttings record, and cuttings are entirely lacking from sections drilled with total loss of circulation. A study was made of the natural gamma ray, neutron-neutron and resistivity logs in the production part of well KJ-32. Through detailed comparison and correlation between the logs and the cuttings record it was possible to make significant improvements to the litho-stratigraphy of the reservoir. The litho-stratigraphic boundary depths determined from the cuttings were found to be shifted upwards by 3.5-6 m relative to the more accurate depths recorded by the logs. The thickness of individual units determined from cuttings was found to deviate by up to 2.5 m from the logs. Due to the higher resolution of the logs, 120 new stratigraphical and structural boundaries were identified, bringing the total up to 205 from the 85 boundaries identified in the cuttings analysis. A total of 43 rock units, comprising 165 m or 22% of the litho-stratigraphic column, were found to have been misidentified in the cuttings analysis and an alternative interpretation is suggested on the basis of the logs. Furthermore, predictions of lithology were made for the two intervals drilled with a total loss of circulation which total 60 m in thickness. In the new and improved litho-stratigraphic section, 9 out of 12 feed zones in the production part of the well fall within one metre's distance from a lithological boundary, compared with only 5 of the feed zones in the original section. All of these boundaries turned out to be intrusive contacts. On the basis of the improved litho-stratigraphic section, a subdivision of the reservoir into three main formations is suggested; a lower formation dominated by gabbro intrusives, a middle formation of hyaloclastites with inter-layers of intrusives and an upper formation dominated by dolerite intrusives. In view of the location of the feed zones, fluid flow within the reservoir is probably controlled by intrusive contacts.

1. INTRODUCTION

The Krafla high-temperature geothermal area is situated within the volcanic rift zone in NE-Iceland (Figure 1). One of the main production fields in this area is Leirbotnar. It is the largest geothermal field within the Krafla caldera. The Krafla power plant is owned by Landsvirkjun (National Power Company) and presently generates 60 MWe. Recovery of steam from Krafla reservoirs has been relatively poor, the main cause being magmatic activity in the area. Drilling in the Leirbotnar area played an important role in expanding the generating capacity of the plant from 30 to 60 MWe.

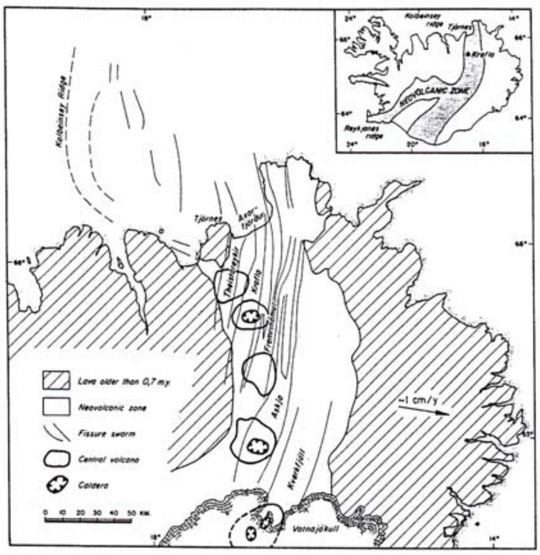

FIGURE 1: Simplified tectonic map of NE-Iceland (Björnsson, 1985)

Well KJ-32 was drilled during 1998 in Leirbotnar to a depth of 1875 m. It is located about 1000 m northeast of the power plant. After pre-drilling of a surface hole, drilling for the surface casing proceeded with a 22” bit to 61.6 m depth. After drilling and casing the surface hole, a shallow cellar was made and the drill site was prepared for a large rig. The work continued with the drilling rig Jötunn of the Icelandic drilling contractor Jardboranir. Drilled with a 17 1/2” bit, the intermediate part of the well was cased with a 13 3/8” casing to 285.8 m. The production casing part of the well was drilled with a 12 1/4” bit to 1080 m, and the production casing ran to 1079.9 m. The kick-off-point (KOP) was at 450 m depth where the drift angle would be built up to 30˚ at a build rate of 1.5˚/30 m. The directional work was carried out with a stearable mud motor and measurement-while-drilling (MWD) logging from the KOP to the bottom of the well. The well target was to intersect faults at Hveragil. The final stage of the well was drilled with an 8 1/2” bit, mud motor and MWD to 1875 m. The maximum inclination was 33˚ with an azimuth of 260˚. A 7” slotted liner was run to 1831.5 m (see Figure 2).

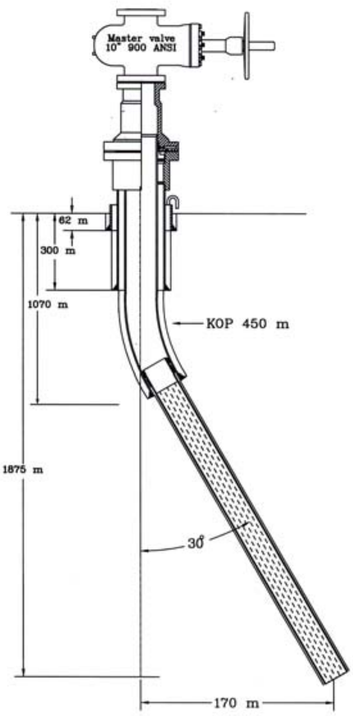

FIGURE 2: Directional design and casing programme of well KJ-32

The purpose of this study is to improve the understanding of the litho-stratigraphy of the geothermal reservoir rocks in the Leirbotnar field of the Krafla geothermal area. Due to the use of a mud motor, the depth resolution of the cuttings record is very low, and cuttings are also lacking from sections drilled with a total loss of circulation. The main limitations of cuttings analysis are:

a. The effect of the time delay when cuttings are carried to the surface by drilling fluid which leads to depth errors;
b. Smearing-out of the cuttings record caused by the presence of large cavities in the well and a separation of the cuttings according to size during upward transportation;
c. Misidentification of lithology when the cuttings are too finely ground by the drill bit.

These problems have become more common with the increased use of mud motor drilling in Iceland. Therefore, a study was made of the natural gamma ray, neutron-neutron, resistivity and caliper logs in the production part of well KJ-32. A relationship exists between the silica content of Icelandic rocks and their natural gamma ray radioactivity. Acidic rock units are easily identified as prominent maxima in the logs. Such rock units are often used as stratigraphic markers in the correlation between wells. Neutron-neutron logs react mainly to the water-content (i.e. porosity) of the surrounding rock formations. The water-content, salinity and temperature of the formation fluids and the electrical conductivity of the rock matrix affect resistivity logs, and finally caliper logs measure the well diameter and locate the cavities in the well.

Through detailed comparison and correlation between logs and the cuttings record it was possible to make significant improvements to litho-stratigraphy of the reservoir.

2. THE KRAFLA GEOTHERMAL AREA

2.1 Geology of the Krafla area

The Krafla geothermal area is located in the volcanic rift zone in NE-Iceland (Figure 1), about 10 km northeast of Lake Mývatn. It is located within the Krafla caldera, which was formed about 100 thousand years ago. The axial part of the rift zone is under tensional stress parallel to the spreading direction, and is characterised by numerous volcanic systems. Volcanic activity in the Krafla region is extensive and there have been several eruptive periods during the last few thousand years. The most recent period of volcanic activity with 9 eruptions, lasted from 1975-1984. The Krafla volcanic system is transected by a fissure swarm, some 100 km long and 4-10 km wide (Björnsson, 1985).

The Krafla caldera, is characterised by a topographical high. Surface manifestations like steaming fumaroles and altered ground cover an area of 15 km^2. The Krafla caldera and its volcanic features formed during the early part of the last interglacial period, about 100 thousand years ago. Acidic volcanism was initiated during its formation as is evident from an ashflow surrounding it and the rhyolite ridges in and near the eastern and western parts of the caldera rim. In December 1975, a major rifting episode started in the Krafla fissure swarm comprising 21 rifting events, nine of which resulted in volcanic eruptions (Björnsson et al., 1977). A magma chamber has been located at a depth of 3-8 km in the roots of the caldera (Einarsson and Brandsdóttir, 1980). The geothermal manifestations appear on the surface as mudpots and fumaroles, mostly connected to the tectonic fractures and faults. Hot springs are absent.

2.2 The Krafla reservoir

Investigation of subsurface geology based on the analysis of drill cuttings from the wells has allowed definition of the distribution of individual lithological units, the correlation of aquifers with these and the degree of rock alteration. The general subsurface geological and alteration model of the Leirbotnar field based on the first eleven wells was established in 1978 (Stefánsson, 1981). Drilling in new fields from 1980 to 1999 provided valuable additional information on the lithology. One cross-section, is shown in Figure 3 along with well positions and the main tectonic features of Leirbotnar and Sudurhlídar. This cross-section extends from well KJ-11 in Leirbotnar to well KJ-18 in Sudurhlídar. Intrusives are the dominant features below 1200-1300 m depth. The top horizon (B-1) is a postglacial lava formation (<10.000 years old), next is a hyaloclasite formation (M-1) probably dating from the last glacial period. Below that is another group of lavas (B-2) dating from the latter part of the last interglacial period. This is underlain by the second hyaloclasite formation (M-2) which is considered to represent the bottom of the caldera filling. Below this level there are lavas (B-3) from the first part of the last interglacial period followed by basaltic and doleritic intrusions which dominate the strata down to 2000-2200 m depth in the Leirbotnar field. All the drilling fields are within the caldera. At Leirbotnar where the geothermal system is divided into an upper and a lower zone (Stefánsson, 1981), the main aquifers in the lower zone seem to be connected to fissures and intrusive contacts.

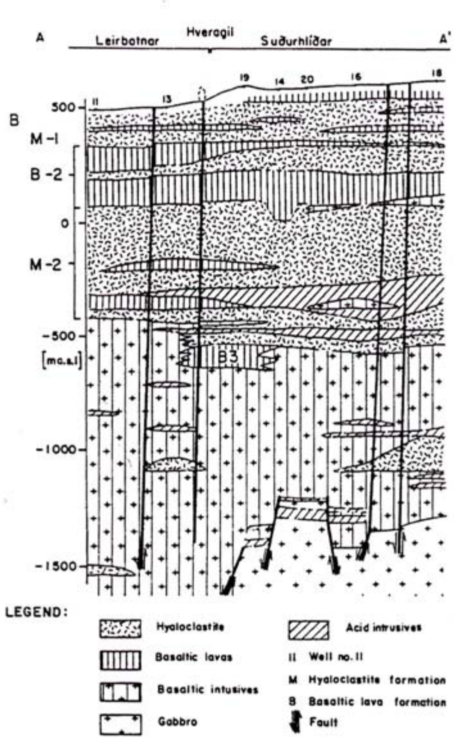

FIGURE 3: Geological cross-section of the Leirbotnar and Sudurhlídar well fields (Ármannson et al., 1987)

Three main production fields have been drilled in the Krafla area: the Leirbotnar, Sudurhlídar and Hvíthólar fields. Recovery of steam from the Krafla reservoir has been relatively poor, the main cause being the magmatic activity in the area. The subsurface characteristics of the three fields are very different. The Leirbotnar field is divided into an upper, water saturated, zone with a mean temperature of 205˚C down to about 1000 m depth and a lower boiling, zone with temperatures from 300 to 350˚C. The Sudurhlídar field is a boiling system, and the Hvíthólar field exhibits boiling characteristics down to 700 m depth with a cooler regime below.

In 1976 the reservoir fluid at Leirbotnar became contaminated with magmatic gases causing deposition and corrosion in wells with a concomitant decline in their productivity. Extensive studies of the chemistry of fumarole steam performed in the area, in 1978 and 1979, resulted in the definition of three major upflow zones in the Krafla caldera (Gíslason et al., 1978; Ármannsson and Hauksson, 1980). The Leirbotnar and Leirhnjúkur upflows were found to be contaminated by magmatic gas, but the Sudurhlídar upflow in the southern flanks of Mt. Krafla was unaffected.

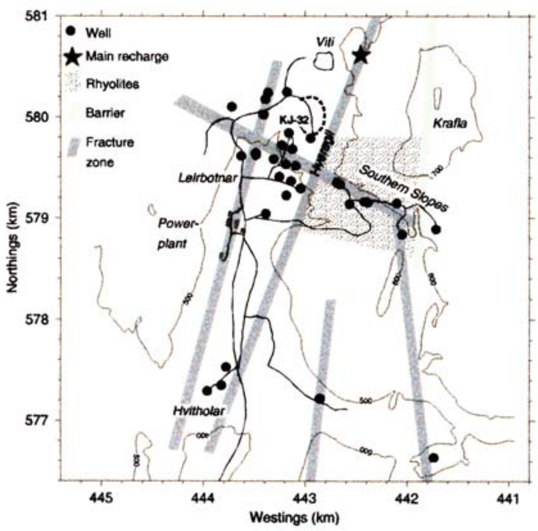

FIGURE 4: Location map of the Krafla well fields and the three main production fields of the caldera

Five wells were drilled in the Sudurhlídar field in 1981 and 1982. These draw sufficient steam for the production of 15 MWe. In the last few years, the most interesting prospect has been the Leirbotnar field, the largest geothermal field within the Krafla caldera (see Figure 4).

Numerical modelling studies of the Krafla geothermal area were carried out in 1982-1983. The natural state model reproduced the observed pressure and temperature data for the field. The model consisted of a vertical cross section, which included both Leirbotnar and Sudurhlídar (Figure 5). The simulation model is in agreement with the assumption that two upflow zones, one at Hveragil and the other close to the eastern border of Sudurhlídar, control the reservoir system. The lower reservoir in Leirbotnar and the Sudurhlídar reservoir are two-phase reservoirs with average vapour saturation of 10-20% (volumetric) in the fracture system. The porosity of the reservoir rock was assumed to be 5%. The permeability of the reservoirs is 1-4 mD with an average of 2.0 mD.

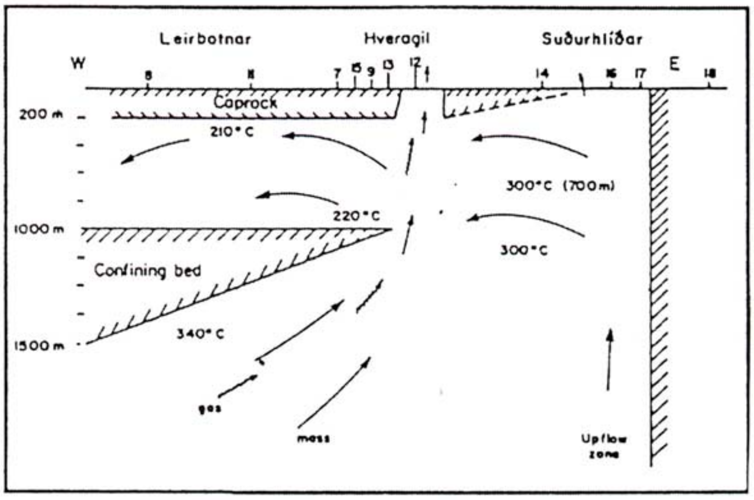

FIGURE 5: The conceptual model of the Leirbotnar and Sudurhlídar geothermal fields (Stefánsson, 1981)

3. GEOPHYSICAL LOGS

A log is defined as "a record of sequential data". In geophysics this word is mainly connected with continuous measurements carried out in boreholes. In these measurements a sonde is moved at a constant speed either up or down the well. The signal from the downhole sonde is fed through a cable to the surface and registered there. In general, logs are profitable for two reasons. Firstly, they give information on well performance and design (specific problems during drilling). Secondly, and more importantly, logs give information on structure, physical properties and performance of the geothermal system penetrated by the well.

Some important logs, which are frequently used today in geothermal reservoir investigations, are described in the following chapters.

3.1 Caliper log

The log of the diameter of the well, or the caliper log, is important in well log analysis. Several types of measuring sondes exist. The ordinary type is a three-arm caliper, but tools with up to 60 arms are available. The arms are in all cases motorised, i.e. an electrical motor is present inside the caliper tool and it is possible to control this motor and open or close the arms on demand. The arms will centralise the tool in the well, and the position of the arms is sensed through variable resistance. A caliper log is measured continuously from bottom to top (Stefánsson and Steingrímsson, 1990).

Because of the electrical cable and the downhole electronics, high-temperature wells can only be caliper-logged with this technique after quenching with cold water has cooled them down. In geothermal drilling activities, caliper logs are mainly used for

a) Detection of cavities in the well;
b) Measurement of wellbore volume in order to obtain an estimation of the cement volume needed;
c) Determining the placing of the casing centralisers in the well bore;
d) Inspecting casing for damage either during drilling or later in the lifetime of a well;
e) Establishing a depth reference for depth calibration of lithological logs, i.e. n-n and gamma ray.

3.2 Natural gamma ray log

Natural radiation of unstable elements consists primarily of alpha, beta, and gamma rays; but it is practical to measure only the gamma radiation in a wellbore. Some rocks are naturally radioactive by virtue of the disseminated unstable elements they contain. Most of the 65 unstable nucleides exist in nature but those of significant abundance are

a) Uranium-radium series;
b) Thorium series;
c) Radio-potassium 40 (specially observed in sedimentary rocks).

Investigations in Iceland show, however, that the gamma ray activity in volcanic rock is related to the SiO_2 content of the rock. Geochemical evidence supports this correlation as the content of the radioactive isotopes increases when going from basic to acidic igneous rock. The four basic types of detectors used since the inception of radiation logging are

a) Ionisation chamber;
b) Geiger-Mueller (G-M) detector;
c) Proportional counter; and
d) Scintillation detector.

The G-M counter measures the total gamma intensity, and the scintillation counter can register the energy spectrum of the gamma radiation. The G-M systems are still in use but scintillation detectors are most common (Wood et al., 1974).

Approximately 90% of the measured gamma rays originate within the first six inches of the formation being investigated. The effect of introducing additional media, such as cement and casing, only reduces the total quantity of gamma rays otherwise available for measurement, but generally does not detract from the usable information provided by this measurement.

The "API Gamma Ray Unit" has been adopted industry-wide as the official unit of gamma ray measurement. The detector-measurement systems of all primary service companies are normalised to this unit in the American Petroleum Institute test pit at the University of Houston. Figure 6 illustrates the physical construction of this test pit. The API gamma ray unit is defined as 0.5% of the difference in count rate registered between zones of low and high radioactivity in this test pit. Gamma ray logs are field calibrated at each well by using a radioactive calibrator placed at a specific distance from the detector. This test source represents a given number of API gamma ray units.

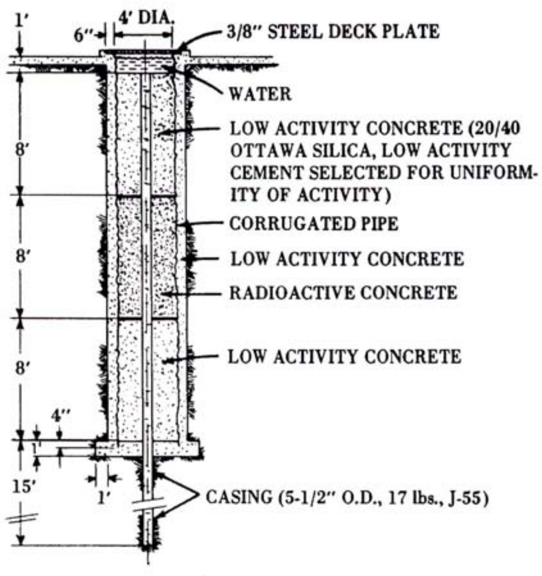

FIGURE 6: API gamma ray calibration pit (Stefánsson and Steingrímsson, 1990)

The gamma ray log is a very good method for identifying acid layers in the basaltic pile of Iceland and correlate them between wells. In acidic rocks the concentrations of all three elements are around ten times greater than in ultrabasic rocks. A linear relationship has been established between the SiO_2 content of volcanic rocks and natural gamma ray intensity.

3.3 Neutron-neutron log

The neutron log is often a standard counterpart of the gamma ray log. This combination provides information as to the lithology (GRL) and the porosity (NL) of the rocks. The neutron log is obtainable in both cased and uncased boreholes and is usually recorded simultaneously with the GRL. Neutron logs respond to the fundamental formation property of hydrogen richness. If all of the formation's hydrogen is contained in the form of liquids, and if these liquids completely occupy the total pore volume, hydrogen richness is an index to porosity. Hence, a neutron log can be used to determine the porosity.

It should be pointed out, however, that the neutrons do not distinguish between protons which belong to formation water and these water-bound in minerals. This is of particular interest in geothermal logging, as hydrothermal alteration is a process of forming minerals with bound water. Furthermore, the water content of secondary minerals which form frequently in fissures in geothermal rock, is often high.

A conventional neutron process follows this generalised sequence: A downhole chemical neutron source (typically, neutron sources are mixtures of beryllium ${}_{4}Be^{9}$ and alpha emitting radioactive element such as radium ${}_{88}Ra^{226}$) emits a continuous flux of energetic neutrons. These neutrons are reduced in energy as they migrate spherically away from the source, across the wellbore and into the rocks. At a very low energy level, the neutrons are eventually absorbed by the nuclei of the wellbore and formation constituents. A radiation detector senses either the low-energy neutrons or the gamma radiation resulting from slow neutron absorption. For example, a neutron capsule source of Radium-Beryllium with 300 millicuries activity generates about 4.5 million neutrons per second with energies from 1 to 13 MeV with an average of 4.5 MeV.

The elastic collision of neutrons with nuclei in the borehole and surrounding rocks leads to a gradual loss of energy. The energy loss is a function of two variables, the angle of collision and the relative mass of the struck nucleus. Since hydrogen atoms are both relatively abundant and nearly equal in mass to the neutron, they are primarily responsible for reducing high-energy neutrons to their thermal state. A neutron at thermal energy level finds itself in a state of equilibrium with the surrounding atoms. It will then undergo random collisions until it is eventually absorbed (captured) by a struck nucleus, whereupon captured gamma rays will normally be emitted by the absorbing nucleus. Whether the detector is responsive to captured gamma rays or slow neutrons, the measurement is indicative of the relative amount of hydrogen in the rocks. Thus, high porosity is indicated by a low neutron-counting rate and vice versa.

One API Neutron unit is defined as $1/1000^{th}$ of the difference between instrument zero, and the log deflection that is opposite the 19.0 percent porosity Indiana limestone section of the calibration pit at the University of Houston.

3.4 Resistivity log

The specific resistivity of the reservoir rock is the result of two different contributions, the resistivity of the rock matrix and the formation fluid. An igneous rock matrix is generally a poor electrical conductor at geothermal temperatures, with typical specific resistivity values on the order of $10^4 – 10^6$ Ωm. With a medium-conductivity formation fluid like geothermal water (resistivity of 1-10 Ωm), the electrical properties of the fluid will define the resistivity of the reservoir rock. This value will, therefore, in general depend on porosity as well as temperature and water salinity.

Two types of electrode arrangements are common in resistivity sondes; the normal device, and lateral device. Here, only the normal resistivity log will be briefly described. The electrode arrangement and basic circuit of the normal device are essentially as illustrated in Figure 7. Electrode A and electrode M are on an insulating mandrel called the probe or tool, which is suspended at the end of the logging cable. Electrode B and N are placed far from A and M, and B and N are either at the surface of the ground or on the cable at a long distance from the probe. The distance *AM* is known as the spacing. The reference point of the measurement is the midpoint between A and M. The usual resistivity probe comprises two normal devices with spacings of 16" (short normal) and 64" (long normal). Under good conditions, the radius of investigation is on the order of twice the spacing.

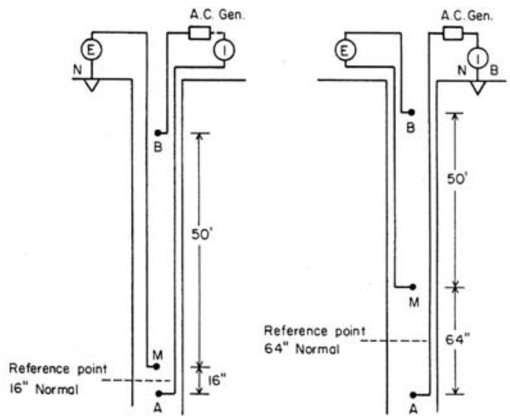

FIGURE 7: Electrode array for the normal resistivity log configuration (Stefánsson and Steingrímsson, 1990)

Assuming an infinite homogeneous medium, the apparent resistivity, ρ, of the formation is given by the following equation:

$$\rho = 4\pi AM\frac{V}{I} \tag{1}$$

4. DATA PROCESSING

4.1 Input data

The geological data that have been used to carry out the present research include cutting samples, alteration data, and information on the location of intrusive layers and feedzones. Available logs included drilling rate curve and geophysical acquired during and after the drilling of well KJ-32.

4.1.1 Analysis of cuttings

This data set included the results of microscopic (binocular stereo-microscope) studies of mineralogy and petrology, degree and kind of alteration and texture and form of the cuttings. Cutting samples were taken at a 2 m interval. The samples were analysed during drilling. The log of the onsite geologist is shown in Appendix I. The drilling speed was very high, and, therefore, one cannot expect the geological section to have the same resolution as obtained under more usual conditions. The geophysical logs have, therefore, been used to improve on the interpretation obtained from the cuttings record.

4.1.2 Geophysical logs

Six geophysical logs were available from end of the casing (1076.9 m depth) or at the beginning of the open hole part of the well to the depth of 1836.4 m. These logs are the X-caliper, Y-caliper, neutron-neutron, natural gamma ray and short and long normal resistivity logs. In Appendix II a composite plot of the original logs is shown. The final composite logs are shown in Appendix III.

4.1.3 Location of feed zones

The location of the main feed zones was inferred by the onsite geologists from temperature logs and records of circulation losses. This information was available in the form given in Appendix IV.

4.2 Data processing

Computer programs used for editing, processing, interpreting and displaying the logs are the following (Arason, 1993):

bhmath: A program to check if content and format of data file is correct.
bhmclip: A program that cuts from top and/or bottom of file so that its depth range will not exceed the depth range of a reference file.
bhmdypi: A program that cuts out lines from input files that are outside a predefined depth range.
bhmcov: A program that finds and plots covariance between two logs as a function of depth-shift.
bhmint: A program that interpolates an input file to the same depths as the reference file depths.
bhmpor: A program that calculates porosity from caliper and nn-log. Caliper can be defined in a file or as a constant value.
bhmsio2: A program that calculates SiO2-content from caliper and natural gamma ray logs. Caliper can be defined in a file or as a constant value.
oralog2: A program for plotting the logs for a given depth range.

The data processing consisted of the following five main steps:

Editing: The most important steps in editing the data were
a) Deletion of erroneous values;
b) Check and correction of depth values;
c) Check for and elimination of noisy data by plotting and editing;
d) Clipping of the data file at the top and bottom.

The software package Logplot 98 was used for final display of the logs.

Depth calibration: The first step in the calibration procedure consisted of covariance calculations to determine the depth shift between pairs of logs (Figure 8). Based on the result of this step, all logs were cut below 1836.9 m in depth. The next step was to identify the end of the casing in the caliper log and adjust the depth scale of all the logs to this reference value. According to the drilling report, the distance between the top of the flange and end of the casing is 1069.5 m and the distance

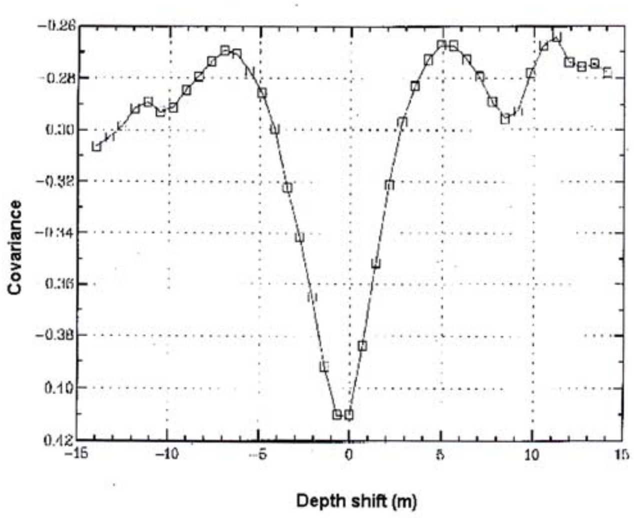

FIGURE 8: Covariance as a function of depth shift between the X-caliper and n-n log

between the rotary table and the flange is 7.36 m. Therefore, the end of the casing must be located at 1069.5 + 7.36 = 1076.86 m. This value was taken as the depth reference.

Caliper log correction: Comparison of the caliper logs with the inside casing diameter given in the drilling report revealed a minor systematic difference between the X and Y logs and a slight deviation from the correct diameter. This was used to correct both logs.

Porosity determination: It is of interest to convert the geophysical logs from well KJ-32 to reservoir parameters such as porosity content. Formation porosity is estimated from the neutron-neutron log values using the diameter of the borehole as a correction factor.

The *bhmpor* program (Arason, 1993) was used to calculate the porosity values from the measured neutron intensity and diameter of the borehole (Figure 9).

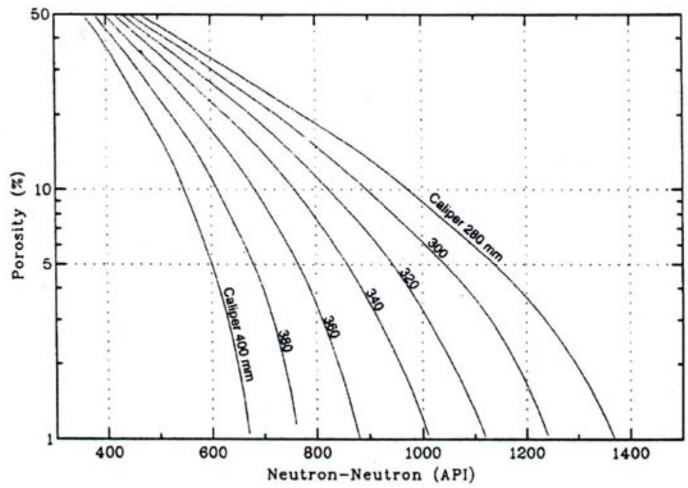

FIGURE 9: Neutron intensity and borehole diameter interpretation curves for porosity determination

Silica content determination: The gamma rays emitted by rocks are, in general, associated with the presence of radioactive elements like potassium (^{40}K), Uranium (^{238}U) and Thorium (^{232}Th). Experimental work, especially in Iceland and the oceanic crust, has shown that the abundance of these elements is related to the silica content of the rock. According to the following equation, where, I_0 is the intensity of gamma radiation in API units and C is a correction factor due to the diameter of the borehole:

$$SiO_2\ (\%) = 40.6 + 0.264 I_o C \tag{2}$$

$$C = \frac{1}{1.192 - 0.3937\log[\frac{cal.(mm)}{20}]} - \frac{0.32}{[\frac{cal.(mm)}{20}]} \tag{3}$$

The program *bhmsio2* was used to determine the SiO_2 content of well KJ-32. This program is based on the above equations (Arason, 1993).

5. INTERPRETATION

This part of the report presents a comparative view of well KJ-32 to show all of the changes resulting from the processing described in the last section and reinterpretation of the cuttings record in view of the corrected logs. For this purpose we divide the final results of the log interpretation into six main subjects that are explained with figures. The first illustrates correlation between the geophysical logs and the cuttings logs. The second shows an example of how the cuttings log has been corrected based on correlation with the geophysical logs. Increased resolution of lithology through identification of more layers is then illustrated, as well as giving an example of improved interpretation of lithology. Finally, a new subdivision of the reservoir rocks into major geological units is presented.

5.1 Correlation of geophysical logs and cuttings logs

During drilling the on-site geologist constructs a lithological column based on cuttings obtained at constant depth intervals. It should be noted that lithology cannot be identified solely on the basis of the conventional combination of geophysical logs used in litho-stratigraphical studies of geothermal reservoirs, i.e. the gamma ray, neutron-neutron and resistivity logs. Therefore, analysis of cuttings is the primary source of information on the litho-stratigraphy. It provides the basic litho-stratigraphic framework with which the geophysical logs can be compared. However, once a litho-stratigraphic framework is established based on the cuttings, the geophysical logs can usually be used to make large improvements in the litho-stratigraphy. The reason for this is that cuttings analysis suffer several limitations that do not affect the logs.

Cuttings are shifted and smeared out relative to the logs. Several processes contribute to this deterioration in the cuttings record, such as

a) *Depth shift*: Cuttings are carried to the surface by the drilling fluid. When a sample of cuttings is taken at the surface, it is marked with the drilling depth at the time the sample is taken. However, the real depth where the cuttings originated is less by the number of meters that were drilled during its travel to the surface. The effect of the time delay is to shift the depth readings of the cuttings downward relative to the logs; i.e. a lithological boundary observed in the cuttings appears to be located at a greater depth than the true depth. The size of the shift depends on well diameter, type of drilling fluid, pumping rate, and circulation loss and drilling rate. Delay times are much greater when the drilling fluid used is water than when mud is used.

The onsite geologist, using a formula which takes into account all the above factors, corrects the depth readings of the cuttings samples. However, the factors are not always accurately known so there is a limit to the accuracy of this method. Furthermore, there is always the possibility of some error affecting the depth readings, due to the many manual steps involved.

After a depth correction based on comparing the geophysical logs with each other and with the end of the casing, the depth readings on the logs are much more accurate than those of the cuttings record. Therefore, they can be used effectively to correct the depth of those geological boundaries determined through analysis of cuttings that are also observed in the logs.

b) *Smearing-out of lithology*: Cuttings of different size travel to the surface with different speed. This leads to a separation of the cuttings according to size during upward transport and therefore a smearing-out of the cuttings record. The presence of large cavities in the well also leads to a decrease in the resolution of the cuttings record, because local circulation of drilling fluid within the cavity leads to a mixing of cuttings from different depths. High and variable drilling rates also contribute to this effect as do low flow rates of returning drilling fluid caused by large circulation losses. The smearing-out effect reduces the resolving power of the cuttings record, i.e. the possibility of identifying thin layers and the accuracy with which the depth and thickness of stratigraphical boundaries can be determined.

Due to the smearing-out effect, the resolving power of the cuttings record is generally much less that that of the geophysical logs. The logs can, therefore, be used to improve the cuttings record considerably through identification of thin layers in the logs and increased accuracy in the positioning of geological boundaries.

c) *Misidentification of lithology*: When the drill bit grinds the cuttings too finely, accurate identification of lithology may become very difficult using standard methods of cuttings analysis. Loss of resolving power due to the smearing-out effect may make this even harder. Drilling with a mud motor often causes the cuttings to be ground to such a small size that interpretation of lithology becomes very difficult. This problem has become more common with increased use of this drilling method in Iceland. Once the typical log signature of the rock types encountered by the well has been established, deviation from this signature can be used to identify intervals where lithology has been misidentified. Usually it is possible to suggest an alternative interpretation of lithology based on the typical log signatures.

Correlation between the original cuttings log and the depth corrected geophysical logs for the depth interval between 1262 and 1400 m is shown in Figure 10.

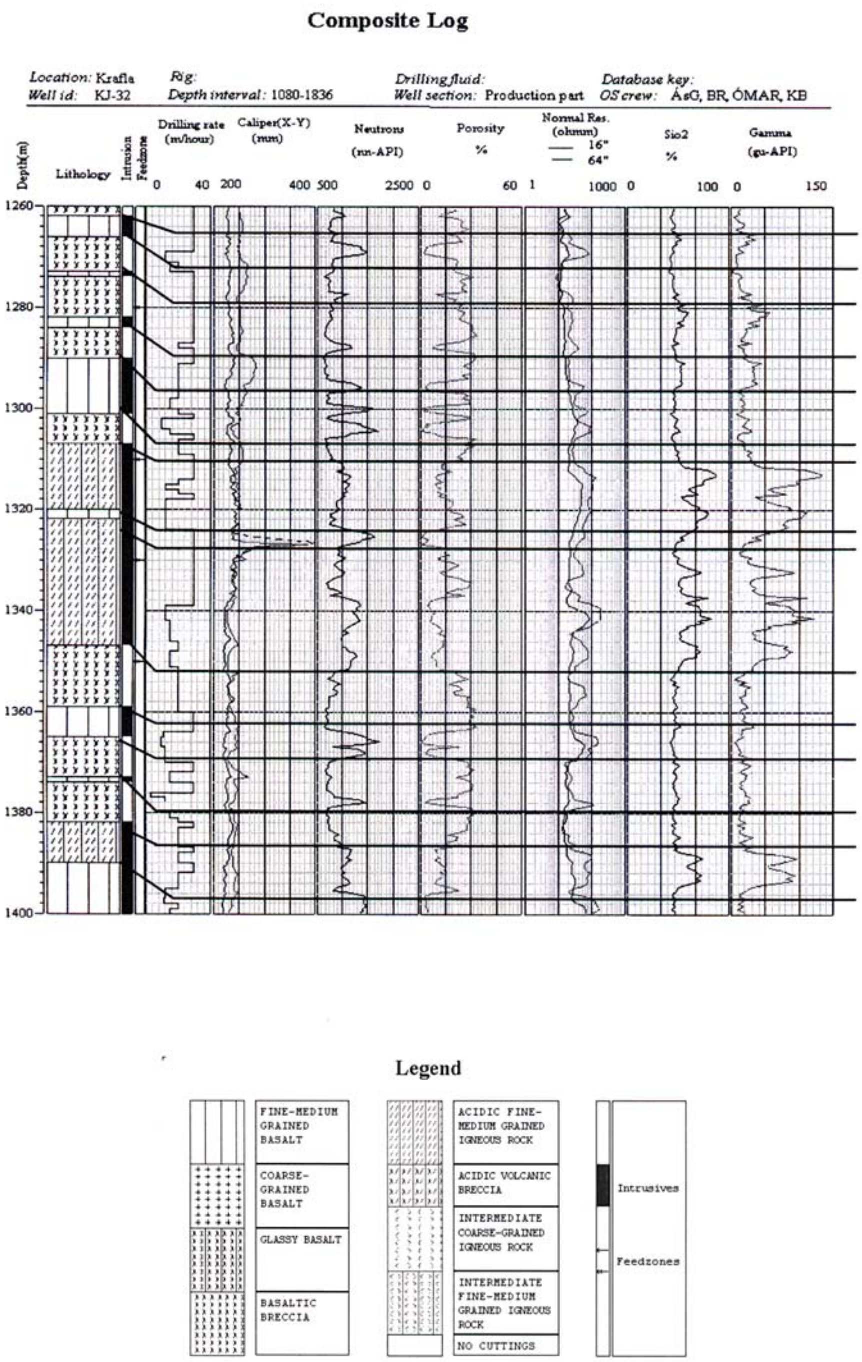

FIGURE 10: Part of the well KJ-32 showing correlation between the original cuttings log and the depth corrected geophysical logs (the legend of lithological units applies also to Figures 12-14)

Note the following:

a) Fine- to medium-grained basalt layers in this part of the well show high neutron values (low water content), low porosity % and also a low drilling rate.
b) Basaltic breccia layers, especially, exhibit the lowest neutron values compared to other rock units and the highest porosity.
c) The main characteristic of acidic fine- to medium-grained igneous layers is very high gamma ray value and SiO_2 content.

The drilling rate in the rock types b) and c) is higher than in the a) type. Based on such characteristics, we have corrected all of the production part of well KJ-32 in the Leirbotnar geothermal reservoir (see Appendix III).

5.2 Correction of cuttings logs

Based on correlations between logs and cuttings, such as those shown in Figure 10, the lithological boundaries identified in the original cuttings record were adjusted to fit the corresponding boundary depths determined from the depth corrected geophysical logs. The size of the depth correction as a function of depth is shown in Figure 11. Figure 12 shows the result of this correction on the geological section in Figure 10.

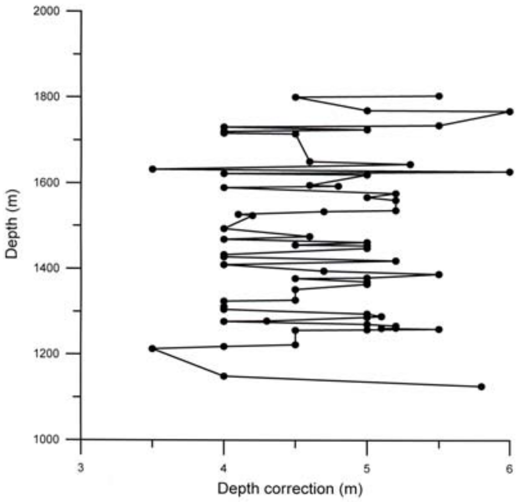

FIGURE 11: Depth correction as a function of depth in well KJ-32

The geophysical logs more accurately determine stratigraphical boundaries and the thickness of individual litho-stratigraphic units than the cuttings. *Neutron-neutron logs* react mainly to the water-content (i.e. porosity) of the surrounding rock formations. The water-content of igneous rocks is to a large extent controlled by the environment in which they were emplaced. Subaerial lava flows typically have a low-porosity core sandwiched between high-porosity vesicular rubble at the top and bottom. The porosity of magma emplaced in water or thrown into the air is generally very high, but depends on the exact mode of emplacement. Hyaloclastite formations, which often contain a mixture of tuff and breccias, often reach a porosity of 30% and more. By contrast, intrusives have a low porosity, often < 5%. The neutron-neutron logs make it possible to make very detailed interpretation of igneous units with variable water content. Once a succession has been identified as consisting of subaerial lava-flows, the neutron-neutron log can be used to locate the boundaries between individual flows with much greater accuracy than can be achieved with cuttings analysis alone.

Resistivity logs are affected by the water-content (porosity) of the surrounding rock formations, the salinity and temperature of the formation fluid and the electrical conductivity of the rock matrix. In geothermal reservoirs, the temperature and salinity usually change rather slowly with depth and, therefore, the response is commonly dominated by the water content of the rocks. There is one important exception, however. High-temperature geothermal systems in igneous rocks are associated with a suite of different clay minerals formed by hydrothermal alteration. Some of these minerals are good electrical conductors and their presence can have a large influence on the resistivity signature. The effect is to both lower the measured resistivity and to reduce the contrasts in resistivity between different rock units caused by varying water content. In active high-temperature systems, the well-conducting clay minerals are usually found in the outer, colder parts of the system. They are not present in significant amounts in temperatures above ca. 250°C. In geothermal reservoirs where the temperature exceeds this limit, the short-scale variations in the resistivity log mostly reflect the water content.

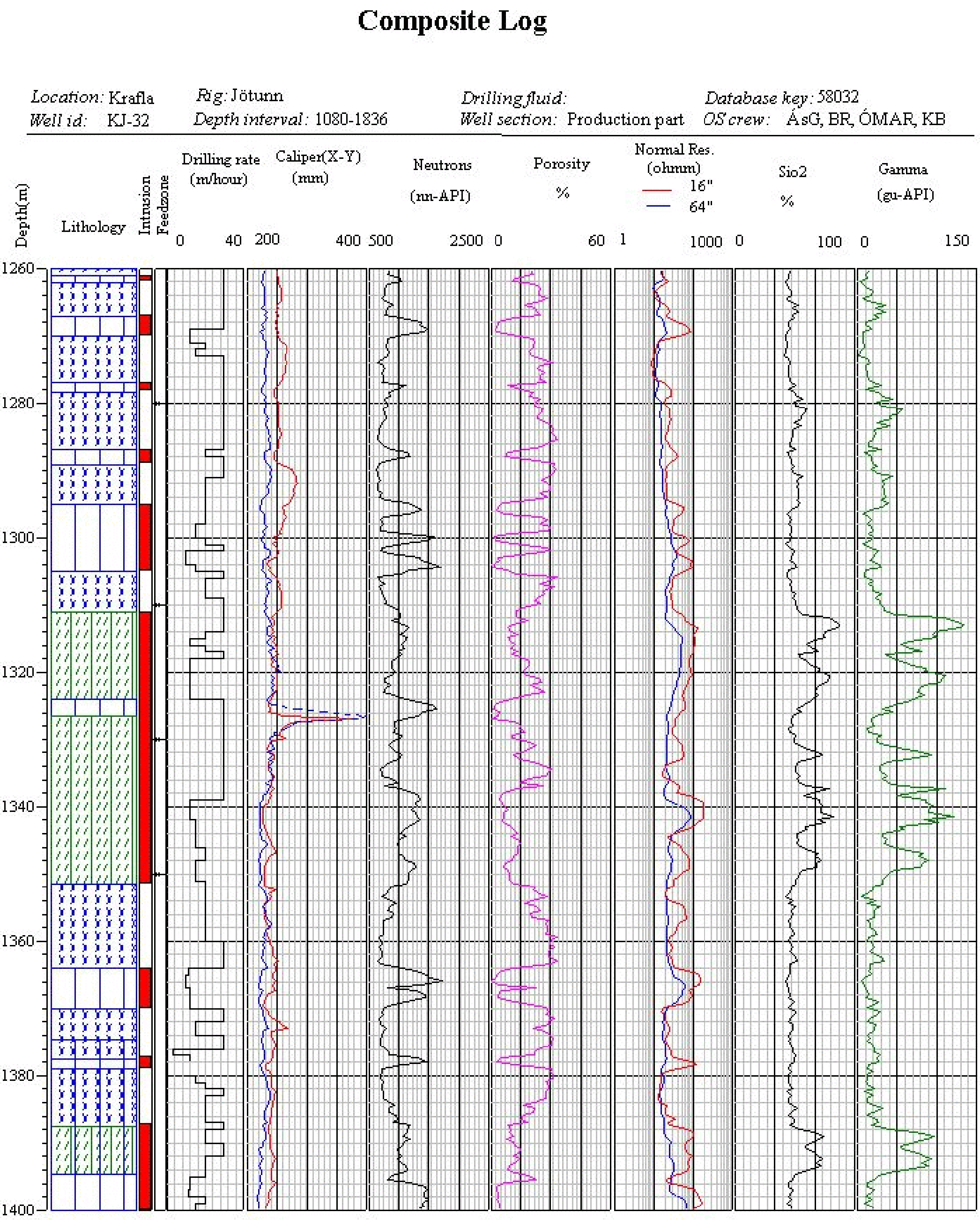

FIGURE 12: Correction of cuttings logs in well KJ-32, Krafla

Radioactive isotopes, mostly of potassium, uranium and thorium cause the natural gamma radiation of rocks. These isotopes are present in very small concentrations in the rocks, but the radiation from then can still be measured. A relationship exists between the silica content of Icelandic rocks and their natural gamma radioactivity and this relationship can, in many cases, be used to estimate the silica content of the rocks from natural gamma ray logs. Acidic rock units are easily identified as prominent maxima in the logs. Such rock units are often used as stratigraphic markers in the correlation between wells.

In well KJ-32, boundary depths determined from cuttings were found to be shifted upwards by 3.5-6 m relative to the same boundaries identified in the logs. The shift was very consistent, having an average of 4.7 m and a standard deviation of 0.6 m. This upward shift of the cuttings, relative to the logs must be due to an error in the depth readings of the cuttings log. Due to the time it takes the cuttings to reach the surface, the cuttings are always shifted downwards in the raw cuttings log relative to the true depth. The cuttings log available for this work (Appendix I) was not the raw cuttings log. It had been corrected for the time delay effect. Therefore, an overcorrection probably caused the observed shift.

As it appears in Figure 12, after correction of the cuttings log, the match between geological section and the geophysical logs is much improved. Nevertheless, there are still several interlayer fluctuations that should be interpreted. This is described in the next section.

5.3 Improved resolution and interpretation of lithology

In subsurface reservoir geology, especially in deep drilling operations, logs help to correct lithology as identified in the cuttings, and allow alternative interpretations to be suggested. After processing geophysical logs from well KJ-32 in Leirbotnar, a much greater number of layer boundaries was identified in the logs than in the original cuttings record. As seen in Figure 13 for the depth range between 1260 m and 1400 m, the interpretation of the lithological column has been improved and a number of new layers added:

a) At a depth of 1265-1267.2 m an intermediate volcanic breccia (IVB) is inferred from the higher value of gamma rays than in the breccia unit above.
b) For the same reason as above an IVB layer is interpreted at the depth of 1278-1284 m and the breccia layer from depth of 1289-1295 m is completely replaced by another IVB layer.
c) At the depth of 1295-1305 m, two thin basaltic breccia interlayers are interpreted to be present in the fine- to medium-grained basalt (FMGB) unit. A lower value of neutron log and higher porosity are the main reasons for this interpretation.
d) At the depth of 1311-1351.5 m, four intermediate- to coarse-grained igneous rock (ICGIR) layers are identified with the acidic fine- to medium-grained igneous rock (AFMGIR) unit in the original log. The value of the neutron and gamma ray logs in the ICGIR layers is lower than the AFMGIR unit.
e) At the depth of 1351.5-1364 m, the basaltic breccia unit is divided into three separate layers.
f) In the depth interval 1364-1370 m an FMGB layer is divided into two layers in order to reflect changes in the neutron log.
g) At the depth of 1387.5-1394.8 m a thin ICGIR layer is inserted into an AFMGIR unit, because of changes in the gamma log.

The interpretation of lithology was improved in a similar way throughout the production part of the well. This includes a prediction of lithology made for the interval from 1650 m to 1693 m where cuttings are lacking due to loss of circulation (see Appendix III)

A total of 120 new boundaries were identified from the logs, which is a 141% increase. A different lithology is suggested for 43 rock units. This corresponds to 165 m or 22% of the geological sequence.

5.4 Subdivision of reservoir rocks into major geological structures

As we explained in Section 2.1 on the reservoir geology, below 1000 m depth in the Leirbotnar field, there are lavas (B-3) from the first part of the last interglacial period followed by basaltic and doleritic intrusions which dominate the reservoir down to 2000-2200 m depth (Figure 3). In the production part of well KJ-32 basaltic intrusions are present both in the upper and lower parts of the well. A thick hyaloclasite unit is observed in the middle part of the well. The main feed zones seem to be connected to acidic intrusive complexes.

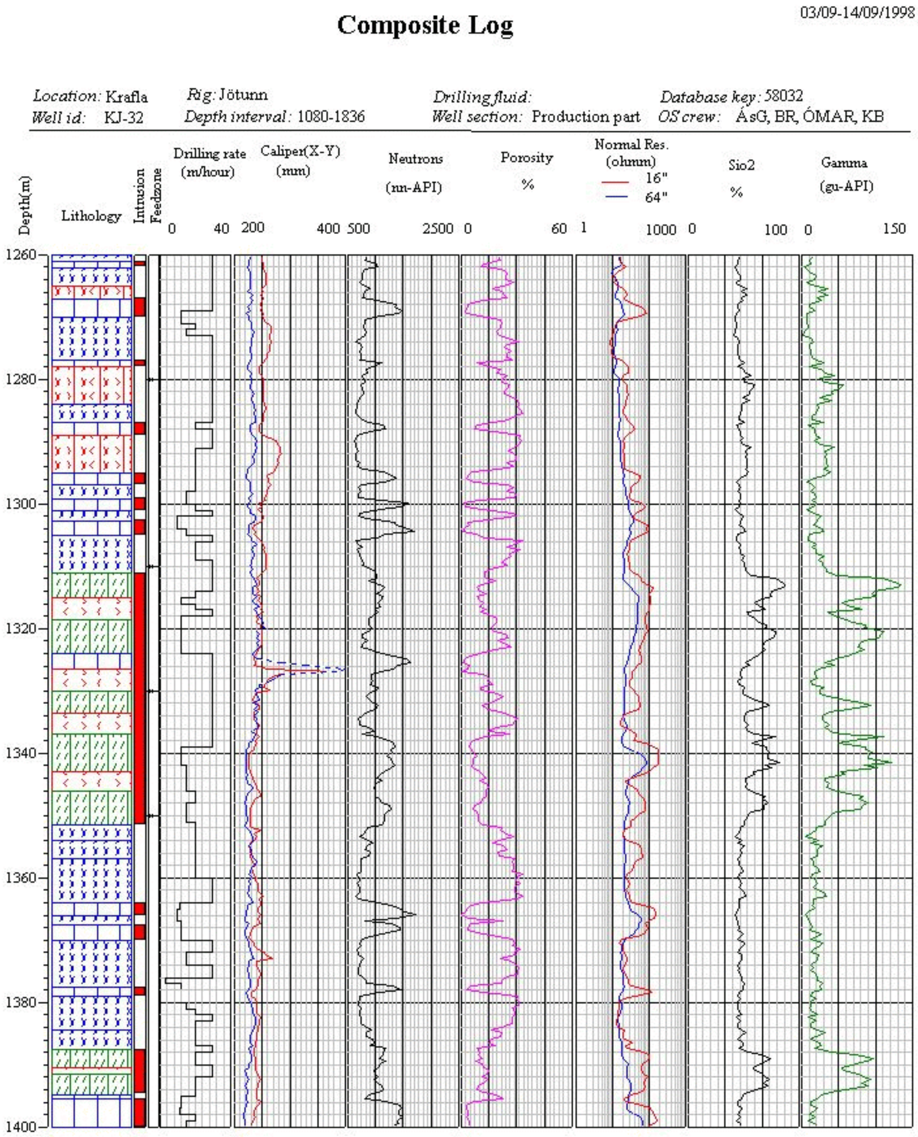

FIGURE 13: Increased resolution and improved interpretation of the lithological column

After processing and interpretation of the logs, based on the new rock sequence a division into major lithological formations is proposed in Figure 14.

5.5 Location of feed zones and geological structures

In the production part of well KJ-32, the main feed zones seem to be connected to fissures and intrusion contacts. Major feed zones are located in hyaloclasites in the middle of the production part of the well. After processing of the logs and depth correction of the cuttings based on the logs, the location of feed zones relative to the geological structures is observed with much greater confidence. During drilling, the location of feed zones was inferred from circulation losses and temperature logs.

The location of the feed zones identified in well KJ-32 is shown on the logs in Appendices II and III. The description of the zones as given in the drilling report (Orkustofnun Geoscience crew, 1998) is included as Appendix IV.

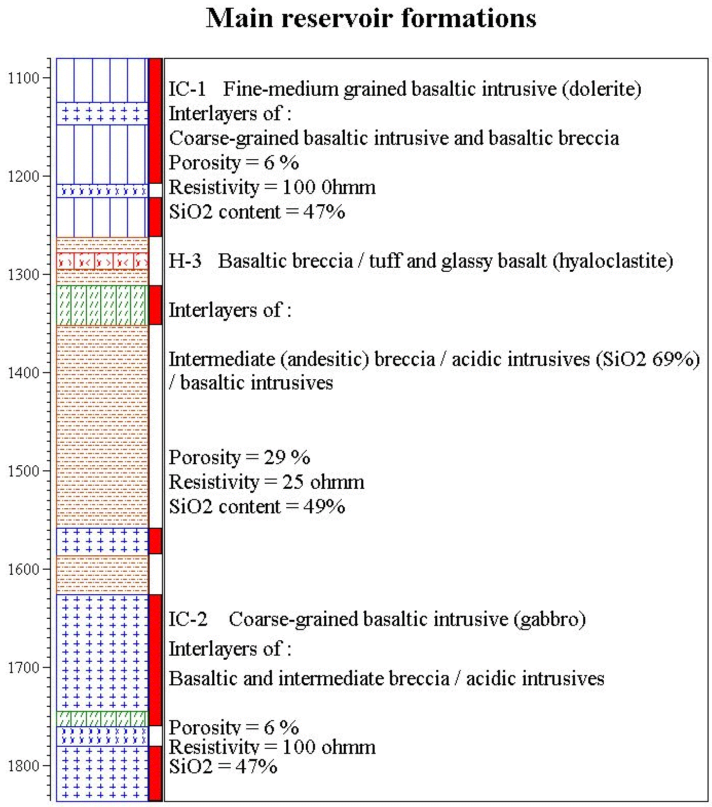

FIGURE 14: Major reservoir formations in the Leirbotnar reservoir

In the improved litho-stratigraphic section, shown in Appendix III, 9 out of 12 feed zones in the production part of the well fall within one metre's distance from a lithological boundary compared with only 5 of the feed zones in the original uncorrected section. All of these boundaries turned out to be intrusive contacts. In view of this preferential location of the feed zones, fluid flow within this part of the Krafla reservoir is probably controlled by intrusive contacts.

During the step re-injection test and pressure response, effects of some internal zones were observed. There it can be seen that two main aquifer zones control the pressure response, between 1100-1320 m and at the bottom of the well. More than 25 l/s and probably more than 40 l/s are needed to quench the internal flow. The temperature in aquifers at 1100 m, 1200 m and 1320 m is 145°, 133° and 125˚C, respectively. Therefore, it is difficult to obtain estimates for transmissivity. For KJ-32 it is assumed to be roughly 3.8 x 10^{-8} m^3/Pas. This corresponds to transmissivities obtained for the more productive wells in Krafla.

6. CONCLUSIONS

The main conclusions that can be drawn from the study of well KJ-32 are as follows:

a. Cuttings analysis and geophysical logs are strongly complementary methods in the study of litho-stratigraphy in igneous geothermal reservoirs.

b. In well KJ-32 lithology cannot be identified accurately on the basis of neutron-neutron, resistivity and gamma ray logs alone. The cuttings log suffers from depth shifts, low depth resolution and occasional misidentification of lithology. Due to loss of circulation, cuttings were also missing from parts of the well. However, integrated interpretation of the two data sets led to significant improvements in the litho-stratigraphy of the geothermal reservoir at Leirbotnar. It was also possible to predict the lithology in the intervals of missing cuttings.

c. Lithological units identified by cuttings analysis correlate well with neutron-neutron, resistivity and gamma ray logs from well KJ-32.

d. Stratigraphic and structural boundaries between different rock units and the thickness of individual units are generally better resolved in geophysical logs than in cuttings. This is very clear in well KJ-32, where a combination of finely ground cuttings, high and variable drilling rate, and large circulation losses make the cuttings record difficult to interpret.

e. Litho-stratigraphic boundary depths determined from cuttings were found to be shifted upwards by 3.5-6 m relative to the same boundaries identified in the logs. The shift was very consistent, having an average of 4.7 m and a standard deviation of 0.6 m. The observed shift is in the opposite direction to that expected from the time-delay shift which affects raw cuttings logs and was probably caused by overcorrecting for the delay.

f. Differences in the thickness of individual layers as determined by cuttings versus logs ranged from 0 to 2.5 m with an average of 0.6 and a standard deviation of 0.5 m. The difference can mostly be attributed to low depth resolution of the cuttings record.

g. A total of 120 new boundaries were identified from the logs, bringing the total up to 205 from the 85 boundaries identified in the cuttings analysis.

h. Geophysical logs are an important aid in locating intervals where the lithology has been misidentified in the cuttings record and allow alternative interpretations to be suggested. In KJ-32, a different lithology is suggested for 43 rock units. This corresponds to 165 m or 22% of the geological sequence.

i. A litho-stratigraphy is proposed for two well sections (1650-1690 m, 1815-1836 m) drilled with a total loss of circulation on the basis of typical log signatures established in other parts of the well.

j. On the basis of the improved litho-stratigraphic section, the following subdivision of the reservoir into three main formations is proposed:
   - A lower formation dominated by gabbro intrusives, with inter-layers of basaltic and intermediate breccia and acidic intrusives.
   - A middle formation of hyaloclastite (basaltic breccia, tuff and glassy basalt) with inter-layers of acidic and basaltic intrusives and intermediate breccia.
   - An upper formation of dolerite intrusives with inter-layers of gabbro and basaltic breccia.

k. In the improved litho-stratigraphic section, 9 out of 12 feed zones in the production part of the well fall within one meter's distance from a lithological boundary compared to only 5 of the feed zones in the original section. All of these boundaries turned out to be intrusive contacts. In view of this preferential location of the feed zones, it can be suggested that fluid flow within this part of the Krafla reservoir is probably controlled by intrusive contacts.

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APPENDIX I: Analysis of cuttings, rock sequence and alteration

Cuttings samples were taken at 2 m interval. The samples were analysed during drilling and the degree of alteration was also determined. The drilling speed was very high; therefore, one cannot expect the geological section to have the same resolution as obtained under more usual conditions. The geophysical (lithological) logs have been used to fill out the picture. It should be noted that after processing of data the depths of the cuttings samples have been corrected. The geological section penetrated by the well is similar to the section in well KJ-20 as shown in Figure 3.

1065 – 1120 m. *Basalt intrusion*. Continued in the same type of rock as was encountered during drilling for production casing. Fine-grained, grey to black, fresh basalt intrusion. A few fine fractures, mostly quartz-filled, but trace amounts of epidote and chlorite are also observed.

1120 – 1145 m. *Coarse-grained basalt.* Greenish, medium- to coarse-grained, altered intrusion often showing white spots. The alteration minerals epidote, quartz, chlorite, pyrite and wollastonite are seen in fractures and some calcite is also observed.

1145 – 1164 m. *Fine- to medium-grained basalt*. Greyish black, similar to the intrusion at the base of the production casing. The alteration minerals quartz and pyrite are found in fractures, but in the upper boundary, some breccia-like rock is present, containing a considerable amount of hydrothermal deposits, dominated by epidote.

1164 – 1204 m. *Fine- to medium-grained basalt*. Fine-grained greyish green rock. At times, almost coarse-grained and breccia-like, as if drilling through basaltic lavas. Chlorite is observed in matrix, but epidote, quartz, prehnite, chlorite, pyrite and wollastonite are observed in fractures and vesicles.

1204 – 1218 m. *Breccia and basalt*. Greenish, strongly altered basalt breccia, rich in hydrothermal deposits. Followed by a fine-grained basalt layer to 1214 m, and strongly altered glassy basalt further down. The main hydrothermal deposits are epodote, quartz, prehnite, chlorite, pyrite and wollastonite.

1218 – 1252 m. *Fine- to medium-grained basalt*. Fine-grained greenish grey basalt intrusions characterise this interval. Three intrusions are observed, the interface between them being located at 1228 and 1236m depth. The same hydrothermal deposits are observed as above, i.e. quartz, epidote, pyrite, chlorite and wollastonite.

1252 – 1307 m. *Basalt breccia and basalt intrusion*. Basalt breccia dominates this interval. The basalt breccia is light green, altered and rich in hydrothermal deposits. The main alteration minerals are epidote, quartz, chlorite, wollastonite, and pyrite. Trace amounts of calcite are also observed. Fine-grained greyish black and greyish green basalts are found as intrusives in the breccia. The intrusions are seen in the neutron-neutron log, but at a depth of 1275-1280m the presence of intermediate igneous rock is indicated in the natural gamma ray log.

1307 – 1347 m. *Acid igneous rocks*. The rocks are light-coloured or almost white. Illite appears to replace chlorite and the epidote is lighter in colour than above. In addition, quartz, wollastonite, prehnite and pyrite are observed. During drilling, this was thought to be an acid igneous rock formation, which is known to characterise the Sudurhlídar area. When it became apparent that the direction of the well deviated strongly from the planned course, a new interpretation was necessary. This is probably the acidic rock complex associated with the Hveragil fault. The natural gamma ray log shows that the complex consists of multiple intrusions, possibly separated by some kind of breccia.

1347 – 1382 m. *Basalt breccias and intrusions*. Light-coloured basalt breccia, strongly altered and rich in hydrothermal deposits. The same alteration are observed as above, except the chlorite has become abundant again and illite is scarce. Fine-grained greyish black to greyish green basalt intrusions are observed from 1359-1374 m and 1373-1374 m depth.

1382 – 1390 m. *Acid igneous rock*. Same kind of acid rock as described above. Very clear in the natural gamma ray log.

1390 – 1489 m. *Fine-grained basalt and breccias*. Fine- to medium-grained, greyish green basalt intrusions dominate this interval and are well defined in the neutron-neutron log. The breccias could originally have been fine-grained, glassy basalt layers. They have since been strongly altered, become green in colour, and very little remains of primary minerals. The main alteration minerals are epidote, quartz, wollastonite, prehnite, actinolite and pyrite (also pyrohtite and chalcopyrite). Trace amounts of calcite are also observed.

1489 – 1620 m. *Breccia and coarse-grained intrusions*. Light green, strongly altered breccia dominates as can be seen from the lithological logs. It is impossible to determine with certainty whether the breccia is tuff breccia or a basalt breccia. Low values in the neutron-neutron logs indicate high porosity. Where the intrusions appear the values increase and the porosity decreases. Alteration minerals such as epidote, quartz, prehnite, wollastonite, actinolite, chlorite and pyrite are abundant. The two uppermost basalt intrusions are located at 1519-1522 m and 1528-1530 m depth. They are fine-grained and greyish black to greyish green in colour. Four altered, greenish, coarse-grained basalt or dolerite intrusions are found at depths of 1554-1561, 1570-1585, 1588-1590 and 1614-1618 m.

1620 – 1650 m. *Acid intrusions and coarse-grained basalt intrusion*. Two, almost white, acid igneous intrusions are observed at 1620-1628 m and 1638-1645 m depth. They probably are cut by coarse-grained greyish green basalt intrusions (or dolerites) that can be seen between and below them. The same alteration minerals are present as above.

1650 – 1690 m. *No cuttings*. Based on the lithological logs (low natural gamma ray intensity, rather high, but variable neutron count, continuously high resistivity), this is probably a basalt intrusion.

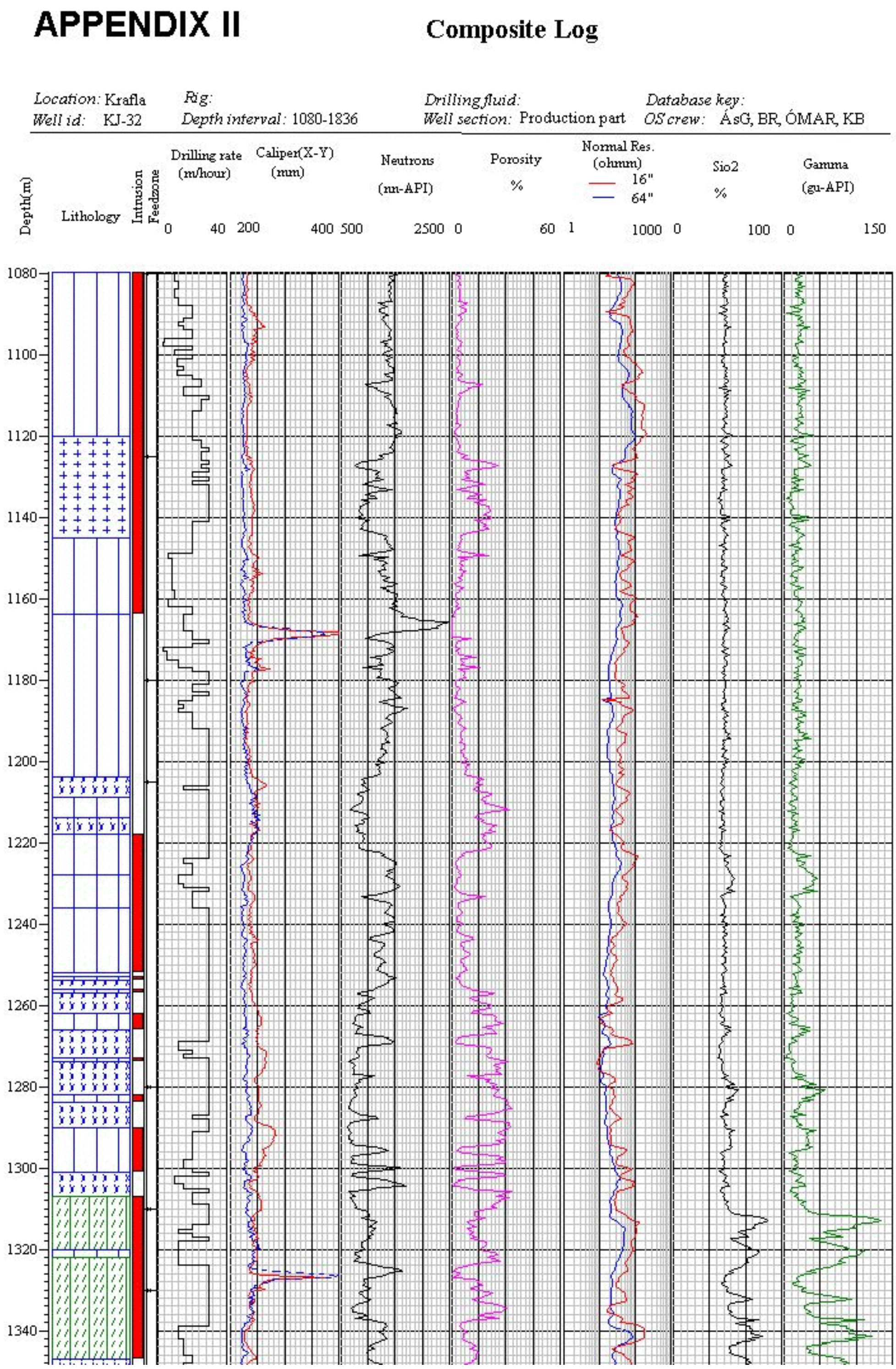
1690 – 1726 m. *Coarse-grained basalt*. Medium- to coarse-grained greenish basalt, most likely an intrusion. The intrusion is not continuous and some kind of breccia or basalt is found at 1710-1712 and 1716-1719 m depth.

1726 – 1738 m. *Basalt intrusion*. Difficult to determine whether the intrusion is fine-grained or coarse-grained because the cuttings are so finely crushed, but a coarse-grained intrusion seems more likely. The alteration minerals are the same as above.

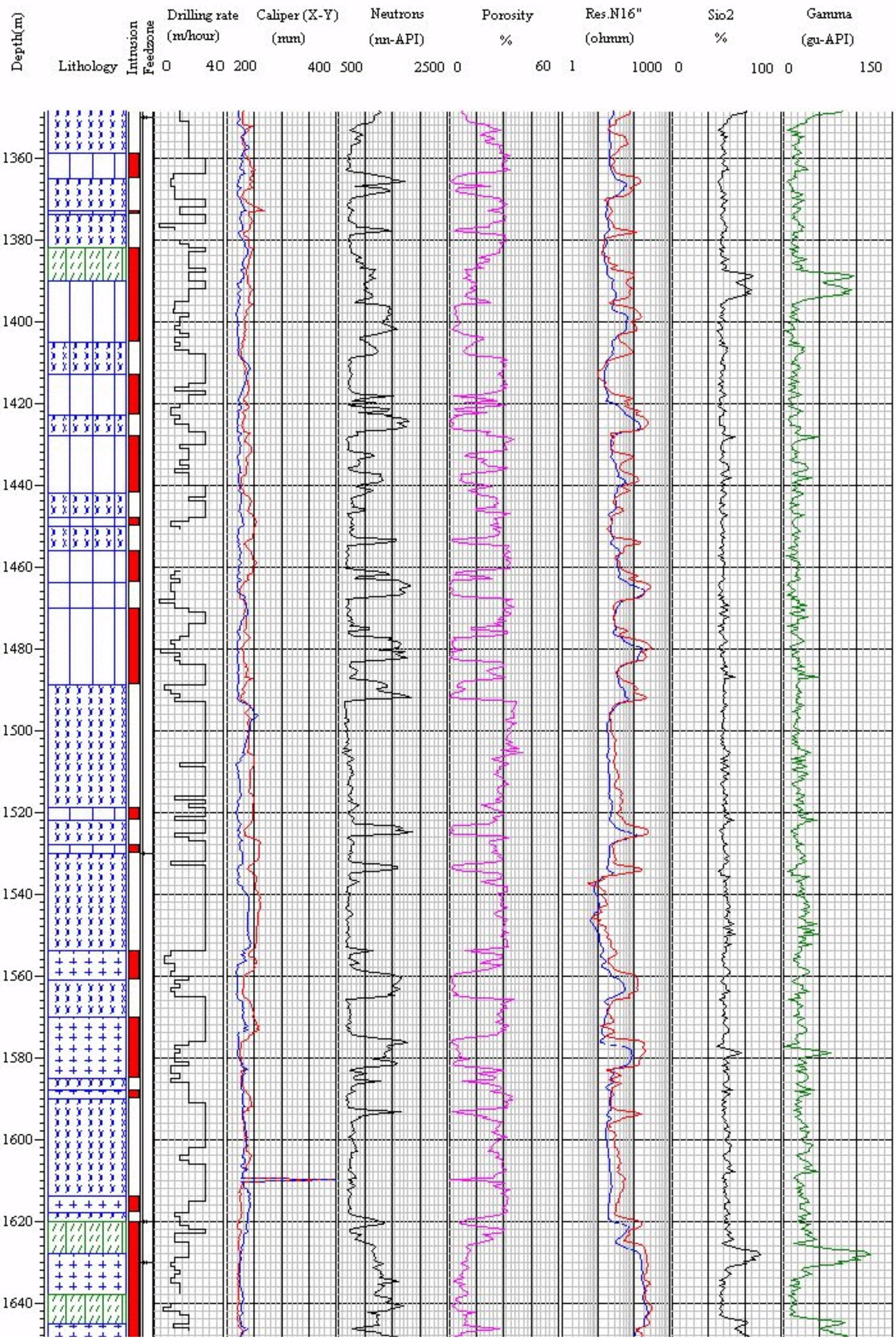
1738 – 1763 m. *Acid igneous rock and basalt intrusion*. An acidic igneous rock and a basalt intrusion are observed, although the cuttings are as finely crushed as in the interval above. The boundary between units is determined on the basis of the lithological logs.

1763 – 1816 m. *Probably a coarse-grained basalt intrusion*. The cuttings finely crushed as above.

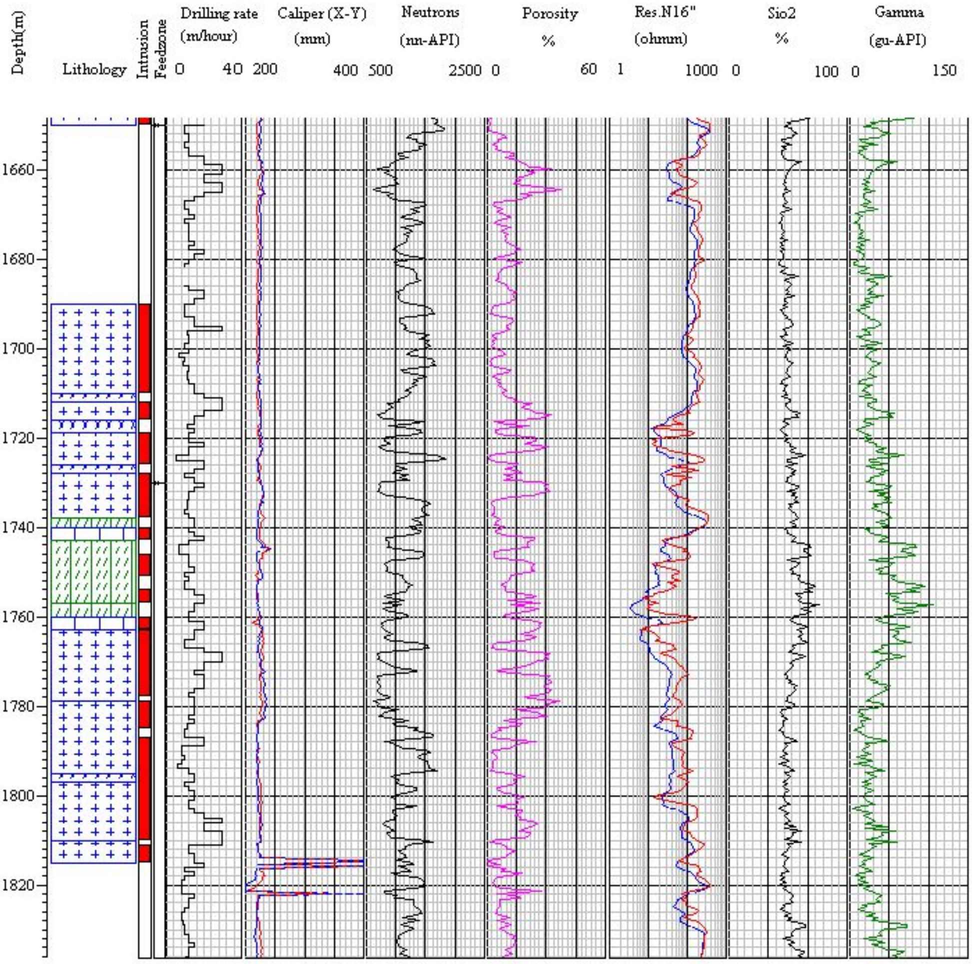
APPENDIX II: Original well logs from well KJ-32, Krafla



APPENDIX II

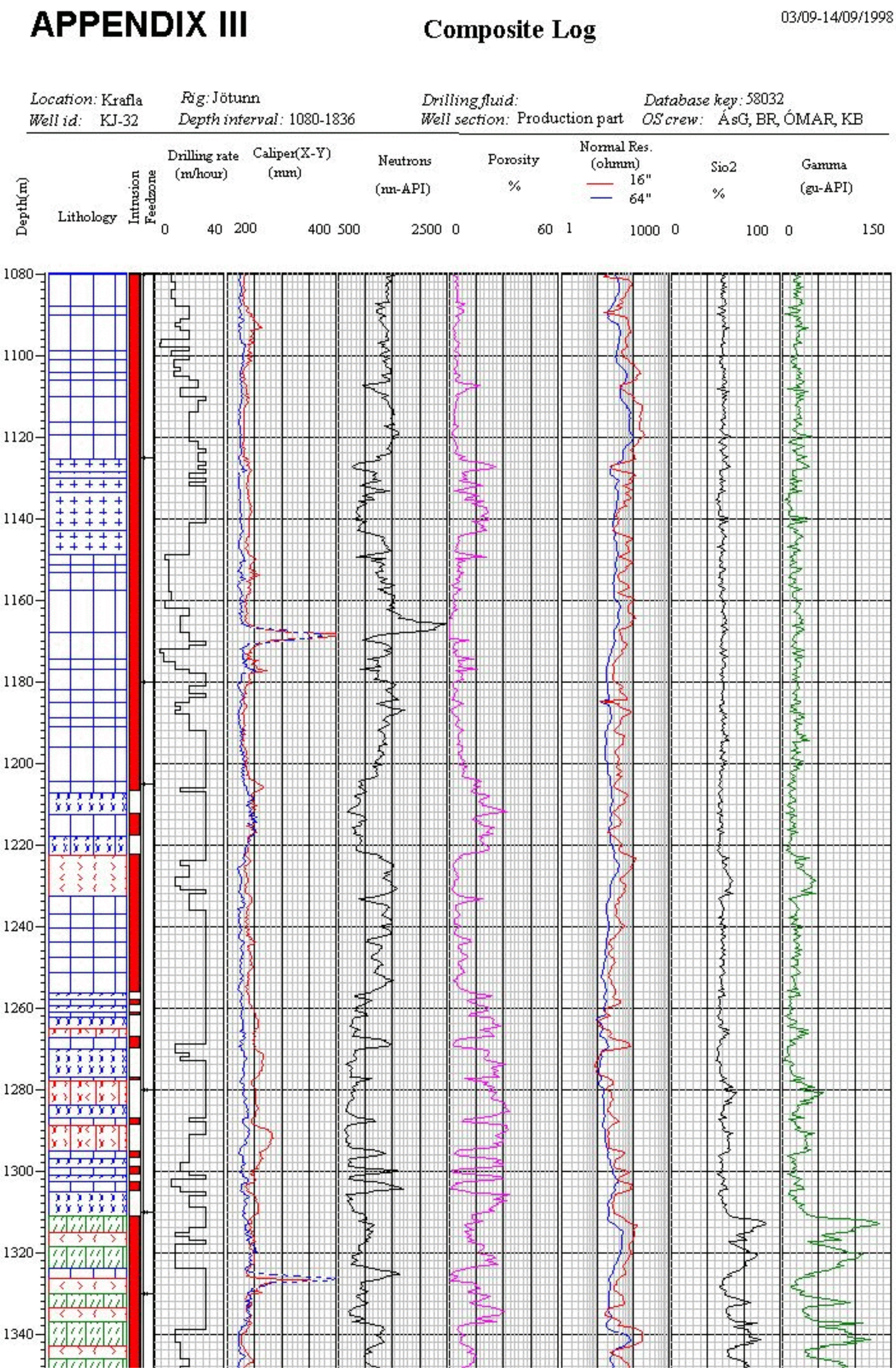

Depth(m)
Lithology
Intrusion
Feedzone
Drilling rate (m/hour) 0 40
Caliper (X-Y) (mm) 200 400
Neutrons (nn-API) 500 2500
Porosity % 0 60
Res.N16" (ohmm) 1 1000
Sio2 % 0 100
Gamma (gu-API) 0 150
1360
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
1620
1640

APPENDIX II

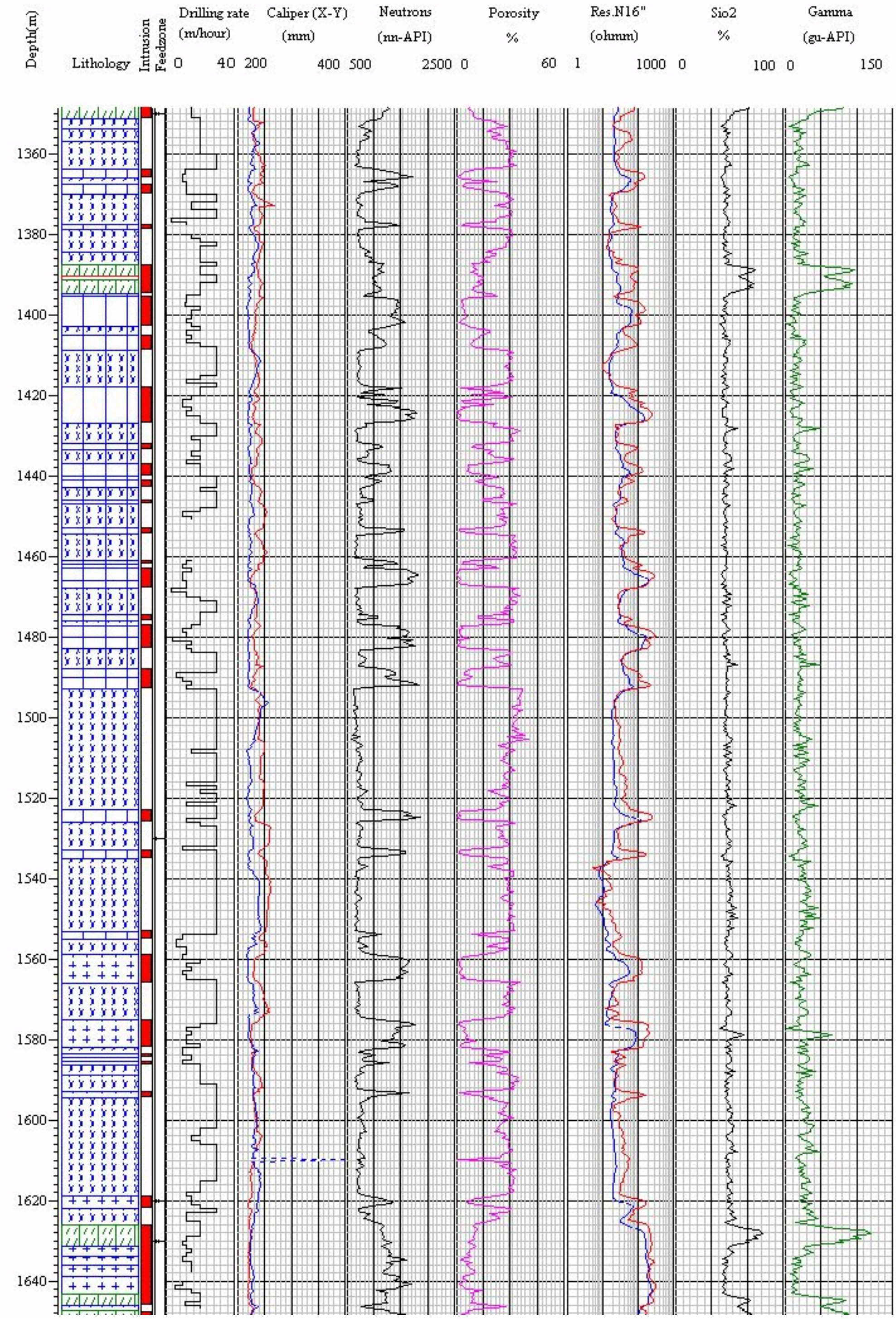


Depth(m)
Lithology
Intrusion
Feedzone
Drilling rate (m/hour)
0 40
Caliper (X-Y) (mm)
200 400
Neutrons (nn-API)
500 2500
Porosity %
0 60
Res.N16" (ohmm)
1 1000
Sio2 %
0 100
Gamma (gu-API)
0 150
1660
1680
1700
1720
1740
1760
1780
1800
1820

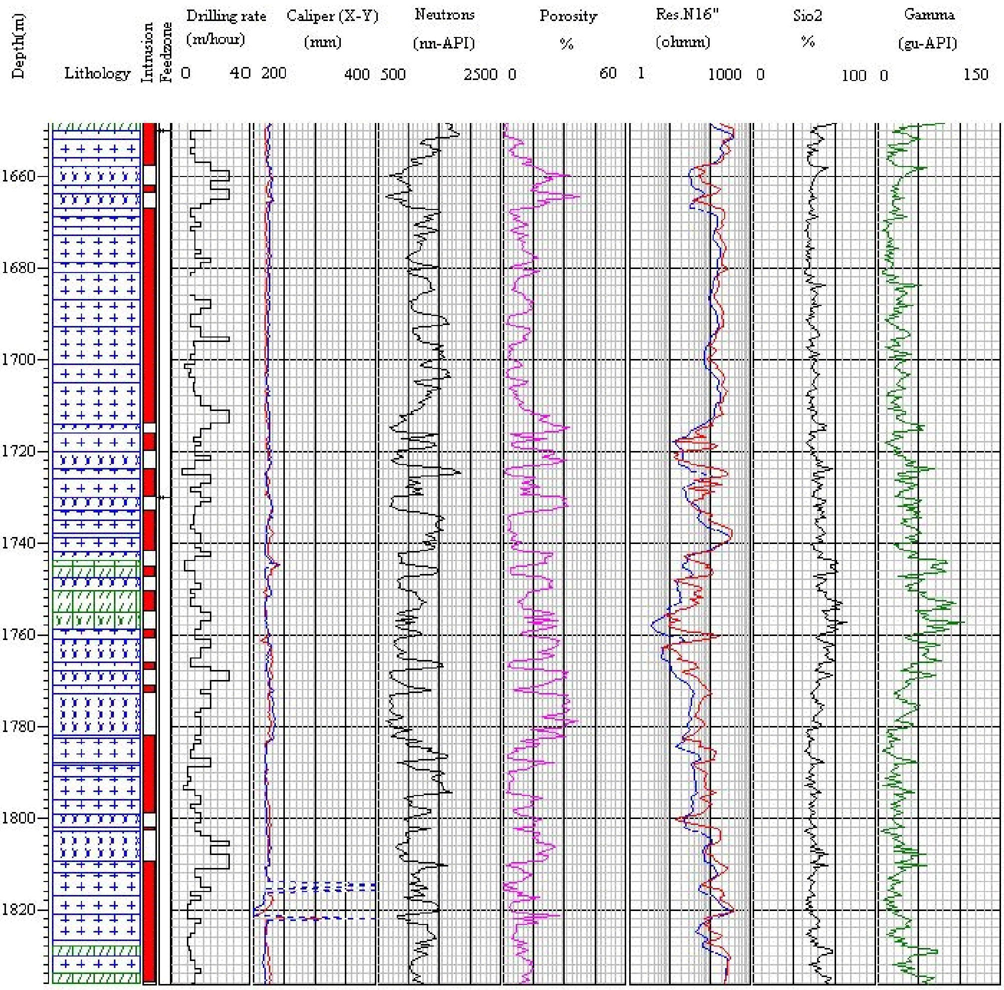
APPENDIX III: Processed logs and reinterpreted geological column from well KJ-32, Krafla



APPENDIX III



APPENDIX III



APPENDIX IV: The location of the feed zones from well KJ-32, Krafla

The main feed zones (aquifers) observed during drilling were as follows:

1. The first measurement of circulation loss during the drilling of the production part of the well gave a value of 2 l/s. A bend in the temperature curve is seen in fine-grained rocks just below casing.
2. At a depth of 1125 m, at the boundary between fine- and coarse-grained intrusions, the circulation loss increased by 2 l/s. This is consistent with the MWD-temperature log (MWD=measured well depth).
3. At 1180 m, there seems to be a feed point according to the temperature logs and circulation loss in basaltic lavas.
4. At a depth of 1205 m according to wireline temperature logs, circulation loss and the MWD-temperature log. In strongly altered breccias in the vicinity of dyke intrusions. The total circulation loss had by then increased to nearly 10 l/s.
5. At a depth of 1280-1310 m based on increased circulation loss and temperature logs (both wireline and MWD). Total circulation losses 15 l/s. The feed zones are associated with the Hveragil fault, as this interval is located in an acidic rock complex, interpreted to be associated with the fault.
6. At 1330 and 1350 m depth based on increased circulation loss and temperature logs (both wireline and MWD). The feed zones are associated with the Hveragil fault and are located within the acidic rock complex. Circulation losses of 20 l/s were measured at this point.
7. At a depth of 1530 m, based on an MWD-temperature log.
8. At a depth of 1620-1730 m, based on increased circulation losses and an MWD-temperature log. Total circulation losses are 35 l/s. The feed zones are associated with acidic intrusions in fractures to the west of Hveragil fault.
9. At 1860-1870 m depth, i.e. just above the bottom of the well, based on temperature logs (both wireline and MWD) and increased circulation losses.