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REYKJANES HIGH-TEMPERATURE FIELD, SW-ICELAND. GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL RN-10

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ABSTRACT

Geological and geothermal data from the recently drilled 2054 m deep well, RN-10, in the Reykjanes high-temperature field are discussed. The strata range from probable pillow basalt formations at the deepest level to shallower tuffaceous volcanic succession intercalated with reworked shallow marine fossil-rich sediments, and lastly pillow basalt and subaerial lavas. The formations are relatively high-porosity and low permeability, and the aquifers encountered in the well are largely related to fractures along sub-vertical dyke intrusions. The largest aquifer near the bottom is related to a sub-vertical fracture. The hydrothermal alteration shows that the well enters into the high-temperature system below about 500 m depth, where it shows a progressive alteration zonation ranging from smectite-zeolite > chlorite > chlorite-epidote > epidote-actinolite zone. The sequence of mineral deposition in rock cavities indicates that the geothermal system has from its initial stage been progressively heating up. The highest bottom temperature logged is about 320°C. Th-measurements in fluid inclusions show a good correlation with alteration and measured formation temperatures, while Tm-measurements show a wide salinity range, irrespective of depth, from fresh to seawater compositions, the latter being near to the present salinity of the field. Evidence suggests that well RN-10 is sited further away from an upflow zone than RN-9. However, at >1000 m depth, temperatures in well RN-10 are up to 20°C higher than found elsewhere in the reservoir, reaching a maximum of about 320°C.

INTRODUCTION

The Reykjanes high-temperature system is located at the boundary where the sub-marine Reykjanes Ridge connects to the rift zone of Iceland (Fig.1). The pertinent surface geological features include an historic Stampar fissure eruption from 1226, an underlying 2000 yr old fissure eruptive lava, a picritic lavashield of 2-10 thousand years and lastly hyaloclastite ridges of probably from last glacial episode (12-115 thousand years). The field is situated within a dense NE-SW fissure and fault zone.

Since systematic exploration started on the Reykjanes system in the late sixties several studies have been made on the geological and hydrothermal alteration including Tomasson (1971), Tomasson and Kristmannsdottir (1972), Lonker et al. (1993), isotopic studies Sveinbjornsdottir et al. (1986), and Olafsson and Riley (1978), and fluid inclusion studies (Franzson 2000). Karlsdottir (1998) has interpreted the most recent resistivity survey in the area.

The well, which is the tenth to be drilled into the Reykjanes system, was sited near the north-western boundary of the surface thermal manifestations of the area (Fig. 1). The purpose was to explore the geothermal reservoir towards west. The well is near the crest of the high-resitivity core (Karlsdottir 1998) as shown in Fig. 1.

The well was drilled by the Iceland Drilling Company. This was done in four separate stages, and took 66 days to complete: A 23” anchor casing was cemented down to 78 m, a 18 5/8” safety casing down to 251 m, and a 13 3/8” production casing down to 691 m depth. The production part of the well was drilled using a 12 ¼” bit down to 2054 m depth, and cased with a 9 5/8” slotted liner down to 2029 m depth. Mud circulation was used during drilling, except for the production part where fresh water was used. The well is straight with the bottom displaced some 65 meters horizontal from the wellhead.

The geological data from the well is based on cutting samples taken at 2 m intervals during drilling. The well was extensively logged during and after its completion, including several temperature and pressure logs, neutron-neutron, natural-gamma and resistivity.

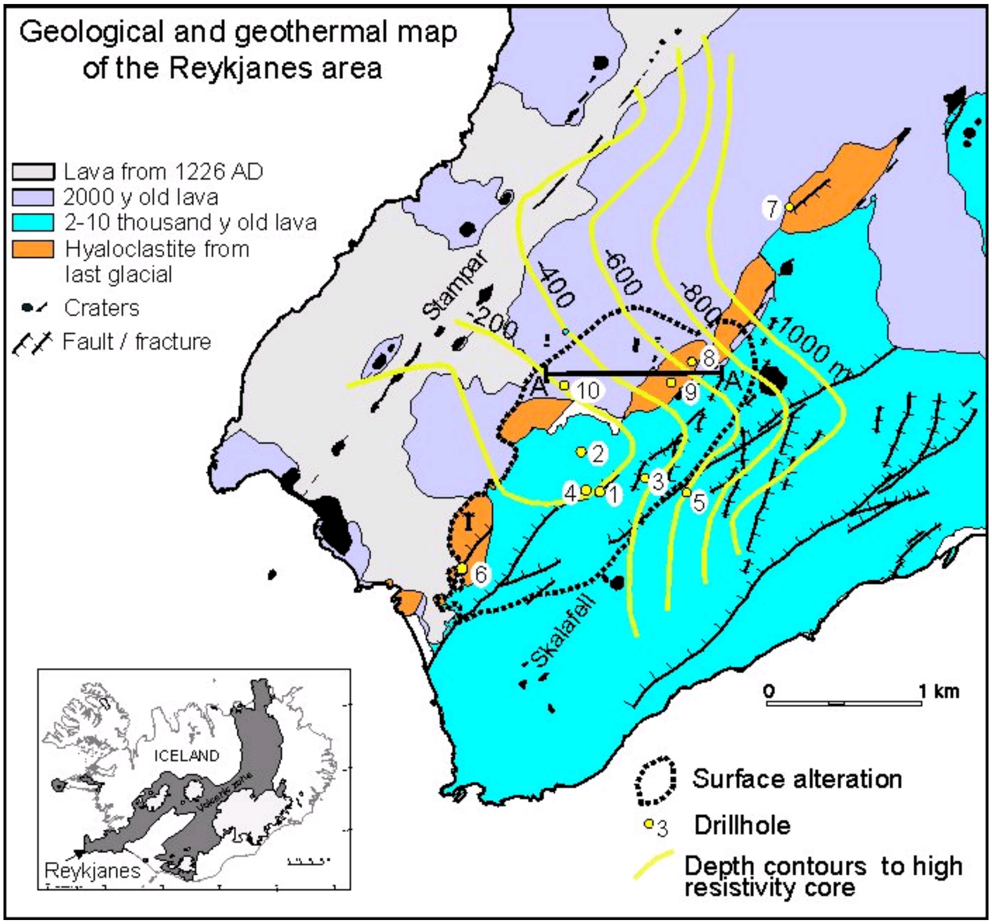

Figure 1. Surface geological map of the Reykjanes high-temperature, drillholes and resistivity contours (map adapted from Saemundsson 2000, Karlsdottir 1998 and Fridleifsson et al. 2000).

Data was systematically gathered on penetration rate and circulation losses. Reports have been published on the drilling and preliminary geological results (Fridleifsson et al. 1999, and Franzson et al. 1999) and a final report on the geological investigation is being published (Franzson et al. 2002). Reykjanes has been selected as one of the possible sites for deep exploration drilling down to some 4-5 km (Fridleifsson and Albertsson 2000). Well RN-10 has not yet been discharged, but all available data suggest that it will become a major producer of fluids exceeding 300°C.

This paper first describes the geological formations found in RN-10, followed by a summary of the hydrothermal alteration and a fluid inclusion study and lastly these data are used to define the geological and hydrothermal character of the system.

GEOLOGY

Franzson et al. (2002) have described the stratigraphy of the well in detail, based on cutting analysis, geophysical logs and other relevant drillhole data. The salient geological features are summarized in Fig. 2. The succession is made of basaltic rocks of variable crystallinity and their division into separate units is partly based on their petrographic characteristics and mode of formation as indicated in the central part in the figure.

The stratigraphy can be divided into four main units: The uppermost 120 m consist of a few sub-aerial lava flows, and underlain by a formation of pillow basalt. Below is a series of dominant hyaloclastite tuff formations, with a probable c. 30 m thick lava horizon separating two hyaloclastite tuff formations. Below 470 m and down to about 970 m, a succession rich in reworked tuff dominates along with about 130 m thick formation of pillow basalt. The former, especially in the lower part shows a specific rhythmic layering, where each formation appears to consist of a hyaloclastite tuff overlain by a reworked tuff from the same formation and lastly overlain by a more heterogeneous sediment sometimes showing signs of grain rounding. Calcareous fossil remains have been recognized in three of these sedimentary horizons,

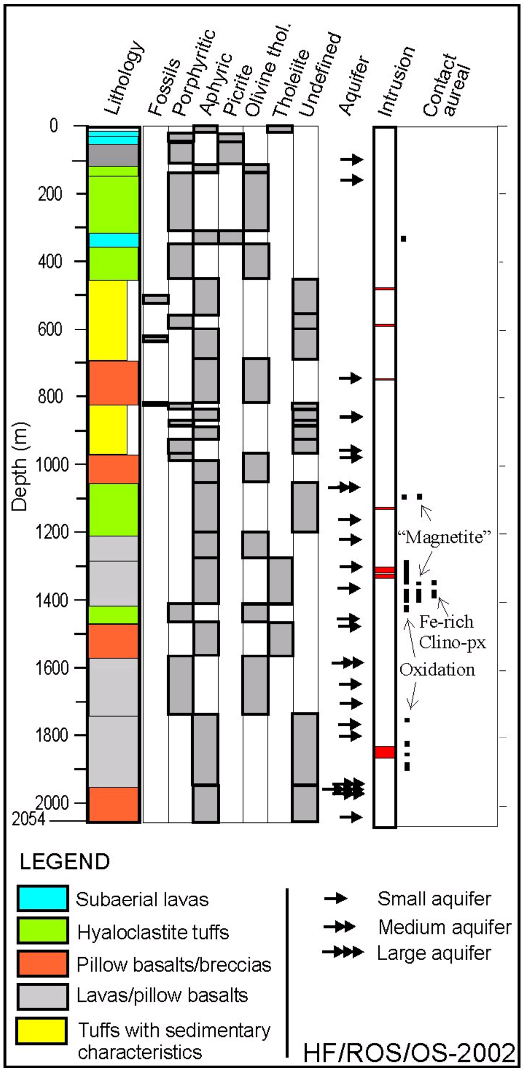

Figure 2. Simplified lithological section, main petrograhic character, aquifers and intrusions with associated contact aureoles.

indicating shallow water marine environment (<50 m depth). Below 970 m depth the majority of the rocks are crystalline basalts. The basalts are mostly olivine tholeiites, which in thin section show a relatively coarse grained crystallinity, even though sometimes only partially crystallized, and that poses some problems during cutting analysis in interpreting whether they represent sub-aerial lava flows or pillow basalts. Circumstantial evidence, such as small scale variation in neutron-neutron and resistivity logs, and relatively uniform and high rock porosity, suggest that these are more likely pillow basalts. Stratigraphic correlation between other neighboring wells are also problematic (Tomasson and Kristmannsdottir 1972) suggesting the same. A more detailed stratigraphic correlation is, however, needed to confirm this.

The well only intersected seven minor intrusives with an average apparent thickness of just over 9 m. The relative scarcity is concomitant with findings in the neighboring well 9. (Franzson et al. 1983). Pronounced thermal effect can be observed around the intrusions found below 1000 m depth (see Fig. 2), which strongly suggests that these are sub vertical dykes, which would strike NE-SW, assuming that they follow the dominant tectonic trend at the Reykjanes peninsula. Intrusion intensity is apparently much lower in the Reykjanes field than found in many other high-temperature areas in Iceland.

PERMEABILITY

The location and assessment of aquifers was determined assimilating data including circulation losses, temperature logs, drilling data, and comparisons with geological and alteration data. The location of these are shown in Figs 2 and 3, and their geological connections are summarized in Table 1.

Depth (m)	Size	Strat.	Int.	Fra.	Unk.
90	S	X			
130-180	S	X?			
720-742	S		X		
840-850	S	X			
940-950	S				X
960-970	S	X?			
1025-1097	M		X		
1140-1155	S		X		
1205	S				X
1283-1290	S		X		
1343-1350	S		X		
1438	S				X
1454-1460	S				X
1560-1575	M				X
1630	S	X			
1678-1688	S		X?		
1743-1752	S				X
1780	S		X?		
1922	M			X	
1940-1960	L		X?	X	
>2000	S		X?	X	

Table 1. Depth of aquifers and their geological relation. Explanation: S=small, M=medium, L=large. Strat=stratification boundary, Int=Intrusion, Fra=fracture, Unk=Unknown relation.

No circulation losses were observed above 1100 m depth, minor below that down to 1900 m depth, whereas the main losses were experienced from there down to the bottom of the well. Indeed, many of the aquifers would have gone unnoticed, if not for the very open bottom aquifer, which caused an inflow of all aquifers into the well above 1600 m depth and into the bottom aquifers. It has been shown above that the well dissects sub-vertical dykes below 1000 m depth, and some of the aquifers are related directly to them. It is believed likely that most of the other aquifers in this depth interval may, in one way or another, be related to fractures near to these dykes. The large aquifers found below 1900 m depth are linked to a pronounced sub-vertical fracture zone clearly evidenced in the cutting samples, where these fractures were partially filled by amphibole (actinolite), wollastonite and quartz. Whether this fracture relates to the dyke found at 1800-1900 m depth (see figure 2) can only be implied. Some of the minor aquifers above 1000 m depth coincide with rocks with relatively high primary porosity, and that porosity may contribute to the permeability. However, the limited void filling implies that these are rather local stagnant "water pockets".

HYDROTHERMAL ALTERATION

Hydrothermal alteration has successfully been used to define several parameters of geothermal systems, such as temperature distribution, permeability, and thermal evolution. The hydrothermal minerals were analyzed using stereo- and petrographic microscopes and aided by XRD-analysis, especially for clay identification.

Fig. 3 summarizes the distribution of the alteration minerals with depth, where the width of individual lines indicate the relative abundance of the respective minerals. Although the general features are similar to other high-temperature areas, some interesting aspects are noted. Calcite is found down to about 1100 m depth, which coincides with a temperature of about 300°C, and conforms to the upper stability limit of the mineral. It is noteworthy that the relative abundance of calcite increased somewhat near aquifers located between 1000-1100 m depth, inferring boiling condition in these aquifers. Zeolites, with the exception of wairakite, are found above 500 m depth, indicating temperatures below 200°C. Epidote becomes quite abundant in vesicles and veins right from its first apearance at about 600 m depth. Epidote abundance in the crystallized basalts below 1200 m depth is relatively constant which conforms to the speculation above that most of the crystallized basalts are vesicular pillow basalts, rather than sub-aerial lava flows, which would be expected to show a more varied abundance. Wollastonite appears below about 800 m depth and amphibole at about 1150 m depth. Both minerals become quite abundant below about 1900 m depth especially in open fracture fillings and near to active aquifers. Albite occurs both as an alteration of primary plagioclase and commonly also as vesicle fillings, which is unusual compared to other high-temperature areas. The albite deposition is notably more common in the hyaloclastite tuff. The

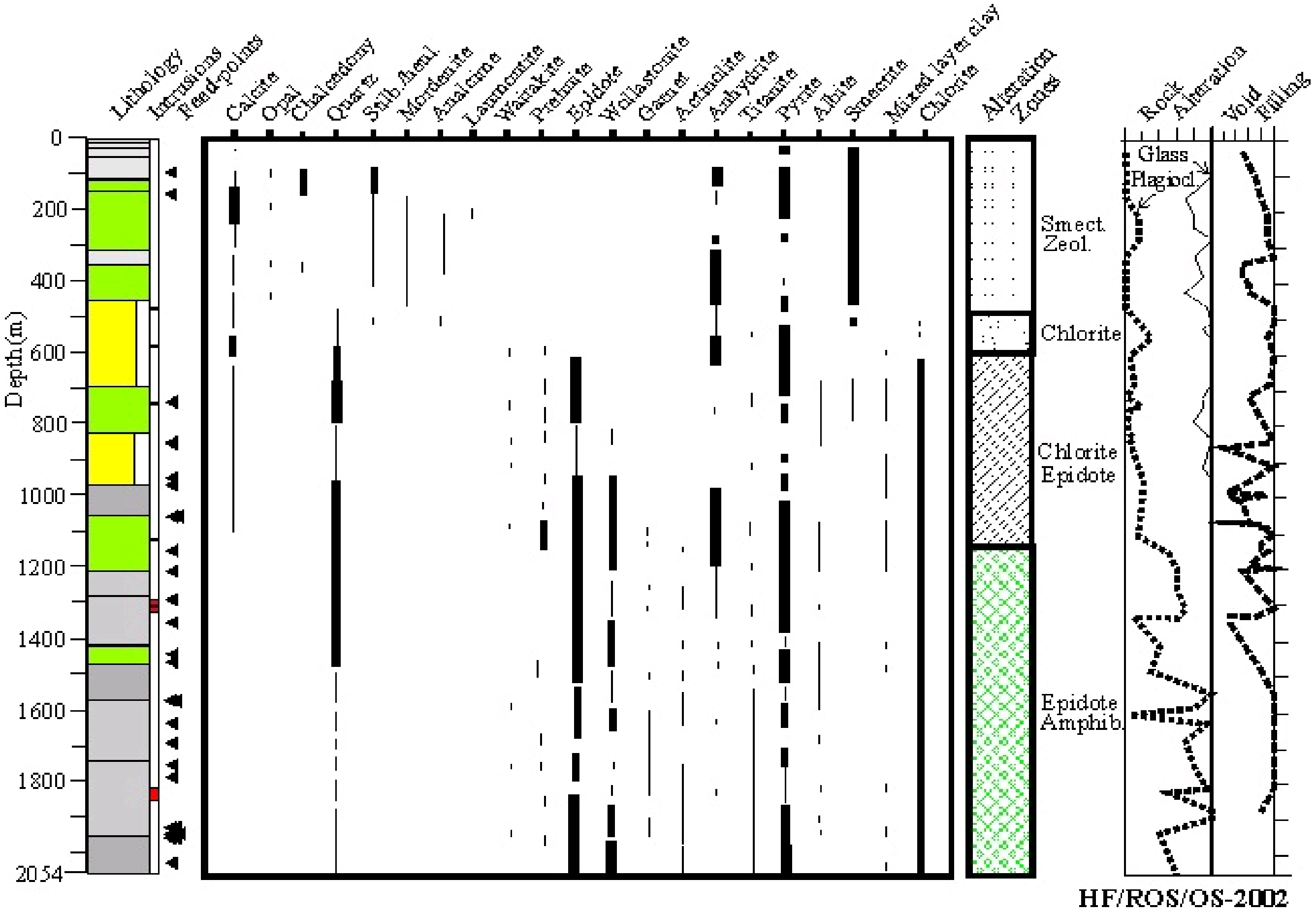

Figure 3. Distribution of alteration minerals, alteration zones, glass and plagioclase alteration and degree of void filling.

clays were assessed by microscopic analysis, and confirmed by XRD-analysis. Smectite and smectite-illite dominate in the upper 500 m but are not seen below about 900 m depth. Mixed layer clays, according to XRD analysis, start appearing at about 600 m depth, which is slightly deeper than chlorite (500 m). Mixed layer clays are found down to about 1200 m depth and traces all the way down to the bottom of the well, which is unusual at such high temperatures. Chlorite is the main clay mineral below 600 m depth. It behaves unstably as the 7 Å peak collapses on heating in the depth interval between 500-850 and 1100-1600 m but appears stable at other depths. Its more stable state seems to correlate with zones of higher permeability.

The alteration zones (figure 3) show the smectite zeolite zone extending down to about 500 m depth. The mixed layer clay zone is apparently absent, and the first indication of chlorite at about 500 m marks the upper boundary of the chlorite zone. The chlorite epidote zone extends from about 600 m down to 1150 m where the first appearance of amphibole marks the upper boundary of the epidote-amphibole zone.

Rock alteration adds an interesting aspect to the hydrothermal scene, as the degree of rock alteration to some extend reflects the flux of geothermal fluid through the rock, as would the amount of filling in the voids of the rock. The visual assessment of plagioclase and glass alteration, shown to the right in Fig. 3, brings out the differential alteration sensitivity of these two components, where the former is relatively resistant, and the latter very sensitive to alteration. Plagioclase shows relatively little alteration down to the base of the chlorite-epidote zone, but increases below, and at few places it seems to have been completely altered. Fresh glass can be traced down to about 500 m depth. At 700-950 m a recurrence of black glass is observed. Though its complete freshness remains to be verified, its alteration is certainly very limited. The amount of void filling shows on the whole similar trends as the rock alteration, in that voids tend to be less filled where alteration is less intense. The existence of open pores below 500 meters is unusual, as in most other high-temperature fields in Iceland vesicles appear largely filled below the mixed layer clay zone (based on cutting analysis). It is even more anomalous that the rocks in this depth range consist mostly of glass rich tuffs and breccias some of which have very high primary porosity. One way to explain this phenomena is that even though high temperatures have been reached in the system, fluid flow has been limited. The persistence of mixed layered clays and unstable chlorite at similar depth intervals corroborates that interpretation, as transformation from low- to high-temperature clays appears to be partly permeability related.

The order by which minerals deposit into empty voids of the rock inform on the evolution of the geothermal system. About 200 sequences of such mineral depositions were studied in the petrographic and binocular microscopes, and are summarized in Fig. 4. Above the high-temperature system (<600 m) smectite linings fall nearest to the walls of the voids, and then succeeded by aragonite, chalcedony (possibly initially deposited as opal) and zeolites. Possible wairakite deposition occurs and the youngest deposition found are calcite and anhydrite.

The mineral sequence below 600 m differs significantly from the upper one. Possible anhydrite is succeeded by chloritic clays. Whether these precipitated originally as chlorite or as a lower temperature clay is unknown. These are succeeded by prehnite, anhydrite, quartz and minor calcite. Albite is a very notable deposition, especially within tuff-rich formations, and form relatively large euhedral crystals. Albite generally shows distinct corrosion textures, indicative of partial dissolution, and some of these dissolved holes in the crystals presently contain fluid inclusions or epidote, the latter indicating that the apparent dissolution took place prior to epidote deposition. Albite has been recognized as void fillings in the Reykjanes and Svartsengi fields, where the corrosion and dissolution of the mineral was also noted (Lonker et al. 1993), and they further report an earlier deposition of K-feldspar, which was not recognized in this study. Indications are of an episode of chlorite deposition postdating the albite and predating epidote, wollastonite and pyrite deposition. The last two minerals to deposit are amphibole and quartz.

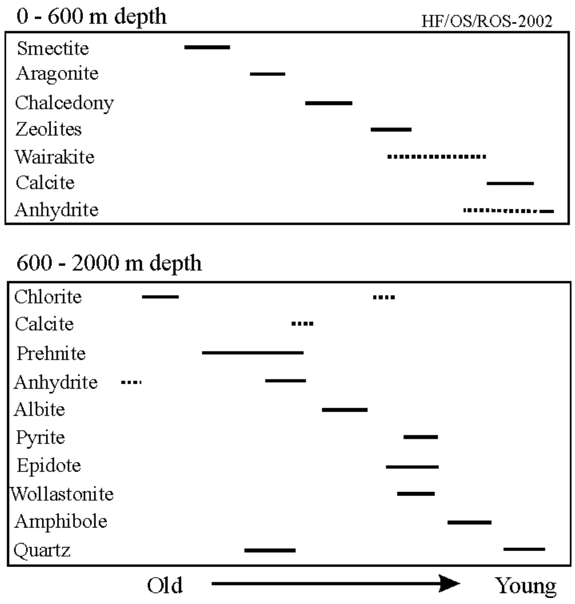

Figure 4. Probable time sequence of mineral deposition in RN-10.

Although the relatively few observations limit the confidence of the sequence, especially in separating in time some of the deposited minerals, it confirms that the geothermal system is moving towards higher temperatures and no cooling indications are found.

A preliminary study of homogenization (Th) and melting (Tm) temperatures has been done in the Reykjanes system (Franzson 2000). The Th values in the deeper parts of well RN-10 (Fig. 7) show a narrow temperature range and conform closely to the expected present formation temperatures as discussed below. Th values measured at about 526 m depth on the other hand show a large temperature span, which conforms to other evidence that it represents a very steep thermal gradient boundary of the cap rock to the geothermal system. Tm data from wells RN-9 and 10, on the other hand show a very wide range of values (Fig. 5), ranging from about –2.3 to –0.1°C, while the present salinity of the geothermal fluid is considered to be equivalent to that of seawater (c.f. Fig. 5). This wide salinity range has been interpreted as being due to a change from a dominantly fresh water environment proposed to have been prevalent during the last glacial period to a dominantly more saline environment in postglacial times. Tm values from the neighbouring Svartsengi and Eldvorp fields show slightly less scatter, in agreement with their lower present salinities (Franzson 2000).

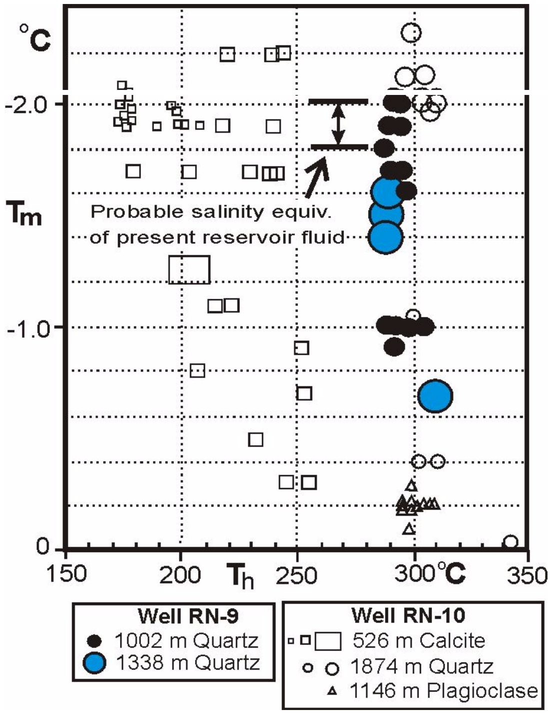

Figure 5. Tm plotted against Th for fluid inclusions in wells RN-9 and RN-10.

DISCUSSION AND CONCLUSIONS

The geological succession at Reykjanes high-temperature field differs significantly from that of the neighboring Svartsengi and Eldvorp fields (Franzson 1987, 1995) in that interglacial lava series are essentially missing in the former. Indeed, a distinction between hyaloclastites formed in glacial and marine environments are in most instances difficult on grounds of borehole data.

A detailed correlation between the stratification in well RN-10 and other wells has not been done. There are, however, strong similarities, which can be seen in a more dominant sedimentary tuff formations above 1000 m and more crystallized basalt formations at greater depths (Tomasson 1971). Assuming that the lower crystallized basalts are mostly pillow basalts, a conceptual modeling of the paleo-environment of the Reykjanes strata can be attempted, and is shown in figure 6. The pillow basalt formations are formed as a result of sub-marine volcanic eruptions at depths below vigorous gas exsolution of the magma. When eruptions reach to shallower depths, the eruption style changes to a Surtseyan type with thick hyalo-tuff layers forming. A shallow marine environment is clearly depicted in the sedimentary part of the tuff formations and the overlying more heterogeneous sediments, some of which contain shallow marine fossil fragments. The uppermost part of the strata (<120 m) is characterized by pillow basalt and topped by sub-aerial basalt flows of postglacial age. The sequence as a whole thus shows a gradual volcanic accumulation and an emergence of a submarine segment of the Reykjanes Ridge.

The hydrothermal alteration provides a significant insight into the character of the geothermal system. The temperature dependency of many of the alteration minerals allows a temperature curve to be drawn as shown in figure 7. The Th values from fluid inclusions closely resemble the alteration temperature assessment and the data from the present temperature measurements also show a close affinity to the afore-mentioned values. This, along with the depositional sequence of alteration minerals, confirms that the Reykjanes geothermal system is a young progressively heating system showing no signs of cooling, as opposed to the neighboring Svartsengi and Eldvorp systems (Franzson 2000). Measured temperature logs indicate that the geothermal system follows the boiling point curve below the cap rock at 500 m down to about 1300 m, but shows a convective type of thermal condition below that depth. A similar thermal condition is evidenced in the neighboring well 9 (Franzson 2000). The temperature assessment based on the alteration assemblage conforms to the measured

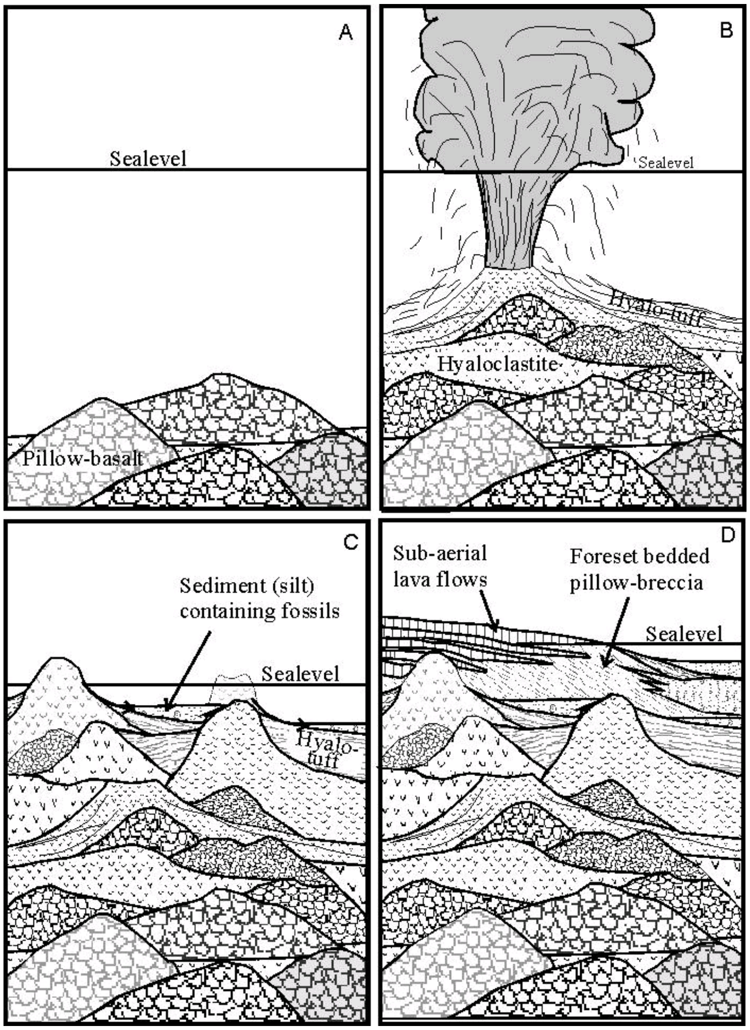

Figure 6. Conceptual model of the evolution of the lithological succession of the Reykjanes high-temperature area.

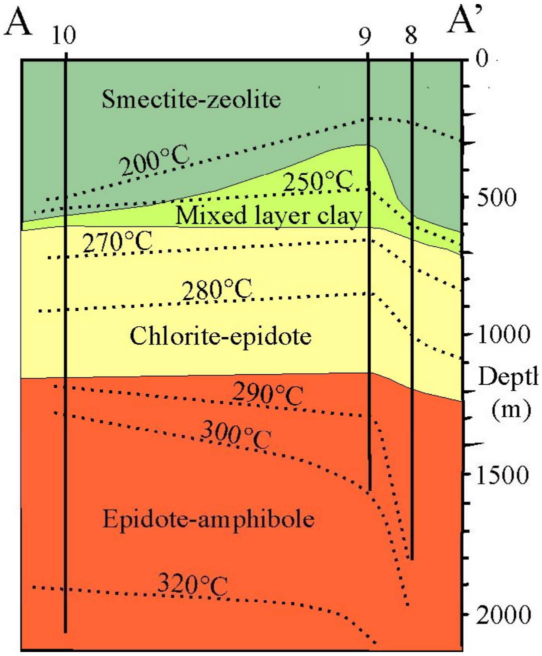

Figure 8. An E-W cross-section between wells 8, 9 and 10 showing alteration zones and formation temperatures.

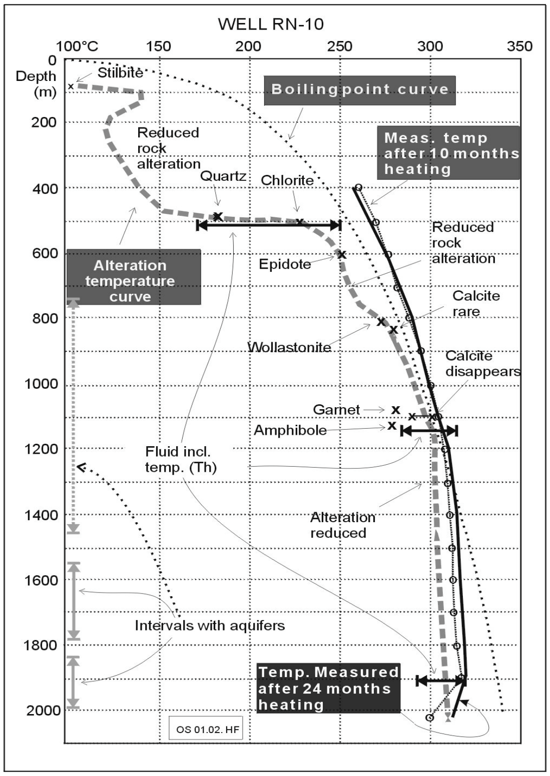

Figure 7. Alteration and formation temperature curves along with (Th) temperature range of fluid inclusions.

temperature profile in RN-10, except that lower temperatures are postulated between 600-800 m depth. The fluid inclusion study also shows that the hydrothermal alteration is only partially derived from a sub-marine environment. An interesting aspect of the significant freshwater component, is that it infers that the recharge into the geothermal system, is largely confined to the maximum depth range of the freshwater lens during glacial episode.

The E-W cross section in figure 8 shows the alteration zones and measured formation temperature between wells 8, 9 and 10. It shows that both measured temperatures and alteration zones rise to shallower depths in the eastern part of the field, which is also in accordance with the more dominant surface hydrothermal manifestations (c.f. Fig. 1). However, temperatures are lower in the deeper part of the system to the east. Th measurements in well 9 show a close comparison with measured and alteration temperatures, and no indication of cooling (Franzson 2000). It is tentatively concluded here that the lower temperatures at deeper levels is due to a more convective nature of the geothermal system in the eastern part of the system, and consequently higher vertical permeability in the depth range of the drill holes. If this is the case, it may also be concluded that this higher convective permeability has been present in the system during its progressive heating. The higher temperatures measured in the deeper part of well 10, does not, however, exclude the possibility of other high permeability convective zones in the geothermal system, as might be implied from resistivity data in the area of the historical Stampar fissure eruption further west from well 10 (c.f. Fig. 1).

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