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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL KJ-29 IN THE KRAFLA HIGH-TEMPERATURE AREA, NE-ICELAND

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ABSTRACT

KJ-29 is a 2103 m deep well in the Leirbotnar field of the Krafla high-temperature area, NE-Iceland. It was drilled this year to mine steam for electrical production. The discharge of the well is very high. This study deals with the upper 1000 m of the well. The rock formation dissected by the well consists of basaltic hyaloclastite formations and basaltic lava series which are believed to have accumulated during the last glacial and interglacial periods. Intrusive rocks of basalt/dolerite composition occur below 530 m depth and predominate from 990 m down to the bottom of the well. Aquifers were confirmed at 100-155, 275, 600, 680, 730, 800 and 930 m depth, mostly related to intrusion contacts and fractures. Five alteration zones are identified including a smectite-zeolite zone (<200°C) down to 212 m depth, a mixed-layer clay zone (200-230°C) down to 420 m depth, a chlorite zone (230-250°C) down to 822 m depth, a chlorite-epidote zone (250-280°C) down to 998 m depth and an epidote-actinolite zone (>280°C) from there down to the bottom of the well. Measured temperatures in the lower part of the well are roughly comparable with the alteration temperatures. These evidences indicate a stable high-temperature environment. The early occurrence of wairakite and quartz may be related to an earlier hydrothermal event, presumably within the last glacial period. Hydrothermal evolution, as seen through alteration, indicates an initial low-temperature condition followed through intermediate to a high-temperature environment. The geology of the well confirmed that it is situated inside the horst system in the Krafla caldera, close to a fault related upflow zone causing an elevation of alteration zones to shallow depths.

1. INTRODUCTION

1.1 Scope of work

Iran´s Ministry of Energy has recently begun a long-term development programme of utilising renewable energy resources to increase power generation capacity. Attention is largely focussed on a geothermal energy project, now being set up by the Electric Power Research Centre.

Drilling is one of the principal tasks in the development of geothermal fields. It is important to have an appropriate design of the well as well as complete control of subsurface lithology through cuttings and cores. With this information, it is possible to see how the geological structures control the movement of geothermal fluids in the reservoir, as well as the relationship between alteration minerals and the past to present conditions within the geothermal system.

This report deals with the borehole geology and alteration mineralogy of well KJ-29 recently drilled in the Krafla geothermal area, NE-Iceland, as seen mostly from analysis of the drill cuttings down to 1002 m depth which were studied with respect to petrography, mineralogy and hydrothermal alteration history.

1.2 General information

Iceland is located on the Mid-Atlantic Ridge, where the American and Eurasian continental plates are drifting apart and a new crust is continuously forming. The general stratigraphic division of Iceland is shown in Figure 1. The oldest formation is composed of a lava pile of Plio-Miocene age (3.1-16 m.y.), generally dipping gently towards the volcanic zones. The second formation is of Plio-Pleistocene age (0.7-3.1 m.y.), composed of alternating sequences of lavas and hyaloclastites. The lavas were formed during the interglacial periods, whereas the hyaloclastites were formed as a result of subglacial eruptions during the glacial periods. The third and youngest formation is composed of Upper-Pleistocene and Holocene formations (<0.7 m.y.), which is confined to the neovolcanic zones. These zones delimit the rift zones (Figure 1). The rifting within the neovolcanic zones is mainly confined to distinct fissure swarms. A central volcano usually forms in the central part of each fissure swarm. These volcanoes are the foci of magmatic activity within the fissure swarms and it has been shown from studies in the deeply eroded regions (of Tertiary and Quaternary age) that a high percentage of intrusions occur in the core of these volcanoes (Saemundsson, 1979).
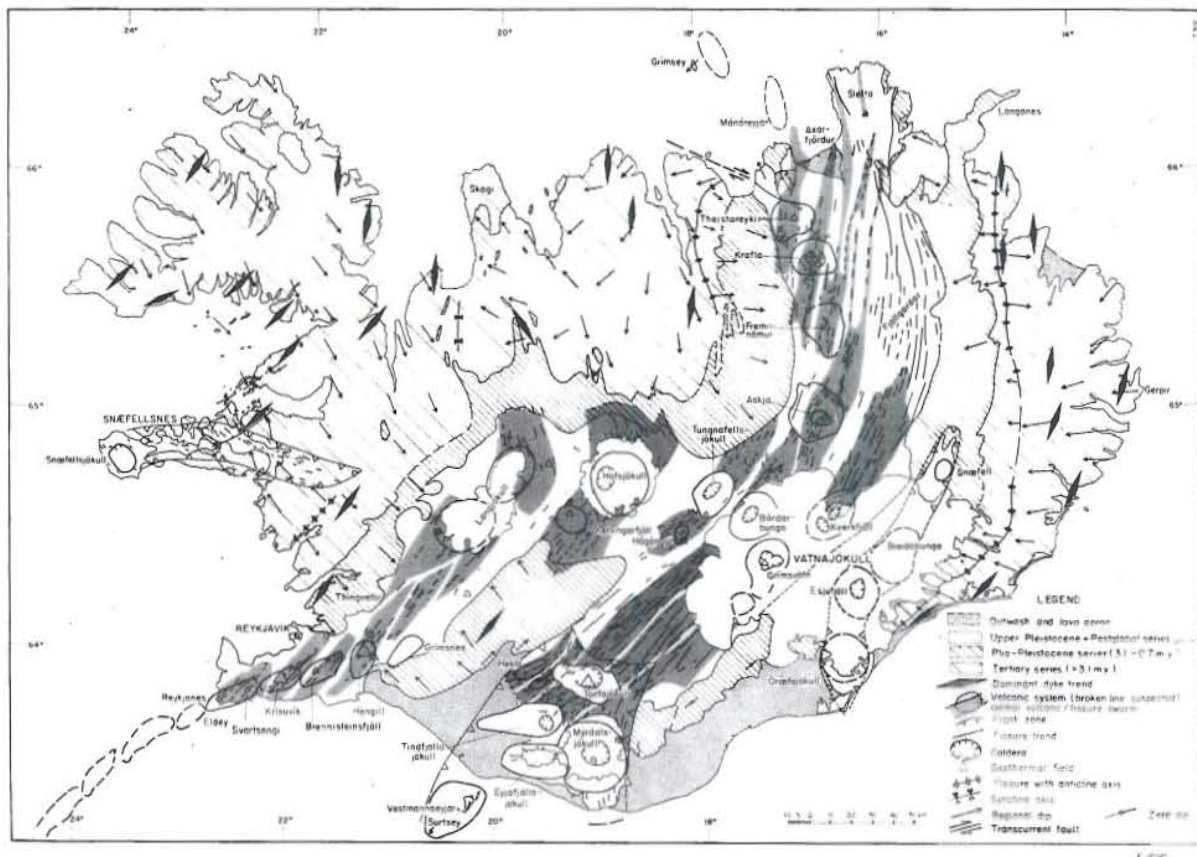

FIGURE 1: Geological map of Iceland (Saemundsson, 1979)

The geothermal areas in Iceland are divided into two distinct groups (Pálmason et al., 1979). The low-temperature areas are in Quaternary and Tertiary volcanics with temperatures of $\leq 150°C$ at 1 km depth, and the high-temperature areas are in the active neovolcanic rift zones with temperatures of $\geq 200°C$ at 1 km depth. The high-temperature areas are confined largely to the central volcanoes of the active neovolcanic rift zones, and are thought to draw heat mainly from local accumulations of igneous intrusions located at a shallow level in the crust (Fridleifsson, 1979).

1.3 Geology of the Krafla area

The axial rift zone in NE-Iceland is characterized by five sub-parallel volcanic systems, which are a part of the neovolcanic zone (Figure 2). The Krafla volcanic centre, situated northeast of Lake Mývatn is inside a 100 km long, NNE-SSW trending fissure swarm, which bisects the volcanic centre in the form of a graben. The geological features of the Mývatn region are mostly connected to the Krafla fissure swarm. The Krafla central volcano features a caldera which is considered to have formed during the last interglacial period about 115,000 years ago (Figure 3). Since then the volcano has been very active and virtually filled the caldera with eruptive products. The caldera filling is considered to be up to 1 km thick (while opinions differ on this) and is shaped like a reverse cone. Acidic volcanism was initiated during its formation, evident from an ashflow surrounding it and the rhyolite ridges in and near the eastern and western parts of the caldera rim (Jörundur, Hrafntinnuhryggur and Hlídarfjall). In the neovolcanic zone outside the caldera, the basalts are mostly of olivine normative composition but predominantly quartz normative inside the caldera. The dominant geological features inside it are hyaloclastite ridges, parallel to the fissure swarm and postglacial lava flows. Glacial alluvium are found close to the southern rim of the caldera and large areas of the surface are covered with pyroclastics, clay and mud from explosive craters. As shown in Figure 3, the geothermal area (15 km²) is located within the Krafla caldera (64 km²). The geothermal manifestations appear on the surface as mudpots and fumaroles, mostly connected to tectonic features like faults or eruptive fissures. The
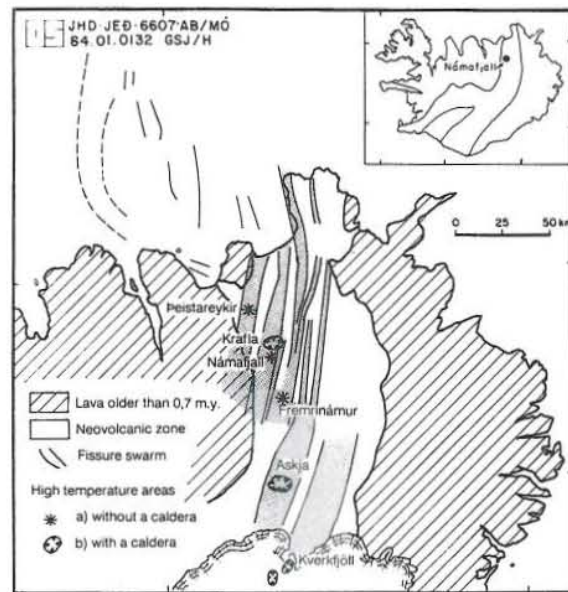

FIGURE 2: The central volcanoes and fissure swarms within the neovolcanic zone in NE-Iceland (Björnsson, 1985)
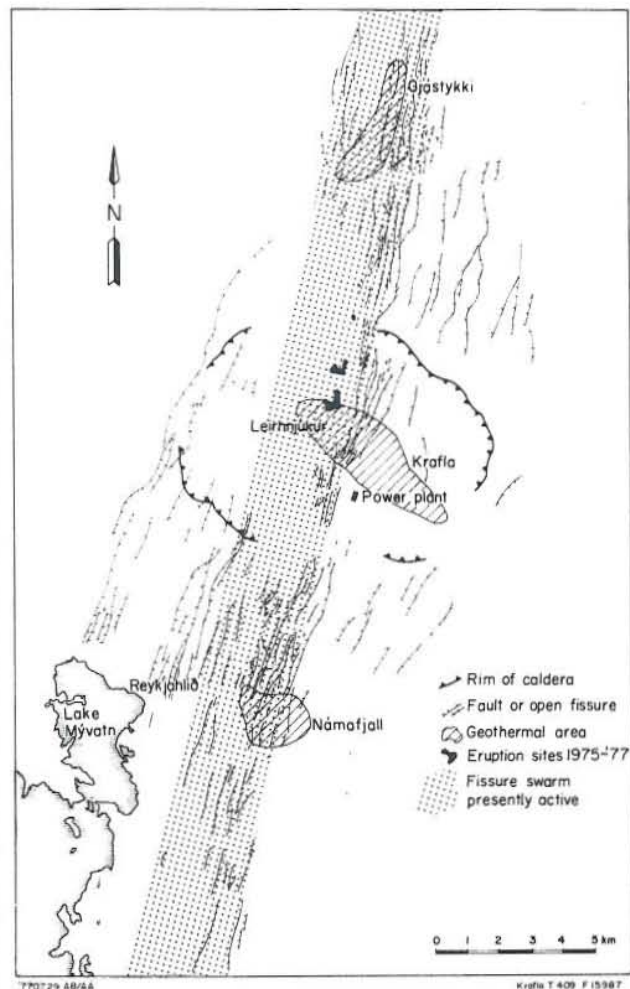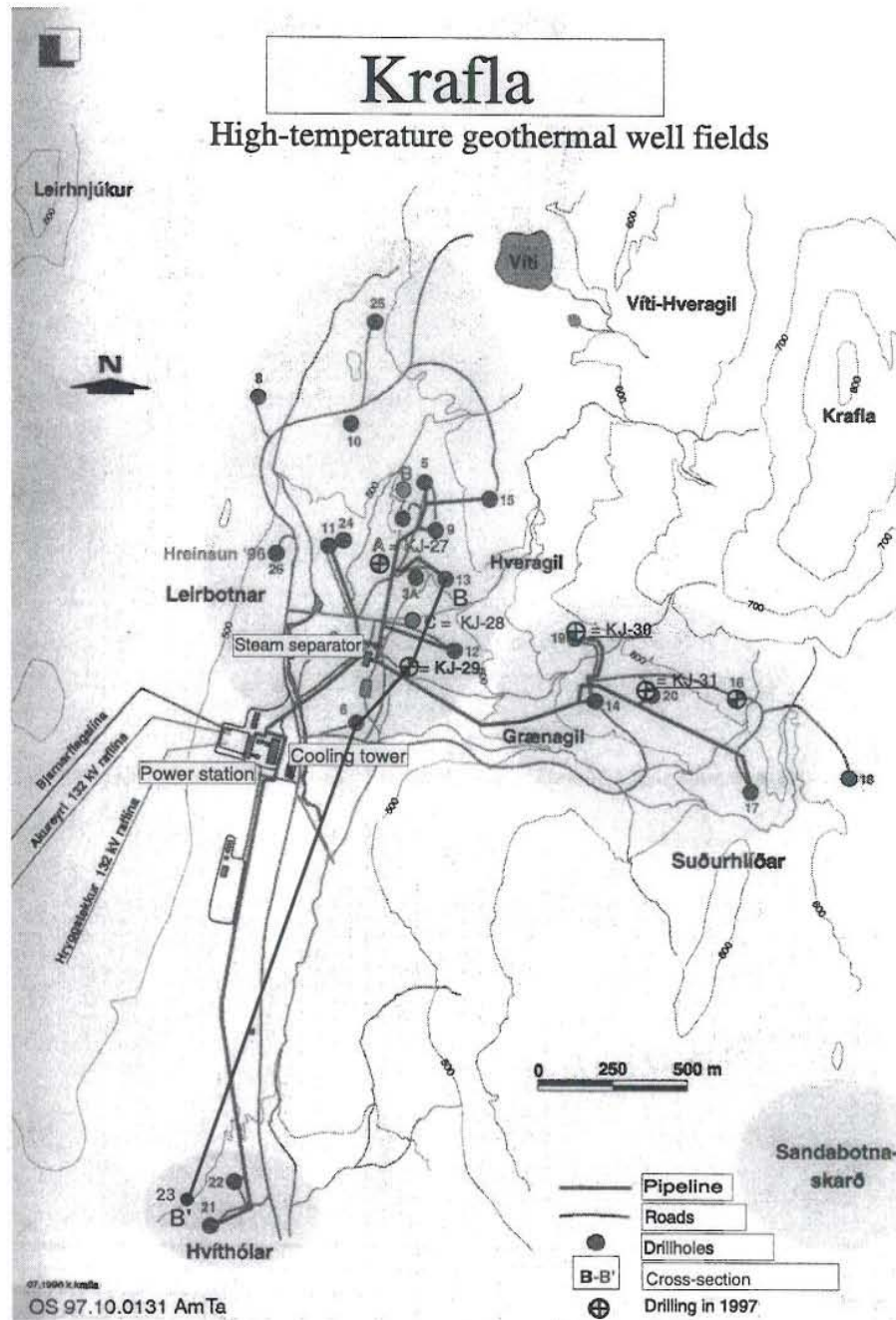

FIGURE 3: Structural map of the Krafla area, showing caldera, active fissure swarm, geothermal area and power plant (Stefánsson, 1981)

colourful soil also indicates relics of powerful geothermal surface activity. Hot springs are absent due to a low water table (Ármannsson et al., 1987).

Volcanic activity in the Krafla area is extensive and several eruptive periods are recorded during Holocene. The most recent volcanic episode started in late 1975, with nine eruptions taking place the last one in September 1984 (Björnsson, 1985).

1.4 The Krafla well fields

The exploration programme of the Krafla high-temperature area was initiated in 1970, and the first wells were drilled in 1974. To date, a total of 30 deep wells have been drilled to provide geothermal steam for the Krafla electric power plant, which is now under exploitation and development (Figure 4). A large part of the geothermal reservoir is close to boiling point and the maximum recorded temperature is 350°C at a depth of 2000 m. The Krafla drillholes are situated in three different fields, Leirbotnar, Sudurhlídar and Hvíthólar (Figure 4). They differ considerably in size, production and subsurface characteristics. Figure 5 shows simplified temperature-depth profiles for the three mentioned fields. The Leirbotnar field is divided into two distinct reservoir zones. The upper zone, which extends down to approximately 1 km depth, is water saturated with a mean temperature of 205°C. The temperature of the lower zone below 1 km

FIGURE 4: Location of the power plant, wells and three well fields at Krafla; location of cross section B-B´(Figure 11) is also shown

depth is in excess of 300°C and boiling conditions extend down below 2 km depth where the temperature is 350°C. The upper zone vanishes at the Hveragil gully. To the east in the Sudurhlídar field a boiling reservoir extends from the surface down to at least 2 km depth. In the Hvíthólar field, a boiling system extends from the surface down to 700 m depth. Below that the temperature drops fairly sharply to about 180°C where a deeper water-saturated zone is entered, increasing again to reach about 250°C at 1900 m depth (Ármannsson et al., 1987).

Numerical simulation studies of the present well fields indicate that they can sustain 60 MW electrical production for at least 30 years.

Well KJ-29 is located in the Leirbotnar field, about 500 m northeast of the power station and 150 m south of well KJ-28 (Figure 4).
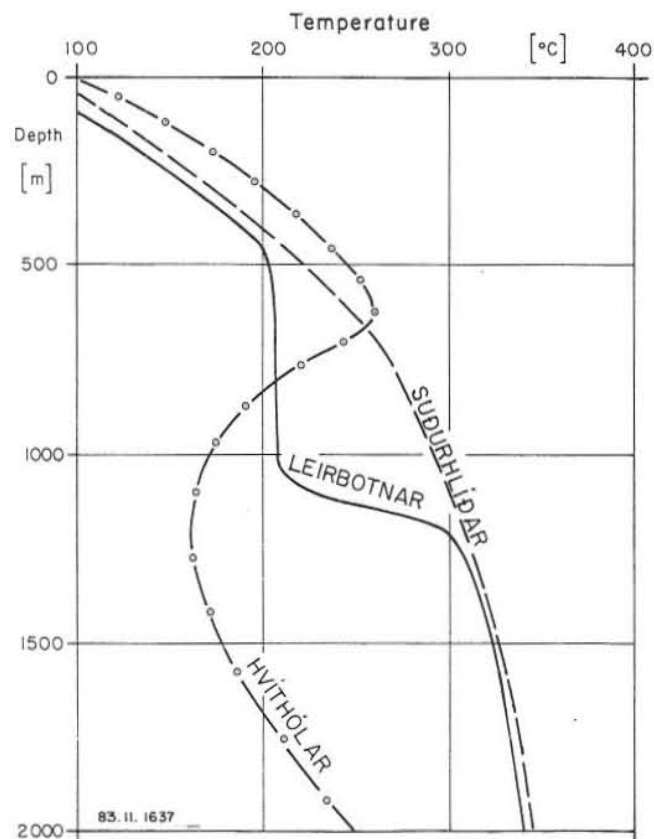
FIGURE 5: Typical temperature profiles for the three well fields at Krafla (Ármannsson et al.,1987)

2. BOREHOLE GEOLOGY OF WELL KJ-29

2.1 Introduction

Detailed cutting analyses along with various borehole logs were used to assess the borehole geology and geothermal system into which KJ-29 was drilled. During drilling, rock cuttings were taken regularly at 2 m intervals, collected in 100 ml boxes and properly labelled. The circulation fluid was monitored every four hours and under some circumstances more often. The penetration rate was calculated for every 1 m interval. Temperature logs were run during drilling to locate aquifers and to assess the condition of the well. After the drill string was pulled out of the borehole at the end of each drilling phase, geophysical logs including caliper, temperature, neutron-neutron, natural gamma, resistivity and pressure were done to evaluate the well. Regular temperature and pressure measurements were conducted during the warming-up period of the well.

The cuttings are a very reliable indicator of the thermal history of the reservoir. The samples from the field, after being properly logged, are transported to a petrographic laboratory. At the laboratory, the samples are air-dried for proper safekeeping and storage. Before cutting analysis, the samples in the boxes are washed and wetted by pouring water onto them to enhance visibility of the minerals and rock types. The wet samples are then placed under binocular microscope for investigation. Essential features and characteristics to be noted during binocular study are rock type, rock fabric, grain size, primary minerals, secondary minerals and alteration intensity, colour, presence of veins or vesicles, evidence of faulting, size and shape of drill chips, and type and amount of probable contaminants. Examination was

done using a Wild Heerbrugg binocular microscope with a magnification of 6-80x. Initial information obtained included stratigraphy, alteration mineralogy and evidence of permeabilities. In addition to binocular microscopic study, selected thin sections were made for petrographic study, in order to expand or confirm preliminary findings of the cuttings. Thin section samples were analysed using a Leitz Wetzlar petrographic microscope. Moreover, X-ray diffractometry analyses were done to confirm and identify the types of zeolites and clay minerals present in the cuttings.

All of the information gathered from cutting analyses and borehole measurements were combined and assessed to explain geological structures that control the movement of geothermal fluid in the reservoirs and to relate the hydrothermal alteration to the condition of the geothermal system into which the well was drilled.

2.2 Drilling of well KJ-29

Well KJ-29 is the 29th borehole which has been drilled in the Leirbotnar field (Figure 4). It was drilled to a depth of 2103 m (1632 m b.s.l.), and is located at 579223.25 N, 443181.38 E at an elevation of 471.05 m a.s.l. The hole was completed in 53 working days between 22nd April and 14th June 1997. First stage was percussion drilling with a 22" hammer down to 63 m depth and the well was cased off with a 18 5/8" surface casing and cemented. Then a larger drillrig was installed on the well. First it was drilled for safety casing down to 396 m with a 17 1/2" bit, and cased off to 388 m with a 13 3/8" anchor casing and cemented. Drilling was continued with a 12 1/4" bit down to 1004.6 m depth and cased off with a 9 5/8" production casing to 1000 m and the casing cemented. The production part of the well was finally drilled with a 8 1/2" bit down to 2103 m depth. Then a slotted liner was placed into the well down to 2083 m depth. Final depth and casing length are relative to the drillrig rotary table which is 6.87 m above the drilling platform.

The penetration rate, which shows speed of drilling, was monitored by a geolograph which is located at the rig and is a part of the drilling tools. Its range was variable due to differential lithology and change of weight on the drillbit. Drilling proceeded smoothly except for some minor water pump problems and loss of circulation. During drilling, the well inclination was monitored. The results are in Table 1.

TABLE 1: Drilling inclination of well KJ-29

Depth (m)	Deviation (°)
195	0.2
350	0
490	0.2
600	0.2
690	0.2
800	1
900	1

This production well, together with several other wells, was drilled to mine steam to increase the steam production for a second steam turbine of 30 MWe, presently being installed. The maximum rated capacity of 60 MWe in the Krafla power plant will be reached next year.

2.3 Stratigraphy

The majority of Icelandic volcanic rocks are basaltic which means that SiO_2 content is 45-52% by weight. Two types of basaltic rocks are distinguished. The first type, olivine tholeiite, commonly exhibits a sub-ophitic texture where the plagioclase laths are enclosed in patches of pyroxene. Pyroxene appears as aggregates rather than single crystals. The ore minerals are interstitial which implies later growth. This crystallization habit is characteristic of olivine tholeiite basalt whereas the second type, tholeiite basalt is generally fine- grained and has equigranular texture, with the ore minerals more or less evenly distributed within the rock. Certain lava types are characteristic for distinct types of lava morphology. Thus, the olivine tholeiite eruptions often produce lava shields which are seen in the lava pile as thick pahoehoe flows whereas olivine-poor tholeiite is characteristic of fissure erupted aa lavas.

The hyaloclastite formations were formed under an ice sheet as a result of the quenching of magma in water. It consists, consequently, of a mixture of vitroclastic glass and partially crystalline basalt. The hyaloclastite unit is divided into three lithological types. The first type, the hyaloclastite tuff, is predominantly composed of volcanic glass. The second type is the hyaloclastite breccia made up of similar amounts of glass and partially crystallized basalt. The third type is the basaltic breccia (pillow lava) which consists of partially crystallized basalt in majority with lesser amount of glass. Petrographically, the hyaloclastite unit shows a similar grading in crystallinity from pure vitroclastic near opaque glass to holocrystalline basalt, the latter mostly of granular texture and only rarely showing sub-ophitic texture.

These three lithological types of hyaloclastites vary in appearance from one depth to the next upon increased alteration. The hyaloclastite formations occur commonly as heaps, ridges or clastic sediments close to their vents (Kamah, 1996).

Intrusive rocks of basaltic composition are common, and are both of olivine tholeiite and tholeiite composition. Commonly they are coarser grained than the lavas of the same composition, due to slower cooling. Narrow intrusions may still be fine to medium-grained. They have often intruded sub-vertically into the hyaloclastites. It can sometimes be difficult to distinguish between lavas and intrusions in drill cuttings, but one of the criteria used is the apparent freshness of the intrusive rocks as compared to the surrounding volcanics. This usually relates to lower porosity, lower permeability and younger age of the intrusive rocks. Figure 6 shows a simplified stratigraphic column and the penetration rate of well KJ-29 along with the geophysical logs.

The volcanic rock formations in well KJ-29 are divided into two main groups, extrusive and intrusive rocks.

2.3.1 Extrusive rocks

Extrusive volcanic rocks of subglacial hyaloclastites and subaerial basaltic lavas comprise the upper part of the well down to about 990 m depth. Intrusive rocks found in the well are treated separately. It appears that the extrusive succession is composed of five different hyaloclastite series and one intervening lava series, based mainly on the lithological differences (Figure 6). The main characteristics of the series are described below:

Hyaloclastite series-1 (<100 m). On the surface, the ground is covered with soil and some outwash deposits from craters and bedrock near the well. This formation probably extends from the surface down to about 100 m depth. No cuttings are available down to 60 m depth. The rest is mostly composed of vesicular aphyric tuff. In the upper part down to 68 m depth, the sedimentary tuff is mostly partially
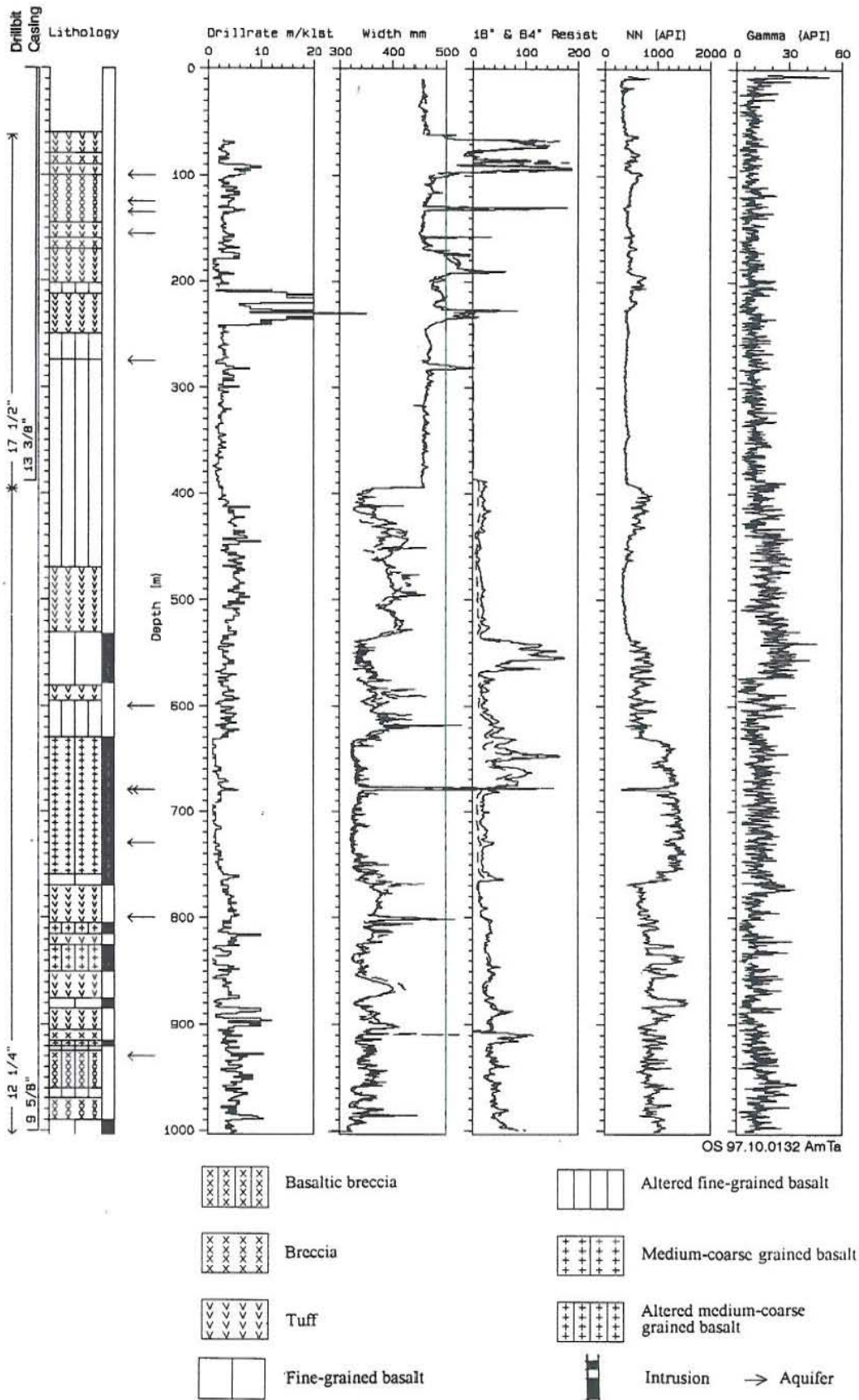
FIGURE 6: Simplified stratigraphic column, location of aquifers and geophysical logs
of well KJ-29, Krafla

crystallized, but below that depth it is intercalated by a partially crystallized breccia. There is little fresh glass left in the samples and the intensity of alteration is noteworthy greater than in the lower series. Veins and vesicles are mostly filled with calcite. This reworked hyaloclastite formation shows, in parts, a crystallization with sub-ophitic texture corresponding to olivine tholeiite composition.

Hyaloclastite series-2 (100-202 m). This formation is plagioclase porphyritic, and consists of tuff, breccia and basaltic breccia. It is quite vesicular and mostly unaltered. Some samples show sedimentary textures. Oxidation in the deeper part is insignificant. Some veins of quartz, calcite and zeolite are seen. Fine-grained crystallization is seen in some thin sections, suggesting an olivine tholeiite composition.

Hyaloclastite series-3 (202-274 m). This vesicular hyaloclastite unit consists of tuff and breccia in the middle part, but has, respectively, 10 m and 24 m thick fine to medium-grained basaltic lavas in the upper and lower parts. It is aphyric and, thus, distinct from the porphyritic formations above and below. The clay minerals differ from those above both in colour and crystallinity. Oxidation is widespread. Relics of the original texture of the volcanic glass can still be seen in the replacement clay. Vesicles are filled with calcite, quartz, mixed layer clays and chalcedony lining, whereas veins are mostly filled with calcite, quartz and zeolites. The basalts are sub-ophitic olivine tholeiites.

Basaltic lava series (274-470 m). This series consists of fine to medium-grained basalt. It is intercalated with thin breccias and basaltic breccia lavas in the lower and upper parts. The lavas are all plagioclase porphyritic, and quite vesicular. They are highly altered and extensively replaced by calcite. Platy calcite is relatively abundant. Some oxidation is seen. Veins and vesicles are filled with quartz, calcite, pyrite and fine-grained clay. Intensity of alteration in the 380-420 m depth interval is relatively low. The anchor casing shoe was placed in the middle part of this interval. Thin sections at 308 and 340 m depths show sub-ophitic olivine tholeiite, at 370 and 380 m show both tholeiite and olivine tholeiite composition and at 406 and 440 m, the rocks exhibit equigranular tholeiite basalt texture.

Hyaloclastite series-4 (470-630 m). This formation is mostly composed of vesicular aphyric tuff probably a tholeiite, which partly exhibits sedimentary textures and clay pseudomorphs after glass. The rock is greenish grey to light brown in colour, due to the variable glass alteration. The hyaloclastites are intruded by several thin intrusions, and a few medium to coarse-grained basaltic lavas are analysed from the deepest part. Pseudomorphed zeolites and chalcedony are also seen in thin sections. Alteration is widespread. Veins and vesicles are mostly filled with quartz, calcite and pyrite. Pyrite deposition is heavier than elsewhere. Very nice bladed calcite intergrowth within a large wairakite crystal is found in the cuttings at 588 m depth.

Hyaloclastite series-5 (770-990 m). This series consists mostly of vesicular tuff and breccia with several intrusions, and a few basaltic lavas in the lower part. It is distinctively plagioclase porphyritic and has suffered intense alteration. Epidote, prehnite, actinolite, wollastonite and probably adularia all appear in this series. Oxidation is pronounced. Vesicles are filled with quartz, calcite, chlorite and sometimes epidote, wairakite, prehnite and pyrite. This hyaloclastite formation exhibits, in some portions, crystallized growth of groundmass plagioclases, characteristic of olivine tholeiite composition.

The extrusive succession depicts, as mentioned earlier, two types of environments, subglacial hyaloclastites and subaerial basaltic lava formations. The approximate geological time scale of the succession is such that the upper hyaloclastite formation (series 1 to 3) may date from the last glacial period. Below that is a basaltic lava formation probably dating back to the last interglacial period (~115,000 years ago). It is underlaid by the second hyaloclastite formation (series 4,5) which some believe was also formed within the Krafla caldera, while others believe it is from the 2nd last glacial period (~ 200,000 years ago). Below this depth, the lower hyaloclastite formation is followed by basaltic and doleritic intrusions which dominate the strata down to the bottom of the well (2103 m depth). They have intruded extrusive successions of earlier glacial and interglacial periods, but will not be dealt with any further in this report, apart from a general discussion in Section 5.

2.3.2 Intrusive rocks

Intrusive volcanic rocks of the well are younger, less altered, darker coloured and coarser grained than the surrounding extrusive rocks. They occur mostly at three different depth intervals.

Intrusive rocks at 520-600 m. These are about 9 separate thin intrusions in the hyaloclastite tuff. They are fine to medium-grained, relatively fresh looking basaltic intrusions. Thin sections from 542 and 558 m depth show intense veining with abundant pyrite, quartz and calcite infillings.

Intrusive rocks at 630-770 m. This intrusive unit is continuous, except for a few very thin layers of tuff or breccia. It is composed of medium to coarse-grained basalt referred to as dolerite, which is fine-grained at the margins. It seems to be both plagioclase and pyroxene porphyritic. The intrusion is mostly unaltered except in heavily veined intervals with high grade alteration. The veined intervals seem to match with the location of aquifers, as seen from circulation loss at around 680 and 730 m depths. Some veins are filled with quartz, calcite, pyrite, anhydrite and clay minerals. Crushed cutting fragments are relatively abundant because of the hardness of the intrusion. The intrusion is probably equigranular tholeiite, except in the 760-770 m depth interval which is a separate fresh, medium-grained olivine tholeiite.

Intrusive rocks at 805-1000 m. Several thin intrusions occur in the hyaloclastite formation at this depth interval. Some are highly altered, medium to coarse-grained, whereas others are mostly fresh, fine to medium-grained basalts. Quartz, calcite, pyrite, chlorite and epidote veinings are also seen in deeper intrusions. Crushing of the cuttings is common due to hardness of the intrusive rocks. Oxidation is relatively widespread at the margins of the intrusions. The intrusive rocks exhibit both equigranular tholeiite and sub-ophitic olivine tholeiite composition, and some are slightly porphyritic as well.

The intrusive rocks appear to be of at least two different ages. The older ones are more altered, medium to coarse-grained basalt intrusions, whereas the younger comprise fine-grained basalts markedly less altered.

2.3.3 Comparison with geophysical logs

Geophysical logging during drilling of a well is made firstly for operation and control of the well, and secondly in order to obtain information on the structure and the physical properties of the geothermal system penetrated by the well, regarding both the rock formations and the geothermal fluid (Stefánsson and Steingrímsson, 1980).

Geophysical logs of well KJ-29, as seen in Figure 6, include caliper and lithological logs of resistivity, neutron-neutron, and gamma ray, while the penetration rate is monitored by a geolograph during drilling and is shown for comparison. In the upper part of the well where the borehole diameter is 17 1/2", correlation between lithological logs and lithology of the well is poor, due to sensitivity of the logging tools to hole diameter. But in the lower part (>396 m) with a 12 1/4" well diameter, reasonable correlation can be made.

Natural gamma ray log reflects the chemical composition of the rock (sensitive to ^{40}K, U, Th), and is specially used for detecting acid rocks. The log of KJ-29 does not show high values, meaning that there is no acid rock in the well.

Neutron-neutron log gives information on the porosity of the rock. It is an indirect measure of the H_2O content in the rock formation, and, therefore, high amplitude reflects dense rock with low water content. It shows high values at the 630-770 m depth interval which matches with a dense thick intrusion, except for 680 and 730 m depth where aquifers occur.

Resistivity log reflects porosity of the rock, salinity and temperature of the fluid. Therefore, resistivity is high alongside the dense intrusive rocks, but low in porous hyaloclastites and aquifer zones within the well.

Caliper log, which shows the diameter of the well, is necessary for correcting lithological logs. It investigates soft formations or cavities in the well, and may be used to locate intrusive contacts and fractures, e.g. at 600, 680 and 800 m depths.

One of the most important uses of geophysical logs is locating aquifers, discussed further in Section 4.

3. HYDROTHERMAL ALTERATION IN WELL KJ-29

The hydrothermal alteration is a product of water-rock interaction, depending on the rock type, composition of the fluid, duration, temperature and pressure. The environment of the geothermal system can be assessed on the grounds of present hydrothermal alteration suites or mineral alteration assemblages in a rock formation. These hydrothermal mineral suites are useful in the interpretation of the thermal history of the area and, in general, alteration minerals can be used as an indication of the physico-chemical conditions of the geothermal system (Reyes, 1990). For example, the hydrothermal mineral assemblages can be used as geothermometers; they can help in deciding the minimum depth of production casings; they can be used as indicative of scaling or corrosion tendencies; they can be suggestive of high or low permeability and, in general, give guidance to hydrological conditions in the past as well as the present.

3.1 Analytical techniques

The study of hydrothermal alteration of the formations penetrated by drillhole KJ-29 involved three main techniques as follows:

1) The stereo-binocular microscope;
2) The polarized-petrographic microscope;
3) The X-ray diffractometer.

The binocular microscope is an important analytical instrument in drill cutting analysis, and is simply a proper magnifying glass. It is commonly the only research tool used during drilling to collect information on the rock formation, helping to make decisions such as the depths of the casings, predicting loss zones, or deciding final drilling depths. A number of hydrothermal minerals have been found to indicate a particular formation temperature in Iceland. Wairakite, for example has been very useful in determining casing depth, especially in high-temperature areas. During the present study, the cuttings (470 samples) were studied with this technique in great detail to carry out a more detailed work on the rocks and minerals in thin sections and to pick out some alteration minerals for XRD analysis.

The petrographic microscope is a useful instrument in the study of drill cuttings in thin sections. Microscopic study of drill cuttings is a part of the geological and mineralogical research which aims towards a more thorough geological understanding of geothermal reservoirs. The essential use of this microscope relates to the small size of the primary and secondary minerals in the rocks. The petrographic microscope may thus be used to:

1) Determine the rock type in more detail;
2) Identify additional primary and secondary minerals;
3) Study the type of replacement mineralogy;

4) Study the sequence of secondary mineral evolution, especially in veins and vesicles;
5) Study textural features like the partial pseudomorphism of early secondary minerals by later minerals.

Some minerals cannot be identified under the polarizing microscope. Included in this group are iron ore minerals which need to be studied in a polished section and by reflected light microscope (not applied here). However, an idea of the relative ore composition can be formed by using an external light source and the reflection properties of the ore. In the present study, 35 thin sections of borehole KJ-29 were selected and used.

The X-ray diffractometer (XRD) is mostly used for identifying clay minerals and for cross-checking observations made under both the polarized and binocular microscope, especially where zeolites and other white minerals could not be identified individually. For instance, this technique was employed to confirm the presence of wairakite in this well at a depth as shallow as 76 m as is discussed later. In this study, 26 samples of zeolites and other alteration minerals were selected and run. The zeolites identified by this technique were stilbite, stellerite (a variety of stilbite), heulandite, analcime, chabazite, scolecite/mesolite, wairakite, mordenite, laumontite. The characteristic peaks for stilbite, scolecite, analcime and chabazite occurring together at 108 m depth are shown in Figure 7. While only a fair picture of the different clay minerals can be obtained from both the binocular and polarizing microscopes, especially on the basis of colour and relative grain size, a more accurate identification and classification of them is possible with the help of the XRD. In this study, 25 runs of clay minerals were performed and identified. The standard methods of sample preparation, both for zeolites and clay minerals treated under the X-ray diffraction, are discussed in the Appendix.

The result of XRD analysis is most important for interpreting the rock formation temperature when referring to mineral alteration. It also provides fundamental data for the construction of alteration zones.
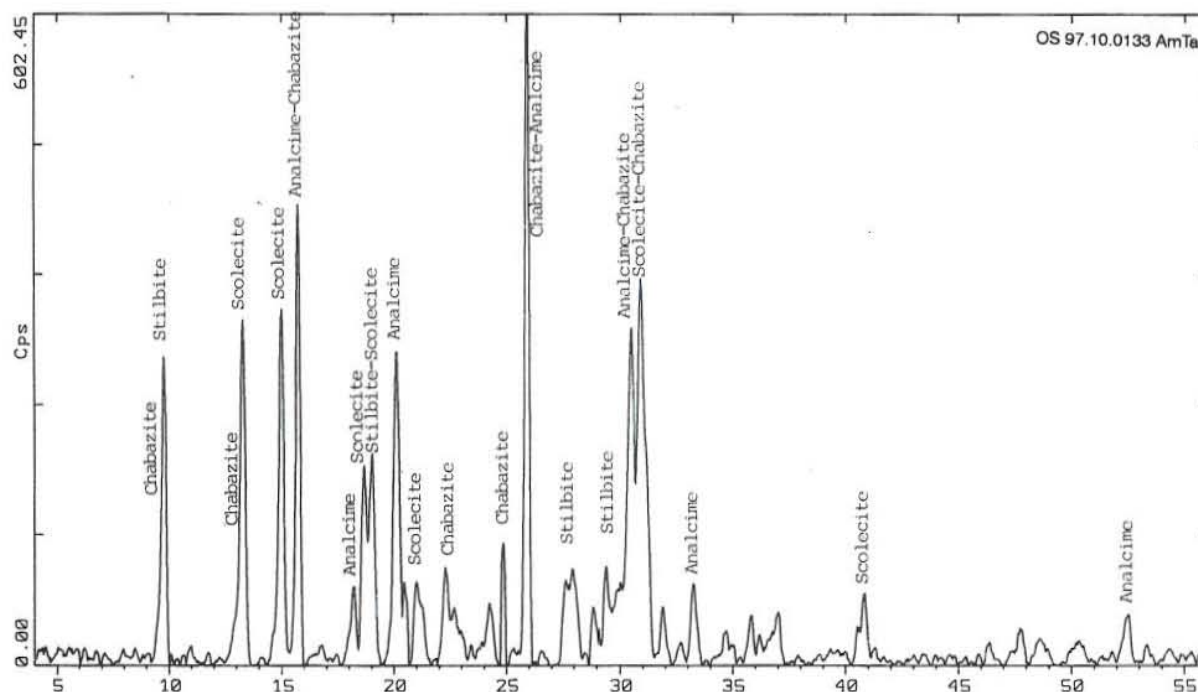

FIGURE 7: Characteristic XRD patterns for some zeolites found at 108 m depth in well KJ-29

3.2 Rock alteration

The primary mineral constituents of basalt are olivine, pyroxene, plagioclase feldspar (higher in Ca) and iron ore minerals like magnetite and ilmenite. Glass is also commonly found, formed during the rapid quenching of magma. Under the influence of hydrothermal fluids, the above constituents undergo transformation in an incipent, partial or complete manner in response to a changing alteration environment. The grade of preservation of primary textures is a function of formation permeability and the type, abundance, and grain size of primary minerals (Lonker et al., 1993). The alteration products of primary minerals are as follows:

1)   Glass alters mostly to clays, titanite, epidote or calcite;
2)   Olivine alters to iddingsite or clays, titanite or calcite;
3)   Pyroxene alters mainly to clays, it is relatively resistant to hydrothermal alteration;
4)   Plagioclase is also relatively resistant to alteration but the first indications of alteration are tiny fractures filled with clay at temperatures of about 200°C and deeper down albite is seen to replace it. Later on calcite, titanite, chlorite, epidote, adularia and quartz appear. Wairakite is a common replacement mineral of plagioclase phenocrysts;
5)   Iron ore minerals alter mainly to titanite and sulfides (usually pyrite and pyrrhotite).

In general, the order of susceptibility to alteration is glass, olivine, plagioclase and pyroxene. In well KJ-29, glass is mostly altered from the top to around 102 m. Fresh glass occurs in the 102-172 m depth interval. Deeper down it is again mostly altered. Calcite and mainly clay minerals are the most common replacement minerals of the glass in this well. Olivine is also mostly altered from the top of the well, the alteration commonly developing from diagonal fractures into green coloured clay minerals. They are normally smectites which then convert to higher-grade clay minerals with increasing temperature and depth of burial. Pyroxene is the mineral most resistant to alteration. It is observed to develop a cloudy rim at the edges and starts to disintegrate at around 600 m depth. In the plagioclase phenocrysts tiny clay fractures start to form at 108 m depth thin section. But albitization of plagioclase laths first appears at higher temperatures, at around 230 m depth. In a thin section from 270 m depth, plagioclase was altered mainly to calcite. It is altered to quartz, wairakite and epidote in the deeper parts of the well. Iron ore minerals were first observed to alter to titanite at 210 m depth. It was recognized by a reaction rim at the edges which displayed yellow to reddish brown colours.

3.3 Distribution of hydrothermal alteration minerals

The occurrence and distribution of hydrothermal alteration minerals along with the simplified stratigraphy of well KJ-29 are shown in Figure 8. The entire depth penetrated by the drill hole is characterized by the presence of clays, calcite, quartz, pyrite, and zeolite. Other minerals occur less abundantly. The secondary minerals occur as replacement minerals, vein fillings along fractures and disseminations, e.g. pyrite in the groundmass. Clays are common as alteration products of volcanic glasses. Calcite showed the widest range of occurrences in fractures, as void fillings, or as an interstitial replacement mineral. Quartz was typically observed as a secondary vein mineral and cavity fillings. Pyrite is widespread, disseminated in matrices and veins and sometimes also the major sulphide in quartz veins. A brief description of each mineral is outlined below.

Calcite is the most common alteration mineral with a formation temperature extending up to 270°C (Kristmannsdóttir, 1978). However, its formation depends essentially on how the interplay of temperature, load pressure, and concentration of free CO_2 in the solution affects the solubility of calcite and also on the availability of Ca^{2+} ions in the solutions (Steiner, 1977). Calcite in well KJ-29 showed a wide range of occurrences especially among the hyaloclastites but less in denser holocrystalline basaltic
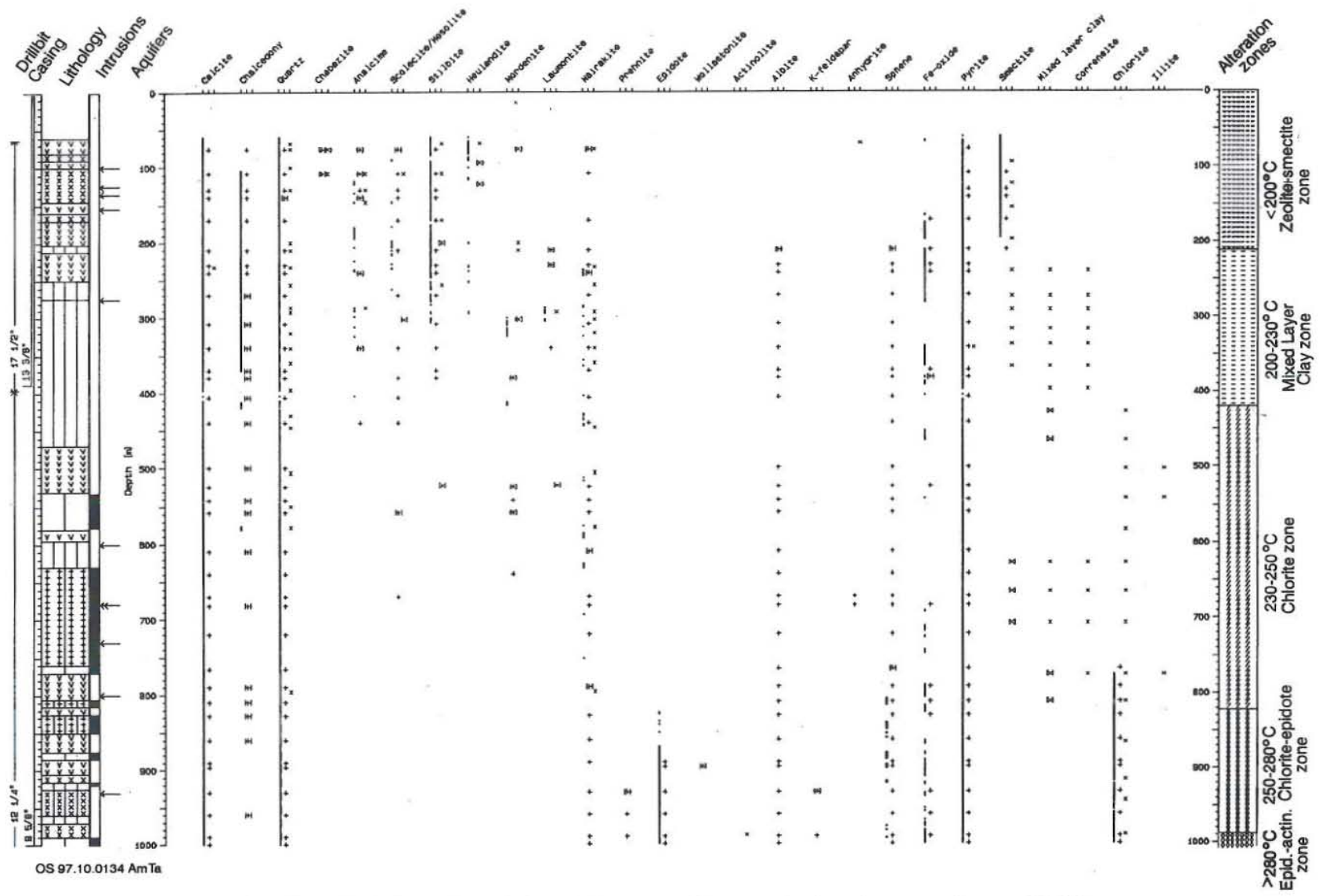
FIGURE 8: Lithology, distribution of alteration minerals and alteration zones in well KJ-29
(analytical methods: • Binocular, + Petrographic microscope, × XRD)

lavas and intrusions. The calcite observed is generally of two types, a normal rhombohedral calcite, or with a bladed morphology, commonly called "platy calcite". The first type is usually indiscriminately distributed in the interstitial pore-spaces of the rock matrix and cavities, whereas platy calcite was observed filling up fractures and as intergrowth with other minerals. The presence of the bladed morphology is probably an indication of a zone of boiling and is observed sporadically from 290 to 630 m depth and abundantly at 680 m depth in a fractured intrusion. Thin sections from 370, 406, 440, 500, and 810 m depth show an extensive calcite replacement of the rock, where calcite is also the most abundant vein and vug mineral. Calcite disappears at greater depth than around 1000 m, where the production casing shoe was placed. In XRD, calcite shows typical peak values at 3.03, 2.28, 2.09 and 1.87 Å.

Chalcedony is a secondary mineral in the cavities of igneous rocks, sometimes only lining the walls of the vesicles. It is often associated with quartz, clay and zeolites. In thin sections it ranges from being colourless to pale bluish milky colour and often exhibits a spherulitic form. The temperature range of chalcedony seems to be lower than that of quartz. In this well, chalcedony is relatively common between 102 and 240 m depth but is seen less from there down to about 370 m depth. Deeper down it shows pseudomorphism and has transformed into quartz but is recognized by its constant thickness on the wall of the vesicle.

Quartz is seldom found as groundmass alteration but is rather abundant as open-space fillings, often as crystal growth in the clay-lined or calcite-filled vesicles or as an intergrowth with calcite. Quartz replaces chalcedony at higher temperatures. It is also seen as a replacement mineral in plagioclase. In XRD, it shows typical peaks at 3.35, 4.25, 3.34, 4.24, 2.46 and 1.82 Å. Quartz was first observed in this well in the XRD run of 68 m depth and continued down to the bottom of the well. It occurs as small, euhedral prismatic crystals in the upper part of the well, but large crystals are found at greater depth especially in vugs associated with wairakite. In the deeper part, quartz is seen to replace zeolites, in response to increased temperature.

Zeolites are hydrated calcium aluminum silicates that commonly occur as secondary minerals in rock cavities, especially basalt (Kerr, 1959). They are widespread as fillings between 60 and 410 m depths, but rare in the lower part of the well, except wairakite. There, one may see pseudomorphs of the low-temperature zeolites, which are replaced for quartz, wairakite or other minerals. Zeolites are often associated with calcite, quartz and, rarely, with pyrite. There are three dominant groups of zeolites identified by XRD, binocular and petrographic analysis. These groups are the scolecite-mesolite group (T= ~70°C), the heulandite-stilbite group (T= ~90°C) and the mordenite-laumontite group (T= 100-200°C). Wairakite (>200°C) is the highest temperature zeolite and continued down to the deeper parts of the well. The following zeolites were found in the well:

> **Chabazite** in cuttings, is recognized in vesicles by its euhedral crystals that approach the cube. It is restricted to 76 and 108 m depth of this well identified by thin section study and XRD analysis. Characteristic peaks at 9.4, 4.32 and 2.93 Å distinguish it from other zeolites.
> **Analcime** is found in this well from the top to around 440 m and in deeper parts wairakite predominates. The main XRD characteristic peaks of analcime were at 3.43 and 5.61 Å, and smaller peaks at 2.93 and 4.85 Å were identified distinctly in the 108, 146 and 286 m depth samples. The crystal is isotropic.
> **Scolecite/Mesolite** appears sporadically from 76 to 406 m depth, found in cavities and vesicles. It had a tiny fibrous structure under the binocular and petrographic microscope. Peaks at 6.64, 4.44 and 2.89 Å are characteristic for this mineral by XRD. In thin section from 108 m depth, some parts of scolecite are replaced by stilbite and partly altered to quartz.
> **Stilbite** under the petrographic microscope shows sheaf-like aggregates. The crystal has parallel extinction. It exhibits white tabular and radial form with lustre reflection in binocular

microscope. Stilbite is the most abundant zeolite in this well in the depth range of 66-380 m. At greater depth, it is replaced by quartz. The predominance of stilbite over heulandite in this well was proven by XRD and a thin section study. In XRD, it commonly peaks at 9.15, 4.06, 3.74, 3.42, 3.19 and 3.04 Å. Stellerite, a Ca-rich stilbite in shallower samples, showed better match in XRD peaks.

Heulandite is recognized by its distinct tabular crystals. It shows characteristic XRD peaks at 9.07, 4.66, 3.96, 3.42, 3.19, 3.04 and 2.7 Å. Heulandite is found from the top of the well (66 m) and continues rarely in the upper hyaloclastite series.

Mordenite shows an irregular very tiny fibrous form under the petrographic microscope. It gives the main peak at 9.10 Å, but smaller peaks at 13.7, 6.60 and 4.00 Å also occur. It is found distinctly at 200 and 210 m depth and probably also at 76 and 302 m depth by XRD. It exists sporadically in trace amounts deeper down to 640 m depth, proven by petrographic microscope study. At 542 m depth it occurs as pseudomorphs, replaced by quartz, calcite, and pyrite.

Laumontite has a prismatic and fibrous structure and is mainly found as cavity fillings. In hand specimen it is a very soft mineral which is easily crushed between two fingers. Laumontite is seen sporadically from 210 to 340 m depth. In XRD, it gives the main peak at 9.49 Å, but smaller peaks at 6.84, 4.15 and 3.5 Å are seen at 292 m depth.

Wairakite, the Ca analogue of analcime is found from the top (76 m depth) of KJ-29 and continues almost to the bottom of the well (1000 m). It is recognized distinctly by three analytical techniques. In cuttings, it exhibits a cloudy appearance due to the high abundance of fluid inclusions. At greater depth, typical igloo-shaped crystals occur. It is mostly found together with quartz as open-space fillings. In a thin-section study, it is recognized by a dull colour and the characteristic cross-thatched twinning similar to the polysynthetic twinning in plagioclase. In XRD analysis, it is detected by the typical peaks at 5.58, 3.41, 3.39 and 2.91 Å which distinguishes it from analcime, its Na analogue.

Prehnite in thin sections is colourless, shows no pleochroism and a typical bow-tie structure. It indicates high-temperatures (>200°C). Prehnite is recognized in thin sections from 930, 960, and 990 m depths together with epidote, inside vesicles of hyaloclastite tuff and breccia.

Epidote is used as an index mineral in high-temperature geothermal systems, indicating temperatures above about 250°C. It is identified in the stereo-microscope by its yellowish green colour and acicular euhedral crystals, first seen at 822 m depth, but continuously below that depth. Sometimes it is very abundant, possibly related to aquifer zones. In thin sections, it first appeared at 890 m depth with characteristic greenish yellow colours in plane-polarized, high pleochroism and high relief, and showed very strong colours in cross-polarized light. Epidote usually occurred together with chlorite, calcite, quartz, wairakite and prehnite in vesicles, and was also observed as a vein mineral. The grain size and degree of crystallinity of epidote was seen to increase with depth. Replacement of plagioclase phenocrysts by epidote is common as well.

Wollastonite first seemed to appear at 896 m depth. It exists with certainty from 1350 m depth, below the disappearance depth of calcite (supervisors pers. com.). It is identified by its colourless and fibrous aggregate form radiating outwards in close association with epidote. Wollastonite is mostly recorded as a contact metamorphic replacement of calcite and quartz, near dykes intruding the geothermal system. It appears to form hydrothermally at rock temperatures near to and above 300°C (Kristmannsdóttir, 1978).

Actinolite was detected by XRD technique together with chlorite at 988 m depth. It showed a constant typical peak of 8.5 Å in all untreated, glycolated and heated clay specimens. The first appearance of actinolite is set at approximately 280°C, while it becomes quite common at temperatures above 300°C (Fridleifsson, 1991).

Albite was observed in partially altered plagioclase in all thin sections from 230 m depth down to the bottom of the well (1000 m). It is found in basaltic rocks as an alteration product (replacement) of the Ca-rich plagioclase (labradorite), and indicates rock temperatures above 200°C. The only technique used for recognization of albite was petrographic microscope. It was recognized by its lower refractive index than balsam and its extinction angle that is near to parallel. Albitization in this well occurred partially in plagioclase from approximately the same depth, as mixed layered clays became the dominant sheet-silicate.

K-feldspar is much more abundant in acidic and intermediate rocks than basaltic rocks. In this well, adularia (a relatively low-temperature hydrothermal variety of K-feldspar) was recognized in thin sections at 930 and 990 m depth. It shows colourless diamond-shaped crystals that form at temperatures above 200°C. In New Zealand it has been used as a good indicator of high permeability (Browne, 1978). In well KJ-29 it occurs in the aquifer zone at 930 m depth.

Anhydrite is found sporadically in geothermal areas with non-saline fluids. It was recognized in thin sections at 670 and 682 m depth, by its typical perpendicular cleavage which distinguishes it from calcite. Anhydrite was detected also at 70 m depth by XRD technique by its main strong peak at 3.49 Å.

Titanite (Sphene) is generally formed as a replacement mineral of opaque minerals (magnetite-ilmenite), but sometimes as a replacement of glass, pyroxene and plagioclase. It was identified in petrographic microscope, by its greenish brown and somewhat cloudy coloured crystals but in binocular microscope, showed light grey colour like calcite. It was observed in all thin sections from 230 m depth down to the bottom of the well (1000 m) from the same depths as albite occurs.

Fe-oxide, usually limonite, appears as a replacement product of opaque minerals like pyrite or magnetite, but is also found deposited in vesicles. It is reddish brown in colour. Sometimes it was seen in smaller amounts because of contact with drill-pipe iron chips. It first appeared at 65-66 m depth but disappeared until 174 m depth and was then observed virtually throughout the well, with intensities varying with depth. Its presence in large quantities indicates that the rock may have at some time been in contact with oxygen-rich groundwater.

Pyrite is the most common iron sulfide occurring as disseminations and fracture-fillings. It is very common in this well from the top (60 m) down to the bottom (1000 m) together with calcite and quartz. Pyrite forms as a deposition, or as a replacement mineral of opaque minerals. Relative abundance of pyrite has turned out to be very useful in assessing permeability in Icelandic hydrothermal systems and to identify past to present aquifer zones. Under a binocular microscope, it is easily identified with its distinctive brass yellow colour and metallic luster. It is common as euhedral crystals, often as cubes or with rectangular, triangular or even hexagonal outlines. Under oxidizing conditions, pyrite may be altered to limonite. An increase in the proportion of pyrite in the groundmass was observed, as well, in the quartz and calcite veins at 536-544 m depth and at 680 m depth, related to intrusions.

The sheet silicates or **clay minerals** are the most common and voluminous group of minerals formed by geothermal alteration. They replace basalt glass, olivine, and partly plagioclase and pyroxene. The clay minerals found in this well include smectites, predominantly saponite, mixed layer clays, swelling chlorite (corrensite), chlorite and illite. A detailed study of clay minerals as well as their relationship to other alteration minerals can be very useful in the interpretation of the thermal history of a geothermal area (Kristmannsdóttir, 1978; Elders et al., 1979; Reyes, 1990). Twenty-five samples were selected for analysis, all limited down to the 1000 m depth of the well. The results are shown in Table 2. The clays in this well showed textural generation from fine-grained to coarse-grained with increasing depth. This textural evolution is suggestive of increasing temperature with depth.

TABLE 2: The X-ray diffractometry results for clay samples in well KJ-29

Depth (m)	Untreated d (Å)	Glycolated d (Å)	Heated d (Å)	Result
94	16.87, 9.07	16.95, 9.07	9.9	Smectite, (heulandite)
122	17.08, 9.04	16.98, 9	9.86	Smectite, (heulandite)
154	17.15	17.10	9.8	Smectite
196	17.29	17.19	9.97	Smectite
238	33.17, 16.79, 15, 7.19	32.77, 16.66, 15.22, 7.18	14.16, 10.2, 7.16	MLC, smectite, corrensite
272	30.58, 14.71, 7.19	31.51, 16.89, 15.47, 14.67, 7.14	14.47, 12.57	MLC, smectite, corrensite
290	32.11, 17.02, 14.56, 7.19	32.27, 17.02, 15.28, 14.74, 7.16	14.54, 12.44, 10.16	MLC, smectite, corrensite
316	29.11, 14.02, 7.02	31.48, 16.84, 15.47, 14.57, 7.15	No reflection	MLC, smectite, corrensite
336	28.91, 14.13, 7.10	31.8, 16.97, 15.57, 14.67, 7.16	14.38, 12.58, 9.83	MLC, smectite, corrensite
366	31.51, 16.81, 14.60, 7.15	31.65, 16.9, 15.55, 14.54, 7.12	14.46, 12.55, 9.88	MLC, smectite, corrensite
396	31.86, 14.78, 7.15	31.84, 15.22, 14.3, 7.12	14.64, 12.51	MLC, corrensite
426	30.62, 14.35, 7.13	30.44, 14.27, 7.09	14.41, 7.25	Chlorite, (MLC)
464	28.29, 14.46, 7.14	26.99, 14.35, 7.11	14.53, 7.18	Chlorite, (MLC)
502	14.50, 10.08, 7.15	14.40, 10.03, 7.12	14.45, 10.13, 7.17	Chlorite, illite
540	14.44, 10.14, 7.14	14.39, 10.06, 7.12	14.81, 10.16, 7.39	Chlorite, illite
582	14.53, 7.16	14.41, 7.13	14.45, 7.24	Chlorite
626	32.14, 16.83, 14.54, 7.15	32.34, 16.88, 15.7, 14.55, 7.15	14.50, 12	Chlorite, corrensite, MLC, (smectite)
664	14.64, 7.18	33.51, 16.85, 15.7, 14.53, 7.13	14.87, 10, 7.43	Chlorite, corrensite, MLC, (smectite)
706	31.82, 16.45, 14.77, 7.15	32.05, 16.72, 15.24, 14.62, 7.14	14.74, 11.86, 10.25	Chlorite, corrensite, MLC, (smectite)
774	31.53, 14.37, 10.06, 7.12	31.85, 16.49, 15.7, 14.30, 10.07, 7.09	14.03, 9.98	Chlorite, corrensite, illite, (MLC)
810	32.41, 14.56, 7.16	32.67, 14.48, 7.15	14.63, 9.02	Chlorite, (MLC)
864	14.48, 7.16	14.45, 7.14	14.59	Chlorite
914	14.37, 7.13	14.29, 7.11	14.62, 7.15	Chlorite
942	14.38, 7.14	No reflection	14.56, 7.17	Chlorite
988	14.48, 8.54, 7.15	14.43, 8.53, 7.13	14.53, 8.49, 7.18	Chlorite, actinolite

Smectites are the only clays found from the top of this well down to around 210 m depth. They, however, occur also down to about 366 m depth (Table 2) and disappear at greater depths. Their presence in the intrusion at 626-706 m depth is questioned, based on the XRD result. In the stereo-microscope, smectite appears as brownish-green coloured, poorly-crystallized masses lining openings. In thin section, it shows brownish colour with low birefringence. On the XRD, it has peaks commonly occurring at 13.5-15 Å (for constant humidity at 35%), expanding to about 16.5-17 Å on treatment with ethylene glycol, and collapsing to about 10 Å when heated to 550-600°C (Brown and Brindley, 1980).

Mixed layer clays (MLC) found in this well are mainly interlayered smectite-chlorite. In thin section, they show light green colours in plane polarized light but in cross-polarized light they show radial needles of brownish yellow colours with low birefringence. They generally show variable optical properties owing to their transitional nature. They usually respond to XRD peaks of 15-17 Å (at constant humidity), expanding to 29-30 Å (glycolated) and collapsing to 12-14 Å when heated up to 550-600°C. The mixed layer clays are identified in samples from 238 to 396 m depth, and again at greater depth from 626 to 706 m (Table 2). Although mixed layer clays could be identified petrographically based on their colour, texture and optical characteristics, the XRD technique still remains essential as the final determinant.

Swelling chlorite or **corrensite** is another variety of chlorite which occurs in this well. It has peaks at 14-14.5 Å (for constant humidity), swells to 15.5 Å on treatment with glycol and drops back to 14-14.5 Å when heated to 550-600°C. Swelling chlorite is detected in samples at 238-396 m depth together with smectite and mixed layer clays, and again at greater depth from 626 to 774 m together with mixed layer clays and chlorite (Table 2).

Chlorites are distinguished by conspicuous peaks at 7-7.5 Å and 14-14.7 Å in the untreated, glycolated and the oven-heated samples. Chlorites were first observed at 426 m depth occurring as infilling and replacement of ferromagnesian minerals, and was detected in XRD down to the bottom of the well (Table 2). In the binocular microscope, it is identified by its light-greenish colour and coarse-grained texture. In thin sections, they are equally pale-greenish and coarse-grained, showing pleochroism and very low birefringence.

Illite was first detected by XRD at 502 and 540 m depth together with chlorite, and then at 774 m depth with chlorite, swelling chlorite and traces of mixed layer clays (Table 2). Illite shows a very distinct peak at approximately 10 Å which does not change when treated with glycol and when heated to over 550°C. It occurs partly as a replacement of K-feldspars and indicates alteration temperatures above 200°C in Icelandic rocks.

3.4 Alteration mineral zonation

The degree of hydrothermal alteration and the amount of hydrothermal minerals formed in a geothermal reservoir depend largely on the following parameters: 1) the type and permeability of the rock; 2) the temperature and chemical composition of the fluid; and 3) the duration of the geothermal activity, the latter being related to the age of magmatic activity (Kristmannsdóttir and Tómasson, 1978; Elders et al., 1979; Browne, 1984; and Reyes, 1990). Hydrothermal alteration in Iceland is highly temperature dependent where definite mineralogical changes are seen to take place with increasing temperature (e.g. Pálmason et al., 1979). According to Browne (1984), the minerals commonly used as geothermometers are the zeolites, clays, epidote and amphiboles. In Icelandic geothermal fields, most zeolites are common before 100°C and disappear around 200°C where they are transformed to wairakite or quartz. Quartz is found at temperatures above ca. 180°C, and calcite appears to be stable up to temperatures around 270-280°C. Epidote forms at temperatures above 240-250°C. Actinolite appears at temperatures above 280°C. Smectite is the dominant clay mineral up to a temperature of about 200°C where mixed layer clays start to form, and chlorite starts forming at temperatures above 230°C (Kristmannsdóttir, 1978).

The original mineralogy of the rock seems to have a minor effect on the type of secondary mineral assemblages in permeable zones and where temperatures exceed 250°C. It is controlled mostly by the porosity/permeability.

In active geothermal fields (New Zealand, Cerro Prieto, Iceland and Philippines), alteration zones were derived by empirical data found between rock temperatures and secondary minerals. For example, different alteration zones were obtained regarding the formation of smectites, mixed layer clays and chlorite in Iceland than were found elsewhere. Figure 8 shows a similar scheme employed in creating alteration zones. A correlation of alteration zones with rock temperature in active high-temperature areas

FIGURE 9: Alteration zones in the high-temperature geothermal areas in Iceland correlated to rock temperature and metamorphic facies (Kristmannsdóttir, 1978)

in Iceland is shown in Figure 9. Also shown are the index minerals and mineralogical changes characterizing each alteration zone.

Alteration mineral zones in well KJ-29 are divided into a smectite-zeolite zone, a mixed layer clay zone, a chlorite zone, a chlorite-epidote zone and an epidote-actinolite zone (Figure 8). Each zone is characterized by a definite assemblage of hydrothermal minerals and is defined by the first appearance of its index mineral. The following is a description of the alteration zonation with temperature approximations.

Smectite-zeolite zone. This zone extends from the top (60 m) of the well down to about 212 m depth. It is marked by the presence of smectite (fine-grained clay) and zeolites, mainly chabazite, analcime, scolecite/mesolite, stilbite, heulandite and mordenite. The temperature range is below 200°C. Quartz and wairakite occur sporadically in this zone and relate to higher pressure-temperature formation during the last glacial age, which will be discussed later.

Mixed layer clays zone (MLC). It is made up of an assemblage of smectite, corrensite and mixed layer clays (coarse-grained clays) and supported by quartz, wairakite and albite. It ranges from about 212 m down to around 420 m depth where chlorite first appears, and characterizes a temperature range of about 200-230°C. In Icelandic geothermal fields, mixed layer clays are present where measured temperatures are in the range of 200-230°C (Kristmannsdóttir, 1978).

Chlorite zone. This zone is marked by the presence of chlorite and, partly, illite. The top of the chlorite zone is found at about 420 m depth and it extends down to about 822 m depth. The chlorite zone represents a temperature range of 230-250°C.

Chlorite-epidote zone. It is defined by the appearance of both epidote and chlorite at around 822 m depth and extends down to about 988 m depth where actinolite first appears. This zone represents a temperature range above 250°C. According to Browne (1984), in many fields epidote first appears at 250°C and the lithology does not influence its formation.

Epidote-actinolite zone. It is marked by the presence of both epidote and actinolite at 988 m depth and probably persists to the bottom of the well (less information available from greater depths than 1000 m). It represents a temperature > 280°C. The disappearance of calcite at around 1000 m and the continuous appearance of wollastonite at about 1350 m depth is in agreement with this temperature estimate.

3.5 Depositional sequence and temperature evolution

A detailed examination of drill cuttings and thin sections enables the determination of the chronological order of rock-mineral and mineral-mineral interaction in the well. Depositional sequences in cavities,

fractures and interstitial spaces in the groundmass are all being considered.

Clay is the major hydrothermal mineral lining walls of the vesicles and fractures. Table 3 shows the hydrothermal mineral evolution in well KJ-29 commonly observed in most of the thin sections. The upper zone is characterized by the initial deposition of smectite and/or chalcedony followed by zeolite (scolecite-stilbite), and then quartz and calcite deposits. This indicates an increase in temperature of deposition sequence from <100°C up to <200°C. In the MLC zone, spherulitic structure is typical for chalcedony, later pseudomorphed by quartz; the sequences indicate an evolution from low temperature (<100°C) where chalcedony first formed, succeeded by zeolites, first scolecite-stilbite and then mordenite-wairakite upon increase in temperature, and later by MLC/corrensite, quartz and calcite (>200°C). Similar evidence occurs with mineral sequences in the chlorite zone, except that zeolites, as seen in the 542 m depth sample are followed by alteration mineral assemblages of chlorite, quartz, calcite and pyrite, indicating higher temperatures than 230°C. In the chlorite-epidote zone, the mineral sequence consists of chlorite followed by quartz and calcite. It may indicate a temperature rise from >230°C up to 270-280°C, near 1000 m depth where calcite disappears from high-temperature mineral assemblages.

TABLE 3: Sequence of hydrothermal mineral deposition in well KJ-29

Depth (m)	Depositional sequence (early → late)
76	Smectite-Stilbite-Quartz-Calcite
108	Scolecite-Stilbite-Quartz-Calcite
140	Stilbite-Quartz-Calcite
210	Chalcedony-Scolecite-Calcite
230	Quartz-Calcite
240	Chalcedony-Quartz
270	Smectite-Chalcedony-Mixed layer clay-Quartz-Calcite
308	Chalcedony-Quartz
340	Smectite-Chalcedony-Scolecite-Corrensite-Quartz
370	Chalcedony-Stilbite-Wairakite-Quartz-Calcite
380	Chalcedony-Scolecite-Mordenite-Corrensite-Quartz
406	Chalcedony-Scolecite-Corrensite-Quartz-Calcite
440	Chalcedony-Scolecite-Quartz-Calcite
524	Mordenite-Quartz
542	Chalcedony-Mordenite-Wairakite-Chlorite-Quartz-Calcite-Pyrite
558	Scolecite-Mordenite-Chlorite-Quartz
588	Platy Calcite-Wairakite
610	Quartz-Calcite-Chlorite
640	Mordenite-Calcite
670	Scolecite-Quartz-Calcite-Chlorite
810	Chalcedony-Chlorite-Quartz
930	Chlorite-Quartz-Calcite
960	Chlorite-Calcite
990	Chlorite-Calcite

The depositional sequences, as seen in Table 3, accordingly show an evolution from a low-temperature condition to a high-temperature condition.
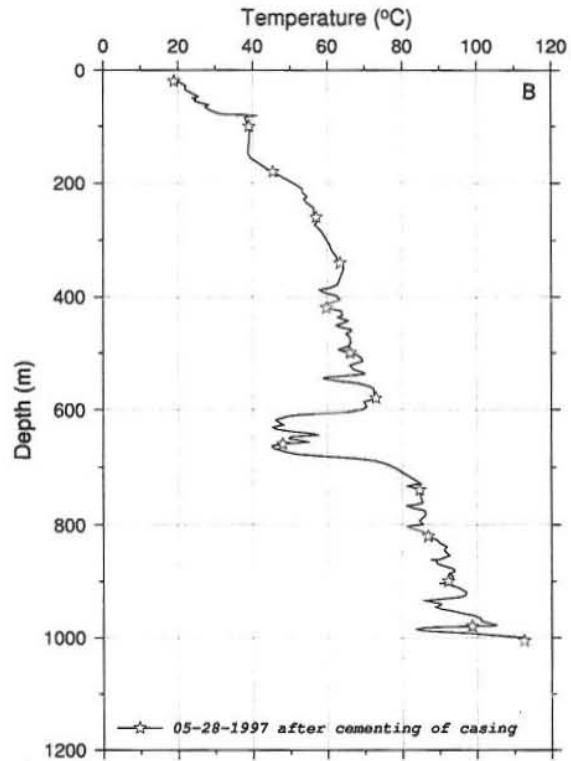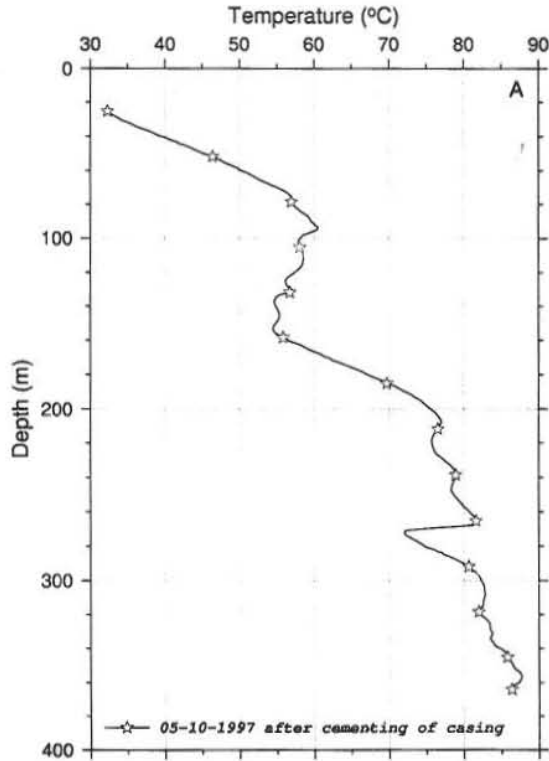
4. AQUIFERS

An aquifer is defined as a zone in the well where an unquantifiable volume of circulating groundwater is stored. Groundwater movement is controlled by hydraulic gradient, formation permeability, porosity and differential pressure and temperature. In fact, determination of the aquifer zone is vital in the search for a geothermal reservoir. Aquifers in the geothermal environment are characterized by the presence of a permeable rock formation, feed zone or geological structures and natural recharge areas. Diagnostically, their presence is directly determined from records of circulation losses during drilling, and anomalous geophysical logs such as penetration rate, caliper, resistivity, neutron-neutron, and most important, temperature logs (during drilling, heating up and discharge). An aquifer zone may also be recognized from anomalous hydrothermal alteration as a function of permeability, such as an abundance of quartz, anhydrite, pyrite, epidote, abundant oxidation and the presence of adularia (Franzson, 1995, and pers. com.).
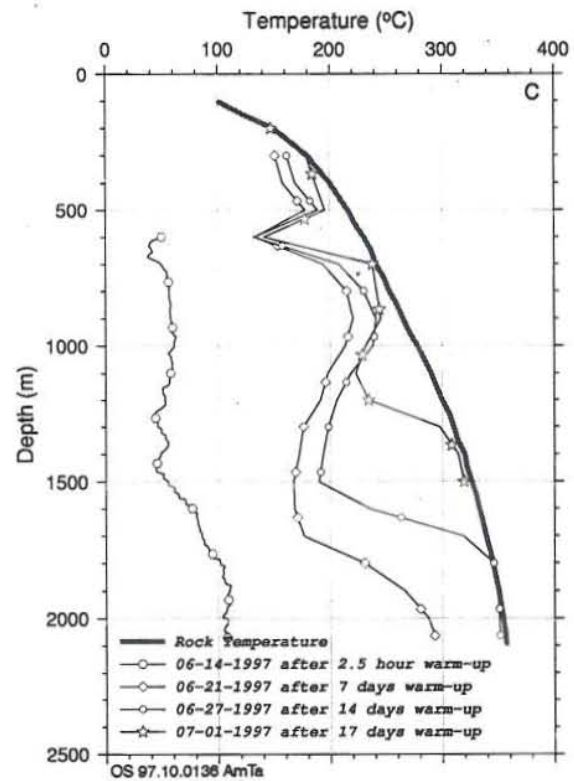
FIGURE 10: Temperature logs of well KJ-29; a) at anchor casing depth (388 m); b) at production casing depth (1000 m); c) warming-up period after drilling (2103 m)

Seven aquifer zones are identified in well KJ-29, as determined from the geophysical logs and records of circulation losses. Figures 6 and 8 show the location of aquifer zones in the well alongside the lithology and their correlation with geophysical logs and alteration mineral distribution and zonation. Also Figure 10 exhibits temperature logs of the well

during drilling and while heating up. The aquifers are identified as follows:

Aquifer 1 is located at the 100-155 m depth interval in the hyaloclastite breccia which is highly porous, more permeable, less altered and contains higher percolating water than the lower and upper tuffs. It was detected from the temperature log due to a break zone involving four feed points at 100, 125, 135, and 155 m depths (Figure 10A). The presence of some cave-in, as seen in the caliper log, as well as the result of the neutron-neutron log also indicate this aquifer (Figure 6). Circulation loss at the aquifer is 1 l/s at 99 m depth.

Below 155 m depth, there is no big cooling break in the temperature log until at 275 m depth, except for small feed points at 220 and 250 m depths (Figure 10A), which may relate to stratigraphic boundaries.

Aquifer 2 is located at 275 m depth at the stratigraphic boundary between aphyric hyaloclastite series and underlying porphyritic basaltic lava series, both altered (see Section 2.3.1). It was detected from a distinctive cooling point at this depth in the temperature log (Figure 10A). There is also a cave-in at the mentioned lithologic boundary as seen by the caliper log (Figure 6).

Aquifer 3 is located at 600 m depth, indicated by circulation loss of 2 l/s at 593 m and increasing up to 6 l/s at 635 m depth. In some instances, high permeability occurs more or less continuously over a large depth interval in a well, interpreted as representing a single aquifer. In this case, fine- to medium-grained intrusions (probably dykes) seem to have intruded subvertically into the hyaloclastites, at the same depth range as the zone of increasing circulation loss. This aquifer may also be determined by a cooling point in the temperature logs, measured during and several days after drilling (Figure 10B,C). There are also some changes in the curves of other geophysical logs, which may relate to this aquifer (Figure 6).

Aquifer 4 is situated at 680 m depth, related to a subvertical intrusion. Circulation loss of 14 l/s at 665 m depth which decreased to 10 l/s at 674 m depth was recorded from this aquifer zone. It is also determined by a cooling point in the temperature curve in Figure 10B and rapid warming up of the well at that depth (Figure 10C). Other marks are a distinct decreasing break point in the resistivity and neutron-neutron logs, and a rapid jump in the caliper log curve (Figure 6). The rock is identified as highly altered with heavy depositions of platy calcite, quartz, pyrite and anhydrite with several veins that could be related to a fracture system.

Aquifer 5 is located at 730 m depth, related to an intrusion. It is marked by high circulation loss of 12 l/s at 721 m increasing to 14 l/s at 733 m depth. It can also be seen in the temperature profile in Figure 10B. Quartz filled veins, related to small fractures at this depth, were seen in the cuttings.

Aquifer 6 is situated at 800 m depth in the very highly altered vesicular tuff underlain by an altered coarse-grained intrusion. A noteworthy circulation loss of 11 l/s at 796 m increasing up to 16 l/s at 841 m depth was observed. A cooling point is seen at this depth in Figure 10B. Also a distinct cave-in near the boundary of tuff and intrusion is seen in the caliper log (Figure 6).

Aquifer 7 is located at 930 m depth in the very highly altered vesicular basaltic breccia which is situated a few metres below a highly altered basaltic lava. Abundant vesicles are filled with epidote, chlorite, wairakite, quartz and calcite which, with the occurrence of adularia, are indicators of high permeability in the aquifer. A relatively high circulation loss of 15 l/s at 933 m increases to 17 l/s at 951 m depth. A distinct cooling point on the temperature profile in Figure 10B is seen as well.

All the above aquifers are cased off in well KJ-29, designed to collect high-pressure and high-temperature (7 bar-a, 170°C) steam. Other drillholes, like KJ-28, are designed to collect steam for the low-pressure and low-temperature step in the steam turbine (1 bar-a, 120°C).

5. DISCUSSION

Two major hyaloclastite formations are found in well KJ-29 with a basaltic lava series between them. The upper hyaloclastite sequence is placed above 274 m depth and shows a repetitive stratification feature which is commonly observed in the Icelandic volcanic zone. Lower hyaloclastite series below 470 m depth also show repetition but are intruded and separated by several subvertical dykes or basaltic intrusions. Hyaloclastite formations usually consist of tuff, breccia and basaltic breccia repetition, whereas basaltic lava series (at 274-470 m depth) consist of individual lavas with thicknesses ranging between 2 and 20 m. The classification of the volcanic succession of hyaloclastites and lava formations, was based on the petrographic characteristics rather than its genetic origin due to similar chemical composition. Intrusive rocks occur in the extrusive volcanic succession below 530 m depth and dominate the strata from about 990 m depth down to the bottom of the well (2103 m). The age of the stratigraphic sequence can be roughly assessed by comparison with ages of the glacial and interglacial periods. Thus, it is likely that the upper hyaloclastite formation was formed during the last glacial period, the basaltic lava series during the last interglacial period, and the lower hyaloclastite formation during the 2nd last glacial period.

An attempt was made to correlate the stratigraphy and alteration temperature gradients of KJ-29 with neighbouring wells KJ-6 and KJ-13 in the Leirbotnar field, and also wells KJ-21, 22 and 23 from Hvíthólar field along line B-B´shown in Figure 4. Figure 11 shows the mentioned cross-section in the NE-SW direction very close to the wells (modified from Ármannsson et al., 1987). A general correlation
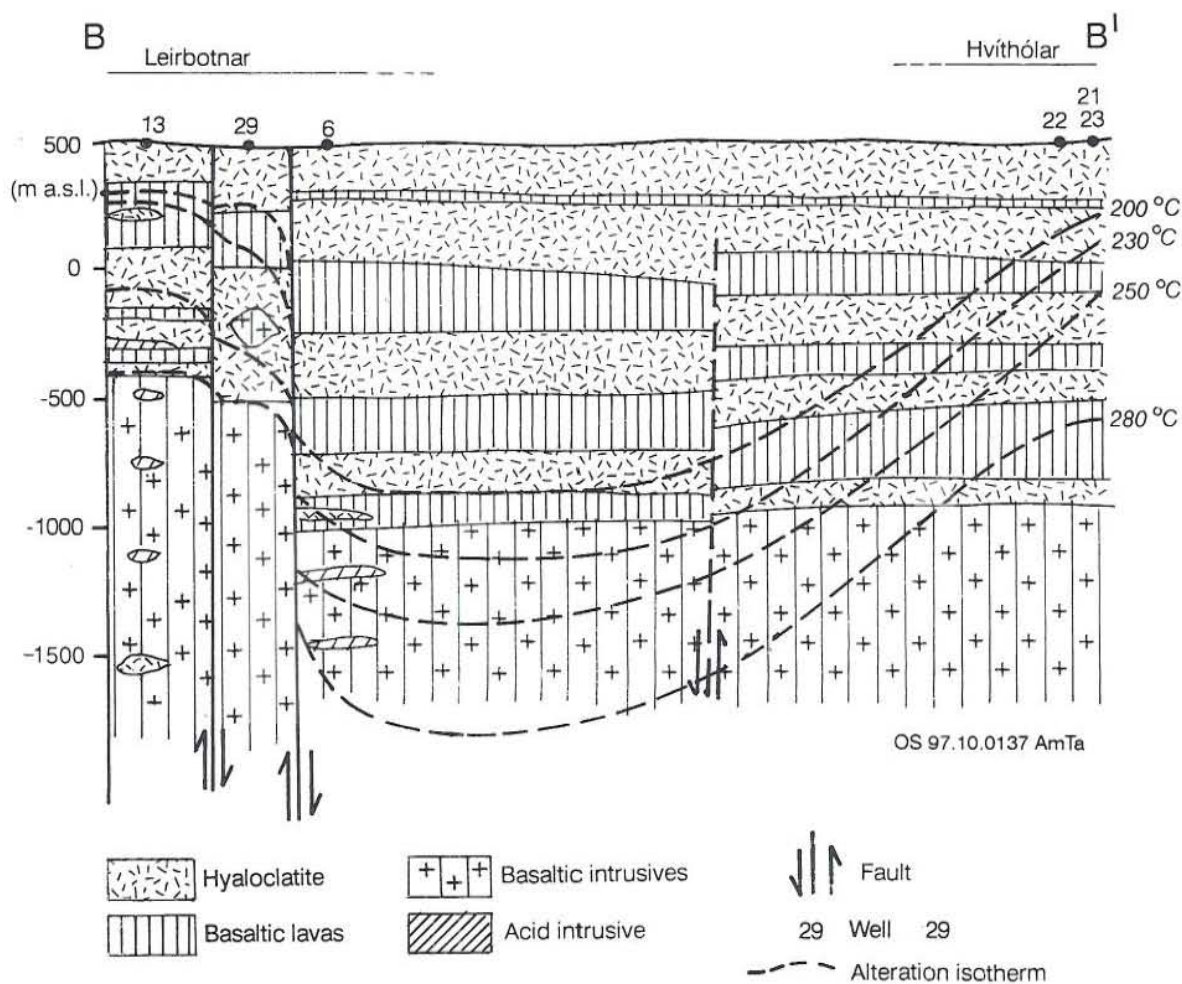

FIGURE 11: Stratigraphic and alteration temperature correlation of well KJ-29 with other wells; location is shown in Figure 4

between all the wells is possible and could be observed and distinguished by the marker units of hyaloclastite and lava formations and their boundaries. A possible fault displacement of about 220 m is present between wells KJ-6 and KJ-29, which seems attributable to a horst striking NW-SE. Another possible fault with displacement of about 90 m is also shown in Figure 11.

Hydrothermal alteration in this well shows progressive zonation with increasing depth. The five zones represent progressively increasing formation temperatures and can be sorted into the following zones; smectite-zeolite (<212 m), mixed layer clays (212-420 m), chlorite (420-822 m), chlorite-epidote (822-988 m) and epidote-actinolite (>988 m) zones representing ≤200, 200-230, 230-250, 250-280, and over 280°C, respectively. Veins appear to be more common in intrusions related to chilled margins and fractures, indicating higher permeability there. Vesicles are abundant in both hyaloclastites and lavas, and are mostly filled with secondary minerals. Depositional sequences of hydrothermal minerals show general temperature evolution of a geothermal system from low-temperature to high-temperature conditions.

Temperature is assessed from two data sources, i.e. temperature estimates based on alteration mineral assemblages on one hand and measured (formation) temperature on the other. The former shows a temperature range usually slightly below temperatures of the boiling point curve (Figure 12). Alteration temperatures together with depositional sequences show an increasing temperature from early to late time in the hydrothermal system. No temperature logs are available later than 17 days after drilling, as the well was brought to a discharge before equilibrium had been reached. From this and earlier temperature logs, the formation temperature has been estimated as shown in Figures 10C and 12 (Steingrímsson, pers. com.).
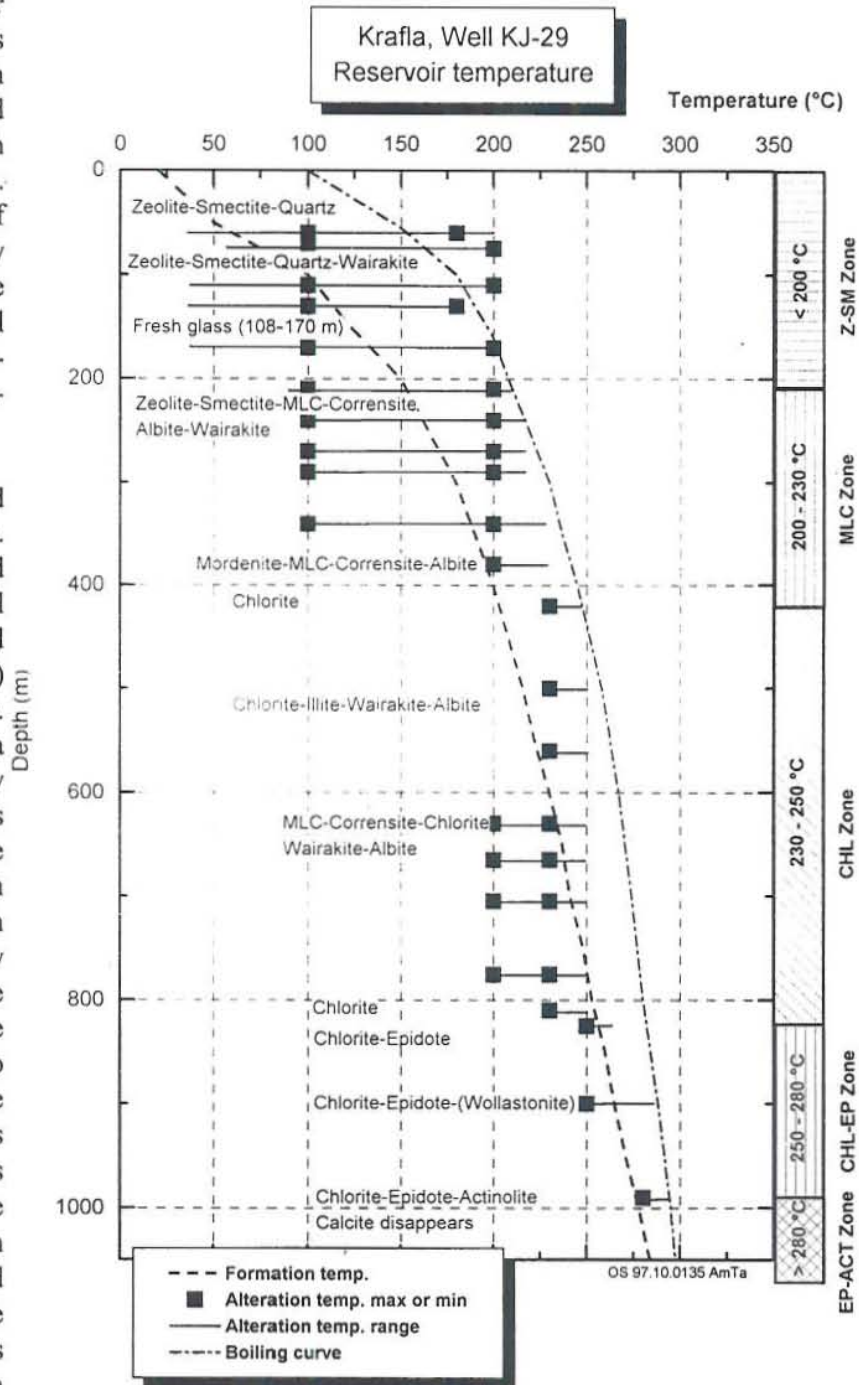

FIGURE 12: Correlation of hydrothermal alteration, formation and boiling temperatures in well KJ-29

Alteration and formation temperatures are roughly comparable below about 300 m depth and both are below but more or less parallel to the boiling point curve with increasing depth, indicating a stable high-temperature environment. The existence of lower temperature clays together with chlorite in the chlorite zone, is probably due to the relatively young age of the intrusion.

A plausible explanation for wairakite and quartz being found at shallow depth and apparently at temperatures above the boiling point curve (Figure 12), is that they were formed during the glacial period when the hydrostatic pressure in the reservoir was most likely being controlled by the water table within the glacier and not the current water table. The same explanation was used for the adjacent Námafjall geothermal area, according to the occurrence of early epidote (Isabirye, 1994). This presumably implies age of about 12,000-115,000 years. The water table at that time is estimated to have been at least 100 m higher than that at present. Another explanation may be pseudo-deposition of wairakite or quartz due to several eruptions and explosive craters in the area which could shift them from deeper to shallower parts of the well.

Platy calcite is first seen at 290 m (Section 3.3) suggesting boiling, according to the boiling point-depth curve, at this depth at temperatures about 230°C or lower at any one time in the history of the reservoir. Since this kind of calcite continued to deeper parts, it can be inferred that the reservoir had been boiling in the past at this shallow depth before it cooled to temperatures below the boiling point curve, above 1000 m depth, as it is today (Figures 5 and 12).

A prograde hydrothermal alteration pattern is observed with depth and correlates well with measured temperatures at Hvíthólar and Sudurhlídar (Figure 5), but in the Leirbotnar field an invasion of 190-200°C water from the north has overprinted the earlier alteration mineral assemblages by calcite down to a depth of 1000-1200 m (Ármannsson et al., 1987). The alteration zones protrude to shallow depths in most of the Sudurhlídar wells, but they plunge steeply across the Hveragil gully from Sudurhlídar to the Leirbotnar field. The high-temperature alteration also reaches relatively shallow depths in wells KJ-21 and 23 but is deeper in well KJ-22 farther to the north (Figure 11). Further to the northeast, between wells KJ-6 and 29, there is a fault which possibly relates to the horst system as well. At the northern part of the fault (close to KJ-29), alteration zones protrude to shallower depths and seem to be related to an upflow zone associated with the horst.

In total, seven aquifers could be indicated from circulation losses, temperature logs and alteration data. Most of the aquifers in this well are related to the contacts and fractures of the intrusive dykes or basalts found in the lower part of the chlorite zone, and some of them are located at the boundaries of extrusive volcanic successions or within a given rock formation. All these aquifers were cased off by 9 5/8" production casing, and high pressure-high temperature steam is collected from below 1000 m depth. At the Leirbotnar field, where the geothermal system is divided into an "upper" (water-dominated) and a "lower" (steam-dominated) zone (Stefánsson, 1981), the main aquifers in the lower zone seem to be connected to fissures and intrusion contacts, whereas in the upper zone they occur at the margins of the lower hyaloclastite formation (Steingrímsson et al., 1984). In the southern part of Leirbotnar field, the Hveragil fracture, and another fracture to the west, feed the wells (Ármannsson et al., 1987).

6. CONCLUSIONS

The following conclusions can be put forward, based on evidence gathered from the study of the uppermost 1000 m of well KJ-29:

1.   The rocks are basaltic and divided into hyaloclastites and lava series representing eruptions from last glacial-interglacial and 2nd last glacial periods (12,000-200,000 years ago). Intrusive rocks are found below 530 m depth.

2. Seven aquifer zones were detected at 100-155, 275, 600, 680, 730, 800 and 930 m depths. The main aquifers are related to intrusion contacts and fractures.

3. Extensive deposition of alteration minerals including epidote, chlorite, quartz, wairakite and calcite, together with the occurrence of adularia, is an indication of high permeability of the deepest aquifer at 930 m depth.

4. A comparison of well KJ-29 with the nearest wells shows that it is located inside a horst system in the centre of the caldera, very close to a fault which protrudes alteration zones to shallow depths. Therefore, it may be related to a nearby upflow zone.

5. Five alteration zones defined by alteration mineral assemblages, i.e. smectite-zeolite (<212 m), mixed layer clays (212-420 m), chlorite (420-822 m), chlorite-epidote (822-988 m), and epidote-actinolite (>988 m) zones, represent <200, 200-230, 230-250, 250-280, >280°C, respectively.

6. Measured temperatures below around 300 m depth are roughly comparable with alteration temperatures, while alteration temperatures above that depth are significantly higher than those measured. The latter may indicate a thermal condition under glacial environment (12,000-115,000 years ago).

7. Temperature evolution from past to present, as seen in depositional sequences, indicates an ascending trend from low-temperature through intermediate to high-temperature conditions.

8. The production part of the well is located in the epidote-actinolite zone at depths greater than 1000 m and temperatures >280°C where calcite disappears but actinolite and wollastonite form.

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APPENDIX: Preparation of sample minerals for analysis by the XRD technique

The preparation of samples with hydrothermal alteration and clay minerals for identification and classification is done as follows:

Procedure A: For zeolite and other hydrothermal mineral analysis

1. Hand pick grain filling either vesicles or veins from the cuttings under the binocular microscope. The sample depth is dependant on the worker's purpose and objectives. There is no strict rule on the sampling methodology.

2. Crush the sample in an agate bowl to a grain size of 5-10 microns. Acetone is added to prevent loss of sample while powdering.

3. Fill the sample holder with an appropriate amount of powdered sample and make it firm, flat and level.

4. Run the sample from 4 to 56 θ on XRD.

Procedure B: For clay mineral analysis

1. Place approximately two teaspoons of cuttings into a test tube, wash out dust with distilled water. Fill the tube 2/3 with distilled water and plug with rubber stoppers. Place the tube in a mechanical shaker 4-8 hours, depending on the alteration grade of the samples.

2. Remove the test tubes from the shaker and allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few mm from each tube, halfway below the level of the sample, and place about ten drops on a labelled glass slide. Avoid having the samples thick. Make a duplicate for each sample and let them dry at room temperature overnight.

3. Place one set of samples in a desiccator containing ethylene glycol ($C_2H_6O_2$) solution and the other in a desiccator containing $CaCl_2 2H_2O$. Store at room temperature for at least 24 hours. A thick sample will need a longer time in the desiccator, at least 48 hours.

4. Run both sets of samples from 2 to 14 θ on the XRD.

5. Place one set of samples on an asbestos plate and heat in a preheated oven at 550-600°C. The exact location of individual samples on the asbestos plate must be known before heating, because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment, but do not forget the labelling of the samples.

6. Run samples from 2 to 14 θ on the XRD.