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THE ELDVORP HIGH-TEMPERATURE AREA, SW-ICELAND. GEOTHERMAL GEOLOGY OF FIRST EXPLORATION WELL.

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ABSTRACT

Surface geology and resistivity data show that the eruption episode of 2100-2500 years ago in the Eldvorp region causes a downflow of colder groundwater in the northern part of the "fissure swarm" while an upflow characterizes its central part. The first exploration well EG-2 disects two vertical dyke feeders; the older one, a dolerite, dates back to less than 12000 yrs while the younger one is the feeder to the 2150 yrs Eldvorp eruption. Hydrothermal alteration pattern shows that these vertical structures provide the main upflow channels of the Eldvorp system. A study of the deposition sequence in veins and vesicles shows evolution stages from a low-temperature to a high temperature system. The last deposition suggests that the system is showing some cooling below 1200 m depth.

INTRODUCTION

The Eldvorp high temperature area is located about 6 km WSW from the Svartsengi high-temperature field on the western part of the Reykjanes Peninsula (fig.1). The field has been investigated by Orkustofnun (National Energy Authority) mainly for the Sudurnes Regional Heating. This paper deals chiefly with the results of the subsurface geology of the first exploratory well drilled in the Eldvorp area. The well discharges 150 kg/sec at 7 bar wellhead pressure, has a maximum temperature of 262 °C and an enthalpy of 1339 kJ/kg. The waters have a salinity of about 2/3 sea-water similar to that found in the Svartsengi field to the east.

SURFACE EXPLORATION

Jonsson (1973, 1978, 1983) mapped in detail the surface geological features in the Reykjanes peninsula, and dated the post-glacial volcanicity. About 2100 to 2500 yrs ago, relatively intense volcanic activity prevailed in a 2.5 km wide zone centering in the main Eldvorp fissure line (fig. 1). Georgsson and Tulinius (1983) mapped the resistivity structures of the western Reykjanes Peninsula. The iso-thermal lines at 600 m depth (fig. 1), which are derived from resistivity values, show a WSW-trending belt of relatively high temperatures culminating at the Svartsengi and Eldvorp fields; this belt coincides with a deeper micro-seismic zone (fig. 1). A marked temperature variation occurs in the area of the Eldvorp fissure "swarm"; anomalously low temperatures in the northeastern part, high in the central part, and a gentle fall in temperature towards the south-east. The anomaly can be explained by the intrusion of apparently cold waters from the northeast along the Eldvorp fissures, whereas in the central part the fissures are providing a passage for ascending hydrothermal fluids which then flow towards southeast. Surface thermal alteration is found at two locations (fig.1), both on or adjacent to an Eldvorp eruptive fissure. The southern one is located on the high temperature resistivity anomaly and is active, whereas the northern one is inactive and is according to the resistivity within a relatively cold area.

DRILLING

The well EG-2 is the first exploration well to be sunk into the Eldvorp high temperature system. It was sited a few tens of meters to the west of the main Eldvorp fissure, at the western end of the low-resistivity anomaly and within the active surface manifestation. It was drilled early 1983 and took 49 days to complete. Although EG-2 was an exploration well it was designed as a production well. The uppermost 60 m were drilled with a percussion drill and cased with a 18 5/8" casing. A rotary drill rig continued with a 17 1/2" bit down to 528 m and a 13 3/8" production casing was cemented in down to 525 m depth. The production part of the well was drilled with a 12 1/4" bit. At 1265 m depth, the bottom of the string became stuck and some 15 m of the string had to be left behind in the well. Further drilling was abandoned due to rapid downflow from aquifers at 535-575 m depth resulting in a rapid heat-up and a subsequent pressure-buildup at wellhead. The well was cased with a slotted 9 5/8" liner down to 1208 m depth. The maximum inclination from vertical is about 3° at 1100 m depth.

SUBSURFACE GEOLOGY

The lithology and the alteration in the cutting samples (taken at 2 m intervals) were identified using binocular stereo-and petrographic microscopes and XRD methods used in identifying alteration minerals. The sampling depth was corrected for the time it took for the cuttings to travel to surface. Geophysical lithological logs were also used to locate formation boundaries. The resolution of the stratigraphy is estimated to be of the order of 1 m for most parts of the well. The primary aim of mapping the geology of the well was to locate the structures that affect the geothermal system.

The simplified geological section of the well (fig. 2) shows the succession to be totally composed of basaltic igneous rocks of two types; accumulative volcanics and intrusive rocks. The former constitutes about 75% of the succession and is divided into subaerial lava sequences intersected by distinct hyaloclastite horizons that represent volcanic eruptions during glaciations. Only a minor part of the hyaloclastites were identified as having been reworked. The sequence can fairly easily be correlated with the stratigraphic sequence found in wells of the Svartsengi field some six kilometers away (fig. 3). The age of the sequence, as evidenced by the number of hyaloclastite horizons (glaciations), ranges from Recent to more than 0.5 m.y. at the base of the Eldvorp borehole.

The uppermost hyaloclastite horizon in the Eldvorp area is very likely to have formed during the last glaciation which ended some 12000 years ago. The overlying lava sequence can be divided into two parts where the upper 30 m belong to the 2150 year old Eldvorp fissure eruption, and the lower 70 m can be related to an older olivine tholeiite shield volcano.

The well penetrated about 25% of intrusives. Their occurrence in the well is unusual because they are most

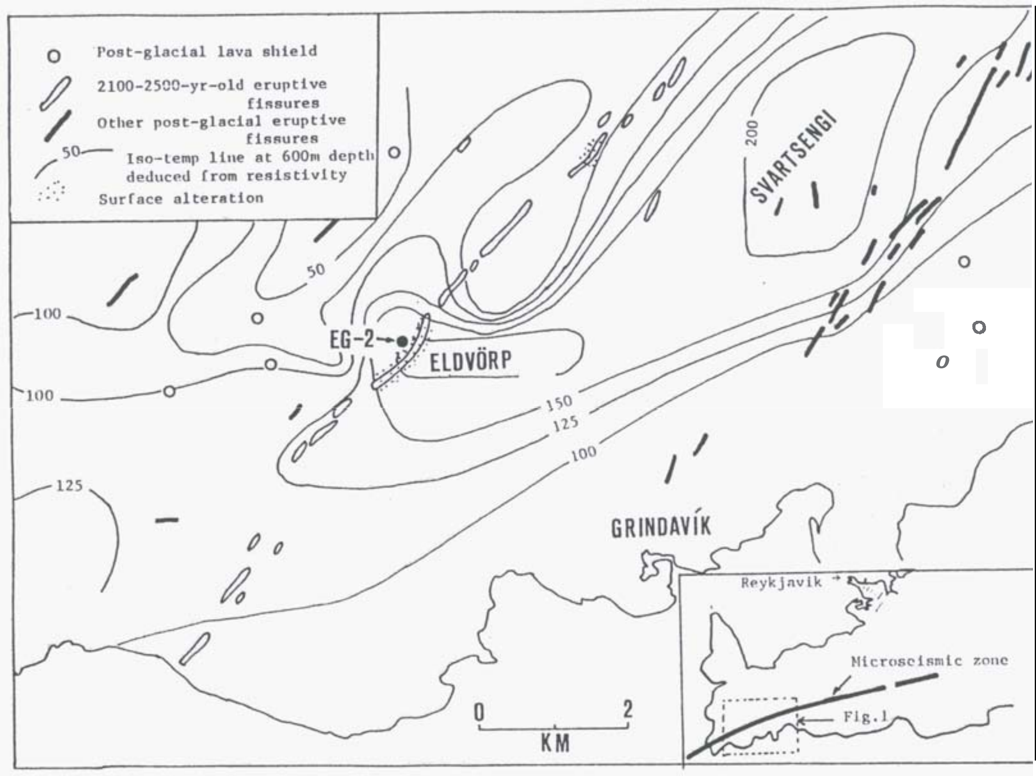

Figure 1. Reykjanes Peninsula with the plate boundary indicated by microseismic zone. Main figure shows postglacial eruption sites (deduced from Jonsson 1978 and 1983), and the iso-temperature lines at 600 m depth b.s.l. (Georgsson and Tulinius 1983).

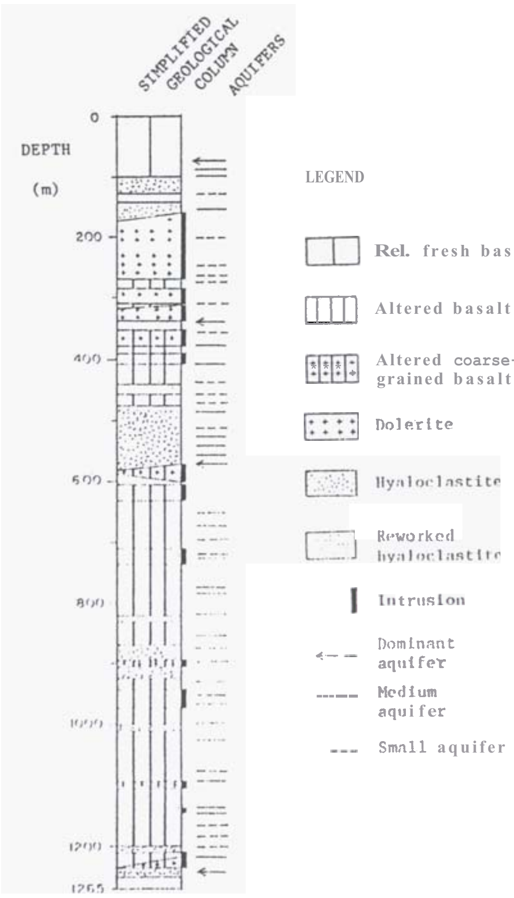

Figure 2. A simplified lithological section of well EG-2 and the location of aquifers.

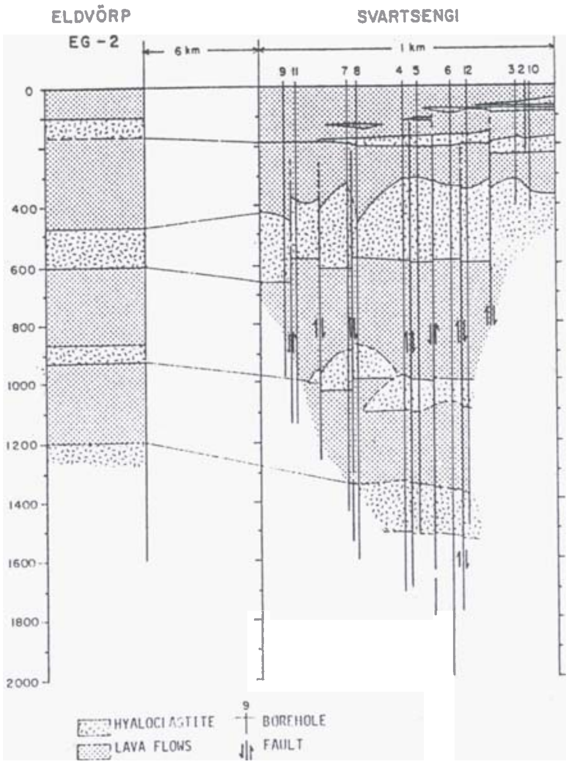

Figure 3. A correlation of accumulative volcanic units in Eldvorp and Svartsengi fields.

abundant in the upper part of the rock sequence. The intrusives can clearly be divided into three petrographically distinct groups (fig. 4).

The most dominant intrusive rock is a dolerite (olivine tholeiite) found between 150-400 m, at about 600 m, near the bottom of the well. A three layered contact metamorphic zone in the country rock can be related to the boundary of the dolerite (figs. 4 and 5). Closest to the dolerite a clino-pyroxene and magnetite are found gradually giving way to a magnetite and oxidation (probable haematite) assemblage and furthest away from the intrusive boundary only oxidation is observed. Although such a metamorphic relationship has been observed adjacent to intrusions in other high temperature areas in Iceland this example is by far the most conspicuous, and would infer that the intrusion may have been a feeder to a prolonged surface eruption. The metamorphic zonation is present in dominant part of the well which indicates the close proximity of the intrusion. The contact metamorphism can be traced up into the uppermost hyaloclastite horizon which dates back to the last glaciation, so the dolerite is younger than 12000 yrs. The olivine tholeiite compound lava unit (shield volcano) directly overlying the hyaloclastite is a likely surface equivalent of the dolerite feeder.

The second intrusion was identified as the feeder of the Eldvorp eruption of 2150 yrs. Contact metamorphism associated with the Eldvorp feeder is insignificant. The third group contains two thin finegrained basalt intrusions, found in the lowest part of the well.

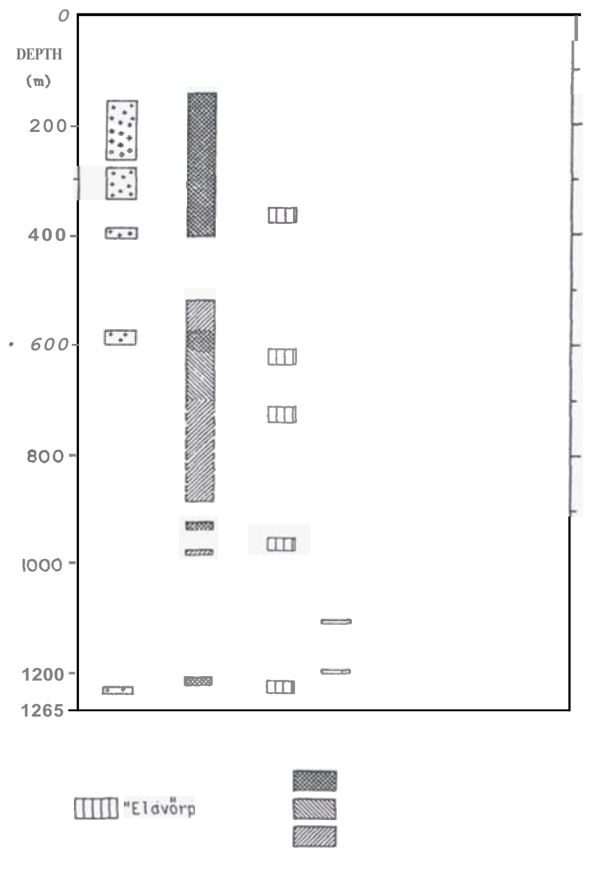

Figure 4. Intrusive rocks and contact metamorphism in **EG-2.**

AQUIFERS

Various methods were used to locate aquifers (feedpoints) accurately (e.g. circulation loss monitoring, Geolograph flowrate monitoring and most importantly a number of temperature logs run at various stages during drilling).

A total of 47 aquifers (feedpoints) were located in the well, of which 29 are within the production part and 18 above. They are divided into 3 size categories; 4 dominant, 21 intermediate and the remaining 23 small. The correlation of the aquifer location with the geology of the well shows the following relationship in table 1.

Geological formation	Aquifers dominant	interm.	small
Within intrusion		1	2
Intrusion boundary	3	11	10
Within lava		1	1
Within hyaloclastite		2	4
Between lava flows	1	4	3
Between lava & hyaloclastite		2	3
TOTAL	4	21	22

Table 1. The geological setting of aquifers in well EG-2

Table 1 shows that the majority of aquifers are related to intrusions; mainly their boundaries. As shown above the well for most part of its entire length is very near to the two vertical dyke feeders, and that implies that the aquifers lying along the horizontal stratification boundaries must be closely related to the vertical intrusion type aquifers.

ALTERATION

The distribution of alteration minerals is shown in figure 5, along with the analytical methods. In general, if a mineral was found within a 10 m interval, the line in figure 5 is drawn continuous. The figure shows that a fairly intense alteration stage has occurred in the upper half of the well where quartz, albite, chlorite and illite have been found just below 100 m indicating temperatures above 200 °C. A clear connection was seen between the appearance of the intrusive rocks in the well and the highest alteration intensity.

Figure 6 shows the alteration zonation deduced from figure 5. It represents the highest alteration stage reached during the life of the hydrothermal system but not necessarily the present condition. A direct transition from smectite to chlorite occurs at about 125 m depth indicating a very sharp temperature increase to about 230 °C. The disappearance of chlorite and the predominance of mixed layered clays at 440-500 m depth may indicate a reversal in temperature. This proposed temperature reversal is also supported by the reduced intensity in the alteration of the primary minerals and a decrease in vug and vein mineral deposition. The "lower" chlorite zone extends to about 640 m where

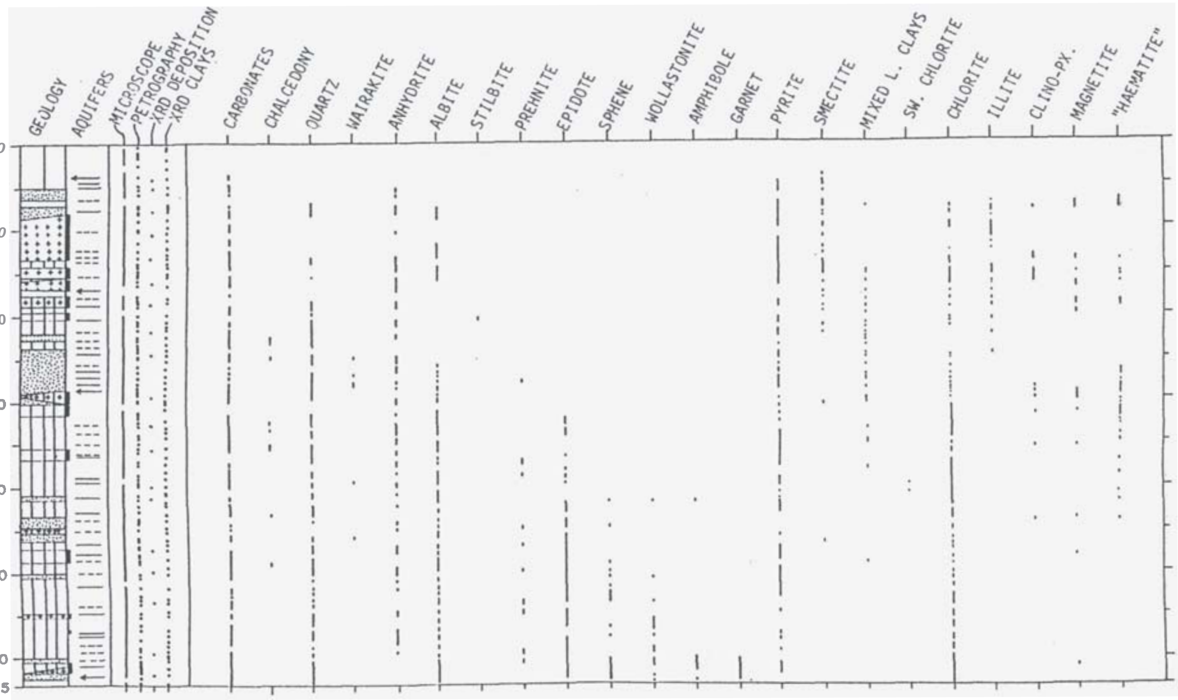

Figure 5. Distribution of alteration minerals in well **EG-2.**

epidote appears indicating a temperature in the region of 250 °C. The appearance of wollastonite at about 1000 m depth may indicate temperatures surpassing 270 °C and the appearance of both amphibole and garnet at about 1200 m infers temperatures above 280 °C.

The primary rock constituents show similar alteration trends as evidenced by the alteration zones. All volcanic glass and olivines have been altered in and below the smectite-zeolite zone. Pyroxenes and the plagioclases show a greater resistance to alteration. They alter preferentially in the dolerite at 150-400 m depth and then again befow 800 m. Clay is the most common alteration of the primary constituents and albite commonly alters the plagioclase. Below about 800 m epidote, sphene and prehnite can be observed to replace plagioclase. It is important to note that calcite is a common alteration product of the primary minerals, especially where aquifers are encountered in the well.

Vein fillings can be divided into three groups: The most common is calcite, found at all depth levels except between 500-700 m. These calcite veins are believed to be the youngest in the system, often enclosing pyrite. Calcite veins often coincide with locations of aquifers.

The second mast common vein mineral group is anhydrite, dominantly occurring on its own in relatively large fractures at the boundary of the dolerite. Although these fractures are more abundant in the upper 800 m they are found as deep as 1150 m.

The third and the least conspicuous group includes those veins where neither calcite or anhydrite appear. Above 800 m these include most commonly clays and chalcedony whereas below about 950 m epidote, wollastonite are found and amphibole and garnet below 1200 m.

Figures 5 and 6 give an overall summary of alteration irrespective of time of formation. A study of relative deposition sequence in vesicles and veins, however, makes it possible to determine their relative ages. the sequence of mineral deposition in vesicles and veins was closely examined in well **EG-2.** Similar studies have been made in the Svartsengi and the Nesjavellir high-temperature fields (Franzson 1983, Stefansson et al 1983, Franzson and Sigvaldason 1985) and in a Tertiary deeply eroded central complex (Fridleifsson 1983a, 1983b). Figure 7 is based on more than 600 observations

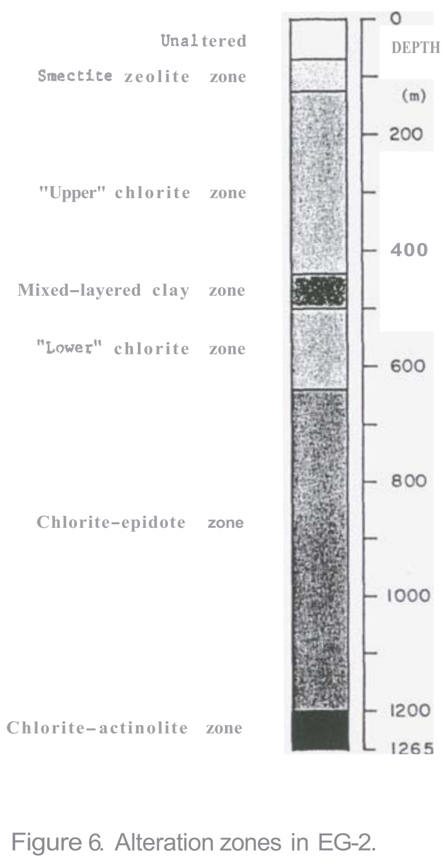

Figure 6. Alteration zones in EG-2.

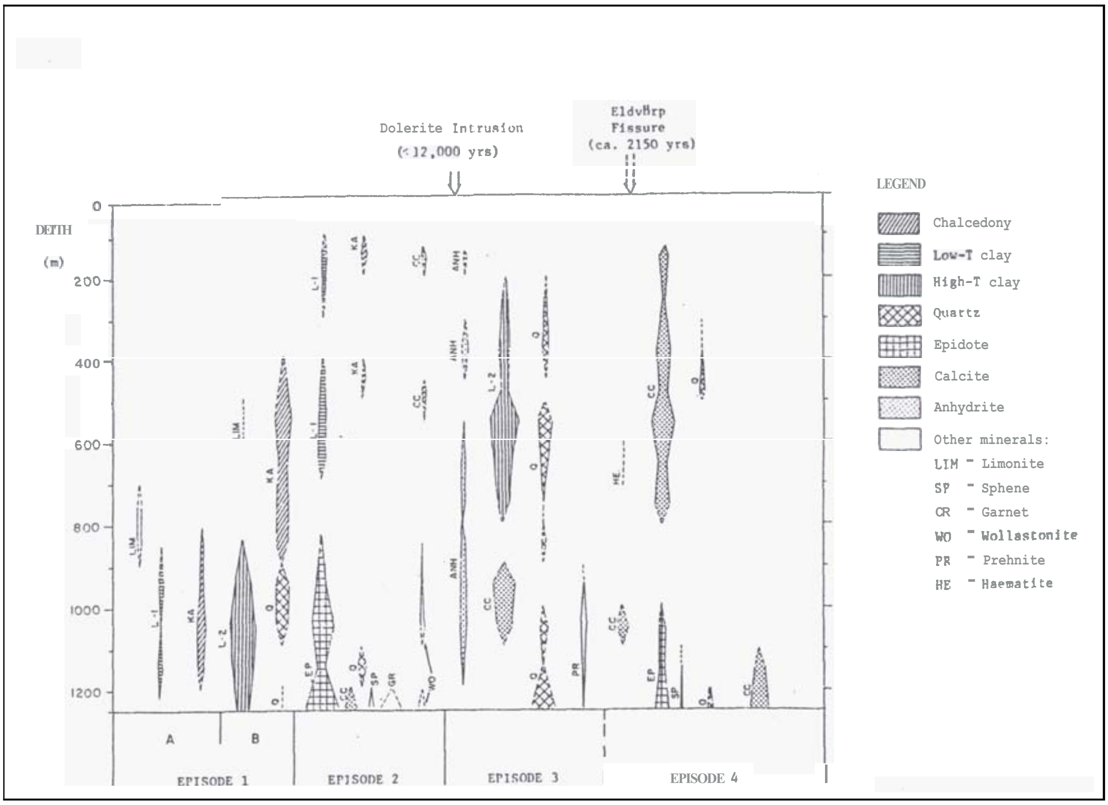

Figure 7. Relative time sequence of mineral deposition in EG-2.

on individual vesicle an vein fillings of which some 450 had a deposition sequence of 2-5 minerals. The width of field of individual minerals is proportional to its relative abundance. Four episodes can be recognized:

During episode 1, which is oldest, low-temperature, limonite clays and chalcedony deposited indicating temperatures of less than 180 °C. These were followed by high-T clays and quartz (>180 °C) up to about 800 m depth while chalcedony deposited between 800 m and to about 400 m depth.

During the second episode heating of the geothermal system continued as epidote appears below 800 m, followed at deeper levels by calcite quartz, sphene, garnet and wollastonite.

The third episode starts off with a very distinct anhydrite deposition conclusively related to the boundary of the < 12000 yrs old dolerite feeder. A detailed alteration study in the Reykjanes high-temperature field, some 10 km west of Eldvorp, shows that anhydrite is deposits during influx of seawater as heats up on its descend into the hydrothermal system (Tomasson and Kristmannsdottir 1972). It is likely that the anhydrite at Eldvorp depicts such an influx and a cooling of the hydrothermal system. Anhydrite was succeeded by the deposition of high-T clays above 800 m and then by quartz indicating elevated temperatures of >180 °C below about 200 m depth.

The onset of the fourth episode is less firmly set, but in the upper part of the section conspicuous calcite deposition occurred which was probably preceeded by haematite. Below 1000 m epidote sphene and quartz were deposited followed by calcite. The calcite was the last major phase to deposit in the hydrothermal system and was as previously observed to be abundant near aquifers. The evidence of the Eldvorp fissure eruption slightly preceding the calcite deposition (c.f. fig.7) is not conclusive but in places traces of haematite can be seen lining the calcite veins.

DISCUSSION

The close relation between the dykes and the hydrothermal system demonstrates how important magma intrusions (dykes) are in the development of the system in the Icelandic geothermal; whether it is causing a cold groundwater flux into the system or providing channels for its thermal upflow. Figure 8 shows a schematic model of the presently active Eldvorp field where it is envisaged that the fissures of the "Eldvorp swarm" provide downflow channels of cold groundwater, whereas within the central part of the "swarm" an upflow of the hydrothermal system is occurring along the same fractures. It is envisaged that a zone of deposition separates these two systems, at least to some extent.

The near absence of calcite at temperatures above about 280 °C (chlorite-actinolite zone) in other Icelandic geothermal fields implies its instability (Kristmannsdottir 1979, Stefansson et al. 1982, Franzson et al. 1983). In Eldvorp, however appreciable amounts of calcite is seen as the last phase to crystallize at depth levels where amphiboles and garnets had crystallized earlier. That suggests that present temperatures at the base of the well have been lowered below 280 °C. That is in accordance with the maximum temperatures of about 260 °C measured in the well.

An interesting repetition occurs in the depositional sequence occurs in the Eldvorp system (fig. 7) where a clay deposition is near invariably followed by silica deposition (chalcedony/quartz). This sequence is in turn followed by minerals containing Ca and Fe (calcite + pyrite, epidote, prehnite, etc.). The start of each deposition sequence coincides with a distinct change in the geothermal system, especially following the elevation of the hydrothermal system into relatively unaltered rocks. Four such occurrences can be seen, two in episode 1, one in episode 2, and one in episode 3. Similar sequences have been observed in the Svartsengi and

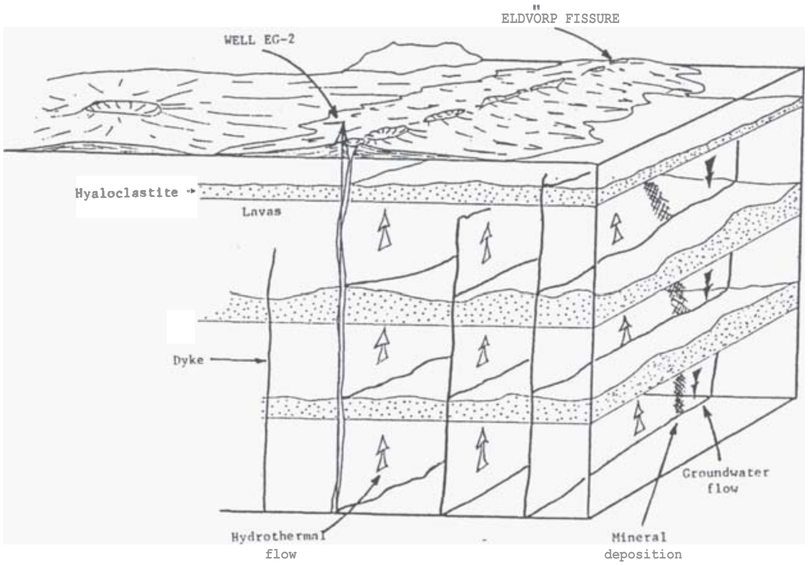

Figure 8. A conceptual geological model of the Eldvorp field.

Nesjavellir high-temperature fields (Franzson 1983, Franzson and Sigvaldason 1985).

The dating of the anhydrite deposition, as being younger than 12000 yrs, emphasizes the relatively rapid changes taking place in the Eldvorp hydrothermal system seen in the deposition sequence following the anhydrite.

MAIN CONCLUSIONS

1. The combination of the resistivity and geological features shows that the Eldvorp "fissure swarm" causes a downflow of cold groundwater in the northern part , but an upflow of the hydrothermal system in its central part.

2. The geology of well EG-2 shows two intrusive dyke events, the earlier one a feeder to a shield volcano of < 12000 yrs, the younger one the dyke feeder to the Eldvorp lava (2150 yrs.)

3. The active hydrothermal system is closely related to the intrusions as the majority of the aquifers relate to fractures created by the intrusions. The hydrothermal alteration is also closely linked with the intrusions especially the dolerite.

4. A study of the deposition sequence in vesicles and veins shows development stages of the hydrothermal system from an initial low-temperature to the present-day high-temperature condition. It also shows that the dolerite dyke first caused a downflow of groundwater followed afterwards by an upflow of hydrothermal fluids.

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REFERENCES

FRANZSON, H., 1983: The Svartsengi high temperature field, Iceland. Subsurface geology and alteration. In: Geothermal Resources Council, Transactions, vol 7, p 141-145.

FRANZSON, H., G. GUDMUNDSSON, J. TOMASSON AND TH. THORSTEINSSON, 1983: Drilling of well RnG-9, Reykjanes high-temperature field, OS-report, 31p. (In Icelandic).

FRANZSON, H. and H. SIGVALDASON 1985: Nesjavellir, well NG-7. Geology, alteration, geophysical logs and aquifers. OS-85124/JHD-18, 80 p. (In Icelandic with an English summary)

FRIDLEIFSSON, G. O., 1983a: The geology and alteration history of the Geitafell central volcano, South-East Iceland. Ph.D. thesis, Edinburgh University, 324 p.

FRIDLEIFSSON, G. O., 1983b: Mineralogical evolution of a hydrothermal system. Geothermal Resources Council, Transactions, vol 7, p 146-152.

GEORGSSON L.S. AND H. TULINIUS, 1983: Resistivity survey on the western Reykjanes Peninsula in 1981 and 1982. Orkustofnun, OS-83049/JHD-09, 70pp. (In Icelandic).

JONSSON J., 1973: Sundhnukahraun vid Grindavik. Natturufraedingurinn, vol 43, p 145-153. (In Icelandic with an English summary).

JONSSON J., 1978: Geological map of the Reykjanes Peninsula: OS-JHD 7831, 303p. (In Icelandic).

JONSSON J., 1983: Volcanic eruptions in historic time on the Reykjanes Peninsula. Natturufraedingurinn, vol 52, p 127-139. (In Icelandic with an English summary).

KRISTMANNSDOTTIR H., 1979: Alteration of basaltic rocks by hydrothermal activity at 100-300 °C. In: International Clay Conference 1978. Edited by M.M. Mortland and V.C. Farmer. Elsevier Publishing Company, Amsterdam, p. 359-367.

STEFANSSON, V., A. GUDMUNDSSON, B. STEINGRIMSSON, G. HALLDORSSON, H. ARMANNSSON, H. FRANZSON, T. HAUKSSON, 1982: Krafla well KJ-14. Drilling, research and discharge characteristics. OS82061/JHD09, 119p. (In Icelandic).

STEFANSSON, V., J. TOMASSON, E. GUNNLAUGSSON, H. SIGVALDASON, H. FRANZSON AND O. SIGURDSSON, 1983: Nesjavellir, well NG-6. Drilling, research and discharge characteristics. OS-83023/JHD-04, 100 p. (In Icelandic).

STEINGRIMSSON B.S., H. FRANZSON, S.H. HARALDSDOTTIR, TH.THORSTEINSSON, G. GUDMUNDSSON, G.O. FRIDLEIFSSON, H. AGUSTSSON AND S. THORHALLSSON, 1983: The drilling of well EG-2, Eldvorp, preliminary report. OS-83107/JHD-42 B, 50p (in Icelandic).

TOMASSON, J. AND H. KRISTMANNSDOTTIR 1972: High temperature alteration minerals and thermal brines, Reykjanes, Iceland. Contr. Miner. Petrol., 36, p 123-134.