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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL KJ-28, KRAFLA HIGH-TEMPERATURE AREA, NE-ICELAND

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Abstract

The report describes the study of drill cuttings of a 1003 m deep drill hole located in the Krafla high-temperature area. The strata penetrated by the drillhole consists of fine- to medium-grained basalts (olivine tholeiites & tholeiites) and altered glassy basalts and basaltic tuffs and breccias which are referred to as hyaloclastites. Intrusions appear at 525, 635, 700, 725, 750 and 780 m depth. There are more than 15 aquifers. Both high-temperature (> 200°C) and low-temperature (40-200°C) hydrothermal minerals are present in the well. According to the distribution of deposition minerals, four alteration zones have been identified. They are a smectite-zeolite zone (< 200°C), down to 180 m depth, a mixed-layer clay zone (200-230°C) down to the depth of 525 m, a chlorite zone (230-250°C) down to 600 m depth and a chlorite-epidote zone (250-280°C) which is continuous down to the depth of 808 m. No cuttings were collected below 808 m to the bottom of the well because of total circulation loss (>40 l/s). The increase in temperature is indicated for example by the transformation of low-grade clays to relatively coarse-grained clays. With increasing depth the smectite becomes interlayered with chlorite and high-temperature minerals, such as wairakite. With increasing depth and temperature, epidote, albite and sphene appear. Calcite, pyrite and quartz are distributed in all the alteration zones. Zeolites are most common above 250 m depth. Comparison of well KJ-28 with other drillholes in the area shows that it is located within a major upflow zone.

1. INTRODUCTION

The Geothermal Training Programme is organised annually at Orkustofnun - National Energy Authority, Reykjavík, Iceland. The programme is jointly financed by the Government of Iceland and the United Nations University. I was awarded a six months fellowship with the programme for specialised training in the field of borehole geology. In Pakistan, there is an ever increasing demand for energy resources. The government is very keen to develop and utilize this different source of energy and is, in this regard, looking forward to co-operation with other countries of the world. It is the role of the Geological Survey of Pakistan, the parent organisation of its kind in the country, to carry out research activities to develop mineral resources. Presently, it is in the process of establishing a group of trained personnel in various fields of geothermal research, for the future development of its already identified geothermal potential.

My association with the highly qualified staff members of Orkustofnun during my training will certainly enhance my capabilities to organise work of a similar nature in my home country.

The UNU Geothermal Training Programme at Orkustofnun comprises an introductory course for about five weeks, covering all aspects of geothermal research followed by an excursion to the main high-temperature and low-temperature geothermal fields of Iceland for about two weeks. Three methods were used for the specialised training. Firstly the drill cuttings, which are collected from every 2 m interval from the drillholes, were studied with the help of a binocular microscope, then a representative batch of samples was analysed in thin sections with a petrographic microscope. Finally, all the mineral studies were supported by X-ray diffractometry techniques which are used for the identification of clays and other secondary minerals.

Geothermal areas are divided into two groups, i.e. high-temperature areas where the rock temperature exceeds 200°C at 1 km depth and low-temperature areas where the rock temperature is below 150°C at 1 km depth (Figure 1). High-temperature areas are located within the zones of rifting and volcanism. A boundary between the American and Eurasian plates runs along the rift zone in Iceland. The rocks there are generally fresher than those within the adjacent Quaternary and Tertiary eroded rock successions, apart from the high-temperature hydrothermal manifestation on the surface within the active rift zone. The zones of recent volcanism comprise the axial rift zone and are the present locus of active plate growth.

The Krafla high-temperature area is located about 10 km from Lake Mývatn in NE-Iceland. All the drillholes are located within the Krafla caldera (Figure 2) which was formed about 100 thousand years ago at the beginning of the last interglacial period (Saemundsson, 1979). A magma chamber is located

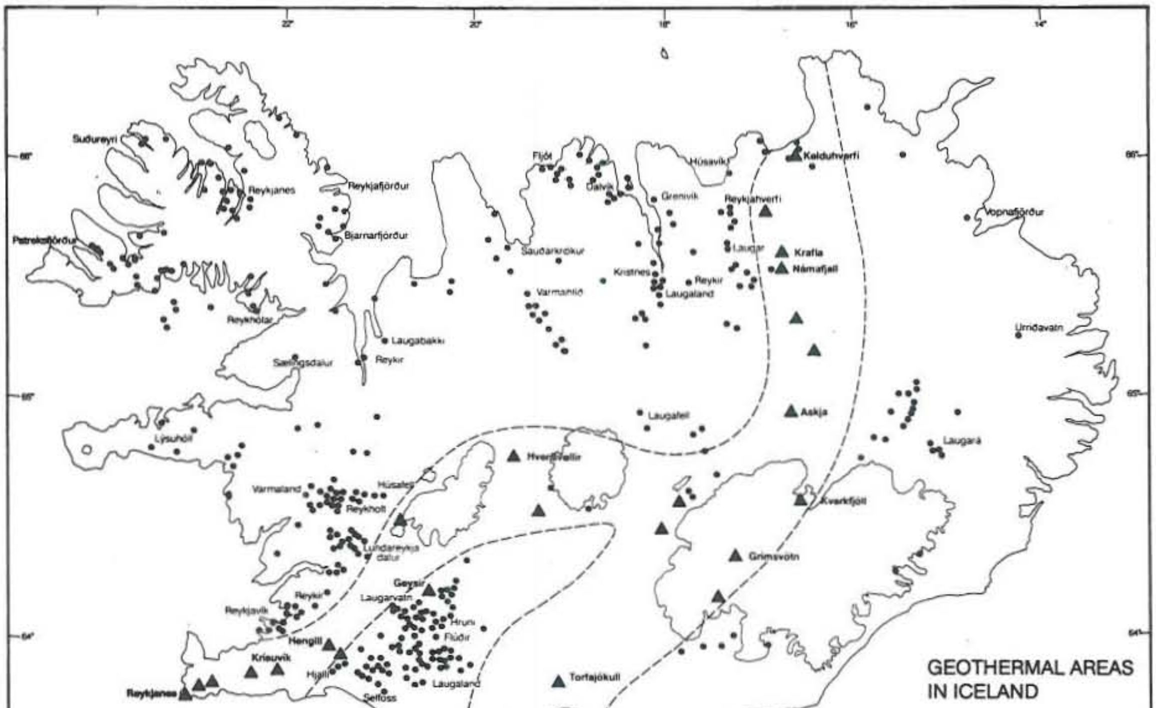

FIGURE 1: A simplified geological map of Iceland showing the location of high-temperature and low-temperature areas

at a 3-8 km depth in the roots of the caldera (Figure 3). The area has been subjected to many volcanic eruptions. The most recent one was in the years 1975-1984, including nine eruptive episodes (Björnsson, 1985). In the Krafla geothermal area the first well was drilled in 1974 and was aimed at collecting subsurface data. Three production wells were drilled in 1975, and by 1978 twelve wells were completed. Since 1982, 30 MW of electric power have been produced in a single steam turbine but that is only half of the rated capacity of the 60 MW plant. Several wells became contaminated with magmatic gases in 1976 which resulted in corrosion and calcite scaling, affecting productivity (Ármannsson et al., 1987). Since 1984 volcanic gases have steadily diminished, and last year a decision was made to increase the electrical production up to 60 MW. To meet this demand, several new wells needed to be drilled including the KJ-28. Figure 4 shows the location of the three different Krafla well fields, Leirbotnar, Sudurhlídar and Hvíthólar. Temperature profiles of the three well fields are shown in Figure 5.

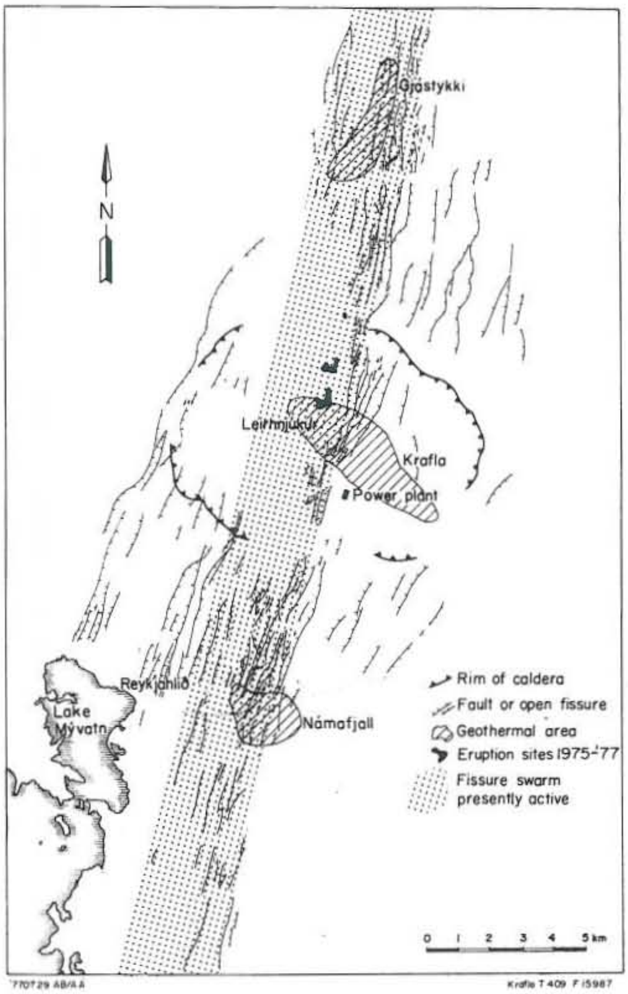

FIGURE 2: Tectonic map of the Krafla area showing the caldera, the active fissure swarm and the location of the Krafla power plant (Stefánsson, 1981)

2. DRILLING AND LOGGING OF WELL KJ-28

Well KJ-28 is located in the Leirbotnar well field (Figure 4). It was drilled in November, 1996. The design of the well is shown in Figure 6. The well was pre-drilled with a small rig and 18 ½ " surface casing was put down to 67 m depth and cemented. Then a larger rig was brought in, a 17 ½" hole drilled down to 395 m depth, and a 13 ⅜" anchor casing was cemented down to that depth. Then the production part of the well was drilled down to 1003 m depth with a 12 ¼" drill bit and a 9 ⅝" slotted liner put into the well to prevent it from collapsing.

Drilling rate (m/h), circulation loss (l/s) (or gain), pump pressure (psi) and the temperature of the circulation fluid (mud or water) was monitored during drilling, and drill cuttings were collected into 100 ml boxes at every 2 m interval by the drill crew. The drill site geologist located the main feed zones in the well by this data. Additional data was collected from the borehole temperature-logs measured during drilling and after, during the heat-up period. All this data was then compared with the lithology from the drill cutting analysis to evaluate the type of aquifer. Aquifers are of different nature, sometimes just a porous rock, sometimes fractures or faults cutting the rock formation, or fractures at intrusive rock

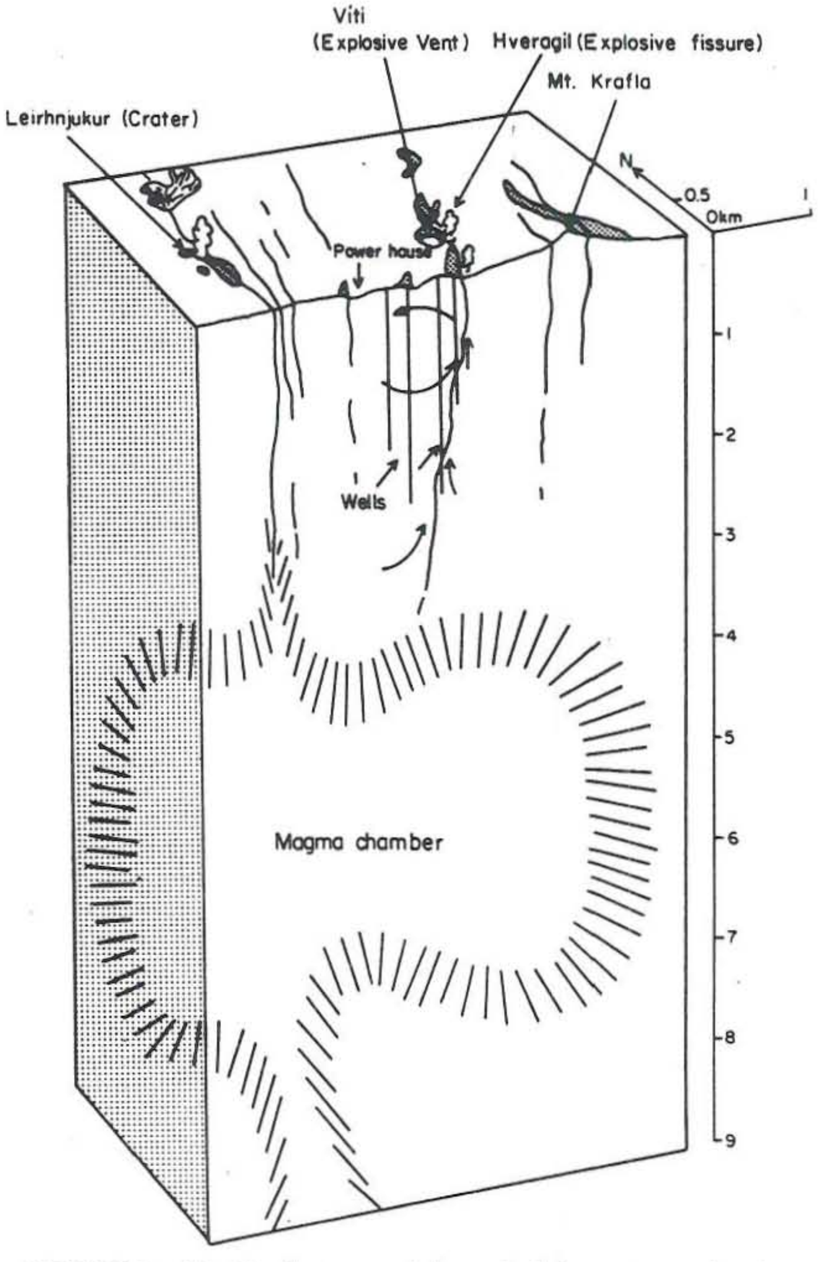

FIGURE 3: The Krafla area and the underlying magma chamber (Stefánsson, 1981)

contacts, or boundaries between lithological units. Knowing the nature of the aquifers is of economic importance, e.g. for siting new drill holes. Figure 7 shows how downhole temperature-logs can be used to locate feed zones and aquifers. A cooling point at 160 m depth in the temperature-log from November 27, 1996, done shortly after the drilling was completed, is suggestive of a small feed zone, and a larger one is suggested by the temperature inversion near 230 m depth. Both these aquifers were cased off by 13 3/8" cemented anchor casing. The main aquifer in the well below 800 m depth, is quite clear on the temperature-logs. From there a total circulation loss (> 40 l/s) was experienced during drilling and remained so until drilling was completed 200 m deeper down. No drill-cuttings came up to the surface from this interval. Therefore, information on the rock type there needs to be evaluated from the geophysical downhole logs. From the first temperature log, it is clear that the interval from 800 m to the bottom of the well had been receiving cooling water. That alone is suggestive of a major fracture aquifer. The location and the supposed type of aquifers in well KJ-28 are discussed in Chapter 3.3.

After the completion of each drilling phase, several downhole geophysical logs are measured in an open hole, before the casings are sunk, and while the well is still cold (below 100°C). The geophysical logs are then corrected for the drillhole width and combined together in a picture like Figure 8, shown alongside the lithological logs, feed zone locations and the drill rate. The calliper log is mostly used for locating cave-in sites. The neutron-neutron log reflects the water content in the formation. The resistivity log reflects the rock density and the gamma log is a measure of radioactivity that has proved useful in distinguishing between acid and basic rocks in Icelandic well fields.

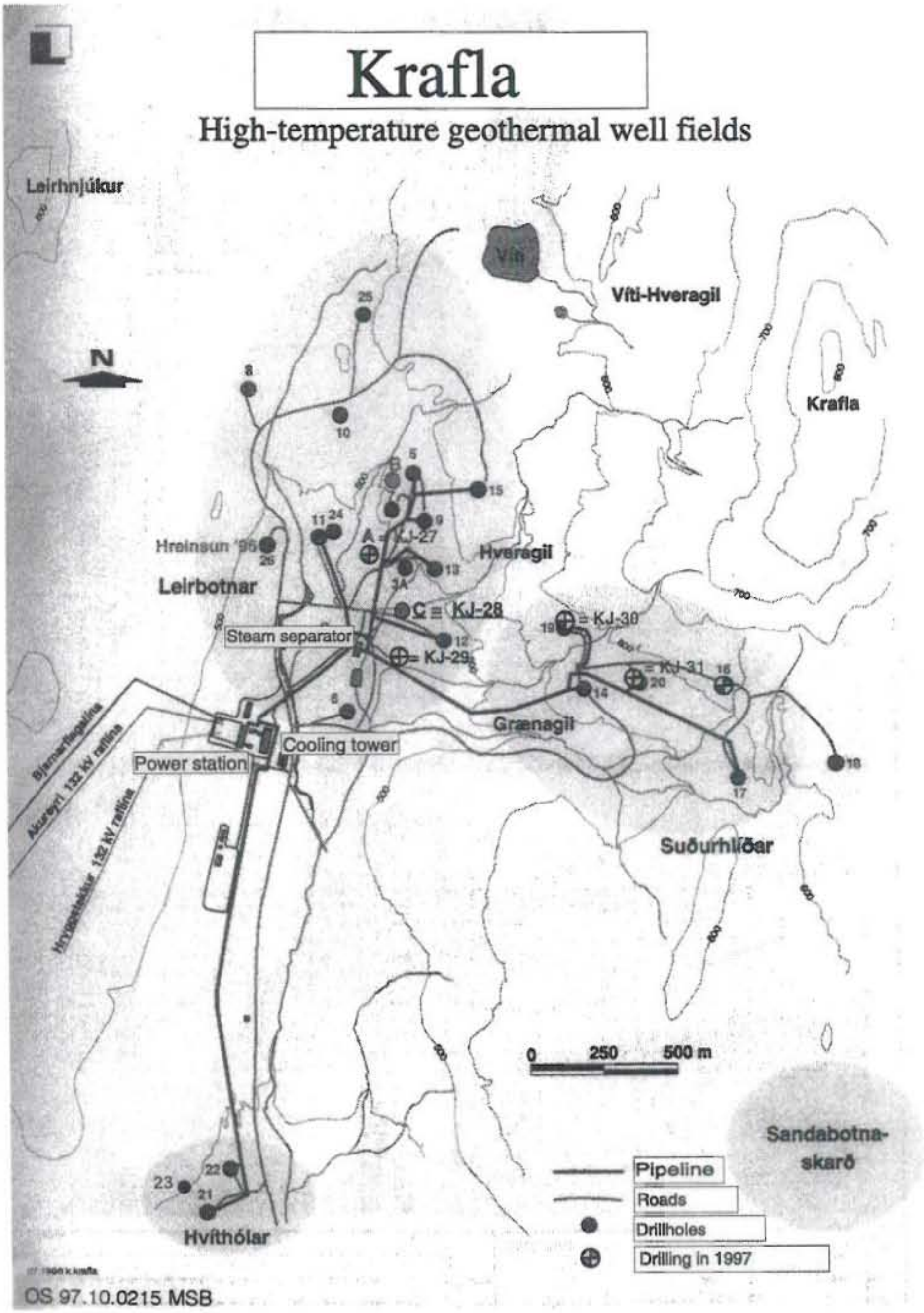

FIGURE 4: Map of the Krafla area, showing the three production fields and location of wells

3. LITHOLOGY AND AQUIFERS

Well KJ-28 was only drilled into basaltic rocks according to the drill cutting analysis and the available geophysical logs. A slightly simplified lithological profile is shown in Figure 8 along with several geophysical logs as discussed in Chapter 2. The basaltic rocks are rather uniform in composition, either constituting coarse-grained olivine tholeiites or finer-grained tholeiites. The lithofacies, however, are more variable ranging from subaerial lava flows with lava scoria in between, to subglacially extruded hyaloclastites, which range from pure glassy tuff, to partly crystalline breccias of clastic rocks. The lavas

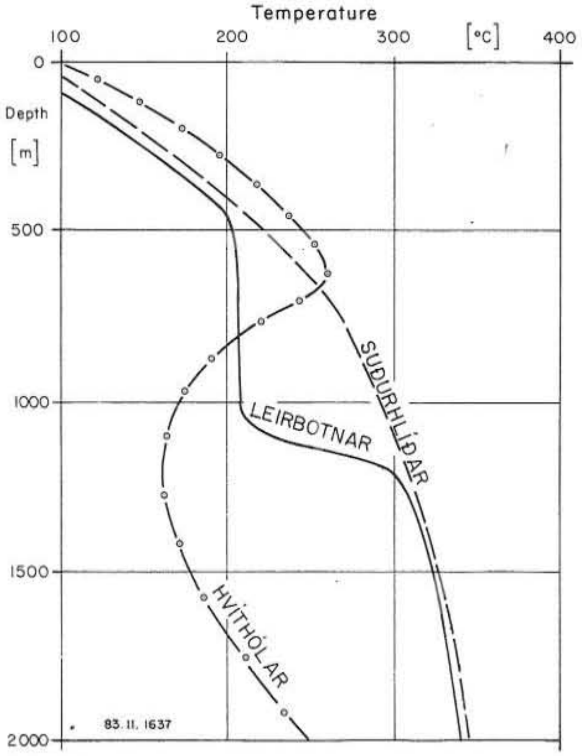

FIGURE 5: Temperature profiles from Krafla's three production fields (Ármannsson et al., 1987)

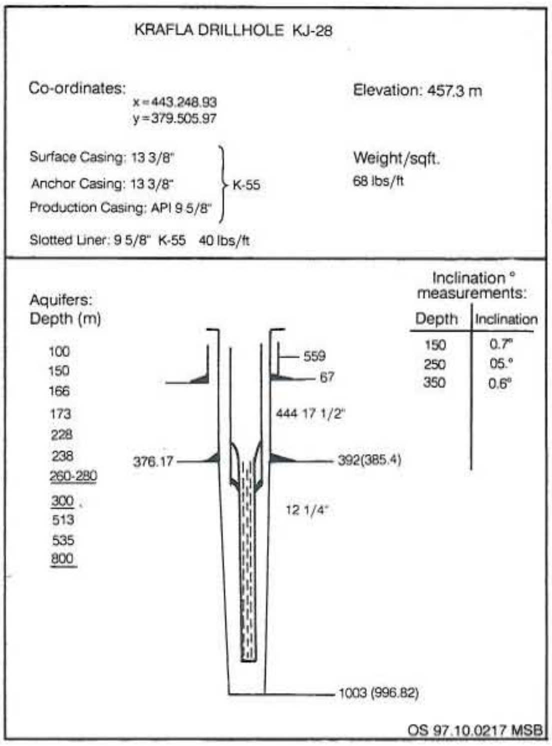

FIGURE 6: A diagram showing the different speciations of well KJ-28

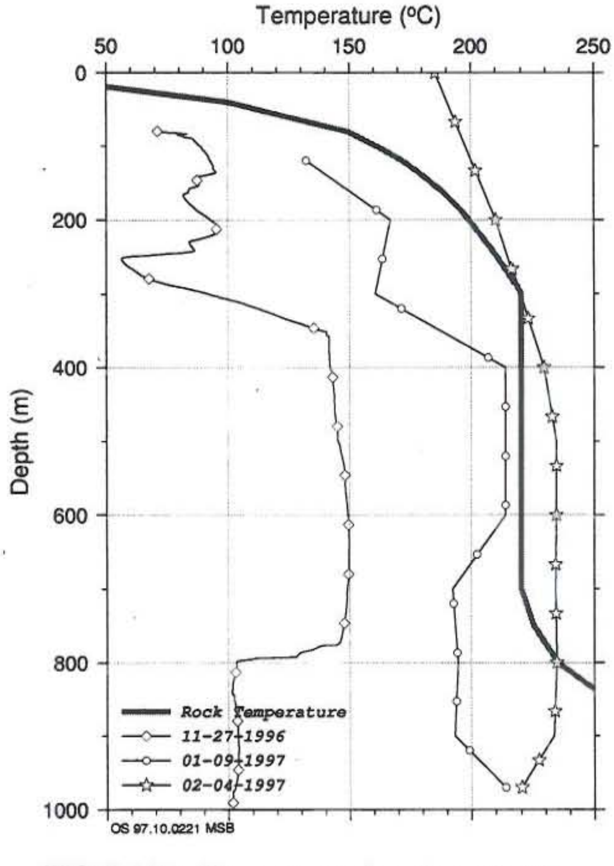

FIGURE 7: Temperature logs from KJ-28 and estimated rock temperature

and hyaloclastites are either aphyric or porphyritic. Several intrusions cut the succession of extrusive rocks. The location of intrusive rocks is shown in a separate column alongside the lithology profile in Figure 8.

3.1 Extrusive rocks

The succession of extrusive rocks can be separated into three main lithological series. Hyaloclastite-I, extends from the surface down to 270 m depth. A basalt lava series extends from there down to 395 m depth, comprising 8-9 individual lava flows. Hyaloclastite-II series extends from there down to the bottom of the well.

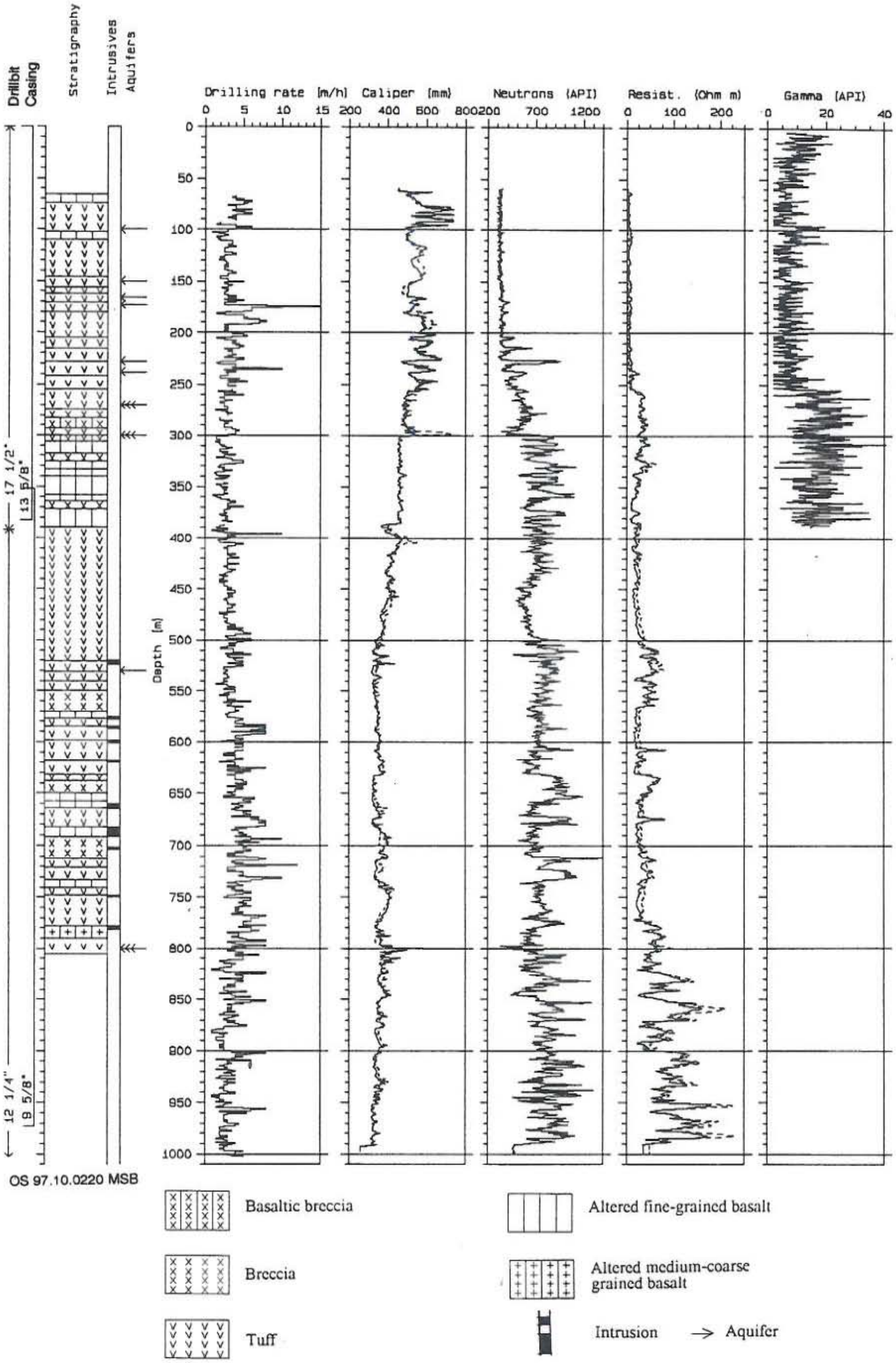

FIGURE 8: Lithology and various geophysical measurements made during drilling of KJ-28

Depth	**Lithology**
0-68 m	No cuttings.
	Hyaloclastite-series I (surface?-270 m), composed of alternating lithofacies.
68-75 m	Relatively fresh fine- to medium-grained olivine tholeiite lava.
75-140 m	Fine- to medium-grained basaltic tuff. The rock is vesicular and the vesicles are lined with low-grade clays. Intercalation of tuff and basaltic layers is observed. Thin-section 16485 shows the formation to be olivine tholeiite basalt.
140-182 m	Basaltic tuff, fine- to medium-grained and fresh looking. Thin-section at 180 m shows basaltic tuff and breccia. It may be a part of the same extrusive unit as above, but the next unit below is probably from a different eruption as it is porphyritic.
182-272 m	Altered basaltic tuff, fine- to medium-grained and plagioclase porphyritic.
	Basalt lava series I (270-395 m)
272-300 m	Altered glassy basalt and basalt breccias characterize the uppermost lavas in this series. Very nice crystals of quartz intergrowths with calcite and dark clays are found near the boundary between the hyaloclastite unit above and this lava series.
300-390 m	Fine- to medium-grained basaltic lavas. Tuff and breccia layers appear at 304, 335, 340 and 370 m, representing scorias between the lava flows. Vesicles are common and they are filled with quartz, calcite and chalcedony. Thin section 16474 shows microcrystalline plagioclase, pyroxene and ore minerals.
	Hyaloclastite series II (395-804 m). The upper part is composed almost entirely of tuff, while an alternating sequence of breccia and tuff characterizes the lower part. Thin basaltic intrusions (dykes and sheets) cut the series as discussed in Section 3.2.
390-550 m	Altered basaltic tuff, quite glassy. Lithic basaltic fragments still show microcrystalline plagioclase, pyroxene and ore minerals.
550-570 m	Altered plagioclase porphyritic basaltic breccia, probably of olivine tholeiite composition. Vesicles are lined with ore minerals.
570-630 m	Altered basaltic tuff, dark greenish grey, fine- to medium-grained, with olivine, pyroxene and plagioclase in the groundmass. Fragments of fresh looking rock.
630-650 m	Altered glassy basalt, fragments of fresh looking rock could be dolerite.
630-804 m	Altered hyaloclastite unit, fine- to medium-grained basaltic tuff and basalt breccia.

No cuttings were collected from the bottom 200 m of the well because of total circulation loss. The resistivity log, however, shows a clear change in the lithological character below 830 m depth (Figure 8). The high- and low-resistivity alternations are suggestive of a layered series of dense rocks separated by hyaloclastite or breccias, probably a lava series.

3.2 Intrusive rocks

Intrusive rocks in general are relatively coarse grained and less altered than the host rocks. Narrow intrusions may still be fine- to medium-grained. Ten separate intrusions have been identified in well KJ-28 as shown in Figure 8. They are present at 500-800 m depth. The average thickness of the intrusions is 3.8 m and they constitute about 12% of the volcanic succession between 500 and 800 m depth. The thickness of the intrusions varies from 1-15 m. The drill cutting samples at 690 m depth show a dark coloured and fresh looking intrusion less altered than the fine to medium grained basalt host. Secondary mineral abundance is relatively low in the intrusive rocks. Aquifers are found near some of the intrusions.

3.3 Aquifers

To know the nature of an aquifer is very important in geothermal prospecting and exploitation. Aquifers in drillholes are located by several means, but the two most important methods are to monitor the circulation fluid (mud or water) during drilling by recording the loss or gain (in l/s), and to study the temperature logs during and after drilling to locate the feed zones. Often the temperature profile reveals an aquifer that was not detected by loss or gain of the circulation fluid. Other downhole geophysical data can be supportive in recognising potential aquifers. The role of the borehole geologist is then to use this data and combine it with the lithology to identify and define the nature of the aquifers, i.e. if they occur at lithological boundaries, at intrusion contacts, or within the fractures or fault zones, etc. Additional information on the presence of closed or sealed aquifers can also arrive from careful analysis of rock cuttings. Extensively mineralized or veined zones within a well, for instance, may be of importance for utilization, e.g. if an injection packer needs to be used to increase the well yield by hydraulic fracturing. In the list below an attempt is made to analyse the type of aquifers existing in well KJ-28. All detected aquifers are listed, but only those below the anchor casing result in the well yield.

Aquifer 1 is present at a depth of around 100 m where 5 l/s circulation loss was measured. The host lithology is basaltic hyaloclastite which contains smectite, pyrite and some other alteration minerals.

Aquifer 2 is located at 150 m depth, in basaltic tuff. A circulation loss of about 5 l/s was measured.

Aquifer 3 is also a small aquifer located at 166 m depth, within a hyaloclastite unit.

Aquifer 4 is a small aquifer located at 170 m depth, within a hyaloclastite tuff. Circulation loss of 8 l/s was measured.

Aquifer 5 is encountered at 228 m depth within a hyaloclastite tuff, with a circulation loss of 5 l/s.

Aquifer 6 is located around 258-280 m depth within basaltic tuff. Circulation loss is about 6 l/s. This could be a feed zone, but was sealed off by casing.

Aquifer 7 is located at 300 m depth at the boundary between fine- to medium-grained basalts and tuff. Pyrite is abundant in this zone.

Aquifer 8 is encountered at a depth of 535 m just below the first intrusion in the well.

Aquifer 9 is a large aquifer which was met at about 800 m where there is a loss of circulation of about 42 l/s. The aquifer was met shortly after drilling through a few basaltic lavas. The drilling continued with total loss of the circulation fluid from 800 m until at 1003 m depth, the final depth of the well. No cuttings were received from this interval but the temperature log of November 27, 1996, together with the circulation losses, indicates that a major fracture or a fault zone was cut below 800 m depth.

4. HYDROTHERMAL ALTERATION

Hydrothermal alteration depends upon several factors such as temperature, pressure, lithology, and subsurface structure of the rocks. For instance, glassy rocks are more susceptible to alteration than crystalline rocks, and a close correlation between temperature and the type of secondary minerals is found in most geothermal systems. The preservation of primary texture in the rocks is a function of permeability, abundance and grain size of the primary minerals (e.g. Lonker et al., 1993). In general hydrothermal alteration in active and fossil high-temperature geothermal systems in Iceland ranges from zeolite facies to greenschist facies (Fridleifsson, 1991). The origin of hydrothermal fluids affects, to some extent, the type of hydrothermal product. For example, base metals are much more common in a saline hydrothermal system than in a meteoric system. The hydrothermal fluid in the Krafla geothermal system is of meteoric origin (Ármannsson et al., 1987).

4.1 Rock alteration

The primary mineral composition of basaltic rocks in Iceland is relatively uniform, comprising calcic plagioclase, clinopyroxene, olivine and magnetite-ilmenite ore. If the basaltic magma cools rapidly, quenched volcanic glass results. Hyaloclastite tuff may be composed of volcanic glass only, while the breccias and the lavas range in glass content from a lot, to little or no glass. Glass is most susceptible to secondary alteration, then olivine, followed by plagioclase, pyroxene and ore minerals. Nevertheless, it is the fluid composition which determines which primary mineral is the first to react with the fluid (G.Ó. Fridleifsson, pers. com.), meaning the susceptibility order above is only a guide to the most common order. Table 1 shows the most common secondary minerals formed at the expense of glass and primary minerals.

TABLE 1: Primary minerals and their alteration products

Primary minerals	**Secondary minerals**
Volcanic glass	Zeolites, quartz, chalcedony, clay, sphene (titanite)
Olivine	Iddingsite, clays and calcite
Plagioclase	Albite, adularia, quartz, chlorite, epidote, titanite, wairakite
Pyroxene	Chlorite, clay, quartz, pyrite and calcite
Ore	Titanite, pyrite, limonite, phyrrotite, and secondary oxides

Volcanic glass seems to have altered into brownish clays and quartz. Olivine starts to alter along diagonal fractures into iddingsite, and converts with increasing temperature to smectite and chlorite. Altered olivine was seen in thin sections at 210-240 m depths.

Plagioclase is commonly labradorite with a higher extinction angle. It starts to alter into clay from 255 m depth; at deeper levels it shows alteration into albite, calcite and quartz. Intensity of alteration is variable.

Pyroxene is found to be more resistant to alteration. The first sign of alteration is seen at 240 m and below 300 m depth. It is altered to clays, chlorite and sphene.

Opaque minerals include ilmenite and magnetite, which show variable degree of alteration. They mostly alter to titanite (sphene) at deeper levels.

4.2 Distribution of alteration minerals

The distribution of hydrothermal minerals found in Krafla drillhole KJ-28 is shown in Figure 9. They are mostly identified by drill cutting analysis, and petrographic thin-section study. They include: calcite, quartz, chalcedony, stilbite, chabazite, analcime, heulandite, mordenite, laumontite, prehnite, wairakite,

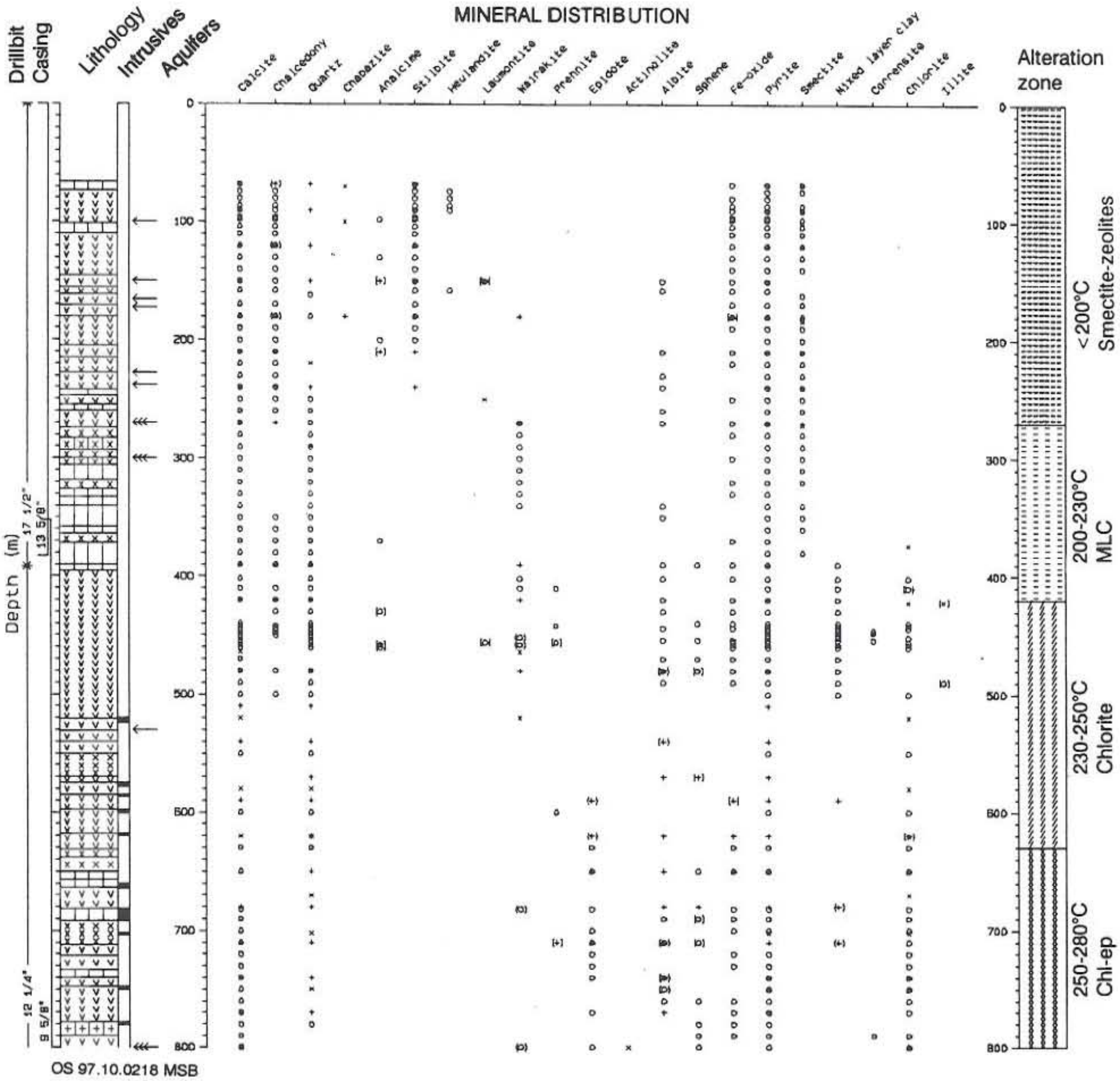

FIGURE 9: Secondary mineral distribution and alteration zones in well KJ-28

epidote, sphene, pyrite, phyrrotite, iron oxide, smectite, mixed layer clays of smectite and chlorite, chlorite, and possibly corrensite (formerly swelling chlorite).

Calcite: It is the most abundant secondary mineral in the well after clays. It is distributed from the top to the bottom of the well, but is rare around the dolerite intrusions near 700 m. Platy calcite is suggestive of boiling within the reservoir.

Pyrite: It is also widely distributed in the well, but at certain levels it is rare. From the relative abundance of pyrite we can conclude a bit on the permeability of the strata. Abundance of pyrite can be suggestive of an aquifer in the past or at present. Its distribution in tuff layers is difficult to ascertain but it is very abundant between 230-280 m depth. Figure 9 shows a good aquifer zone to be located at the same depth interval.

Chalcedony: It is seen in thin sections from 120, 150 and 180 m depth. It is also widely distributed in the smectite-zeolite zone. It occurs mostly as a cavity filling and lines the walls of vesicles.

Zeolites: The zeolite group includes hydrous calcium aluminium silicates that commonly occur as secondary minerals in rock cavities of basalt especially (Kerr, 1959). The zeolite group has been identified by binocular, in petrographic microscope and by the XRD method (Appendix). They commonly indicate low-temperature conditions, except laumontite (formed at 120-180°C) and wairakite (formed between 200 and 300°C). The zeolites identified in the well are chabazite, analcime, stilbite, heulandite, laumontite, and wairakite.

> **Chabazite**: It is the lowest temperature zeolite, and occurs in the drill cuttings at 70, 102, and 110 m. In XRD it shows a typical peak at 3.85 Å.
> **Analcime**: It is formed at similar temperature as chabazite, and is found in the drill cuttings from 100 to 200 m, and in a thin section at 180 m.
> **Stilbite**: It seems to be the most common zeolite found in the drill cuttings from well KJ-28. It is formed at higher temperature than chabazite and analcime, and is largely distributed in the upper 200 m of the well. Its presence has been confirmed by thin section studies where it was identified by its tabular form and parallel extinction. In XRD it shows peak values of 5.38 and 9.11 Å at 70 and 102 m depth.
> **Heulandite**: It is a low-temperature zeolite formed at similar temperature as stilbite, and is encountered at 150 m depth in drill cuttings. In XRD it has peak values between 2.35 and 2.56 Å. It is commonly found in the hyaloclastite series.
> **Laumontite**: It is a common zeolite formed at intermediate temperatures (120-180°C). It is identified in the drill cuttings at 225 m and in thin section it is noted at 255 m depth. Its presence is confirmed between 392 and 490 m. In hand specimen it is very soft and can easily be crushed between fingers. It transforms into wairakite above 200°C. It has characteristic peaks at 1.96, 4.3 and 4.83 Å.
> **Wairakite**: It is a calcium analogue of analcime which is mostly present in tuffaceous sediments, and is believed to be formed from alkaline hydrothermal fluids associated with geothermal steam. It is recognised in well KJ-28 at various levels below 550 m. In XRD it shows typical peaks of 5.67 and 3.71 Å. In New Zealand the actual occurrence is at depth where the observed temperature range is from 200-250°C (Steiner, 1955). Cloudy appearance is characteristic for wairakite due to abundant fluid inclusions. In thin section it is recognised by its characteristic cross-hatched twinning which is comparable to polysynthetic twinning of plagioclase. In Iceland wairakite occurs at temperatures between 200 and 300°C, and its first appearance along with quartz has been used during drilling for determining the depth of the production casings at Nesjavellir high-temperature field, which varies considerably from well to well (Fridleifsson, pers. com).

Prehnite: It is recognised at around 550 m depth. It is identified by its pale green platy crystals and by its habit, usually filling large cavities. In thin section it is recognised by its bow-tie structure. In XRD it is reported to show weak reflection peaks at 2.49 and 2.35 Å. The small size of the cuttings in the lower part of the well makes the recognition of prehnite very difficult in binocular. It has no pleochroism.

Albite: It is found as an alteration product of plagioclase (labradorite). It is found in thin section below 550 m in the deeper part of well KJ-28. It is recognised by its habit and lower refractive index than balsam. Albitisation in plagioclase occurs at the same depth where chlorite becomes the dominant sheet silicate (Kristmannsdóttir, 1982).

Clay minerals: Clay minerals are very important alteration minerals and very common product of basaltic glass, olivine, pyroxene and plagioclase. In well KJ-28 both coarse- and fine-grained clays (smectite) and mixed layer clays were seen in the vesicles and vein fillings.

Smectite: It is green to yellowish brown and mostly found lining the vesicles. In XRD it shows reflection peaks of 14.40 Å (untreated) which expand to 17 Å upon glycolation and collapse to 10.41 Å after being heated to 500-550°C for one hour.

Mixed layer clays: Mixed layer clays found in the well are interlayered smectite and chlorite. In thin section they are brown to yellowish. They give peaks between 14-15 Å, which expand to 17 Å upon glycolation and collapse back to 14 Å upon heating to 500-550°C.

Chlorite: It is found both as infilling and as a replacement mineral in the deeper part of the well. In the binocular study it is identified by its green colour and coarse grained nature. It is characterised by peaks at 14.4 Å which remain unchanged upon glycolation and heating (Brown and Brindley, 1980).

From the distribution of the secondary minerals as shown in Figure 9, it is clear that minerals formed at high and low temperatures co-exist over a wide depth range. This immediately suggests that some of the minerals formed at different times, which is supported by the time sequence study (Chapter 4.4). The distribution of several index minerals is used to outline the fields of index mineral zones discussed in Chapter 4.3.

4.3 Alteration mineral zonation

The degree of hydrothermal alteration in the rocks depends upon certain factors such as rock type, permeability, temperature, chemistry of invading fluids and duration of geothermal activity (Kristmannsdóttir, 1979; Elders et al., 1979). According to Browne (1978, 1984) minerals commonly used as geothermometers are zeolites, clays and amphiboles.

The mineral zonation in Icelandic rock has been studied and described by several authors. The pioneering studies date back to G.P.L.Walker's (1960) studies on the regional zeolite zonations in East-Iceland, and to Kristmannsdóttir and Tómasson's (1978) and Kristmannsdóttir's (1979) studies in both low- and high-temperature fields in Iceland. From these studies and some later modifications it is clear that many minerals can be used to outline index mineral zones, indicating a given temperature environment in either diagenetic- or hydrothermal environments. Most of the zeolites for instance, are formed at temperatures below 100°C. The only exceptions to this are mordenite, and especially laumontite which are formed at temperatures above 100°C up towards 200°C, and then wairakite which is formed at temperatures above 200°C up towards 300°C.

The clay mineral transformation from smectite (Sm) (very low temperatures - 200°C), through mixed layer clays (MLC) (200-230°C)) of smectite-chlorite, to pure chlorite (>230°C) has proved very useful to indicate temperature environments in high-temperature systems. At about 250°C epidote appears along with chlorite, useful to set a boundary to the fourth index mineral zone, and when temperature approaches 300°C actinolite starts to form, sometimes at the expense of chlorite.

The mineral zonation in well KJ-28 is shown at the right margin in Figure 9, based on the distribution of the secondary minerals, and is as follows:

Smectite-zeolite zone: This zone is marked by the presence of smectite, chabazite and stilbite and other zeolites. Temperature is less than 200°C. The zone extends from the top down to the depth of 180 m.

Mixed layer clay zone: This zone is marked by the presence of coarse-grained clays where chlorite is interlayered with smectites in addition to wairakite and albite. It extends from 180 to 500 m depth.

Chlorite zone: This zone is indicated by the presence of chlorite, wairakite, albite and sphene. The top of the chlorite zone is at 550 m depth and it extends down to 620 m depth.

Chlorite-epidote zone: It is mainly characterized by the presence of epidote and chlorite. It extends from 620 down to 808 m. It is not clear if a boundary to the actinolite zone is close but actinolite was found in the last XRD run from the well.

4.4 Mineral time sequences

Depositional sequences observed in thin sections (Table 2) show that most of the sequences begin by the deposition of clay minerals, followed by zeolites and then calcite in veins, and then quartz and chalcedony in the upper 400 m of the well. Sometimes pyrite seems to have been deposited after the clay minerals. Stilbite in the sequence indicated late deposition stage and generally fills the space between coarse-grained clays and calcite. The sequence of deposition seems to have progressed from low temperature (< 100°C) to intermediate temperature (200-230°C). A similar situation occurs with mineral sequence at a greater depth; chalcedony is followed by albite, wairakite and then chlorite. In the chlorite-epidote zone (> 250°C), the mineral sequences consist of fine-grained clays followed by chlorite and last in the sequence is wairakite.

TABLE 2: The sequence of deposition of alteration minerals in well KJ-28

Depth (m)	Rock series	Intensity of alteration	Time sequence of mineral deposition
150	Tuff	Low	Fine smectite-stilbite-calcite-quartz
150-270	Hyaloclastite-I	Medium	Fine smectite-coarse smectite-stilbite-chalcedony-fine-grained clay
270-390	Basaltic lavas	Medium	Coarse smectite-chalcedony-mixed layer clay-calcite-quartz
390-480	Hyaloclastite-II	Medium	Fine smectite-chlorite-calcite-clays-quartz-calcite
480-590	do.	High	Fine smectite-quartz-albite-wairakite-chlorite-calcite
590-804	do.	High	Coarse smectite-albite-chlorite-epidote-wairakite

4.5 Temperatures

Information on the temperature distribution in a geothermal system is sought at several sources. First of all, it is sought to direct temperature measurements on the surface and in drillholes. Then to surface mapping and hydrothermal mineral-temperature estimates in drillholes, which reflect temperatures within the rock formation both in the past and the present. Thirdly, an idea on the temperature distribution within a geothermal system is sought from resisitivity measurements on the surface. The latter two are based on several decades of experience in studying active hydrothermal systems at institutes like Orkustofnun and suchlike in other geothermal countries.

Most high-temperature systems are open to the surface and accordingly are controlled by the hydrostatic boiling curve, where the maximum temperature attainable at any depth is controlled by the weight of the overlying water column, i.e. the maximum temperature is controlled by the pressure. The pressure at a given site in geothermal system can change with time. For instance, during glaciation, several hundred metres of ice resulted in increased pressure at our given site in the geothermal system discussed.

Hydrothermal minerals in our system could preserve evidence for this different pressure regime, and this has in fact been reported from most studied high-temperature systems in Iceland.

In Icelandic borehole research, an effort is made to understand the hydrothermal evolution of the geothermal systems. This is done by estimating the present day formation temperature (rock temperature), which is compared with the secondary mineral temperatures which always reflect some temperature evolution. And commonly, both are compared with the present day boiling point curve, which may reach to the surface, or begin at the depth of the water table, which may be located some tens of metres below the surface. An example of such a comparison is shown in Figure 10 for well KJ-28.

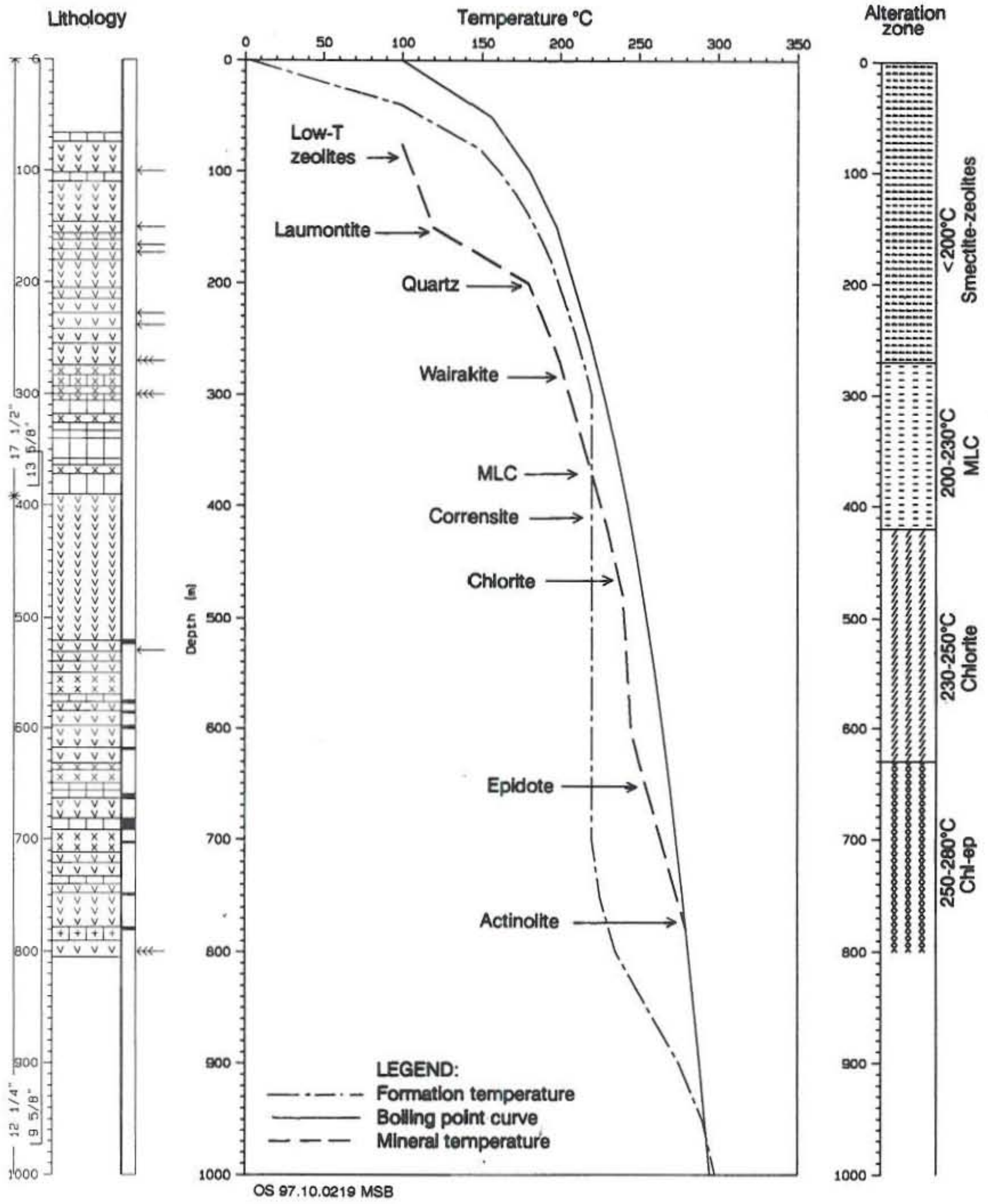

FIGURE 10: A graph showing the formation temperature, the boiling point curve and secondary minerals temperature in well KJ-28

Figure 10 shows the boiling point curve from the surface down, and the present day formation temperature which is estimated from many downhole temperature logs which were made during the heat-up period (as shown in Figure 6). The third temperature profile is the secondary mineral temperatures and is mostly based on the minimum temperature required to form a given mineral. The only exception to this is made at the top of the diagram, where it is set at 100°C (maximum temperature for the low-temperature zeolites). The first appearance of laumontite is set at 120°C, wairakite at 200°C, chlorite at 230°C, epidote at 250°C and actinolite at 280°C.

By comparing these curves it is clear that the undisturbed present-day temperature in the formation is lower than the secondary minerals temperature curve, which implies cooling in the geothermal system at the depth range studied. However, the minimum secondary mineral temperatures are all within the limits set by the boiling point curve, except perhaps actinolite which just surpasses it.

Finally, if the present-day formation temperature is compared to the general formation temperature characterizing the Leirbotnar production field (Figure 5), it is clear that the formation temperature in well KJ-28 is about 30°C higher than elsewhere, which may suggest some heating in the formation in the neighbourhood of well KJ-28. That correlates neatly with the splendid upflow zone penetrated by the drillhole at 808 m depth.

5. DISCUSSION

The currently used model of the Krafla geothermal system was described 10 years ago (e.g. Ármannsson et al., 1987). Three geothermal fields are distinguished, the Hvíthólar field, the Sudurhlídar field and the Leirbotnar field, in which well KJ-28 is located. Figure 11 shows the existing model of the Leirbotnar drillfield (Ármannsson et al., 1987) which is separated into an upper zone and a lower zone. The division between them is below 1000 m depth below the surface. The temperature distribution in these two zones is shown to the right in the figure, where temperatures around 200°C characterize the upper zone, while the lower zone is characterized by much higher temperatures approaching the boiling point curve.

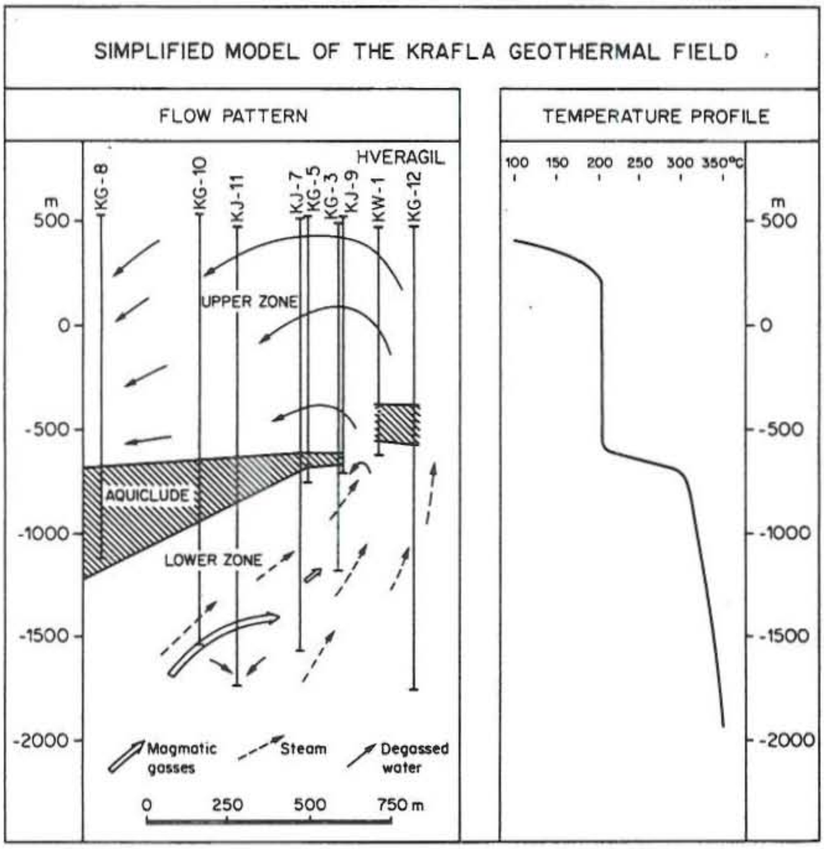

FIGURE 11: A simplified flow model of the Krafla high-temperature system (Ármannsson et al., 1987)

A major upflow zone in the Hveragil fracture area is shown on the hydrothermal model, where hot fluid is moving upwards from the lower zone to the upper zone. Well KJ-28 is located in this upflow zone. It experienced a total circulation loss from 800 m down to 1000 m depth. The subsequent downhole temperature log, done shortly after drilling, is suggestive of a fracture controlled cooling pattern as discussed in Chapter 2. That, and the secondary mineralogical evolution in well KJ-28, as discussed in Chapter 4, support the current model of a major upflow zone in the Hveragil gully.

6. CONCLUSIONS

1. The lithology and distribution of hydrothermal minerals in well KJ-28 in Krafla was studied through drill cuttings, combined with the data from the drilling operation and downhole geophysical logs.

2. The study supports ideas that the well was located in a major fault-controlled hydrothermal upflow zone.

3. The hydrothermal rock alteration is grouped into four hydrothermal index mineral zones which are temperature dependent, with an increasing temperature smectite-zeolite zone (low temperatures up to 200°C), mixed layer clay zone (200-230°C), chlorite zone (230-250°C) and chlorite-epidote zone (250-280°C).

4. Comparison of estimated formation temperatures in the hydrothermal system prior to the drilling, with fossil temperature in the rock formation as suggested by the secondary mineral study, and with the hydrothermal boiling temperature curve, implies that the hydrothermal system has cooled considerably in recent times.

5. Comparison with the other wells in the Leirbotnar field in Krafla suggests that this cooling effect is diminishing and the area around well KJ-28 is recovering, i.e. the formation temperature is increasing again, which supports the suggested location of a major upflow zone in the system.

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APPENDIX: Preparation of samples for analysis by XRD methods and results

Method I - Alteration minerals

1. Pick from the rectangular boxes of the drill cuttings of well KJ-28, the grains of important alteration minerals especially from vesicles or veins. Pick at least three grains for a single run.

2. Crush the sample in an agate bowl to 5-10 microns, acetone is added to make a slurry.

3. Paste the sample slurry on quartz slide MIN B.

4. Run the sample from 3 to 6 θ on XRD.

Method II - Clay minerals

1. Place two teaspoons of cuttings into a test tube. Fill the tube with distilled water and plug with rubber stopper. Place the tube in a mechanical shaker 4-8 hours depending upon the alteration grade of the sample.

2. Remove the test tubes from the shaker and allow it to settle for 1-2 hours. Pippette out a few mm from the test tube, make a duplicate of each sample and leave it to dry for 24 hours.

3. Place one set of samples in dessicator containing ethylene glycol, at room temperature for at least 24 hours.

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

TABLE 1: Results of the XRD analysis of clay minerals

Depth (m)	**Untreated d (Å)**	**Glycolated d (Å)**	**Heated up to 550°C d (Å)**	**Probable clay minerals and secondary minerals**
100	14.4	17.08	10.41, 9.21	Smectite
184	14.25	17.0	9.85	Smectite
272	14.89	16.95	9.6	Smectite
334	14.4, 7.14	14.4, 7.14	14.45	Chlorite
422	14.4, 7.15	14.16, 10.2	13.81, 7.7	Chlorite
520	14.41, 7.13	14.25, 14.48	14.16, 7.7	Chlorite
580	14.41, 7.12	14.02, 7.13	14.41, 7.7	Chlorite
620	14.27, 7.15	14.47, 7.15	14.41, 7.15	Chlorite
670	14.40, 7.12	14.40, 7.15	14.41, 7.2	Chlorite
702	14.45, 7.14	14.41, 7.14	14.25, 7.13	Chlorite
750	14.55, 7.17	14.6, 7.2	14.4	Chlorite
800	14.46, 7.15	14.46, 7.15	14.48, 8.43	Chlorite + actinolite