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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 drillcuttings of 100 3 m deep drillhole located in the Krafla high-temper ature area. The strata penetrated by the drillhole con sist of fine to medium grained basalts (olivine tholeii tes & tholeiites), altered glassy basalts, basaltic tuff a nd breccia which are referred as hyaloclastites. Intru sions appear at various depth levels,and there are m ore than 15 aquifers encountered in the well. Both hi gh-temperature(>200^{0}C) and low temperature (40-20 0^{0}C) hydrothermal alteration minerals are reported fr om the well. According to the distribution of alterati on minerals four alteration zones have been identifie d viz.smectite zeolite zone (<200^{0}C) down to 180 m depth, mix layer clay zone (200-230^{0}C) > 180 to 525 m, Chlorite zone (230-250^{0}C) from 525-600m depth and Chlorite-epidote (250-280^{0}C) continuous down to the depth of 808 m. No cuttings were collected be low 808 m to the bottom of the well because of total circulation loss (>40 l/s). The increase in temperatur e is indicated by transformation of clays from fine t o coarse grained. Zeolites are most common above 2 50 m depth. With the increased depth the smectite becomes ineterlayered with chlorite and high-tempe rature minerals such as wairakite appear. With further increase in depth and temperature minerals such as epidote, albite and sphene appear. Calcite, pyrite, an d quartz are distributed in all alteration zones. Comp arison of the well KJ-28 with other wells in the area shows that it is located in a major upflow zone.

1. INTRODUCTION

Geothermal areas are divided into two groups i.e. hi gh-temperature areas where the rock temperature exc eeds 200^{0}C at 1km and the low temperature areas wh ere the temperature is below 150^{0}C at one km depth. (Fig 1).High temperature areas are located within t he zone of rifting and volcanism. A boundary between American and European plates run along the rift zone in Iceland. The rocks here are generally fresher than those within the adjacent Tertiary and Quaternary successions apart from the high-temperature hydrothermal manifestations 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.

1.1 Study area: Krafla high-temperature area is loc ated about 10 km from Lake Myvatn in NE Iceland (Fig. 2). All the drillholes are located in Krafla Cald era which was formed about 100 thousand years ago at the beginning of the last interglacial period (Sae mundsson, 1979). A magma chamber is located abou t 3-8 km depth in the roots of the Caldera. (Figure 3). The area has been subjected to many volcanic erup tions, the most recent one was in the year 1975-84 co mprising the nine eruptive episodes (Björnsson 198 5). Since 1982 30 MW of electric power is being pro duced in a single steam turbine which is the only hal f of the rated capacity of 60 MW plant. Several wells became contaminated with magmatic gases in 1976 which resulted in corrosion and calcite scaling *(Arm annsson et al., 1987).* Since 1984 volcanic gases hav e steadily diminished and few years it was decided to increase the electricity production upto 60 MW. To meet this requirement several wells were drilled incl uding well KJ-28. These wells are located in the geot hermal fields namely Leirbotnar, Sudurhlidar and H vitholar as shown in the map.

1.2 Methods: Three methods were used for the stud y of the drillcuttings from the well KJ-28 in the Kraf la high-temperature area. Initially the drillcuttings c ollected at every 2 m depth were studied with the hel p of Stereo microscope then a representative batch of samples were analysed in thin section with petrogra phic microscope. Finally the clays and other selective secondary minerals were identified by using X-ray d iffractometric techniques.

1.3 Drilling and Logging of the well KJ-28

Well KJ-28 is located in the Leirbotnar well field of t he Krafla high-temperature area. The well was first drilled with a small rig and 18½” casing was put do wn and cemented. Then a larger rig was brought and a 17½” hole was drilled down to 395 m depth and 13⅜" anchor c asing was cemented down to that depth. The product ion part of the well was drilled down to 1003 m dept h with 121/4" drill bit and 9 5/8" slotted liner.

2. HYDROTHERMAL ALTERATION

Hydrothermal alteration of the rock depends upon several factors such as temperature, pressure, lithology and subsurface structure of the rocks e.g. glassy rocks are more susceptible to alteration than the crystalline rocks and a close correlation between the temperature and the type of secondary minerals is found in most geothermal systems of the world.

2.1 Rock alteration: The primary mineral composition of basaltic rocks in Iceland is relatively uniform comprising calcic plagioclases, clinopyroxene, olivine and magnetite ilmenite. The rapid cooling of basaltic magma results in a quenched volcanic glass. Hyaloclastite tuff may be composed of volcanic glass only, while the breccia and lavas range in glass content from a lot to very minute quantity. Glass is more susceptible to secondary alteration, than olivine follo wed by plagioclases, pyroxenes and the ore minerals. Nevertheless it is the fluid composition which deter mine which primary mineral is first to react with the fluid (Fridleifsson, pers com). Table 1 shows the mo st common secondary minerals formed at the expenc e of glass and primary minerals.

2.2 Distribution of alteration minerals:

The distribution of alteration minerals found in the Krafla well KJ-28 is shown in (Fig: 4) . They are mo stly identified by drillcutting analysis and petrograph ic study. The alteration minerals comprise calcite, qu artz, chalcedony, stilbite, chabazite, analcime, heula ndite, mordenite, laumontite, prehenite, wairakite, e pidote, sphene, pyrite, iron-oxide, smectite, mixed la yer clays and possibly corrensite.

2.3 Mineral time sequences:

Deposition sequences observed by thin section study (Table 2) shows that most of the sequence begins with the deposition of clay minerals followed by zeolites, chlorite 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 indicate the late depositional stage a nd generally fills the space between coarse grained c lays and clacite . The sequence of deposition has progressed from the low temperature (< 100^0C) to intermediate temperature (125-230^0C). A similar situation occurs with minerals at greater depth. Chalcedony is follow ed by albite wairakite and chlorite. In the chlorite-epi dote zone (>250^0C) mineral sequence consists of fine grained clays followed by chlorite and last in the seq uence is wairakite

2.4 Temperatures.

The measurement of temperature distribution in a geothermal system is done by various methods. Temperature measurements on the surface and in the drillholes is the most common method. The estimate of the temperature distribution within a geothermal syst em is sought from the resistivity measurements on the surface. The last two methods are based of several decades of experience in studying active hydrothermal system.. Assemblages in the boreholes reflect the temperatures within the rock formations both present and in the past. The borehole studies in Iceland are made to understand the evolution of geothermal syste m by correlation of present day subsurface temperatu re with the temperature indicated by secondary mine rals. Comparison of the present day temperature esti mated by alteration minerals with the boiling point c urve gives trend of heating/cooling of the geothermal reservoir as shown in (Figure: 5) of the well KJ-28. The figure shows the boiling point curve from the su rface down and the present day formation temperatur e which is estimated from many downhole temperat ure logs which were made during the heating up peri od. The temperature profile of the secondary mineral temperature is mostly based upon the minimum tem perature required to form a mineral except for zeolite s which is 100^0 C maximum. The first appearence of laumontite is set at 120^0C , wairakite at 200^0 C , Chl orite at 230^0C , epidote at 250^0C and actinolite at 28 0^0C. By comparing these curves it is clear that undist urbed present day temperature in the formation is lo wer than the secondary mineral temperature curve w hich implies cooling in the geothermal system at the depth range studied. However the minimum seconda ry temperature are all within the limits set by the boil ing point curve except perhaps actinolite which surp asses it. Finally if the comparison of the present day temperature is made with the formation temperature characterizing the Leirbotnar Field it is clear that the formation temperature in the well is about 30^0 highe r then elsewhere which may suggest some heating in the formation in the neighbourhood of the well KJ-2 8. That correlates neatly with the standard upflow zo ne penetrated by the drillhole at 808 m depth.

3. DISCUSSION

The currently used model of the Krafla geothermal system was described ten years ago *(Armannsson et **al.,1989)**.* The investigations of the subsurface lithol ogy are based on the analysis of the drillcuttings, geo logical structure, the distribution of individual units , the correlation of aquifers with these and the degree of rock alteration. The three geothermal fields are; H vitholar field, the Sudhurlidar Field, and the Leirbot nar Field in which the well KJ-28 is located. All the drill fields are within the Caldera. The surface area o f the Krafla caldera extends over 64 km^2 and the cald era filling is about 1 km thick. Fig 11 shows the exist ing model of the geothermal area which is separated into upper zone and lower zone. The division betwee n them is separated by 1000 m thick strata. The temp erature distribution is shown to the right of the figure . The temperature about 200^0C is characteristic of up per zone while the lower zone is signified by higher t emperature approaching the boiling point curve. Hot fluid is moving upward from the lower zone to the u pper zone i.e. the well KJ-28 is located in the upflow zone. A total circulation loss is experienced from 80 0 m down to 1000 m depth . The subsequent downho le temperature log done shortly after drilling, is sugg estive of a fracture controlled permeability and secon dary mineral evolution in the well KJ-28.

4. CONCLUSIONS

The lithology and distribution of hydrothermal miner als in well KJ-28 in the Krafla area was studied thro ugh the drillcuttings combined with the data obtaine d from the well testing. The study supports the idea t hat the wells were located in a major fault controlled hydrothermal upflow zone. The hydrothermal rock al teration is grouped into four hydrothermal index min eral zones which are temperature dependent in order of the increasing temperature. Smectite-zeolite zone is low temperature is low temperature (upto 200^0C), mix layer clay zone ($200\text{-}230^0$), Chlorite zone (230-2 50^0C) and chlorite-epidote zone ($250\text{-}280^0$C). Compa rison of the measured formation temperature in the h ydrothermal system during the drilling with fossil te mperatures in the rock formation as suggested by sec ondary mineral study and with the hydrothermal boil ing point curve which implies that the hydrothermal system cooled considerably in recent times. The co mparison of well KJ-28 with the other wells in the Li erbotnar field in the Krafla high-temperature area, r eveals that the cooling effect is diminishing and the area around the well is recovering i.e. the formation temperature is increasing again, which supports the suggested location of a major upflow zone in the syst em.

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TABLE 1: Primary minerals and their alteration products.

Primary minerals	**Secondary minerals**.
Volcanic glass	Zeolites, quartz, chalcedony, clay, sphene.
Olivine	Iddingsite, clays and calcite.
Plagioclase	Albite, adularia, quartz, chlorite, epidote, titanite
Pyroxenes	Chlorite, clay, quartz, pyrite and calcite.
Ore	Titanite, pyrite, limonite, phyrrotite, and second ary oxides.

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 grained smectite-stilbite-calcite-quartz.
150-270	Hyaloclastie I	Medium	Fine smectite-coarse smectite-stilbite-chalcedony-fine grained clay.
270-390	Basaltic lavas	Medium	Coarse smectite-chalcedony-mixed layer clay, calcite and quartz.
390-480	Hyaloclastite II	Medium	Fine smectite-chlorite-calcite-clays-quartz.
480-590	-do-	High	Fine smectite-quartz-albite-wairakite-chlorite-calcite.
590-804	- do-	High	Coarse smectite-albite-chlorite-epidote-wairakite.

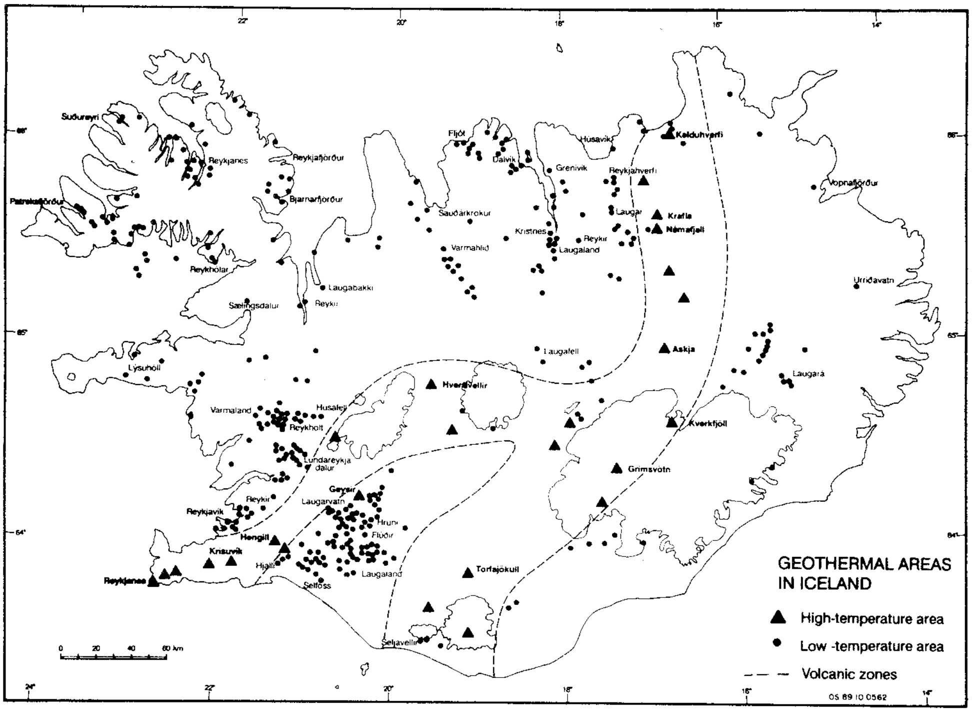

FIGURE 1: A simplified geological map of Iceland showing the location of high-temperature and low-temperature areas

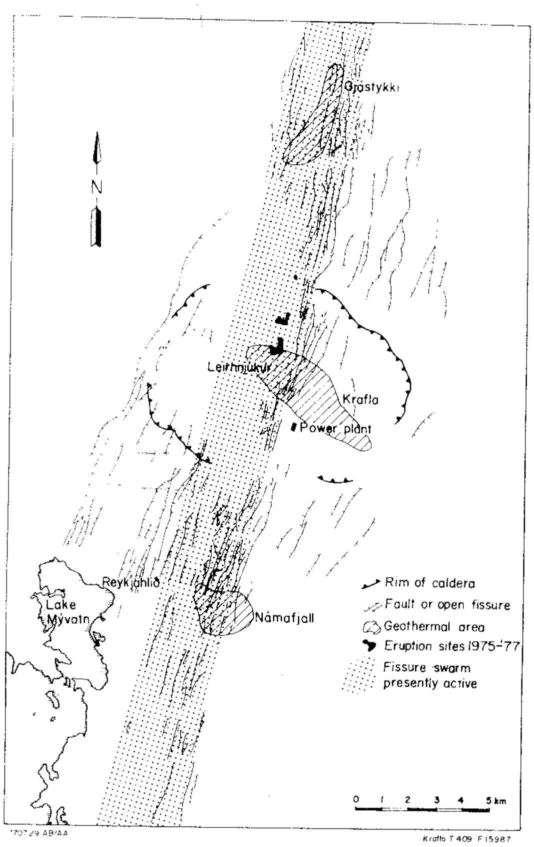

FIGURE 2: Tectonic map of the Krafla area showing the caldera, the active fissure swarm and the location of the Krafla power plant (Stefánsson, 1981)

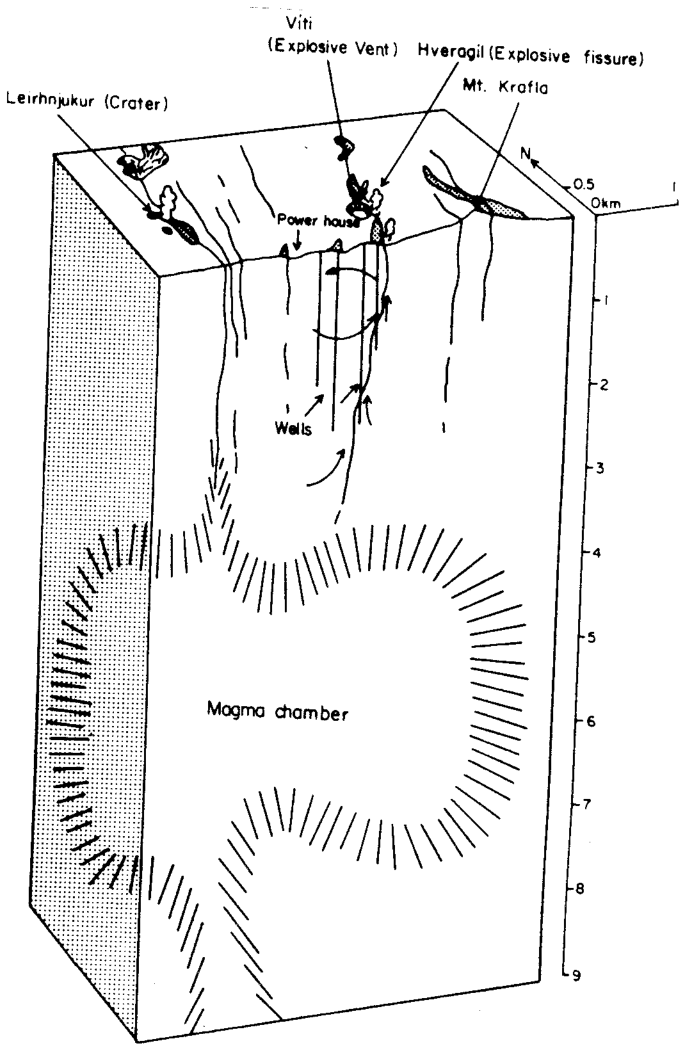

FIGURE 3: The Krafla area and the underlying magma chamber (Stefánsson, 1981)

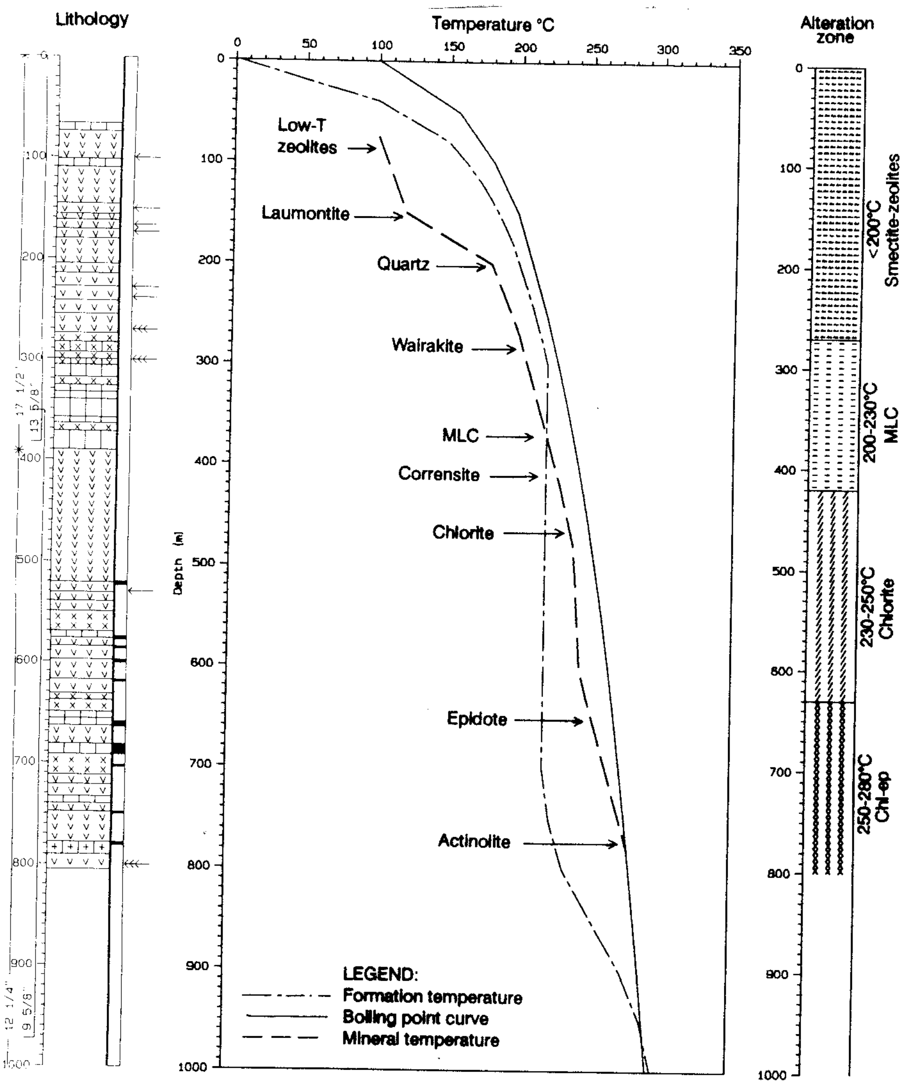

Fig 3: A graph showing the boiling point curve, and the secondary mineral temperatures.

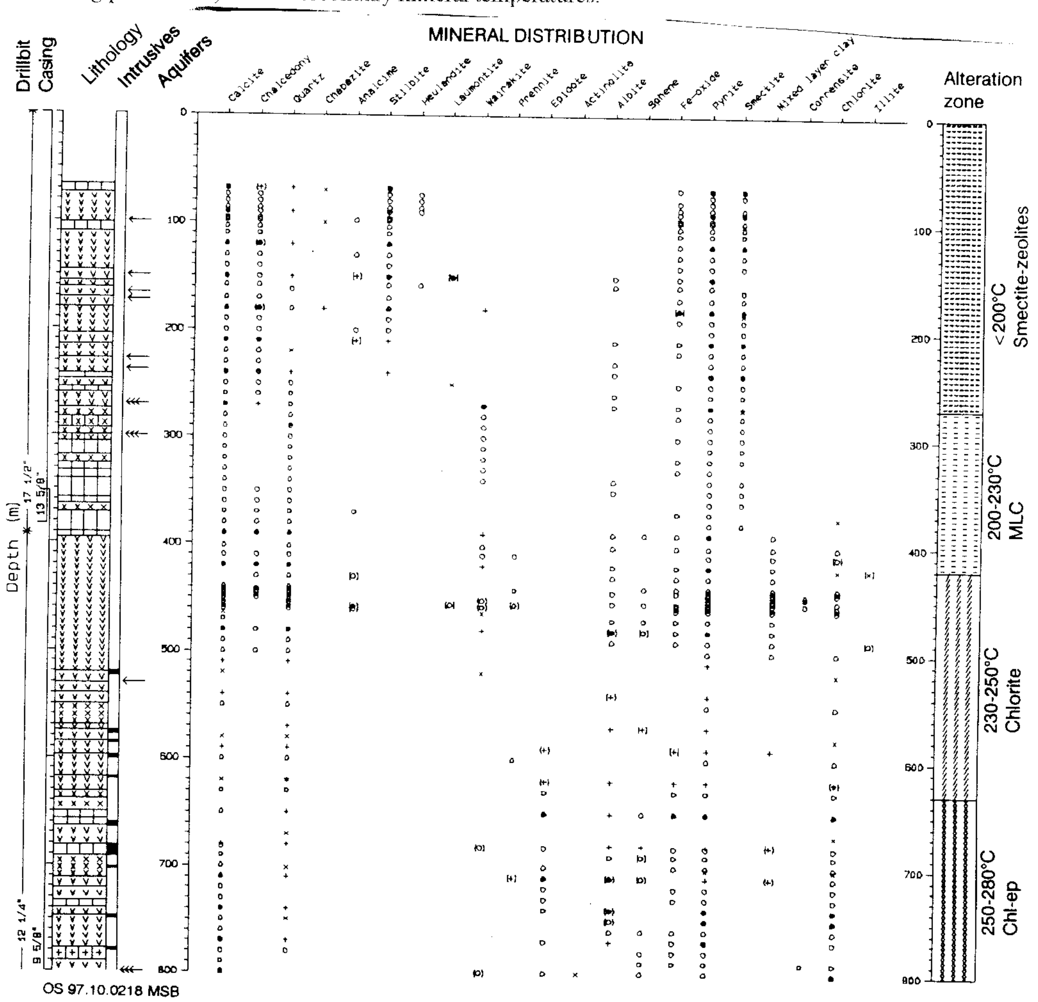

Fig 4: Secondary mineral distribution and alteration zones in well KJ-28.