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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL KR-9, KRÍSUVÍK, SW-ICELAND

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ABSTRACT

KR-9 is a 327 m deep production well drilled in the Krísuvík high-temperature field for space heating purposes. Rock formation consists dominantly of hyaloclastite overlying a lava formation believed to be deposited during the last glacial and interglacial period (~125,000 years). Although these rock series are of similar basaltic composition, they show variable hydrothermal alteration with the hyaloclastites being more sensitive to alteration than the lava formation. As is typical for Icelandic hydrothermal alteration, the well showed smectite-zeolite zones as the most common with probable occurrences of mixed layer clays within the zone. The traces of mixed layer clays signal an approaching disagreement of the smectite-zeolite alteration zone with depth indicating increasing temperature. Mineral formation temperature for smectite-zeolite is <200°C and lower boundary of mixed layer clays arbitrarily fixed at 220-230°C. Functions of alteration are controlled primarily by rock porosity, permeability, temperature and duration of geothermal activities. Aquifers in this well were located on the bases of borehole measurements and records of circulation losses. The aquifers were located at 229, 304 and 317 m. Circulation loss zones could be related to intraformational rock boundaries that serve as channelways for geothermal fluid.

1. INTRODUCTION

Well KR-9 is located in Hveradalir within the Krísuvík high-temperature area. Krísuvík is one of the three areas on the Reykjanes Peninsula (Figure 1) and firs explored before 1950 (Arnórsson et al., 1975). The Krísuvík high-temperature area is generally divided into three parts, the Krísuvík field, the Trölladyngja field, and the Sandfell field. Several exploration activities took place up to 1994 to fully assess the geothermal potential of the area. The initial effort was a site selection for electricity generation including shallow hole drilling. Subsequent studies including deeper exploration drilling and geological research were carried out. In 1970 a systematic exploration programme was started (Arnórsson et al., 1975). Several researches have also been done by previous UNU Fellows including geological mapping of a part of the Trölladyngja area (Muhagaze, 1984, and Kifua, 1986) and Krísuvík valley (Vargas, 1992) and Schlumberger sounding surveys and interpretation of several stations at Krísuvík (Mariita, 1986; Kanyanjua, 1987). In 1994 a study on the possibilities of steam production and transmission to an energy park in the Straumsvík harbour from Krísuvík and Trölladyngja was also done. Results of the study led to a proposal for the drilling of four exploration/production wells equally distributed among the two fields and an additional geophysical survey in the Krísuvík area. The steam to be produced was planned for industrial use (Ármannsson et al., 1994).

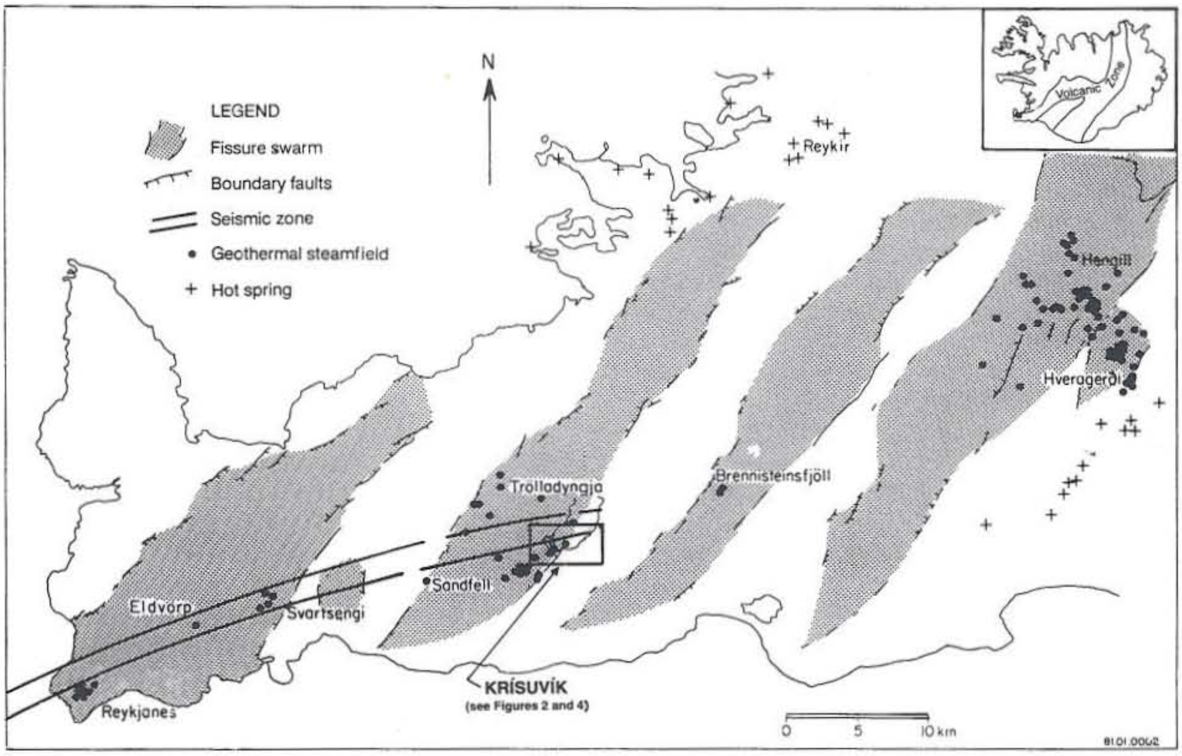

FIGURE 1: Volcanic systems and high-temperature areas of the Reykjanes Peninsula (modified from Saemundsson and Fridleifsson, 1980)

Despite the above activities and drilling of wells in Hveradalir, sub-surface geological information is fragmentary. This study aims to supplement information on the sub-surface geology, mineral alteration pattern and distribution of aquifer zones in well KR-9 in a part of the Krísuvík geothermal field.

1.1 Krísuvík high-temperature field

The Krísuvík high-temperature area is characterized on the surface by extensive post-glacial lavas and steep sided mountains and ridges of pillow lavas, pillow breccias and hyaloclastites. All of the rock formation is of basaltic composition. The topography of the field is characterized by NE-SW trending hyaloclastite ridges in the west and a flat-lying lava field with minor Postglacial volcanic edifices to the east. The last glacial and interglacial periods are responsible for shaping the present perspective of the area. Hyaloclastites formed under ice sheet environment consist of ridges of pillow lavas, breccia and tuff whereas deposition representing ice-free environment are mostly lavas. Figure 2 shows the geological map of the Sveifluháls area, i.e. around the farm of Krísuvík, including the areas of the most intense geothermal activity in the Krísuvík field.

Figure 3 shows the generalized evolution of a sub-glacial volcano similar to what is found in the Krísuvík area. Vargas (1992) in his study of the area classified the volcanic activity and rock formation in terms

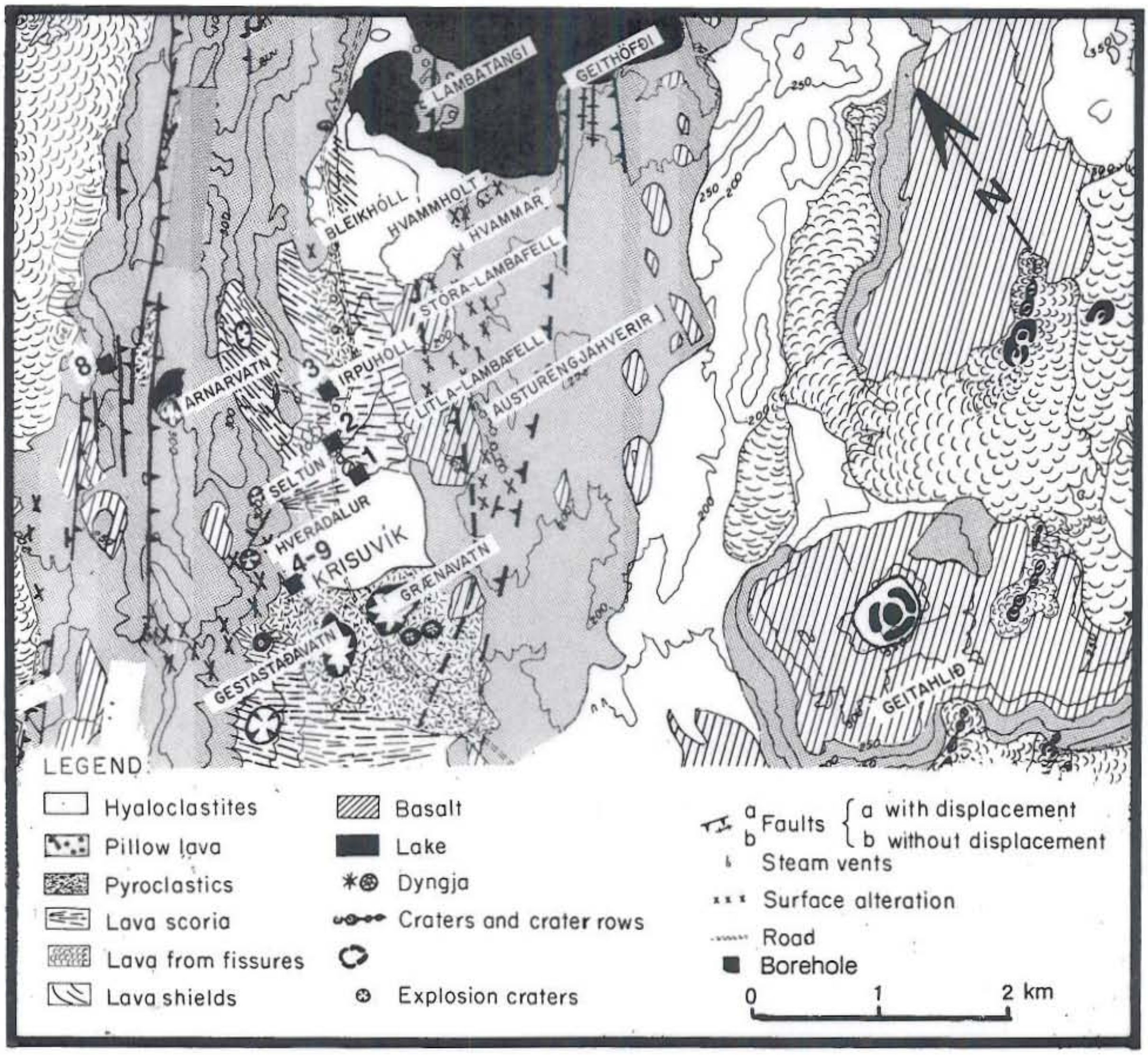

FIGURE 2: Geological map of the Sveifluháls area (Imsland, 1973)

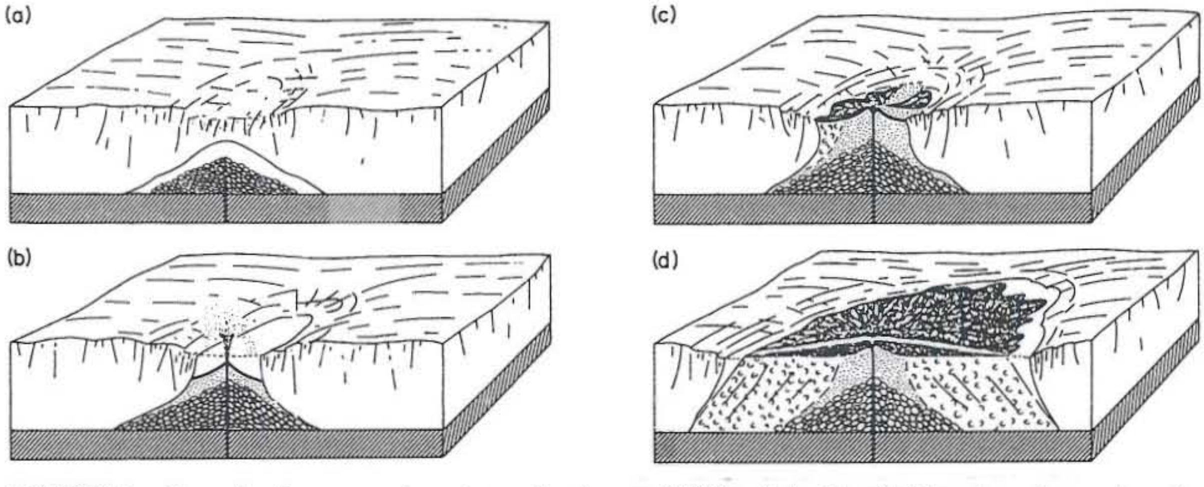

FIGURE 3: Growth of monogenic volcano (by Jones, 1969); a) A pile of pillow lava forms deep in melt water lake; b) Slumping on the flanks of the pillow lava pile produces pillow breccia; c) Hyaloclastite tuffs erupted under shallow water; d) A lava cap progrades across its own delta of foreset breccias

of ice-free and glacial time volcanism. Further subdivision of the two environments includes Inter- and Postglacial volcanism for the former and the latter into sub- and supraglacial volcanism.

Generally the most significant structural element in the Krísuvík area is the presence of a NE-SW oriented fissure swarm (see Figure 1). This fissure swarm is believed to be one of the dominant "en echelon" tectonic features on the Reykjanes Peninsula which control its regional structural framework and is a major force that shaped the present landscape of the peninsula (Vargas, 1992). Accordingly, it has been proposed that the formation of an "en echelon" structural array is produced when a lithospheric belt is subjected to a left-lateral shear strain at a crustal boundary.

Surface thermal manifestations (Figure 4) consist of hot ground where bedrock has been altered at varying degrees by surficial acid leaching (Arnórsson et al., 1975). It includes highly altered ground usually associated with steam vents and mud pools commonly known as solfataras. Alkaline water springs presenting the flashed water fraction of deep water is absent in the area but reheated carbonate

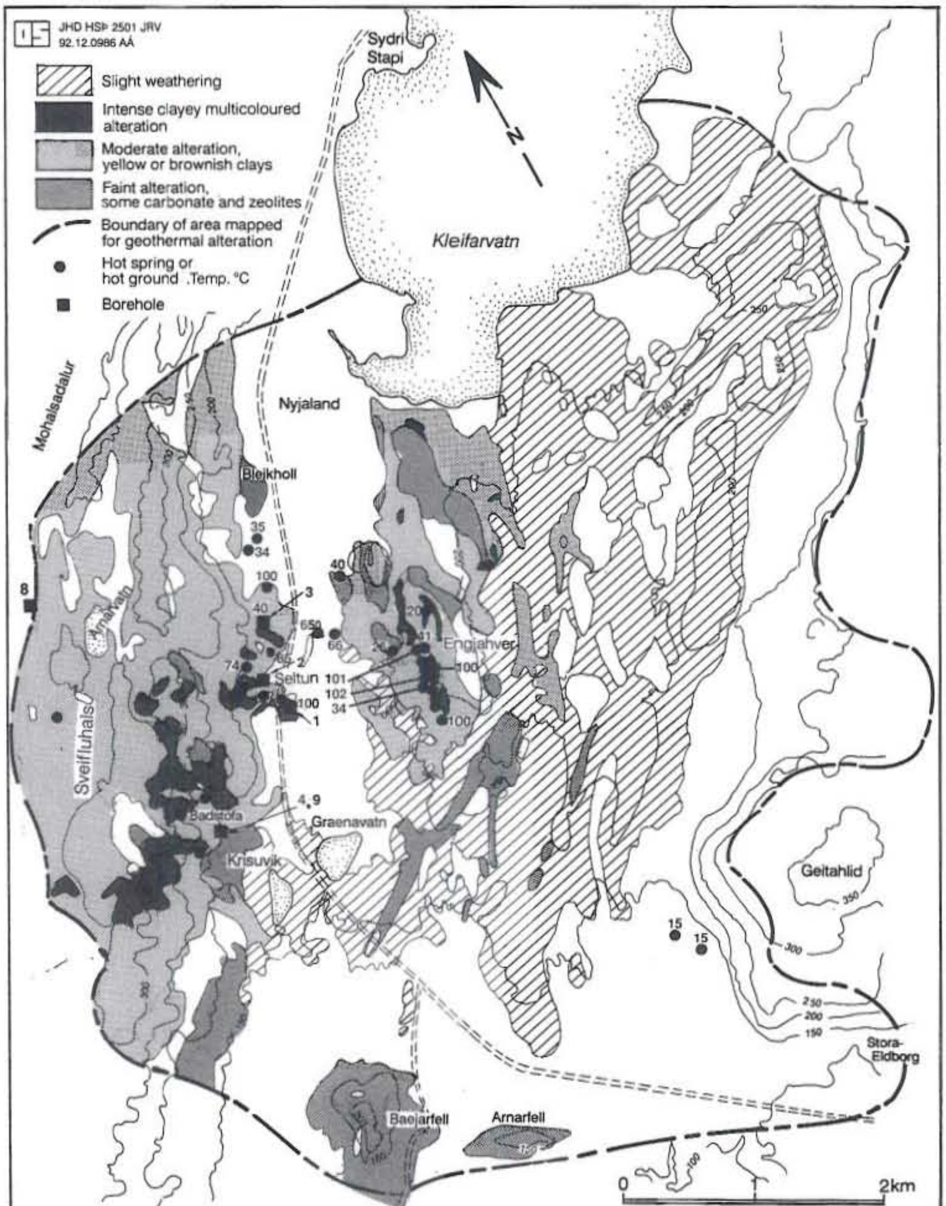

FIGURE 4: Hydrothermal alteration map of Krísuvík valley (Vargas, 1992)

waters appear in a few springs in the localities. Such a phenomenon is related to high underground temperature and low ground-water table (14-52 m). This low ground-water table is believed to reflect the high permeability of the bedrock but not so much the local topography (Arnórsson et al., 1975). Other surface geothermal manifestations include vein fillings, boiling springs, warm springs, hydrothermal explosion craters and mineralized waters (Vargas, 1992). Total surface area of hydrothermal manifestations in Krísuvík is about 5-10 km^2 (Ármannsson et al., 1994).

The thermal water of the Reykjanes Peninsula is highly saline, approaching 20,000 ppm Cl in the outer part, decreasing landwards as a result of the decreasing incursion of sea water into the geothermal system through the permeable volcanic strata. The salinity is anomalously high compared to the average salinity of the Icelandic fresh-water hydrothermal system. Seawater percolates the permeable strata and mixes with meteoric water at depth. In the Krísuvík area this is evidenced by the high total of dissolved solids. This is especially evident in the western fields, i.e. Trölladyngja and Sandfell.

Bedrock resistivity at depth in the Krísuvík area (Figure 5) is influenced by the relative position of the water table, water salinity, acid surface leaching (ground alteration) and underground temperatures. High-resistivity values are predominant at the surface in post-glacial lava fields except in areas affected

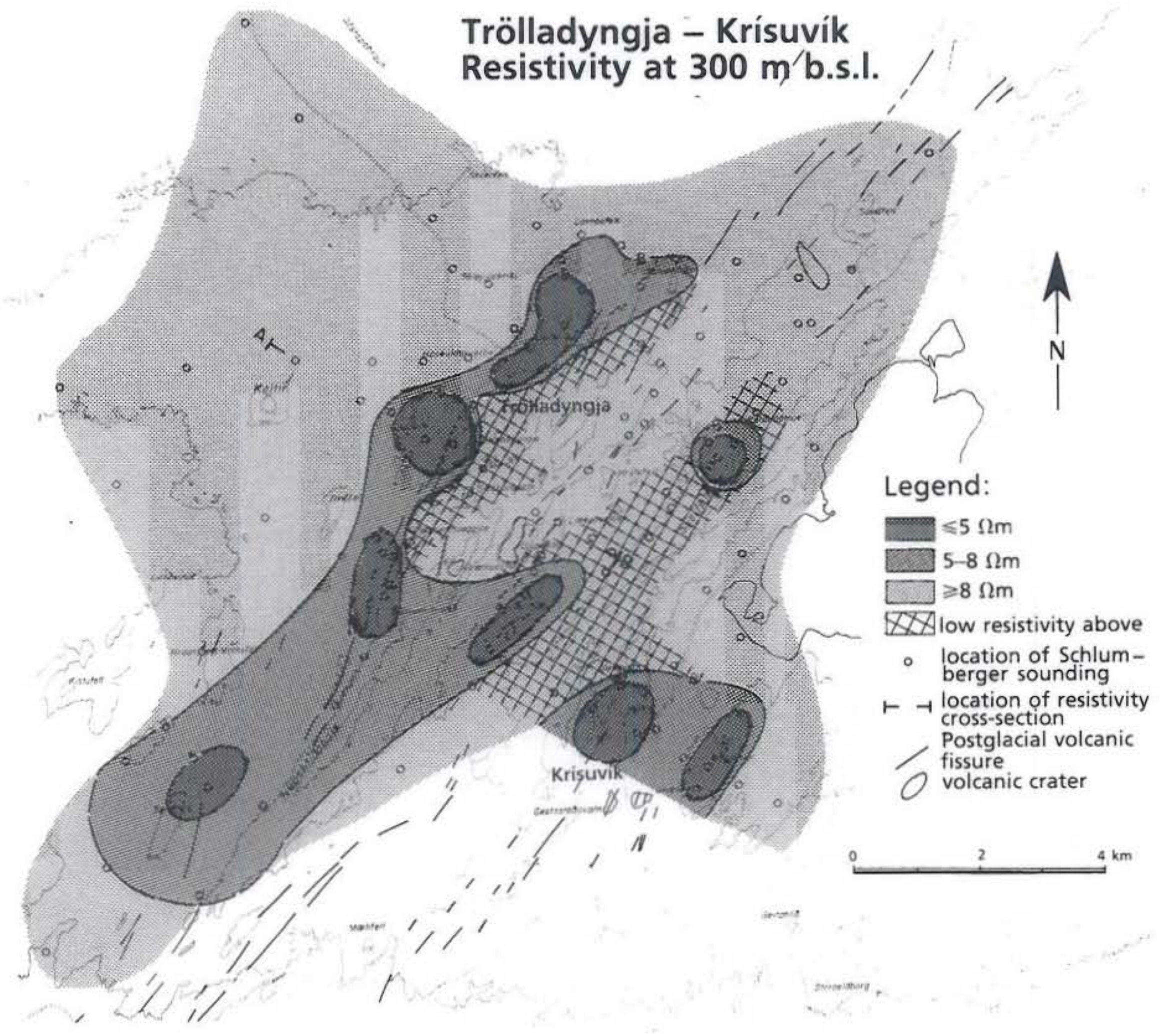

FIGURE 5: Resistivity map of the Krísuvík and Trölladyngja area at 300 m below sea level (Georgsson, 1987)

by surficial acid leaching (Mariita, 1986; Kanyanjua, 1987). Widespread low-resistivity layers (<8 Ωm) in the uppermost 500 m correlate with geothermal activity in permeable near-horizontal layers of hyaloclastite breccia, below which cooler and denser lavas dominate, manifested by increasing resistivity with depth (10-80 Ωm). As shown in Figure 5, inside the low-resistivity area, several smaller areas of extra low resistivity are found (3-5 Ωm) which may represent upflow zones (Georgsson, 1987).

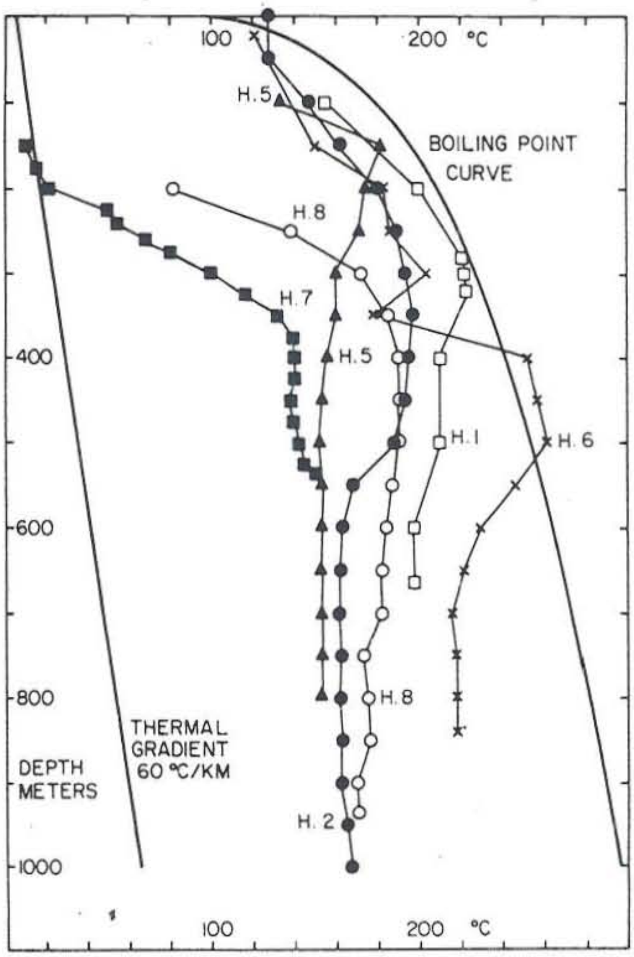

FIGURE 6: Temperature logs of deep wells in the Krísuvík area (Arnórsson et al. 1975)

Previous wells drilled in the Krísuvík area display an inverse thermal gradient below 450 m depth (Figure 6). Possible explanations are: 1) narrow upflow zone(s) and horizontal hot-water movement at shallow depth (cone sheet model), and 2) cooling of an intrusive heat-source complex without much decrease in the flow rate of water through the system (Arnórsson et al., 1975). Kanyanjua (1987) in his study of the Schlumberger vertical sounding at Krísuvík disproved the "cone sheet model" that implies a single heat source and proposed the presence of two resistivity zones (two upflow zones) right under the ridges separated by a high-resistivity barrier. Mariita (1986) concluded that insufficient information was for that Krísuvík field was a "dying" source of heat. He agreed with Arnórsson et al. that further investigations were needed to fully understand the inverse thermal gradient phenomena and the geothermal potential of the area.

2. DESCRIPTION OF WORK

Relatively detailed cutting analyses along with various other borehole logs were used to assess the geothermal system into which KR-9 is drilled. During drilling, rock cuttings were taken at every 2 m depth interval and properly labelled. Circulation losses and rate of penetration were recorded for each drill pipe sunk. The penetration rate is calculated on the basis of the time interval between each drill pipe (~6 m long) sunk. Temperature logs were done during drilling to locate aquifers and assess the condition of the well. After the drill string was pulled out of the borehole at the end of drilling, geophysical logs were conducted. A borehole pressure appraisal was conducted several days after naturally warming up the well. All of these measurements were done to assess the condition of the well.

The cuttings are the most essential indicators of thermal history of the reservoir. The samples from the field, after being properly logged, are transported to a petrographic laboratory. At the laboratory, the samples are cleansed using tap water to remove adhering foreign materials, usually drilling additives and other contaminants. The sample is then air-dried for proper safekeeping and storage. The cuttings for analysis are separated and placed into a labelled rectangular plastic box (56x38x15 mm^3) with cover.

For binocular study, the samples in the boxes are wet by pouring water onto them. Wetting the cuttings is necessary to enhance the visibility of the samples or obscure features such as finely disseminated sulfides, i.e. pyrite. The wet samples are then placed on to the mounting stage of the microscope for investigation. Essential features to be noted during binocular study, to help characterize or locate the resource under investigations, are not limited to the following: colour(s), rock type(s), grain size(s), rock fabrics(s), original mineralogy, alteration mineralogy and intensity, presence of gouge or other evidence of faulting, presence of drill-produced pseudo-gouge, size and shape of drill chips, and types and amounts of contaminants. Examination was done using Wild Heerbrugg Binocular Microscope with a magnification of 6x - 80x. Initial information obtained includes stratigraphy, alteration mineralogy and evidences of permeabilities.

In addition to binocular microscopic study, a thin section for petrographic study was made in order to expand or confirm preliminary findings on the cuttings. However, this method intends to complement rather than replace careful binocular microscopic studies and add the understanding to the mechanics of rock-mineral deposition and alteration. Selected thin-section samples were analysed using Leitz Wetzlar Petrographic Microscope. Moreover X-ray diffraction analyses were done to confirm and identify the types of zeolites and clay minerals present in the cuttings.

All of the data gathered from cutting analyses and borehole measurements were combined and assessed to explain the geothermal system into which the well was drilled.

3. GEOLOGY OF WELL KR-9

3.1 Drilling of well KR-9

KR-9 is the 9th borehole (see Figure 2) drilled in the Krísuvík area since the 1940's. The well pad is located just off the eastern flank of the Sveifluháls hyaloclastite ridge about 500 m north-northeast of Krísuvík Rehabilitation Centre. The well is intended for space heating of the said facility. Well KR-9 is drilled adjacent to an old abandoned well (H-4), drilled during the early part of the exploration history. A correlation with the older well is not possible due to limited data. The well pad is adjacent to grounds with varying degrees of alteration, steam emission and fumaroles.

A truck mounted drill rig with a capacity of approximately 600 m was used for the job. Drilling was done during July 1995 and took a total of 21 drilling days (03-24 July 1995). Production casing of 8 ⅝" was sunk to 127 m depth but the production part of the well was left open down to its total depth of 327 m. The decision to have the well open was based on experience gained in an adjacent non-liner well (H-4) about 10 m from the present well, which did not experience formation collapse during its entire life. However, the more important reasons for not putting liner in the well were economical. Drilling proceeded smoothly except for some minor water pump problems and loss of circulation. Geophysical borehole loggings including caliper, neutron-neutron, temperature, natural-gamma and pressure were done after drilling to evaluate the well.

3.2 The stratigraphy of well KR-9

The formation of the rock in the Krísuvík field is very similar to the origin of the mono-genic volcano under sub-glacial environment (see Figure 3) and interglacial lava formations. These were deposited in the Upper Pleistocene Series or during the last glacial period. A volcanic fissure wells out magma under the glacier forming the base pillow lava (or core of the ridge) and meltwater vault. Continuous magma extrusion results to doming with attendant rock cracking and fragmentation of ascending molten magma as it surges into the glacial meltwater of the subglacial lake. Fragmentation could be both caused by quenching and steam explosive activity. As the dome rises steadily, slope stability becomes critically unstable resulting in the slumping of broken pillow lava downhill forming foreset pillow breccia or hyaloclastite debris flow at the flanks. Continuous volcanism and emergent explosive phase above the meltwater lake leads to a phreatic explosion and ejection of vitric ash and lapilli tuff. If the sub-glacial volcano emerges from the glacial water the phreatic activity shifts to fissure or central lava eruption flattening the crater tops.

The rock formations in well KR-9 are divided into two main groups, hyaloclastites and lava series (Figure 7):

The **hyaloclastites** are found from surface to a depth of about 220 m. It is probable that they constitute of the four following separate hyaloclastite formations, based mainly on the porphyritic nature of the rock:

> **Hyaloclastite A (0-98 m).** This formation probably extends from surface down to about 98 m depth. It is mostly composed of vesicular aphyric tuff. Between 60 and 74 m it is a partially crystallized basaltic breccia.
>
> **Hyaloclastite B (98-132 m).** This 34 m thick formation is identified on grounds of its porphyritic nature (plagioclase), and consists of tuff, breccia and medium to coarse-grained basalt. The basalt is sub-ophitic olivine tholeiite.
>
> **Hyaloclastite C (132-170 m).** This 38 m thick formation consists mostly of tuff but has a 10 m thick medium to coarse-grained basaltic layer. It is aphyric and thus distinct from the hyaloclastites above and below. It shows a crystallization corresponding to olivine tholeiite composition.
>
> **Hyaloclastite D (170-220 m).** This hyaloclastite consists of partially crystallized basalt (probably pillow breccia). This rock is distinctly plagioclase porphyritic and is probably of olivine tholeiite composition.

The **lava series** are found in the interval 220-327 m. Total circulation loss occurs intermittently from 229 m to the bottom of the well. The samples retrieved from the well are largely fine-grained basalt. A thin section from the depth 327 m shows a very fine-grained, equigranular plagioclase porphyritic basalt.

The succession depicts, as mentioned earlier, two types of environment; subglacial hyaloclastites, and a lava formation. The former appears to consist of four individual hyaloclastite eruptions. The age of the hyaloclastites can only tentatively be suggested to be of the last glacial period (12,000-115,000 years) while the underlying lava series might have formed during the last interglacial period (115,000-125,000 years).

Geophysical logs along with penetration rates are plotted alongside the lithological log (Figure 7). While the neutron-neutron log shows a relatively smooth curve with the hyaloclastite, it becomes rugged when entering into the lava succession. The lower boundary of the hyaloclastite and the underlying lava series is therefore suggested to lie at around 220 m depth. The penetration rate similarly shows more variation with the lava series compared to the hyaloclastite.

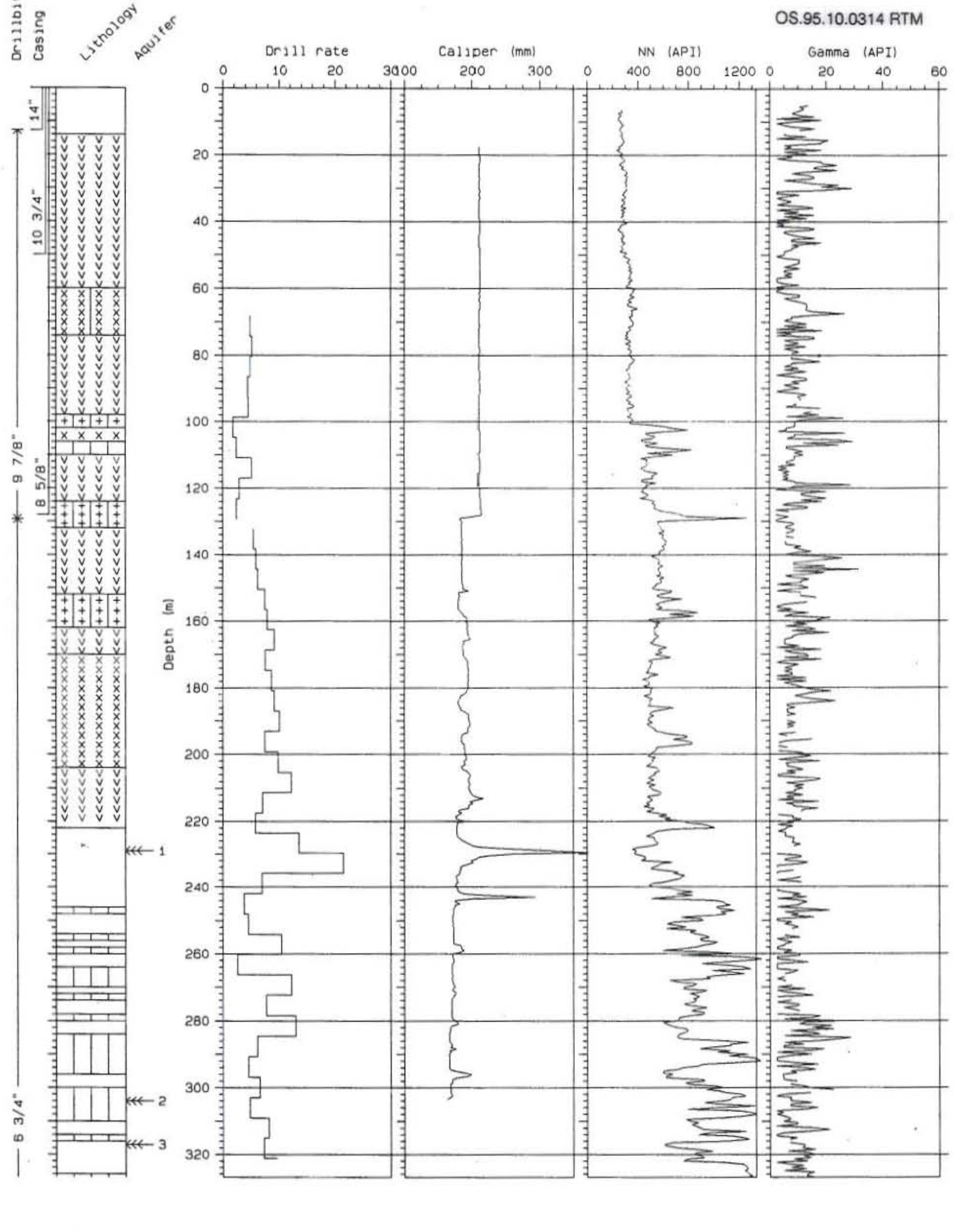

FIGURE 7: Detailed stratigraphy and geophysical logs of well KR-9

4. HYDROTHERMAL ALTERATION

The hydrothermal alteration is a product of water rock-interaction, depending on rock type, composition of the fluid, temperature and pressure. The environment of the geothermal system can be assessed on grounds of present hydrothermal alteration suites or mineral alteration assemblages in a rock formation. These hydrothermal mineral suites are useful in the interpretation of thermal history of the area which are vital in the assessment of the geothermal potential.

Attainment of complete mineral transformation depends upon several factors and varies from field to field such as; a) temperature, b) pressure, c) rock type, d) permeability, e) fluid composition and f) duration of activity (Browne, 1978). Reyes (1990) detailed the use of hydrothermal mineral assemblages as to 1) geothermometers, 2) depth design of production casing, 3) estimate of fluid pH and other chemical parameters, 4) prediction of scaling and corrosion tendencies of fluids, 5) measure of permeability and possible cold water influx, 6) guide to hydrology, and 7) reconstruction of eroded overburden.

4.1 Analytical methods

Determination of both primary and secondary alteration minerals is vital in understanding the geothermal system of the well. First hand information was generally derived from the binocular microscope examination of the cuttings. Deeper probe using the X-ray diffraction method and a petrographic microscope was done to supplement results of binocular microscope analysis especially for clay and zeolite minerals. Methods of sample preparations both for clay and zeolite minerals treated under X-ray diffraction are discussed in Appendix I, while Appendix II shows the XRD clay analysis results for well KR-9.

4.2 Rock alteration

The primary mineral constituents of basalt are olivine, pyroxene, plagioclase feldspar and iron ore minerals like magnetite and ilmenite. Glass is also commonly found, formed during rapid quenching of the magma. Interaction with the invading hydrothermal fluid, the above constituents undergo transformation in a rare, partial or complete manner in response to changing alteration environment. Figure 8 shows the alteration state of these constituents in the well as summarized below:

1. Glass alters mostly to clays and rarely to calcite;
2. Olivine is not common but alters mostly into clay;
3. Pyroxene is the most resistant to alteration of all the constituents, and it is seldom affected by hydrothermal alteration;
4. Plagioclase is relatively resistant to alteration but indications of alteration are the tiny fractures filled with clay at high temperature at the deeper part of the well;
5. Iron ore minerals are usually observed in the form of sulfides (usually pyrite).

In this well the order of decreasing susceptibility to alteration is glass, olivine, plagioclase and pyroxene. The typical mineral to pervasively replace glass is clay and to a lesser extent calcite. Olivine was seldom observed in the well. In thin sections at 114 and 128 m an outline of olivine crystal was visible in the clay. Clay altering the olivine is mostly smectite. Pyroxene is barely affected by hydrothermal alteration. It was only at 220 m depth where pyroxene is very slightly affected by clays concurrent with the observance of wairakite in the same thin section. Plagioclase is resistant to alteration in most parts of the well. Rare reaction with the hydrothermal mineral was observed in thin sections at 220 m and at

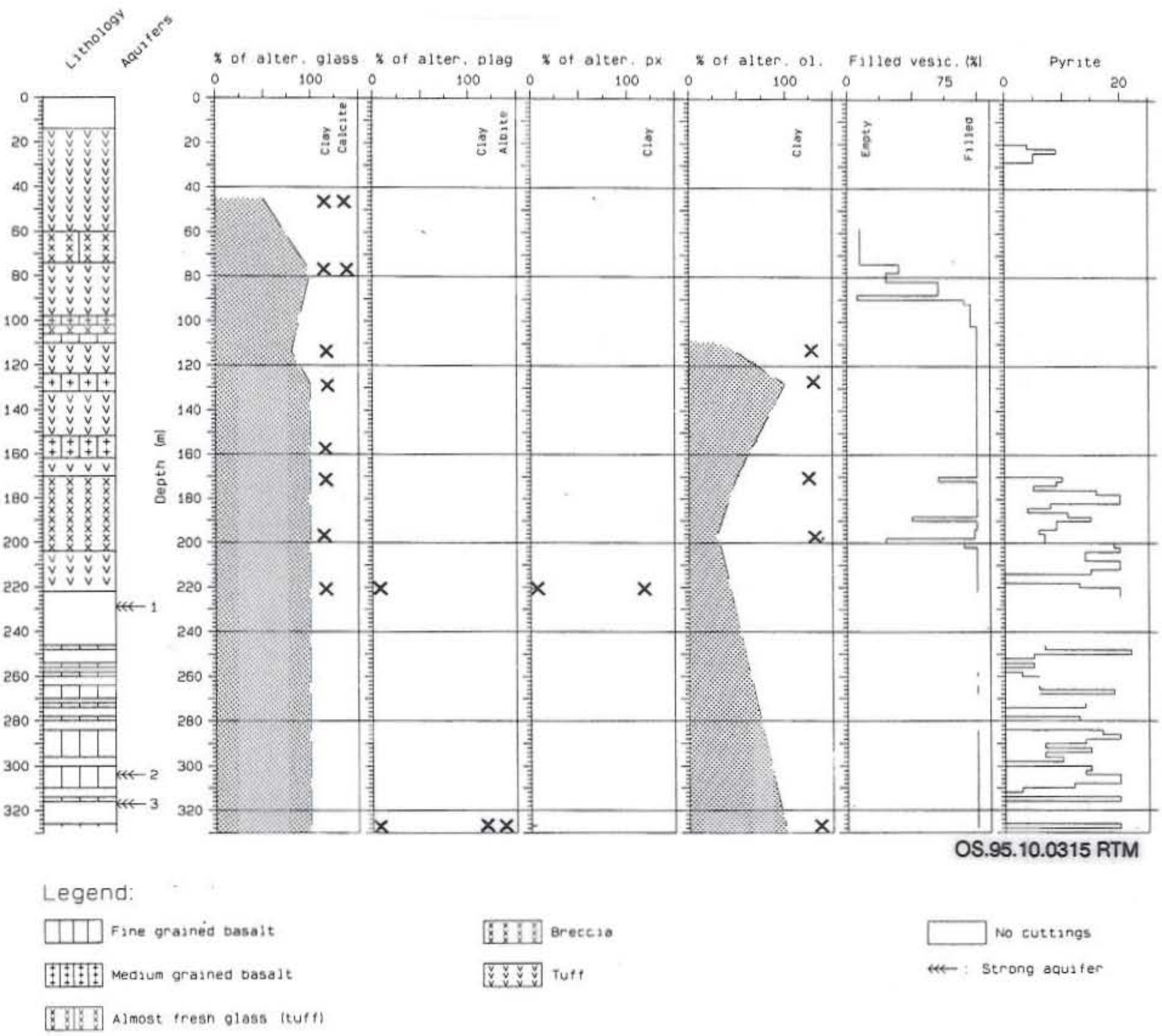

FIGURE 8: Lithology of well KR-9 in Krísuvík, alteration state of primary minerals, glass, filling of vesicles and relative abundance of pyrite (0 = absent; 1-10 = common; 11-20 = abundant; >20 = very abundant)

327 m where a fracture filling of clay minerals was observed. This filling of clay minerals in the fracture line of the plagioclase is indicative of increasing temperature (Franzson, pers. comm.). Wairakite was also observed in both zones. Iron mineral alteration was not observed in the well. Relative pyrite abundance is common from 220 m down to the bottom of the hole. Its abundance is also correlated with the aquifers identified in the well.

4.3 Distribution of hydrothermal minerals

Figure 9 shows the distribution of alteration minerals in well KR-9. The entire depth penetrated by the drill hole is characterized by the presence of clays, calcite, quartz, zeolite, pyrite and other minerals of rare occurrence. These occur as replacement minerals, as vein fillings along fractures and disseminations, e.g. pyrite in the groundmass. Clays are common as alteration products of volcanic glasses. Calcite showed the widest range of occurrences as fracture in-fillings or interstitial minerals. Quartz was typically observed as a secondary vein mineral and cavity fills. Pyrite is widespread, it is disseminated in matrices and veins and sometimes also the major sulphide in quartz veins.

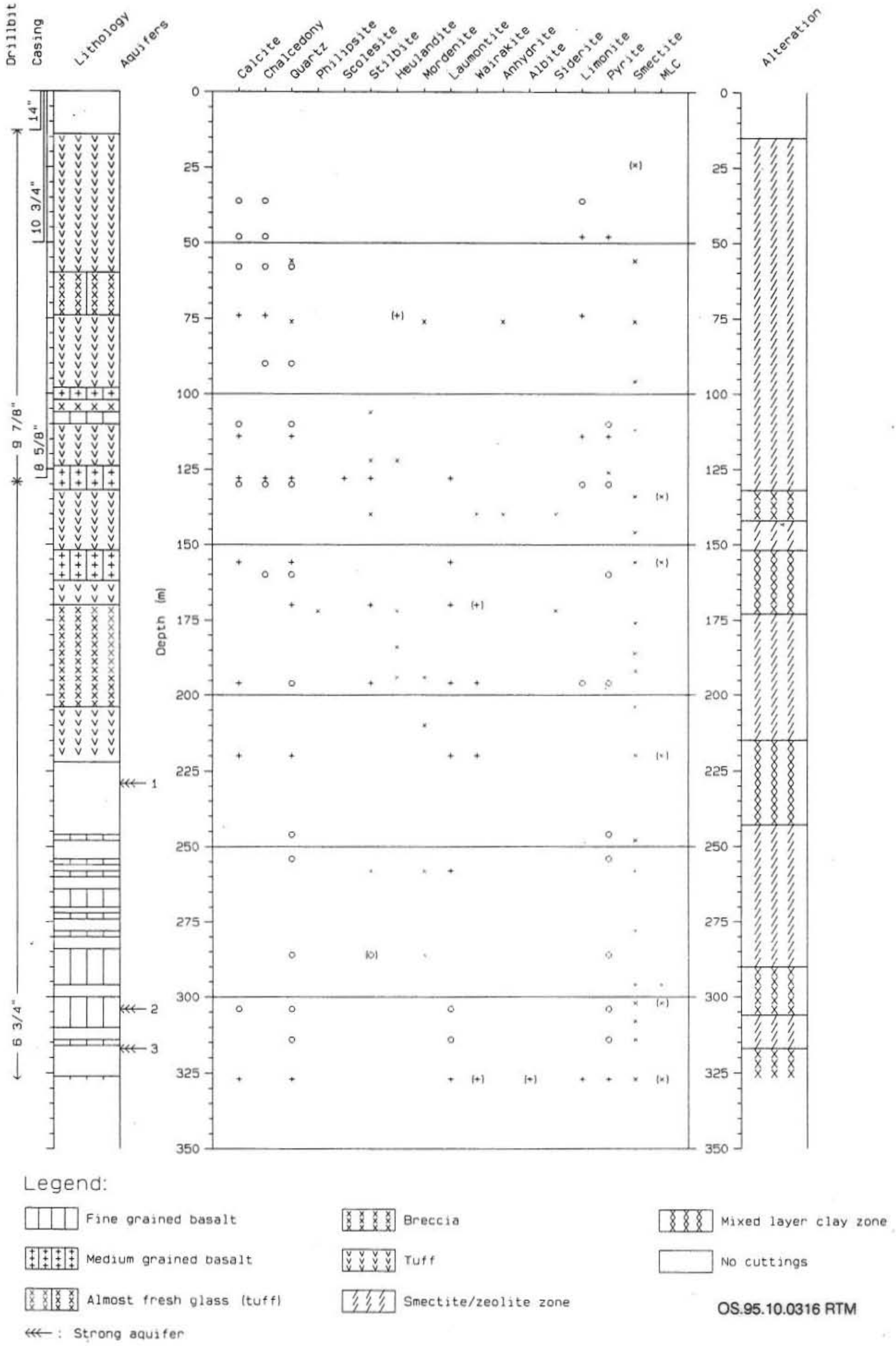

FIGURE 9: Stratigraphy, hydrothermal alteration minerals and alteration zones of well KR-9

Calcite is the most common alteration mineral which temperature of formation extends up to 270°C (Kristmannsdóttir, 1978). However, its formation depends essentially on how the interplay of temperature, load pressure, and concentration of free CO_2 in the solution affects the solubility of calcite and also on the availability of Ca^{2+} ions in the solutions (Steiner, 1977). Calcite in well KR-9 showed the widest range of occurrences especially among the hyaloclastites but seldom in denser holocrystalline basaltic lava. Calcite observed are generally of two types; as a normal rhombohedral calcite and with a bladed morphology commonly called "platy calcite". The first type is usually indiscriminately distributed in the interstitial pore-spaces of the rock matrix and cavities, whereas platy calcite was observed filling up fractures and as intergrowth with other minerals. The presence of the bladed morphology is probably an indication of a zone of boiling which was typical in the upper 100 m depth horizons. Below that the first type is strongly dominating.

Chalcedony was observed in thin sections and cuttings at 48-160 m depth interval occurring as cavity fills, or lining walls of vesicles. In thin sections it is colourless to pale brown and often exhibits a spherulitic form.

Quartz is seldom found as groundmass alteration but was rather abundant as open-space fillings often as crystal growth in the clay-lined or calcite-filled vesicles or as intergrowth with calcite. Quartz formation is most notable in the hyaloclastites and directly above the zones of circulation loss below 246 and 300 m.

Zeolites are hydrous calcium aluminum silicates that commonly occur as secondary minerals in rock cavities, especially basalt (Kerr, 1959). They are widespread as infillings between 100 and 220 m and rarely in the deeper part of the well due to zeolite alteration to quartz and emergence of high-temperature zeolite (wairakite). Although some variety was noticed in binoculars between 50-70 m depth level, their identities are uncertain except for the mordenite (as per XRD) at 76 m. In cuttings they were found usually in free-state (probably freed during drilling) and in thin sections as crystal growth in cavities.

They are often associated with calcite, quartz and rarely with pyrite. There are two dominant groups of zeolites identified by XRD, binocular and petrographic analyses. These groups are the heulandite-stilbite group (T=90-110°C) and the mordenite-laumontite group (T=110-230°C). These are found coexisting from 100 to 258 m where the last stilbite was found. Heulandite was last detected at 194 m. Below 260 m, laumontite-mordenite are the dominating zeolite species down to 286 m where mordenite disappears. Wairakite (T=>200°C) is a high-temperature zeolite variety of rare occurrence from 140 to 327 m. Other rare zeolite varieties are philipsite and scolecite. The following are the descriptions of zeolites encountered in the well:

Heulandite shows characteristic XRD peaks at 8.85, 3.92, 6.65, 3.42, 3.19, 3.13, 2.60, 2.81 and 2.73 Å at 122, 172, 184 and 194 m depth. It is commonly found in the hyaloclastites but less common in the denser type of basalt.

Stilbite under the petrographic microscope shows sheaf-like aggregates and radial form. In XRD it commonly peaks at 9.15, 4.06, 3.74 and 3.19 Å as observed in depth level 106, 122, 140 and 258 m.

Mordenite was detected by the XRD with peaks of 4.53, 3.04 and 3.31 Å at 76, 194, 210, 258 and 286 m.

Laumontite is a columnar variety of zeolites noted under a petrographic microscope from 128 m downhole, abundant in basaltic lava and rare in the hyaloclastites. It has a prismatic and fibrous structure and mainly found as cavity and fracture fills. It occurs along with mordenite from 128-286 m depth.

Wairakite was recognized in the XRD at 140 m with peaks of 5.57, 4.84, 3.64, 3.42, 3.39, 2.68 and 2.489 Å. Under the stereo-microscope it has a distinct igloo-shaped crystal structure, and in a petrographic microscope a dull colour and cross-thatched twinning similarly exhibited by the polysynthetic twinning in plagioclase. In thin section it was observed at 196, 220 and traces at 170 and 327 m.

Philipsite has been detected only at 172 m in the XRD with its characteristic peaks of 4.98, 3.47, 3.19, 2.698 and 1.78 Å.

Scolecite was observed in crystal aggregates with a columnar to fibrous structure intergrowth with laumontite at 128 m. Aside from this depth level, no other occurrence was noted.

Anhydrite was detected by XRD with its characteristic peaks of 1.87, 2.09 and 2.21 Å at 76 and 140 m depth level.

Albite was only found at 327 m in thin section.

Siderite is an iron carbonate mineral with XRD peaks of 2.79, 2.34 and 2.13 Å at 140 and 172 m depth.

Limonite a reddish-brown mineral was noted in the oxidized layer or predicted zone of groundwater fluctuation from 14-52 m. It is a secondary mineral product resulting from oxidation or weathering. In a binocular microscope it was found staining the clay minerals and as rims around the cavities or open spaces. Under the petrographic microscope it appears brown in reflected light and usually borders other minerals especially pyrite.

Pyrite is the most common sulphide occurring as disseminations and fracture-fillings. The fine-grained disseminated pyrite is most abundant in the basaltic lava but sparsely distributed in the hyaloclastites. Relative abundance of pyrite has turned out to be very useful in assessing permeability in Icelandic hydrothermal systems. A relative increase in the proportion of pyrite in the groundmass was observed as well as in the quartz vein from 200 m down to a circulation loss zone at 229-246 m and from 300 m to the bottom of the hole (as indicated by absence of samples). Under a binocular microscope it is easily identified with its distinctive brass yellow colour and metallic luster. This is common as euhedral crystals often cube which yields square, rectangular, triangular or even hexagonal outlines. Under oxidizing condition pyrite may be altered to limonite.

The **clay minerals** are the most voluminous alteration minerals. They alter basalt glass, olivine, and partly plagioclase. The clay minerals are usually fine-grained and poorly crystalline. Clays in the well KR-9 are mainly smectite (as per XRD). This was observed under the binocular microscope as a brownish green, poorly crystalline mineral and thinly lined the walls of the cavities. In thin section it appeared brownish with low birefringence with occasionally a reddish tinge due to oxidation. On XRD it has peaks commonly occurring between 13.5 to 15 Å (constant humidity), 16.3 to 17 Å when treated with glycol and collapsing to 10 Å when heated to 500 to 550°C. The clays in this well also showed textural generation from fine-grained to coarse-grained as the well gets deeper. Fine-grained variety is typical in the shallow level until approximately half of the well depth. Textural variations from fine-grained to medium-grained and to coarse-grained is observed in the remaining parts of the well. The coarser variety of clay was observed to have a pleochroic yellowish brown colour. This textural evolution is relatively suggestive of the increasing temperature with depth (see Section 4.5).

Mixed layer clays (MLC) usually respond to XRD peaks of 15-17 Å (at constant humidity) expanding to 29-31 Å (glycolated) and collapsing to 12-14 Å when heated up to 500-550°C. Evidence in certainty of mixed layer clays occurrence for this well was based on standard Icelandic mixed layer clay calibration with peaks of 12.8-14.6 Å (at constant humidity), peaks at constant humidity to 16 Å when treated with glycol and with a total breakdown to 12 Å when heated to 500-550°C. The probable trace of mixed layer clays was detected as a narrow zone within the smectite-zeolite zones just below 100 m depth to the final well depth. Although mixed layer clays could be identified petrographically based on their colour, texture and optical properties, the XRD technique still remains essential as the final determinant.

4.4 Alteration mineral zonation

Hydrothermal alteration in Iceland is highly temperature dependant where definite mineralogical changes are seen to take place with increasing temperature (e.g. Pálmason et al., 1979). Thus zeolites are found at temperatures up to 200°C where they are transformed to, e.g. wairakite. Quartz is found at temperature above about ~180°C, and calcite appears to be stable up to temperatures around 280-290°C. Epidote forms at temperature above 240-250°C. Smectite is the dominant clay mineral up to a temperature of about 200°C where mixed layer clays start to form, and chlorite starts forming at temperatures above about 230°C (Figure 10).

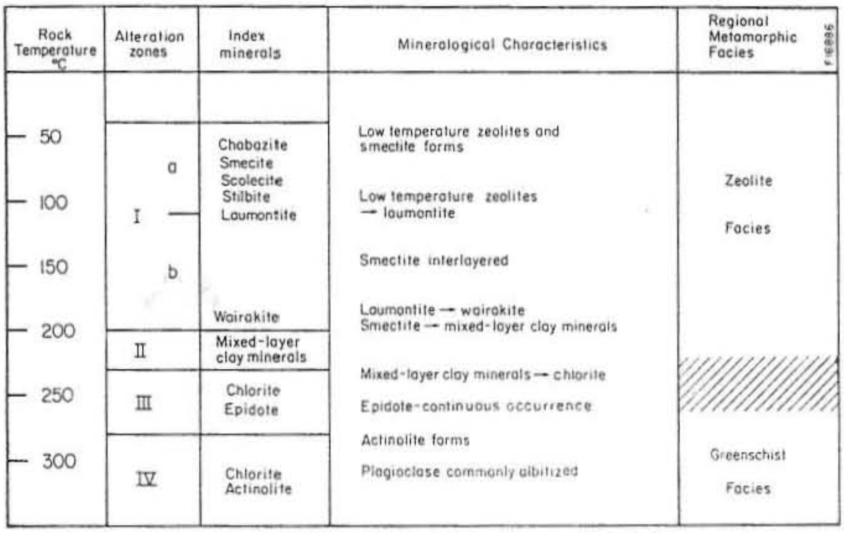

FIGURE 10: Correlation of alteration zonez in high-temperature geothermal areas in Iceland to rock alteration and metamorphic facies (slightly modified from Pálmason et al., 1979)

As well KR-9 is only just over 300 m deep, the alteration found is mainly confined to the smectite-zeolite zone. The boundary between the smectite-zeolite and mixed layer clays is not well defined in the well. Narrow zones of mixed layer clay are probably present within the smectite-zeolite alteration zone. Mixed layer clay zone is postulated to start near to the bottom of the well as observed by XRD-analyses concomitant with clay fracturing in the plagioclase as well as the presence of wairakite, a high-temperature variety of zeolite.

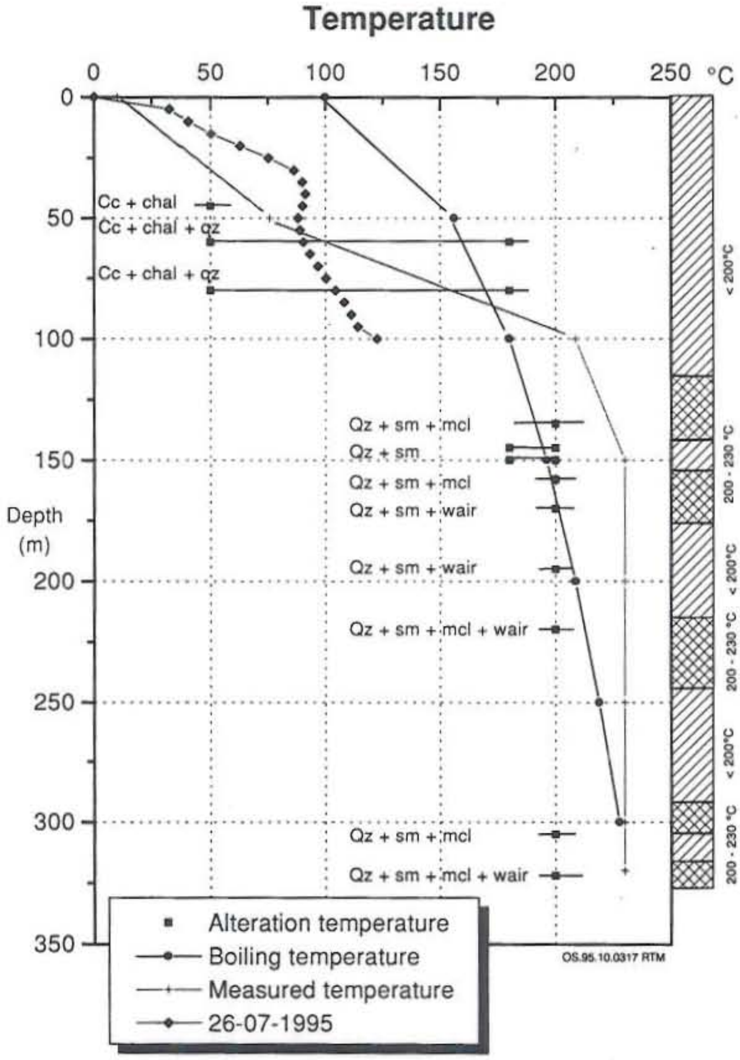

FIGURE 11: Correlation of measured temperature and alteration temperature in well KR-9

As shown in Figure 11 the **smectite-zeolite zone** is the dominant alteration in KR-9 below 100 m to the bottom depth. Common knowledge suggests that this alteration suite indicates temperature of formation of <200°C. Its presence and association with other secondary minerals of known formation temperature give a close correlation with the measured temperature.

The **mixed layer clay zone** although not widespread in the well is inferred to be fast approaching. This was based on the last thin section at 327 m showing clay filled fracture in the plagioclase indicating increasing temperature and alteration progress with depth.

4.5 Deposition sequence

The diagnostic examination of cuttings and thin sections under the microscopes is the main tool used in the determination of the chronological order of rock-mineral and mineral-mineral interaction in the well. Deposition is best observed to occur as full, partial or rare in cavities, fractures and interstitial spaces of the groundmass as it undergoes transformation in response to different changes in the environmental deposition. Clay is the major hydrothermal alteration lining walls of the vesicles and fractures. Table 1 shows the hydrothermal mineral evolution of well KR-9 commonly observed in most of the thin sections. The upper zone down to about 150 m is characterized by the initial deposition of fine-grained clay followed by zeolite and calcite. From thereof to nearly 200 m, clay mineral possessing coarse-grained texture becomes dominant, coupled with rare observation of wairakite. It is interesting to note that the coarse-grained clay appears to precede the zeolite at 156 and 170 m depth, while a closer inspection reveals that the clay is "forcing its way" into the zeolite and is therefore probably younger than the zeolite. Low-temperature zeolites at this depth are also being replaced by quartz. Zeolite replacement by quartz and late deposition of coarse-grained clay characterized the remaining depth zone with the addition of calcite. The early apparent deposition of the zeolites indicates an earlier lower temperature environment succeeded by a higher temperature environment.

TABLE 1: Sequence of hydrothermal minerals deposition commonly observed in thin sections

Depth (m)	Depositional sequence	Remarks
48	fine-grained clay⇛chalcedony⇛calcite	
74	fine-grained clay⇛zeolite⇛calcite	
114	fine-grained clay⇛zeolite⇛calcite	
128	fine-grained clay⇛zeolite⇛coarse-grained clay⇛calcite	
156	zeolite⇛quartz⇛coarse-grained clay	
170	zeolite⇛quartz⇛coarse-grained clay	
196	zeolite⇛quartz⇛coarse-grained clay	
220	zeolite⇛quartz⇛coarse-grained clay	wairakite was observed
327	coarse-grained clay⇛quartz⇛calcite	

5. AQUIFER ZONES

In general, an aquifer is defined as a zone in the sub-surface level where an unquantifiable volume of circulating groundwater (mostly meteoric in origin) is stored. Groundwater movement is generally controlled by hydraulic gradient, formation permeability and porosity and differential pressure and temperature. Determination of the aquifer zone whether wanted or unwanted, is vital in the search of a geothermal reservoir. Geothermal aquifers are characterized by the presence of permeable rock formations, feed zones and natural recharge areas. Diagnostically its presence is directly determined from records of circulation loss during drilling and anomalous temperature logs. Aquifers can also be deduced from the existing hydrothermal alteration mineral assemblages as functions of permeability as commonly used in Philippine geothermal fields and other fields in the world (Reyes, 1990). Among the minerals commonly found or adjacent to aquifers in the form of rock alteration and as veins are quartz, anhydrite, wairakite, illite, adularia, hyalophane, abundant pyrite and abundant calcite.

Well KR-9, although a shallow well, has good aquifer zones due to the good permeability of the lava formation which is typical in the Reykjanes Peninsula. Unfortunately, due to the limited instrumentation of the truck mounted rig, small circulation loss zones were not efficiently recorded, showing mainly the major loss zones. These circulation loss zones are deduced from the temperature logs.

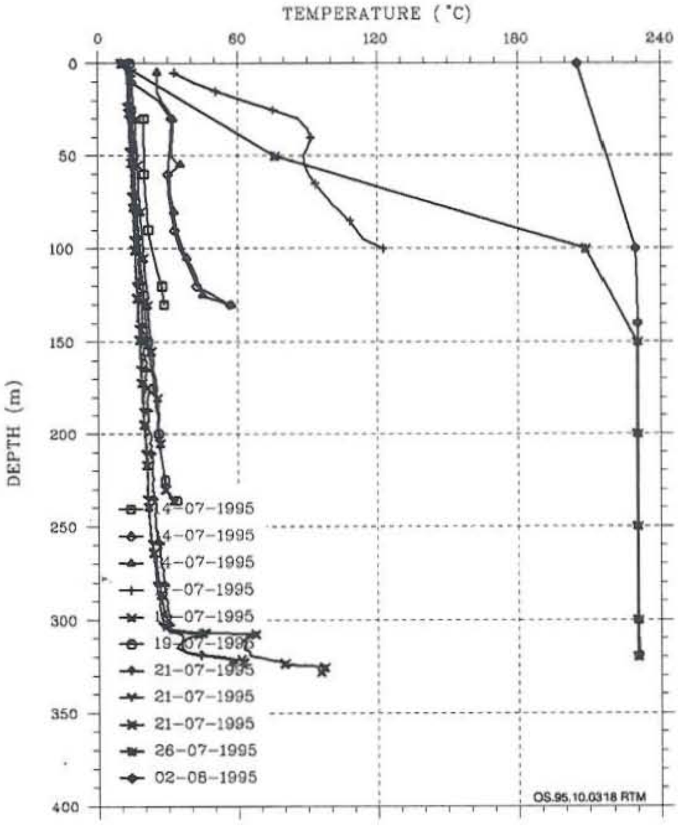

FIGURE 12: Temperature logs of well KR-9

In the absence of an accurate recording of the circulation loss zones, identification of possible aquifer zones will rely largely on the results of both the downhole surveys and mineralogical examinations irrespective of whether it is a major or minor aquifer zone. There are three aquifer zones identified in the well as determined from the geophysical log and records of circulation losses (see Figure 7).

Aquifer 1 is located in the major loss zone at 229 m depth. As shown in Figure 7 (neutron-neutron log results) an aquifer at this depth could be related to a stratification boundary such as bedding planes, lithological contacts or stratigraphic break. This is possibly a lithological boundary between a hyaloclastite formation and the underlying lava series. Such a kind of stratigraphic plane of weakness causes inhomogeneity of the rock and usually results in a cave formation as seen in the caliper log (Figure 7). Absence of cuttings and anomalous temperature log (Figure 12) characterizes this aquifer.

Aquifer 2 is situated at 304 m depth within basaltic lava. This zone was detected from the outcome of temperature logs (Figure 12) due to its anomalous temperature reading. Further borehole measurement using pressure logs (Figure 13) showed constant pressure with time at this depth. Both results suggest this zone to be the strongest aquifer based on steady pressure condition with time. A mineralogical study also suggests a strong correlation with the relative abundance of pyrite in this zone (Figure 8). Pyrite is a useful mineral as an indicator of permeability in Iceland.

Aquifer 3 is located at 317 m in a circulation loss zone. Evidences of anomalous temperature log and absence of cuttings are the character of this zone. As in the case of aquifer 2, this could also be inferred as related to a stratification boundary based on a neutron-neutron log (Figure 7).

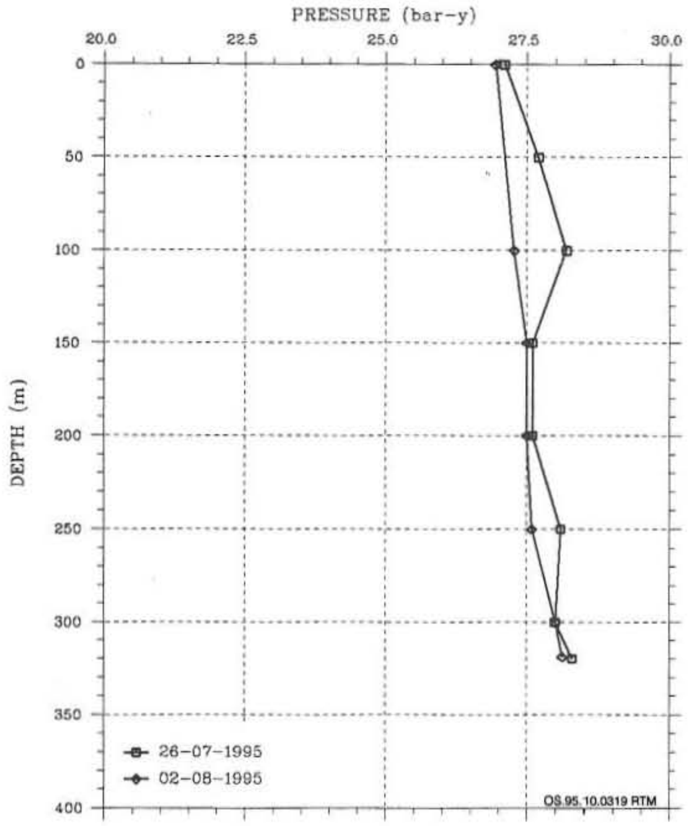

FIGURE 13: Pressure logs of well KR-9

Based on the above information it could be told that two of the aquifers (1 and 3) are related to stratigraphic property and one (aquifer 2) to some formational characteristics of basaltic lava. These aquifers would not be possible to determine unless for the combined evidences of a) circulation loss of return drilling water, b) temperature log surveys, and c) hydrothermal mineral indicators such as quartz, pyrite, zeolite and calcite.

7. DISCUSSION

The upper 300 m of formations penetrated by the well KR-9 have geological, mineralogical and hydrological identities that appear to be similar to other parts of the Krísuvík high-temperature field. Although earlier drilling activities had already been done in the area, initial subsurface records didn't warrant good correlation. The absence is complemented by several surface geological investigation done in Krísuvík geothermal field.

The entire depth horizons penetrated by well KR-9 are made up of basaltic materials subdivided into hyaloclastites and lava formation. Classification of the formation was based on the petrographic characteristic texture rather than its genetic origin due to its unique composition. Time of deposition and its relative environment were also considered in drawing the stratigraphy of the area. There were two contrasting deposition environments which each rock type represents. Hyaloclastites indicate under ice-sheet conditions whereas lava indicates ice-free environment of the intraglacial period. This gives a clue that the upper 300 m are less than 125,000 years old. Hyaloclastites aside from being stratigraphically significant are also petrographically important due to their dexterity to alteration which makes them a reliable indicator of thermal evolution compared to the denser lava.

The hydrothermal alteration shown in this well is mainly in the form of rock alteration and deposition in small veins and amygdule fillings. Typical alteration zonations common in most Icelandic geothermal fields are limited only to smectite-zeolite zones with probable presence of a narrow mixed layer clay zone within the smectite-zeolite zone. Abundance of zeolite was not noted until below 100 m in association with smectite persisting down to 290 m depth. The smectite-zeolite zone has a rock temperature formation of <200°C. Mixed layer clays of probable smectite-chlorite with formation temperature arbitrarily fixed at >200°C were observed at those depths in the hyaloclastites but rarely in basaltic lavas, except at the bottom of the well. It occurs alternately with a smectite-zeolite zone just below 130 m depth until the bottom of the well. This alternating zonal alteration pattern or squeezing of mixed layer clay within the smectite zeolite zone is probably related to the rock susceptibility with the alteration as shown by the variable alteration of hyaloclastite and lava.

Aquifer zones or a geothermal reservoir is the most important factor in a geothermal system. Its presence is governed by an effective rock permeability controlling geothermal fluid flow and circulation in the system. Aquifers in well KR-9 were postulated to be related with the stratification based on a neutron-neutron log except for one aquifer related to lava formation. This stratification anomaly serves as conduit of geothermal fluid to circulate in a geothermal reservoir. Lithological logs combined with the other disciplines are the best methods to identify aquifers.

8. CONCLUSIONS

The following conclusions can be put forward based on evidence gathered from the study of well KR-9:

1. Basalt is the single rock composition in well KR-9. The rocks are divided into hyaloclastites and lava formation based on each petrographical characteristic texture and geophysical property. These two main formations represent contrasting environment and age of deposition between 12,000-125,000 years of the last interglacial and glacial period. Sequence of deposition is hyaloclastites overlying the lava formation.

2. Environment of deposition influence the rock homogeneity and alteration. Hyaloclastites are more vulnerable to alteration as a result of higher glass fraction compared to the denser lavas of the ice-free period.

3. Hydrothermal alteration in the well shows a general progressive alteration with depth. A smectite-zeolite zone with a narrow zone of probable mixed layer clays are common in the well. The sporadic occurrence of the mixed layer clays within the smectite-zeolite zone signals increasing temperature as evidenced by wairakite, emergence of coarse-grained clay and clays in plagioclase fractures with depth. The present smectite-zeolite alteration shows discrepancy with the measured temperature indicating heating up of the geothermal system in well KR-9.

4. Aquifers in the well are related to stratigraphic boundaries of the volcanic succession.

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APPENDIX I: Preparation of sample minerals for analysis by the XRD technique

The following are the step-by-step procedures in the preparation of samples with hydrothermal alteration and clay minerals for identification and classification:

Procedure 1: For zeolite and other hydrothermal mineral analysis

1. Under the binocular microscope, hand pick grain filling either vesicles or veins from the cuttings contained in the rectangular plastic box. The sampling depth is dependent on the worker's purpose and objectives. There is no strict rule on the sampling methodology. The amount of samples should be more than enough to fill-up the sample window used in XRD.
2. Crush the sample in an agate bowl to a grain size of 5-10 microns. Acetone is added to prevent loss of sample while powdering.
3. Fill the sample window slot with an appropriate amount of powdered sample, then press a glass slide against the sample in a slot to make it firm, flat and level.
4. Run the sample from 4-60°.

Procedure 2: For clay mineral analysis

1. Place approximately two teaspoons of drill cuttings into a test tube, wash out dust with distilled water. Fill the tubes ⅔ with distilled water and plug with rubber stoppers. Place the tube in a mechanical shaker 4-8 hours, depending on the alteration grade of the samples.
2. Remove the test tubes from the shaker and allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few mm from each tube, halfway before the level of the sample, and place about ten drops on a labelled glass slide. Avoid having the samples thick. Make a duplicate for each sample and let dry at room temperature overnight.
3. Place one set of samples in a desiccator containing Glycol ($C_2H_6O_2$) solution and the other set in

a desiccator containing $CaCl_2 2H_2O$. Store at room temperature for at least 24 hours. Thick samples will need a longer time in the desiccator, at least 48 hours.

4. Run both sets of samples from 2-15° on the XRD.
5. Place one set of samples (normally the glycolated one) on an asbestos plate and heat in a pre-heated oven at 500-550°C. Oven temperature must not exceed 550°C. The exact location of individual samples on asbestos plate must be known before heating because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment.
6. Run the samples from 2-15° on the XRD.

APPENDIX II: XRD clay analysis results for well KR-9

Depth (m)	Untreated (Lines d Å)	Glycol treated (Lines d Å)	Heated 500-550°C (Lines d Å)	Probable minerals
24	15.77, 14.92, 7.17, 7.12	17.25, 7.65, 7.18	Broad peak	Smectite (?)
80	No reflection	No reflection	No reflection	Weak clay alteration
96	No reflection	No reflection	No reflection	Weak clay alteration
112	15.02	16.92	10	Smectite
126	12.87, 9.05	16.60, 8.34	9.88	Smectite
134	14.97, 9.22	17.18, 9.22	11.90, 7.39	Smectite, mixed-layer clays (?), zeolite
146	13.55	16.41	9.93	Smectite
156	15.17	16.60, 14.97, 9.73	No reflection	Smectite, mixed-layer clays (?)
176	12.80, 8.95	16.35, 8.98	9.73	Smectite, zeolite
186	15.12	16.92	10.09	Smectite
192	15.17, 8.26	17.18, 8.35	9.82	Smectite
204	15.02, 7.68	16.54, 7.58	No reflection	Smectite
220	14.87	16.6	14.77, 10.27	Smectite, mixed-layer clays (?)
248	12.62	17.31, 8.34	9.71	Smectite
260	14.92, 8.11, 7.20	16.98, 8.28	9.95	Smectite
278	14.77, 7.43	16.60, 8.32	10.39	Smectite
296	30.65, 14.87, 7.25	32.45, 31.08, 16.35, 8.29, 7.69, 7.76	9.91	Smectite, mixed-layer clays
302	15.02, 7.20	16.72, 15.71, 8.42 8.34, 7.23, 7.14	10.23, 13.76	Smectite, mixed-layer clays (?)
308	14.92	16.47, 8.26	9.84	Smectite
314	14.97	16.92, 8.42, 7.64	9.95	Smectite
327	13.59	16.47, 8.34, 8.25 7.62	12.48, 9.73	Smectite