PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 29-31, 2001
SGP-TR-168

DRILLHOLE 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 the drill cuttings of a 1003 m deep drill hole located in the Krafla high-temperature area. The strata penetrated by the drillhole comprise fine to medium grained basalts (olivine tholeiites and tholeiites), altered glassy basalts and basaltic tuffs and breccias which are referred to as hyaloclastites. Intrusions in the well appear at 520, 635, 700, 725, and 780 m depth. There are more than 15 aquifers. Both high temperature (>200oC) and low temperature (40-200oC) hydrothermal minerals are present in the well. According to the distribution of deposition minerals four alteration zones have been identified . They are smectite-zeolite zone (<200oC) down to 180 m depth, mix layer clay zone (200-230oC) down to the depth of 525 m, chlorite zone (230-250oC) down to 600 m depth and chlorite-epidote zone (250-280oC) 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 the total circulation loss (>40 l/s) . The increase in the temperature is indicated by the transformation of low grade clays to relatively coarse clays. With increasing depth the smectite becomes inter-layered with chlorite and high-temperature minerals such as wairakite appear. With the further increase in depth and temperature, epidote albite and sphene identified . They are smectite-zeolite zone (<200oC) down to 180 m depth, mix layer clay zone (200-230oC) down to the depth of 525 m, chlorite zone (230-250oC) down to 600 m depth and chlorite-epidote zone (250-280oC) 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 the total circulation loss (>40 l/s) . The increase in the temperature is indicated by the transformation of low grade clays to relatively coarse clays. With increasing depth the smectite becomes inter-layered with chlorite and high-temperature minerals such as wairakite appear. With the further increase in depth and temperature, epidote albite and sphene were identified Calcite pyrite and quartz are identified in all the alteration zones. Zeolites are most common above 250 m depth. Comparison of well KJ-28 with another drillholes in the area shows that it is located in a major upflow zone.

INTRODUCTION

Geothermal areas in Iceland are divided into two groups i.e. high-temperature areas where the rock temperature exceeds (200oC) at 1 km depth and the low temperature areas where the temperature is below 150oC at the same depth. High temperature areas are located with the zone of rifting and volcanism. Boundary between American and European plate run between America and European plates run along the rift zones in Iceland. The rocks here are fresher than those within the adjacent Tertiary and Quaternary successions apart from the high temperature hydrothermal manifestations on the surface.

Study area: Krafla high temperature area is located about 10 km from the lake Myvatn in NE-Iceland (Figure 1). All the drillholes are located in the Krafla caldera which was formed 100 thousand years ago at the beginning of the last interglacial period. (Saemundsson.,1979). A magma chamber is located about 3-8 km depth in the roots of the caldera. The area has been subjected to many volcanic eruptions the recent one was in the year 1975-84 comprising the nine eruptive episodes (Bjornsson., 1985). Since 1982 30 MW of electricity is being produced in a single steam turbine which is the only half of the rated capacity of 60 MW plant Several wells became contaminated with magmatic gases in 1976 which resulted in corrosion and calcite scaling (Armannsson et al., 1987). Since 1984 volcanic gases have diminished and for few years it was decided to increase the electricity production upto 60 MW. To meet this target many wells were drilled including the well KJ-28. These wells are located in the geothermal fields namely Leirbotnar, Sudurhlidar, and Hvitholar (Figure 2).

Methods: Three methods were used for the study of the drillcuttings from the well KJ-28 in the Krafla high temperature area . Initially the drill cuttings collected at every 2 m depth were studied with the help of stereomicroscope, and then a representative batch of samples was analyzed in thin section with petrography microscope. Finally using X-ray diffractometric techniques identified the clays and other selective secondary minerals.

Drilling and logging of the well KJ-28

The well KJ-28 is located in the Leirbotnar well field of the Krafla high-temperature area. The well was initially drilled with small rig and 181/2” casing was put down and cemented. Then a larger rig was brought in and a 171/2” hole was drilled down to 395 m depth and 133/8” anchor casing was cemented down to that depth. The production part of the well drilled down to 1003 m depth with 121/4” drill bit and 95/8” slotted liner.

2. HYDROTHERMAL ALTERATION:

hydrothermal alteration of the rock depends upon several factors such as temperature, pressure, litho logy, nature of fluid and sub surface structure of the rocks e.g. glassy rocks are more susceptible to alteration then the crystalline rocks and a close correlation between the temperature and the type of secondary mineral is found in most geothermal system of the world.

Rock alteration: The primary mineral composition of basaltic rocks in Iceland relatively uniform comprising calcic plagiclases, clinopyroxene, olivine, magnetite and ilmenite. (Table 1) The rapid cooling of basaltic magma results in quenched volcanic glass. Hyaloclastite tuff may be composed of volcanic glass only, while the breccias and lavas range in glass content from a lot to very minute quantity. Glass is more susceptible to secondary alteration then olivine followed by plagioclases, pyroxene and ore minerals. Nevetheless it is the fluid composition which determine primary mineral is first to react with the fluid (Fridleifsson pers. com). Table 1 shows the most common secondary minerals formed at the expense of glass and primary minerals .

Mineral time sequences: Deposition sequences observed by thin section study shows that most of the sequence begins with the deposition of clay minerals followed by zeolites, chlorite in veins an then quartz and chalcedony in the upper 400 m of the well. (Table 2). Sometimes pyrite seems to have been deposited after clay minerals. Stilbite in the sequence indicates the late depositional stage and generally fills the space between the coarse grained clays and calcite. The sequence of deposition has progressed from low temperature (<100oC) to intermediate temperature (<125-230oC) A similar situation occurs with minerals at greater depth . Chalcedony is followed by albite, wairakite and chlorite. In the chlorite epidote zone (>250oC) mineral sequence consist of fine grained clays followed by chlorite and last in the sequence is wairakite.

Alteration mineral zonation

Many hydrothermal minerals in Iceland are highly temperature dependent where definite mineralogical changes are seen to take place with increasing temperature.(Kristmannsdottir.,1978)Figure 3 shows that zeolites are found upto temperature of 200oC where they are transformed to wairakite . Quartz forms at temperature above 180oC and calcite may form upto temperature around 270oC. Alteration mineral zones in well KJ-28 are divided into smectite-zeolite zone, mix layered clay zone, a chlorite zone and a chlorite-epidote zone. Each zone is described as follows:

Smectite-zeolite zone: This zone is marked by the presence of steatite, chalazae, natrolite and stilbite in association with quartz. Temperature in this zone is less than 200oC. This zone extends from top to about 140 m depth.

Mix layer clays zone (MLC): It is marked by the presence of coarse grained clays and supported by wairakite albite and swelling chlorite. Temperature ranges from 200-230oC. This zone extends from 140-380 m depth.

Chlorite zone: This zone is indicated by the presence of chlorite and swelling chlorite (Corrensite) and is also supported by wairakite and albite. The top of the chlorite zone is found at 380 m depth and it extends down to the maximum depth of the well. The temperature ranges 23-250oC.

Chlotite-epidote zone: It is clearly marked by the presence of epidote and chlorite. It is also supported by wairakite, albite, sphene and calcite. Temperature in this zone is above 250o C.

Mineral time sequences

Depositional sequences observed in thin sections (Table 2) shows that most of the series begin by the deposition of clay minerals, followed by zeolites and then calcite in veins, and then quartz and chalcedony in upper 400 m of the well. Sometimes pyrite seems to have been deposited after the clay minerals. Stilbite in the sequence indicates 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 (>100oC) to intermediate temperature (200-230oC). A similar situation occurs with mineral sequences at greater depth, chalcedony is followed by albite, wairakite and then chlorite. In the chlorite-epidote zone (>2500C) the mineral sequence consists of fine grained clays followed by chlorite and last in sequence is wairakite. The temperature and mineral evolution goes from 2000C upto 280oC.

Lithology and Aquifers: Well KJ-28 was only drilled into basaltic rocks according to the drill cutting analysis and the available geophysical logs. These rocks are rather uniform in composition , either constituting olivine tholeiites or finer grained tholeiites. The lithofacies however are more variable ranging from sub aerial lava flows with lava scoria in between, to sub glacially extruded hyaloclastites, which range from pure glassy tuff to partly crystalline breccias of clastic rocks. The lavas and hyaloclastites are either aphyric or porphyritic. Several intrusions cut the succession of extrusive rocks, which can be separated into three main lithological series. Hyaloclastite –I extends from the surface down to 270 m depth. A basaltic 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.

profile of the secondary minerals is mostly based upon the minimum temperature required to form except for zeolite, which is 100oC maximum. The first appearance of laumontite is set at 120oC, wairakite at 200oC, chlorite at 230oC, epidote at 250oC, and actinolite at 280oC. By comparing these it is clear that undisturbed present day temperature in the formation is lower than the sendary mineral temperature curve which implies cooling in the geothermal system at the depth range studied. However the minimum secondary temperature are all within the limits set by boiling pint curve except perhaps actinolite which surpasses 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 is about 30o higher than elsewhere which may suggest some heating in the formation i9n the neighbourhood of the well KJ-28 that correlates neatly with the standard upflow zone penetrated by the drillhole at 808 m depth.

RESERVOIR MODEL:

Extensive numerical modeling studies of the Krafla geothermal area were carried out in 1982-83. These were limited to the main well fields namely Lierbotnar, Sudurhlidar, and Hvitholar the main emphasis was on verifying the conceptual model of the field from the exploitation results (Fig 5) and to quantify the mass heat flow in the reservoir. Further it was also intended to to verify the teransmissivity values obtained from the analysis of injection tests. The Krafla modeling has been described by (Bödvarsson,,et al, 1984). The model comprised vertical cross section which included both Leirbotnar anhd Sudurlidar well fields. The simulation model is in agreement with the assumption that the reservoir system is controlled by two upflow zones one at Hveragil and the other very close to the eastern border of Sudurhlidar. The lower reservoir in Leir botnar and Sudurhlidar are two phase with average vapour saturation of 10-20% in the fracture system. The porosity of the reservoir was assumed to be 5%. The permeability of the reservoir was about 1-4 milli darcy with an average of 2.0 md. The permeability of up flow channels at Hveragil and Sudurhlidar is estimated as 30 md. Fluids from the up- flow channel recharge the reservoir at an estimated rate of 10 kg/s. The two phase fluid mixture flows laterally along highly permeable fracture zone at a depth of 1 km and mixes with the upflow at Hveragil. Lumped parameter model was made to estimate the generating capacity of the reservoir. The results obtained indicate that the generating capacities of Leirbotnar and Sudurhlidar are 30 and 20 MWe for thiry years.

TEMPERATURE:

methods . Temperature measurements on the surface and in the drillhole are the most common method. The estimate of temperature distribution within a geothermal system is sought from the resistivity measurements on the surface. The last two methods are based on several decades of experience in studying the active hydrothermal system . Assemblages in the borehole reflect the temperatures within the rock formation both present and in the past. The borehole studies in Iceland are made to understand the evolution of geothermal system by correlating present day subsurface temperature with the temperature indicated by secondary minerals.

Comparison of present day temperature estimated by alteration minerals with the boiling point curve gives trend of heating cooling of the geothermal reservoir (Fig 5). The figure shows the boiling point curve from the surface down and the present day formation temperature, which is estimated by many downhole temperature logs, which were made during the heating up period recovering, i.e. the formation temperature is increasing again which supports the suggested location of a major upflow zone in the system which is temperature dependent with increasing temperature with depth.

CONCLUSIONS

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

The study supports the idea that the well was located in a major fault controlled upflow zone.

The hydrothermal rock alteration is grouped into four hydrothermal index mineral zones which are temperature dependent with increasing temperature with depth.

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

Comparison with the other wells in the Leirbotnar field in the Krafla area suggests that this cooling effect is diminishing and the area around the 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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