



BOREHOLE GEOLOGY, HYDROTHERMAL ALTERATION AND TEMPERATURE EVOLUTION OF WELL KR-2, KRÝSUVÍK, SW-ICELAND

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ABSTRACT

KR-2 is a 1220 m deep well in the Krýsuvík high-temperature field, situated on the Reykjanes Peninsula. Today, this well is used to heat one hut. The rock formation dissected by the well consists of basaltic lava series, basaltic hyaloclastite formations and minor intrusive rocks, which is believed to have accumulated during the last few hundred thousand years. Four alteration mineral zones have been identified including a smectite-zeolite zone ($< 200^{\circ}\text{C}$) down to 140 m depth, a mixed layered clay zone ($200\text{-}230^{\circ}\text{C}$) down to 380 m depth, a chlorite zone ($> 230^{\circ}\text{C}$) down to 737 m depth and a chlorite-epidote zone ($240\text{-}260^{\circ}\text{C}$) down to at least 1220 m depth. This zonation indicates a past and/or present high-temperature environment. Aquifers were confirmed at 130, 160-166, 920-924 and 1120 m depth, and possibly also at 400, 505-515, and 850 m depth. Hydrothermal evolution as seen through alteration indicates an initial low-temperature condition ($< 200^{\circ}\text{C}$) followed by a high-temperature condition ($240\text{-}260^{\circ}\text{C}$) and then a cooling as indicated by zeolites ($< 200^{\circ}\text{C}$). Present temperature shows an inverse gradient from about 550 m depth where temperature drops from about 200°C to nearly 150°C at around 800 m depth. A conceptual model indicates an upflow zone to the southwest from well K-2 and a cold water influx from the northeast.

1. INTRODUCTION

Well KR-2 is located at Seltún within the Krýsuvík high-temperature geothermal area which is regionally a part of the volcanic active zone on the Reykjanes Peninsula (Figure 1). Studies including surface and subsurface geology, water geochemistry, geophysics and deep exploration drilling have been carried out to some degree.

The first exploration was initiated before 1950 and a more systematic exploration programme started in 1970 (Arnórsson et al., 1975). Additionally, a more regional exploration on the Reykjanes Peninsula has

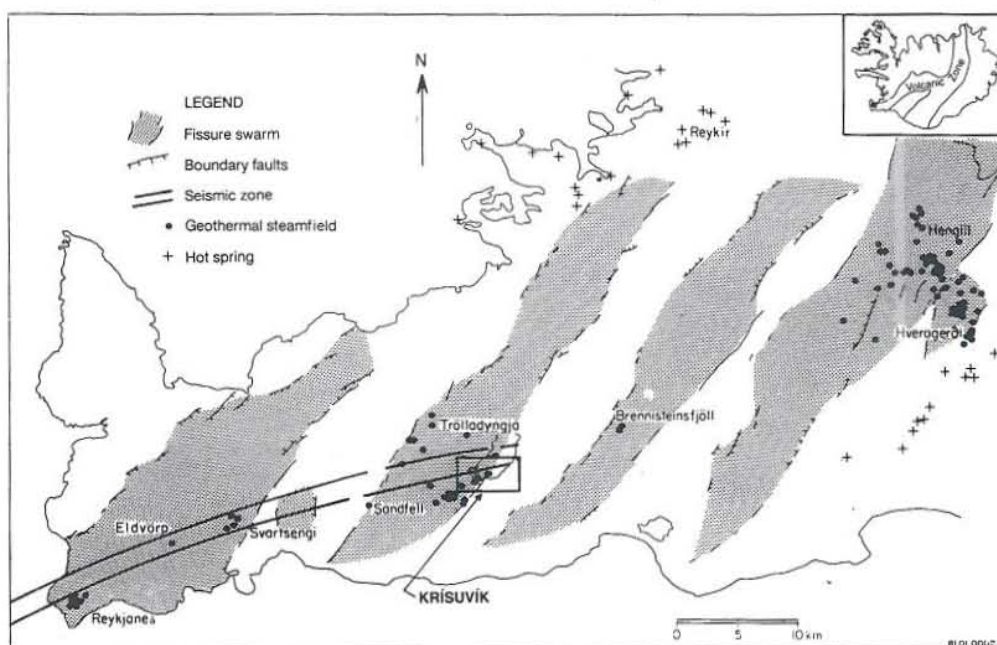


FIGURE 1: Volcanic systems and high-temperature areas on the Reykjanes Peninsula (modified from Saemundsson and Fridleifsson, 1980)

been undertaken including studies of the Reykjanes volcanic zone and the relationship of the fracture zone with the NE-SW trending en-echelon fissure swarms (Saemundsson, 1978), and a resistivity survey in the Trölladyngja and Krýsuvík areas (Georgsson, 1987). Several studies have also been done by UNU fellows including geological mapping of a part of the Trölladyngja area (Muhagaze, 1984; Kifua, 1986), geological and geothermal studies of the Krýsuvík valley (Vargas, 1992), and resistivity sounding and interpretation of various data from Krýsuvík (Mariita, 1986; Kanyanjua, 1987). In 1994 a study on potential steam production and transmission from the Krýsuvík-Trölladyngja area to an energy park at Straumsvík was completed (Ármannsson et al., 1994). A study on borehole geology and hydrothermal alteration of well KR-9, Krýsuvík has also recently been completed (Malapitan, 1995).

The main purpose of this study is to supplement information on the subsurface geothermal conditions and describe the results of the drill cutting analysis from well KR-2 at Krýsuvík (Figure 2) with respect to petrography, hydrothermal alteration, aquifers, and to make an evaluation of temperature evolution of the system over time.

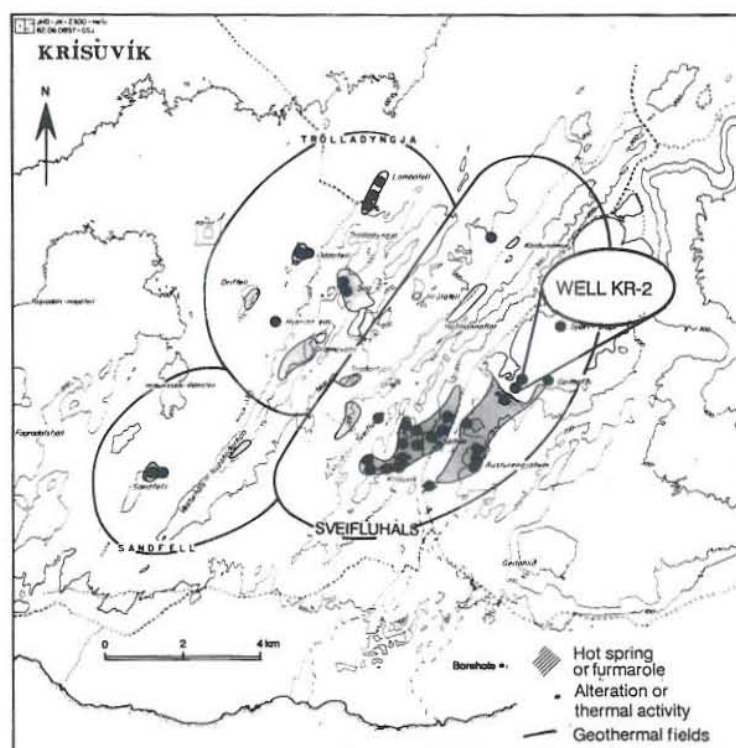


FIGURE 2: Location of well KR-2 in the Krýsuvík area and surface geothermal manifestations (modified from Ármannsson et al., 1994)

2. KRÝSUVÍK HIGH-TEMPERATURE FIELD

Krýsuvík is one of 27 known high-temperature geothermal areas in Iceland. It lies on the Reykjanes Peninsula to the south of the town Hafnarfjörður and is one of four explored high-temperature areas on the Reykjanes Peninsula. The Krýsuvík area is divided into three parts, i.e. the Krýsuvík field, the Trölladyngja field and the Sandfell field. Figure 2 shows the three fields of the Krýsuvík geothermal area.

Krýsuvík is located at the boundary between an area of predominantly supra glacial eruptions (e.g. table mountains) and an area of predominantly subglacial eruptions, to the west, with formations such as hyaloclastite ridges. The Inter- and Postglacial volcanism, i.e. the volcanic activity during the ice free periods is represented by subaerial volcanic products and morphological landscape like explosion craters and lava flows. The common products are lava flows, pyroclastic scoria, welded lava and scoria and explosion breccia (Vargas, 1992). Malapitan (1995) described the rocks of the Krýsuvík high-temperature area as consisting of extensive post-glacial lavas and ridges of pillow lava, pillow breccia and hyaloclastites formed under the ice sheet environment. Figure 3 shows the geological map of Krýsuvík and its surroundings. The generalized evolution of the growth of a monogenetic volcano is shown in Figure 4 which further illustrates the accumulative volcanic sequence in the Krýsuvík area during glacial periods.

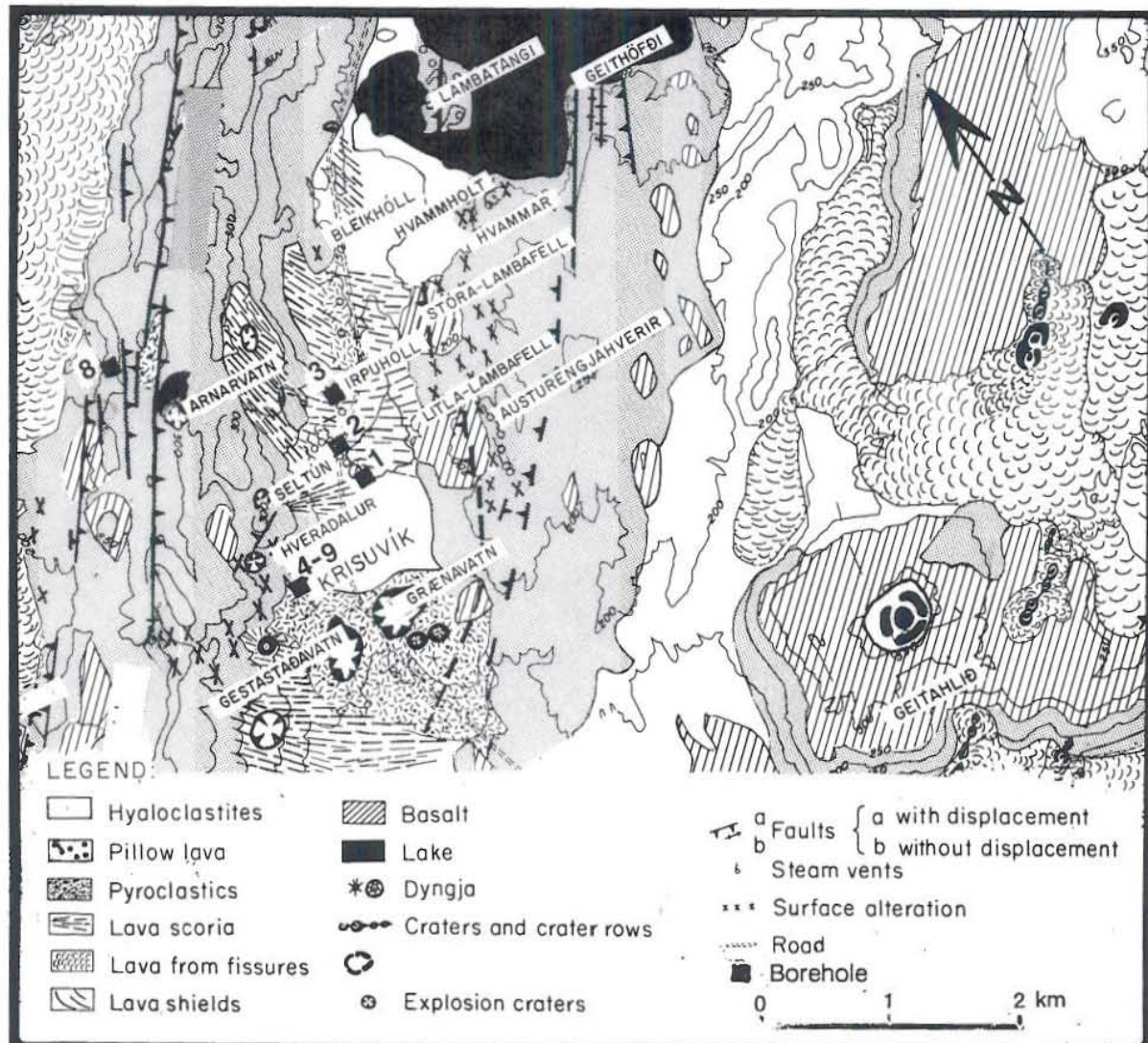


FIGURE 3: Geological map of the Krýsuvík high-temperature field and the surrounding area (modified from Arnórsson et al., 1975)

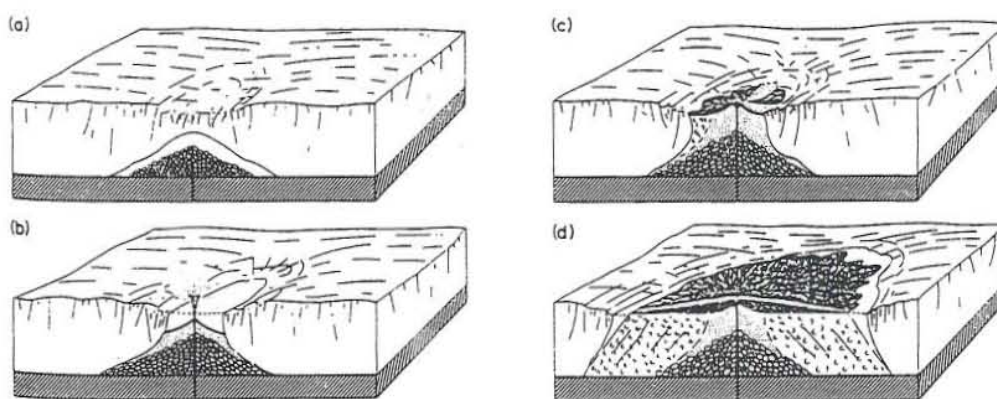


FIGURE 4: Growth of a subglacial, monogenetic volcano (Jones, 1969; Saemundsson, 1979); a) a pile of pillow lava forms deep in melt water lake, b) slumping on the flanks of the pillow lava pile produces pillow lava breccia, c) hyaloclastite tuffs erupted under the shallow water, d) a lava cap progrades across its delta of foreset breccia

Krýsuvík lies in a NE-SW elongated valley within the active volcanic zone which is characterized by fissure swarms striking NE-SW. The Krýsuvík fissure swarm is one of these large en-echelon structural units (fissure swarms) of the Reykjanes Peninsula, and extends from Ellidavatn in the northeast to the south shore and its southeast limits are the Geitahlid and Kistufell table mountains (Vargas, 1992). Surface manifestations of the Krýsuvík geothermal system are marked by a high intensity clay alteration zone, boiling springs, warm springs, mud pools, warm soil, hydrothermal explosion craters and mineralized water in Graenavatn lake (Graenavatn means green lake which relates to hydrothermal fluids emitted into the lake), deposits of silica sinters, oxidation, sulphate deposits, steam vents and mineral veins. The hydrothermal alteration map (Figure 5) shows the boundary of the surface hydrothermal alteration.

Vargas (1992) separated the hydrothermal alteration into three grades. The first grade is marked by yellowish hydrothermal alteration colour and a few vein fillings (about 1 per 30 m²). It mainly affects the hyaloclastites but affecting the lavas somewhat less. Besides these, a widespread microscopic zeolitization was found in pillow basalts and pillow breccias, especially at the Baejarfell and Arnarfell mountains at the southern Krýsuvík boundary. The second alteration grade is characterized by yellow and brown colours affecting more than half a percent of the rocks and by a high quantity of vein fillings (about 1 per 1 m²). The third alteration grade is characterized by a very high intense alteration (about 100% rock alteration) with a range of strong colours from gray, red, brown, yellow and nearly white. Precipitation of sulphide and carbonate minerals are found like calcite, travertine, pyrite, opal, gypsum, sulphur and silica sinter. The occurrence of geothermal veins is very common (about 5 per 1 m²).

Secondary heated carbonate water appears in warm springs in a few localities. This type of surface thermal activity is related to high underground temperatures and a shallow ground watertable. The low ground watertable is believed to reflect the high permeability of the bedrock, but less the local topography (Arnórsson et al., 1975).

The underground temperatures in the Krýsuvík geothermal area were estimated by geochemical methods, using a hydrogen geothermometer in steam vents. In this case, gas in a steam vent rises from the deep water through a body of near surface water which is well below the boiling point. The more water soluble gases, like carbon dioxide and hydrogen sulfide, may have dissolved in this water, leading to a relative enrichment of hydrogen in the gas which in turn escapes to the surface. The silica and alkali

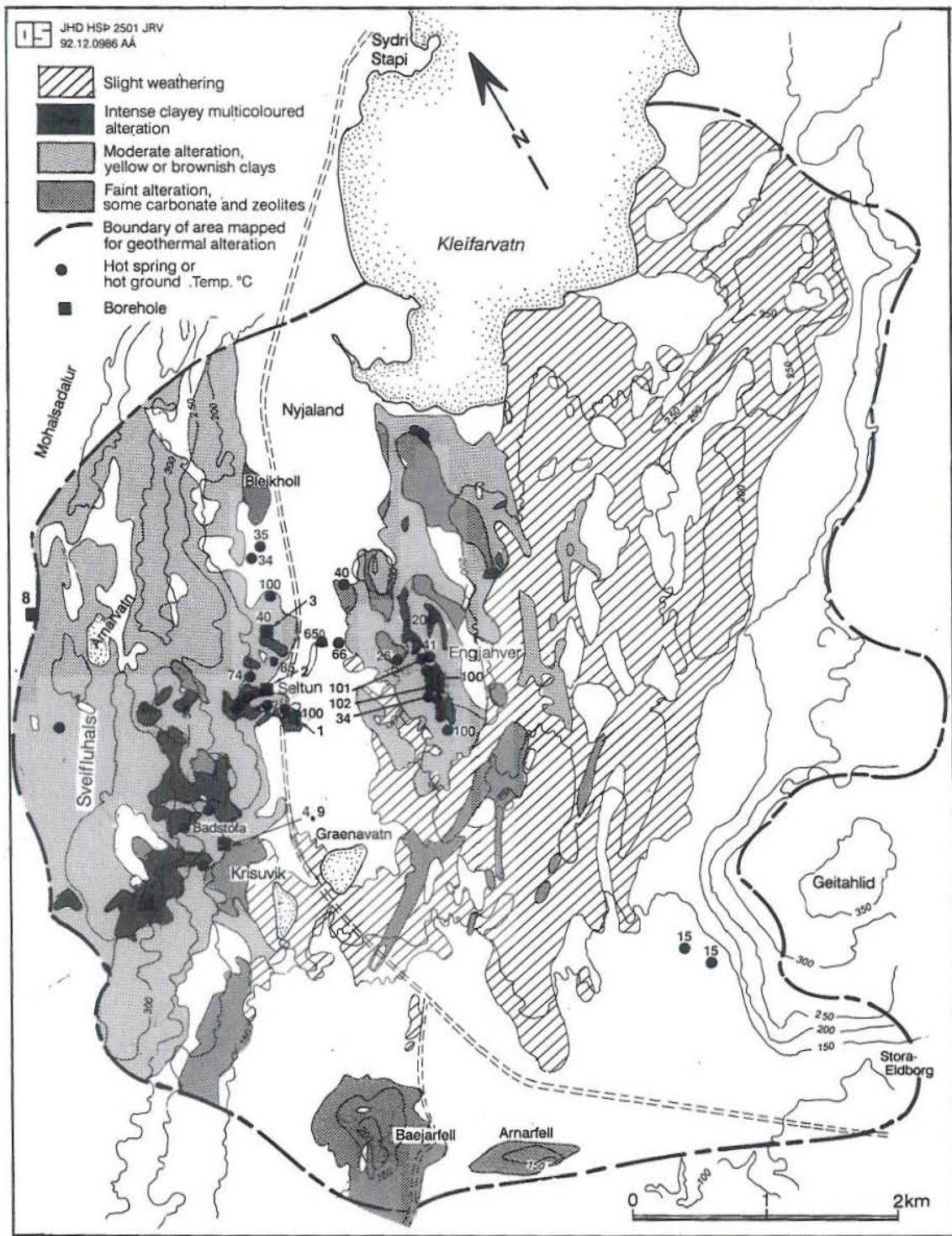


FIGURE 5: Hydrothermal alteration map of the Krýsuvík area (Vargas, 1992)

geothermometers could not be applied because the deep water does not reach the surface. Arnórsson and his colleagues (1975) calculated the underground temperatures using a hydrogen geothermometer to be about 235°C to 260°C, but conceded that those results might be erroneous.

The ground water approximately 30 km inland on Reykjanes Peninsula is sea water (Tómasson and Kristmannsdóttir, 1972). It is saline containing about 20,000 ppm chloride in coastal areas, but

decreasing away from the coast. In the Krýsuvík area, especially at the Trölladyngja and Sandfell fields, the chemical fluid is high in total dissolved solids which is due to a slight mixing of sea water with fresh water within the Krýsuvík hydrothermal system (equal to about 20% sea water). The water table within the thermal system in this area is at a similar depth as that of the ground water surrounding the system.

In the eighties an extensive resistivity survey was carried out in the Krýsuvík area (Flóvenz et al., 1986; Georgsson, 1987) in addition to older surveys (Arnórsson et al., 1975). In general, the resistivity of surface layers above the ground watertable is very high, especially in the Postglacial lava formations where the resistivity values are in the range of about 10,000 Ωm but low where the surface layer has been strongly altered; there the resistivity could go down to less than 10 Ωm . It shows widespread low-resistivity layers ($< 8 \Omega\text{m}$) in the uppermost 500 m as seen in Figure 6 which shows a resistivity map at 300 m below sea level (Georgsson, 1987). The low-resistivity layers are correlated with geothermal activity in permeable near-horizontal layers of hyaloclastite breccias, below which denser and cooler basalts dominate, manifested in increasing resistivity with depth (10-80 Ωm). Inside the low-resistivity zone, several small areas of extra low resistivity are found (3-5 Ωm), which may represent upflow zones.

Figure 6 shows two separate low-resistivity anomalies in the Krýsuvík valley, where the resistivity is less than 5 Ωm at about 300 m depth. More significantly several small low-resistivity anomalies are seen below the two hyaloclastite ridges, Sveifluháls and Vesturháls. It seems to suggest that the main upflow

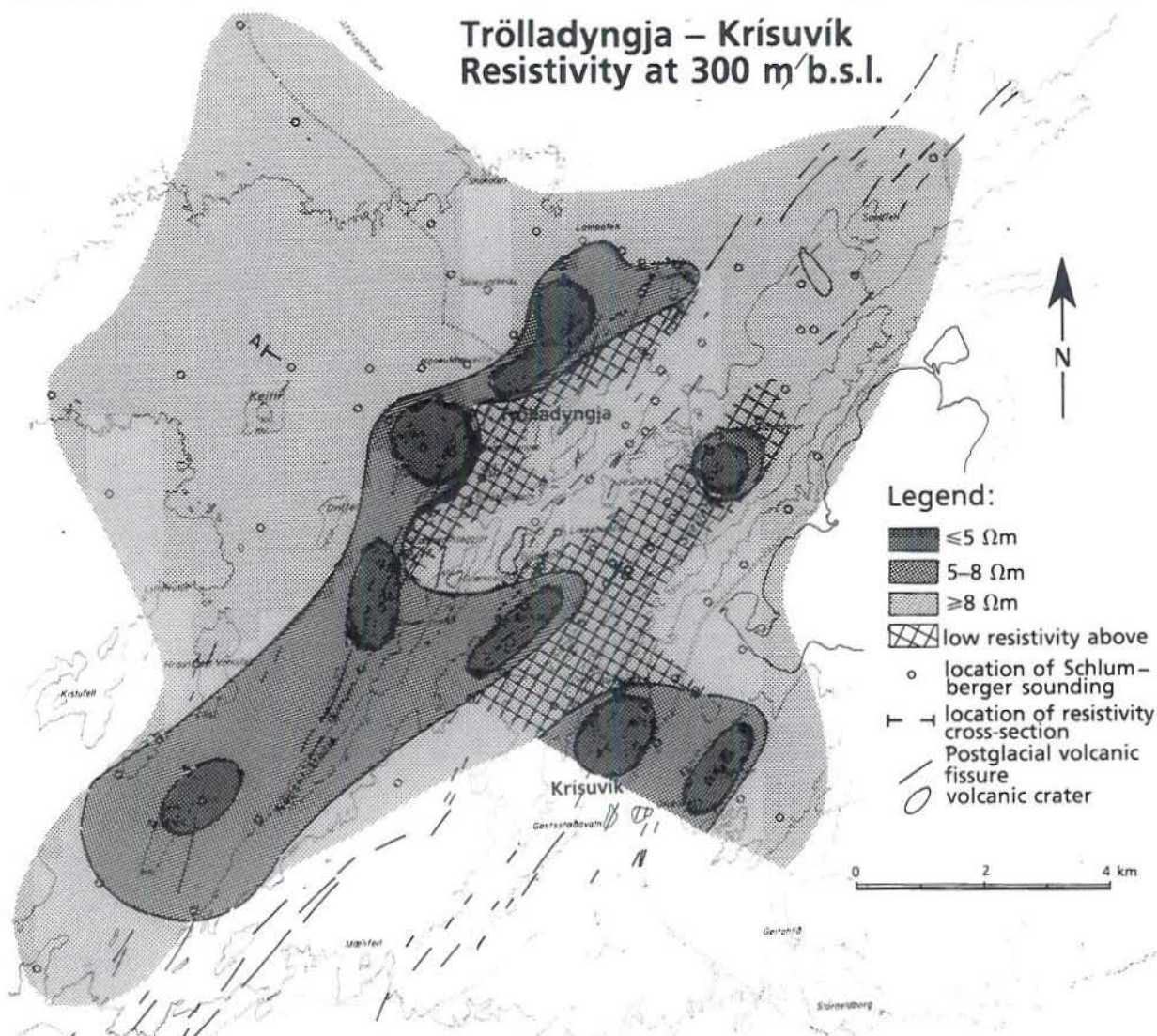


FIGURE 6: Electrical resistivity of the Trölladyngja-Krýsuvík area at 300 m below sea level as determined by Schlumberger soundings (Georgsson, 1987)

of geothermal fluids from deeper levels is in restricted zones, probably associated with volcanic and tectonic fissures. Thus, the Krýsuvík high-temperature area can be divided into several small near-independent fields. Volcanic activity has been confined to few main eruptive periods in Postglacial times and long term periodic activity has been observed in hydrothermal manifestations. This may indicate that local magma intrusions associated with these eruptive events are the deep level heat sources for the geothermal system. Thus, the fields revive periodically, but undergo slow cooling process between events (Flóvenz et al., 1986; Georgsson, 1987). A large negative magnetic anomaly in the Krýsuvík area is believed to reflect a large up-flow zone in the past where a large body of rock has lost a part of its original magnetic properties through alteration (Arnórsson et al., 1975).

The areal extent of the Krýsuvík high-temperature field is estimated to be about 30-35 km² and the Trölladyngja field about 15-20 km² (Ármannsson et al., 1994).

The siting of exploration wells in the Krýsuvík area was mostly based on the result of resistivity surveys and the subsurface temperature distribution calculated with a hydrogen geothermometer. Generally, the wells were located above the low resistivity areas (< 10 Ωm) and near surface manifestations.

Figure 7 shows schematically possible models of hydrothermal characteristics in the reservoir. Two hypotheses have been put forward to explain the distribution of temperature gradients measured in the wells. The first proposes upflow zones not yet located by drilling wells and a mushroom-shaped sideways fluid flow at the top of this zone. The second hypothesis proposes a gradual cooling of the hydrothermal reservoir from above and below by relatively fresh water which is replacing an originally more saline water (Arnórsson et al. 1975; Mariita 1982; Malapitan, 1995).

3. DESCRIPTION OF WORK

The cuttings are one of the most essential indicators used to describe the thermal history or thermal evolution of a reservoir in time and space. The study of hydrothermal alteration by cutting analysis involves three main techniques, namely the stereo-binocular microscope, the petrographic microscope and the X-ray diffractometer (XRD).

The binocular microscope is a very important analytical instrument in cutting analysis, used mainly during drilling. This kind of information is especially important in helping to make decisions during drilling, such as when setting casing shoes, in prediction of loss zones, or deciding on final drilling depth. Wellsite geology, thus, plays an important part during that time. Well KR-2, the object of this study, is

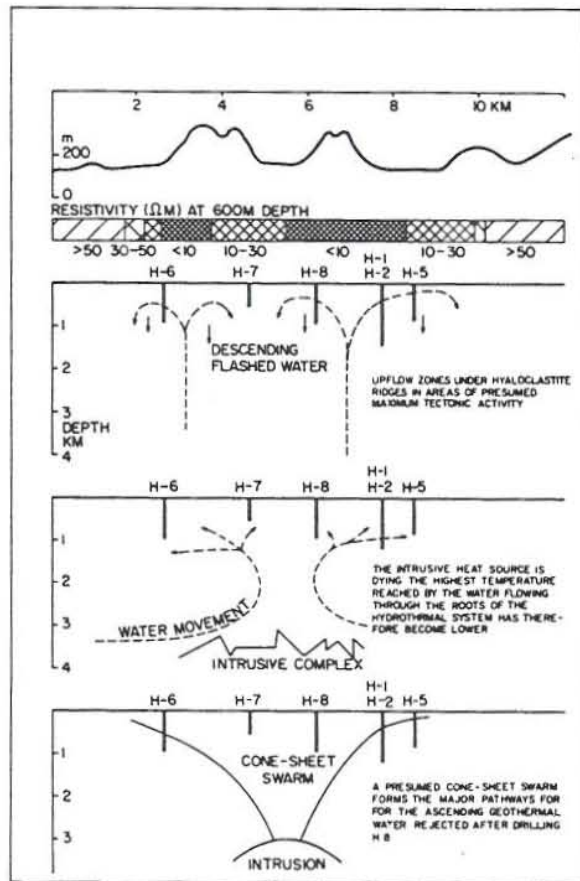


FIGURE 7: Schematic sections showing possible models for water movement characterizing the hydrothermal reservoir (Arnórsson et al., 1975)

an old well drilled in October 1960, so the binocular microscope is used to do a more detailed work on the rocks and minerals of this well and to pick out some alteration minerals for XRD preparation. The binocular microscope used in the laboratory is a *Wild Heerbrugg binocular microscope* with a magnification of 6x-80x.

The **petrographic microscope** is an useful instrument in the study of drill cuttings in thin sections. The essential use of this microscope relates to the small size of the primary and secondary minerals in the rocks where they were formed by action of hydrothermal fluids. The petrographic microscope can be used to determine the rock type in more detail, identify additional primary and secondary minerals, study the type of replacement mineralogy and amygdalites and vein minerals. Petrographical analyses are also good for studying the sequence of secondary mineral evolution, especially in the veins and amygdalites. The type of polarized microscope used in the petrography laboratory is an *Ortholux II POL-BK, Leitz Wetzlar* with binocular magnification of 2.5/0.008 to 63/0.85.

The **X-ray diffractometer** is mostly used for identifying clay minerals and for cross-checking observations made under both the polarized and binocular microscopes, especially where zeolites and other white minerals could not be identified individually. The procedure of sample preparation for clays and deposition minerals and also running XRD machine can be seen in Appendix I.

4. GEOLOGY OF WELL KR-2

4.1 Drilling and present situation

Well KR-2 is located at the eastern slope of the Sveifluháls hyaloclastite ridge about 1 km northeast of the Krýsuvík rehabilitation centre. It is the second borehole drilled in the Krýsuvík field in the second drilling phase. The drilling was completed on 8 October 1960. A production casing shoe 9 5/8" was placed at 247 m depth coinciding with basaltic lava. Borehole temperatures were measured with Amerada 14896 (4 October 1960) and Amerada 14897 (5 October 1960). A downhole temperature of 167°C was measured at 1000 m depth and a maximum temperature of 197°C at 350 m depth (Figure 8). The well has not been monitored since its completion. At present a part of the flow from the well is used for heating a small nearby hut.

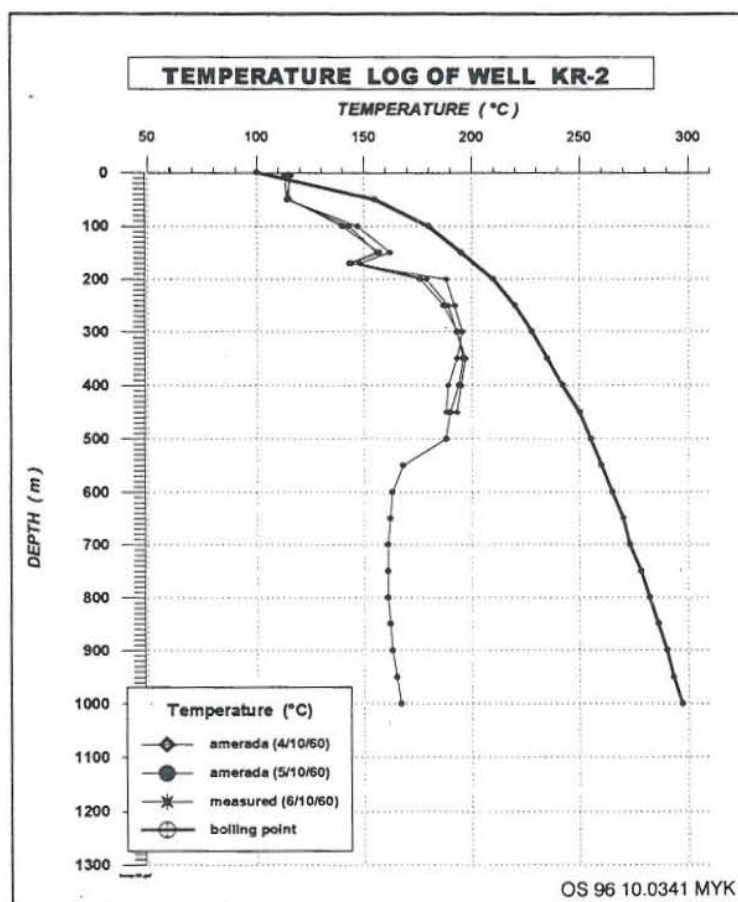


FIGURE 8: Temperature log of well KR-2, Krýsuvík

4.2 Stratigraphy of well KR-2

The Krýsuvík field has rock formations similar to that of a monogenic volcano under a sub-glacial environment (Figure 4) with interstitial interglacial lava formations. The succession belongs to the Upper Pleistocene, i.e. dates from the last glacial and interglacial periods.

4.2.1 Rock terminology

Ganda (1987) summarized the main categories of Icelandic basaltic rocks where tholeiite basalt is usually fine to medium grained, olivine tholeiite basalt is usually medium to coarse grained, dolerite is coarse grained basalt and is often an intrusion, glassy basalt which often refers to pillow lava, basaltic breccia which constitutes basalt fragments in glassy matrix and tuff which is dominantly volcanic glass. The last three types are often a part of a hyaloclastite formation.

The term basalt refers to SiO₂ content of 45-52% by weight. It can sometimes be difficult to distinguish between lavas and dykes in drill cuttings, but one of the main criteria is the relative fresh appearance of the intrusive rocks compared to the surrounding volcanics. This usually relates to lower porosity, lower permeability and younger age. Also it can be difficult sometimes to decide from the drill cuttings whether to group a rock as a pillow lava or a basaltic breccia. Rock cuttings that are partly crystalline and partly glassy are more common in basaltic breccia than in pillow lava. Pillow lava contains less glass than the basaltic breccia and may have originated as supercooled lava flow. Glass in the basaltic breccia is dominantly vesicular.

Tuff is a term used for rocks that have cooled rapidly enough to form predominantly glass, either from subaerial or subaquatic phreatic extrusions. The hyaloclastite formations (pillows, breccias, tuffs) occur commonly as heaps, ridges or clastic sediments close to their vents.

4.2.2 Stratigraphy

The stratigraphic sequence of well KR-2 involves lithologic repetition including fresh basaltic lava, altered basaltic lava, altered basaltic breccia, altered tuff and altered pillow lava. For easy recognition, borehole lithology is divided and separated into series. Figure 9 shows lithologic sequences and alteration mineral distribution in well KR-2.

In all, the series from surface to the bottom include ten different basaltic lava series and nine hyaloclastite series. Intrusive rocks found in the well are treated separately. The main characters of the series are described as follows:

Hyaloclastite series-1 (< 109 m depth). On the surface the ground is covered with soil and some out-wash deposits from bedrock near the well. No cuttings are available down to 10 m depth. Below that to 109 m are found relatively dominant fresh tuff and breccia with intercalation of basaltic lava layers (68-70 m depth).

Basaltic lava series-1 (109-152 m depth). The thickness of this series is about 43 m and it includes relatively fresh basaltic lavas. The alteration increases slightly from 143 m to 193 m depth. The individual lavas were recognized by the more scoriaceous lava tops and more compact and coarse grained lower part. Phenocrysts of plagioclase, pyroxene, olivine and opaque minerals are often found in the aphanitic ground mass. Vesicles and amygdales are common in the fine-medium grained textures

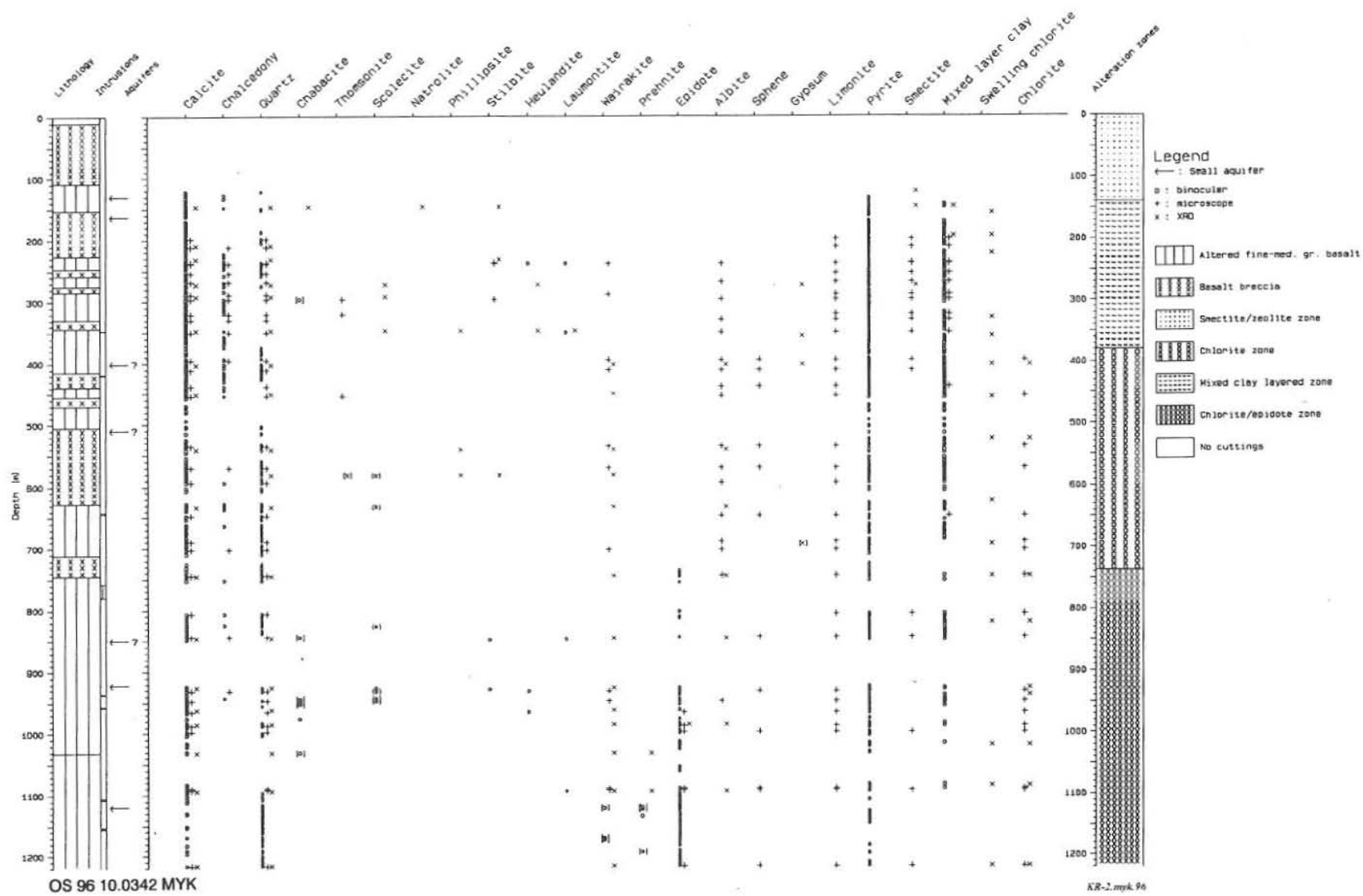


FIGURE 9: Lithology, mineral alteration and alteration zones of well KR-2, Krýsuvík

in the top part of the lava. Very nice crystals of quartz growth in the vesicles together with calcite and dark clays are found at 122 m depth.

Hyaloclastite series-2 (152-226 m depth). This series consists predominantly of tuff except at 199-205 m depth where crystallized basalt is found. Sedimentary tuff appears at 205-208 m depth. This series has suffered low to medium alteration. Vesicles are common in the fresh and low altered glass. Some of them are filled with clays, limonite, chalcedony and sometimes quartz. Opal with conchoidal structure and pyrite also appear.

Basaltic lava series-2 (226-247 m depth). This series consists generally of fine grained basalt. Textures are equigranular with phenocrysts of plagioclase and opaque minerals. This series shows low alteration. Vesicles are common and they are filled with calcite, quartz, chalcedony and zeolite (heulandite/laumontite). In thin sections (P-16307.K-2; 237 m and P-16308.K-2; 239 m depth) the rock shows medium to coarse grained crystallinity with phenocrysts of plagioclase, pyroxene, olivine (low altered) and opaques in a micro-crystalline groundmass. This series shows about 10% alteration.

Hyaloclastite series-3 (247-258 m depth). The series consists predominantly of basaltic breccia and glassy basalt (pillow basalt). The rock is red to dark brown in colour. It shows abundant oxidation and calcite. Vesicles are generally filled with coarse grained clay, chalcedony and sometimes calcite. Quartz is rarely seen. This series shows very low alteration. In thin section (P-1630.K-2; 255 m depth) fine grained textures are seen with micro-crystalline plagioclase and opaque minerals in aphanitic groundmass.

Basaltic lava series-3 (258-275 m depth). This series consists of about 17 m thick fine grained basalt. It is intercalated with the basaltic breccia at 247-258 m depth. Generally this series is red to brown in colour indicating abundant oxidation (limonite). Also appearing rarely are calcite, pyrite, and chalcedony lining vesicles with coarse grained clay. A vein occurring at 275 m depth has been filled with limonite and calcite. Thin section (P-16310.K-2; 269 m depth) shows the rock to be fine grained with phenocrysts of plagioclase, pyroxene and opaque minerals in aphanitic groundmass. Rock shows low intensity (< 10%) alteration.

Hyaloclastite series-4 (275-284 m depth). This series is predominantly a sedimentary tuff. The rock is light brown in colour. Medium alteration. Vesicles appear filled with calcite and clay. Clastic textures.

Basaltic lava series-4 (284-329 m depth). The lavas in the upper part of this 45 m thick series are relatively fresh except for considerable oxidation. The rock is mostly intergranular with phenocrysts of plagioclase, pyroxene, and opaque minerals. Veins are filled with calcite and oxidation minerals. Very nice quartz crystals together with calcite and coarse grained clays were in a vesicle at 327 m depth. Several thin sections were taken in this depth interval showing phenocrysts of plagioclase, pyroxene, olivine, and opaque minerals in a microcrystalline ground mass. Other samples show fine to medium crystallinity. In general the rocks show low to medium alteration. Vesicles have also been filled with calcite and clays.

Hyaloclastite series-5 (329-344 m depth). The rocks are dark green to dark brown in colour and consist of breccia with fragments predominantly of basalt along with minor tuff. This series has medium to high alteration intensity. Petrographical description of basaltic fragments show microcrystalline plagioclase, pyroxene, olivine, and opaque minerals in the aphanitic groundmass.

Basaltic lava series-5 (344-415 m depth). This series is about 70 m thick. The rock is dark green to dark brown in colour and shows medium alteration intensity. A medium altered breccia (369 m depth)

has dark green to dark brown colour. Oxidation is relatively abundant. The petrographical description of samples (P-16316.K-2; 351 m, P-16317.K-2; 396 m and P-16318.K-2; 412 m depth) shows fine to medium crystallinity and phenocrysts of plagioclase, pyroxene, olivine and opaque minerals. These samples show flow texture of microlith plagioclase and common radial structures.

Hyaloclastite series-6 (415-439 m depth). The thickness is about 55 m and the series consist probably of a pillow basalt unit. It is commonly dark green to red brown with relatively abundant limonite and another oxidation minerals. The rock is fairly vesicular but commonly filled by amygdales. Petrographical description of a thin section sample (P-16319.K-2; 439 m depth) shows fine to medium grained rock with phenocrysts of plagioclase and opaque minerals in the fine grained groundmass. Medium to high alteration with rare vesicles.

Basaltic lava series-6 (439-454 m depth). The thickness is about 15 m. The rock is light to dark green in colour and fine to medium grained. Phenocrysts of plagioclase appear in the fine grained groundmass. Rare vesicles are filled with calcite, pyrite, chalcedony, and clays. Thin section (P-16320.K-2; 454 m depth) shows fine to medium crystallinity with phenocrysts of plagioclase and opaque minerals. Vesicles are rare and filled with calcite, quartz and fine grained clays. Veins appear filled with fine grained clay.

Hyaloclastite series-7 (454-470 m depth). The thickness is about 16 m. This series contains pillow lavas with basaltic composition and is dark green to dark brown in colour. Dark clays are abundant. The rock is fine to medium grained with unidentified phenocryst. Vesicles are very rare and filled with calcite, clays and sometimes pyrite. Small pyrite grains are common.

Basaltic lava series-7 (470-505 m depth). The rock is about 35 m thick and gray to light green in colour. Alteration minerals are too small to identify.

Hyaloclastite series-8 (505-627 m depth). This series is 122 m thick and is predominantly composed of probable pillow basalt. Above lies a basaltic lava stratification. Basaltic lavas and pillow lavas show similar primary mineral composition but differ with respect to oxidation and texture. Well crystallized basaltic layers intercalate at 525 m, 542 m, 564 m, 570 m depths where they have light to dark green colour, high alteration, minor vesicles containing very nice calcite crystals together with coarse grained clay. At 570 m depth very nice quartz crystal growth can be seen in a cutting sample. Thin section sample (P-16322.K-2; 570 m depth) shows a high alteration, fine to medium grained crystalline basalt with plagioclase phenocryst in micro-crystalline ground mass. A little altered pyroxene is found there in a finely crystallized groundmass. The pillow lava is highly oxidized and is dark green to dark brown in colour and contain rare vesicles. A thin section (P-16321.K-2; 536 m, P-16323.K-2; 594 m depth) shows medium crystalline basalt with phenocrysts of plagioclase, pyroxene, olivine and opaque minerals in an aphanitic groundmass. Alteration is medium to high.

Basaltic lava series-8 (627-710 m depth). This series is about 83 m thick, dark green to dark brown in colour, hemimorphite and quartz crystals are observed in vesicles. Thin section samples (P-16324. K-2; 648 m, P-16325. K-2; 666 m, P-16326. K-2; 690 m, P-16327. K-2; 703 m depth) where analysed showing fine to medium crystalline basalt, except sample P-16326.K-2 at 690 m depth which shows coarse crystallinity with phenocrysts of plagioclase, pyroxene, olivine and opaque minerals in the porphyro-aphanitic groundmass. About 50% of the rock show medium alteration intensity.

Hyaloclastite series-9 (710-745 m depth). The thickness is about 35 m and the series is composed of pillow basalt, dark grey, green to dark brown in colour. Possible hemimorphite and quartz crystals appear. In the cutting sample at 745 m depth, epidote starts to appear in some quantity (about 2%) always apparently associated with abundant oxidation minerals like limonite (red brown colours). Petrographic description of sample P-16328.K-2 at 745 m depth shows a rock of medium to fine

crystallinity with porphyro-aphanitic of plagioclase, pyroxene, olivine and opaque minerals together in very fine groundmass. There is a high rock alteration.

Basaltic lava series-9 (745-1032 m depth). The thickness of this lava series is about 287 m, varying in colour from gray, dark green to dark brown. Very nice quartz crystal growth is occasionally observed and dark clays. Near the top of the series (810-812 m depth), a 2 m thick basalt breccia intercalates the lavas and is dark green to brownish with abundant oxidation (limonite and other iron oxide minerals). Quartz crystals and dark brown clays are rare. From the top to the bottom textures change from fine to medium crystallinity. Only 25-50% of the vesicles are filled by secondary minerals. A number of thin sections were analysed and show the samples (P-16329; K-2; 807 m, P-16330; K-2; 845 m, P-16331; K-2; 923 m and P-16332; K-2; 948 m depth) to be fine-medium grained and samples (P-16333; K-2; 966 m, P-16334; K-2; 988 m and P-16335; K-2; 998 m depth) coarse grained basalts. Phenocrysts of plagioclase, pyroxene, olivine and opaque minerals are clearly seen as coarse grained textures in the aphanitic groundmass. This lavas series shows high intensity alteration.

Basalt lava series-10 (1032-1220 m depth). The thickness of this series is about 188 m, dark gray to dark brownish green in colour and consists of fine to medium grained basalt lavas. Veins are mostly filled with calcite, clays and sometimes iron oxides. Vesicles are to some extent filled by calcite green clays and rare epidote. Pyrite is rare but oxidation is more dominant. Petrographic thin sections (P-16337; K-2; 1090 m, P-16336; K-2; 1093 m and P-16338; K-2, 1217 m depth) show the rock to contain phenocrysts of plagioclase (labradorite and anorthite), pyroxene, olivine and opaque (magnetite) minerals in the microcrystalline groundmass. The basalts are highly altered.

Intrusive rocks. Ganda (1987) described intrusive rocks to be in general less altered and coarser grained than surrounding rocks. Narrow intrusions (e.g. dykes) may even be fine to medium grained. This was clearly demonstrated during the author's field excursion to the Geitafell central volcano (G.Ó. Fridleifsson, pers. comm.). Thus, the criteria mentioned above along with these features are used to identify intrusions in the cutting analysis.

Eight separate intrusions have been identified in well KR-2. They are at the 347-348, 419-420, 642-644, 791-793, 949-958, 1108, 1150-1151, and 1156 m depths. The thickness of the intrusive rocks vary from 1 to 4 m, except at 945-958 m depth where the thickness is about 7 m. The cutting samples at 954-958 m depth show a relatively dark coloured and fresh looking basalt. The intrusions at 1108 and 1156 m depth are fine to medium grained fresh looking basalt.

Well KR-2 is about 1 km northeast of well KR-9. Malapitan (1995) proposed that the age of the hyaloclastite series (193-250 m depth) is from the last glacial period (12,000-115,000 years) and the underlying lava series (250-327 m depth) formed during the last interglacial period (115,000-125,000 years). During the last glaciation, the ice thickness over Krýsuvík has been estimated to be about 300 m (Arnórsson et al., 1975).

For an age estimate of rocks of well KR-2 an accurate K/Ar-dating is needed. In comparison with other studies, rocks of well KR-2 probably formed during the last glacial period (12,000-115,000 years) down to 258 m. Underlying basaltic lava series at 258-329 m depth may have formed during the last interglacial period (115,000-125,000 years). The hyaloclastite series-5 to series-9 with basaltic lava series -5 to series-10 are most probably volcanic products from older glacial/interglacial periods.

5. HYDROTHERMAL ALTERATION

The hydrothermal alteration depends on many factors such as temperature, permeability, rock type, fluid chemistry, pressure and rock structure (Kristmannsdóttir, 1978; Reyes, 1990; Browne, 1978 and 1993; Malapitan, 1995). Reyes (1990) used identification of hydrothermal minerals during drilling to predict corrosion and scaling tendencies of the fluids, to locate possible cool water influx into the wells and predict permeability, to estimate fluid pH and other chemical parameters, as a guide to field hydrology, and roughly to estimate the thickness of the eroded overburden.

5.1 Rock alteration

Traditionally, geothermal areas in Iceland have been divided into high-temperature and low-temperature areas, where reservoir temperature of over 200°C at less than 1 km depth has been used to distinguish the high-temperature area from the other. In general, rocks and mineral alteration within the active high-temperature systems of Iceland range from zeolite facies to green-schist facies (Fridleifsson, 1991).

The primary mineral composition of the Icelandic rocks are Ca-plagioclase, olivine, pyroxene and opaque (magnetite, ilmenite) minerals. Plagioclase is commonly anorthite, bytownite and labradorite, while pyroxene is commonly clino-pyroxene. Interaction of the invading hydrothermal fluid with the rock component leads to rare, partial or complete rock alteration. Olivine alters commonly to clay and sometimes calcite. Plagioclase alters to clay, calcite, albite, sphene and quartz. One of the typical first stages of plagioclase alteration is the formation of tiny clay fractures which appear to start forming at temperatures of about 200°C. Pyroxene is most resistant to alteration and alters partially to chlorite, clays or sphene. Opaque minerals like magnetite usually alter to sphene, pyrite, phyrrotite or limonite. Table 1 shows primary minerals and their alteration products. In the cuttings of well KR-2, the plagioclase, pyroxene, olivine, glass and opaque minerals have been altered to various extent.

TABLE 1: Primary minerals and their alteration product (adapted from Lagat, 1995)

Primary mineral	Replacement product
Volcanic glass	Zeolite, quartz, calcite, clay, sphene
Pyroxene	Chlorite, clay, quartz, pyrite, calcite
Ca-plagioclase	Calcite, albite (basaltic rock), adularia, quartz, chlorite, epidote, sphene, wairakite
Olivine	Clay, calcite
Opaque, iron oxide	Sphene, pyrite, phyrrotite, limonite, secondary oxides

Olivine. Olivine starts to alter at 199 m depth in very low to low intensity (< 10%) down to 595 m depth with partial alteration into clays. Olivine shows total alteration intensity at 703-1217 m depth into clay and calcite.

Plagioclase. The primary plagioclase composition is commonly labradorite (high extinction angle of twins). It starts to alter at 199-239 m depth and alters (< 10-30%) to clay. At 255-289 m depth, it shows about 50% alteration into clay, calcite and sometimes quartz. Medium to high alteration intensity (50-80%) is found at 297-1217 m depth, where it alters mainly to clay, calcite, quartz, albite, wairakite, chlorite and epidote; the last three only appearing in the deeper part of the well.

Pyroxene. Pyroxene is the mineral most resistant to alteration. It starts altering at 321 m depth into clay (< 10%). It appears fresh again to 536 m depth. From 536-1217 m depth about 10-30% has altered into

clay, chlorite and sphene. At 1217 m depth sphene seems to be the only alteration of pyroxene.

Glass. Glass was only found in tuff fragments and several parts had been altered into yellow brownish (coarse grained clays) clay and quartz.

Opaque minerals. This group is usually ilmenite/magnetite, and shows a variable alteration in the well. Several parts have been altered into limonite and sphene. Sphene is first seen at 412-648 m depth and then again below 845 m depth.

5.2 Distribution of hydrothermal minerals

5.2.1 Hydrothermal minerals

Figure 9 and Appendix II show the distribution of hydrothermal minerals and their analytical methods. A brief description of each mineral is outlined below.

Calcite. Calcite is a very common mineral in this well. It shows a wide range of occurrences and is especially abundant within hyaloclastite series, like pillow lavas but less common in denser basaltic lavas. Medium quantities are found at 329-677 m depth but it is abundant at the 807-932 m depth interval, while a medium quantity is found at 938-1094 m depth. Below that calcite is relatively rare. Calcite veins are rarely found together with other minerals. In a vein at 150 m depth it occurs together with clay, and at 302 m depth it occurs together with iron oxide. In XRD, calcite shows typical peak values (distance in angstrom Å) at 3.03, 2.28, 2.09 and 1.87 Å. In thin section it is sometimes seen replacing plagioclase and olivine. As mentioned above calcite is usually the only mineral in the veins, except at 212 m depth where it occurs along with quartz and stilbite and at 297 m depth where it is found along with smectite.

Chalcedony. This mineral occurs mostly as cavity fills and lines walls of vesicles. Chalcedony is relatively common between 200 and 450 m depth but is rare from there down to about 950 m depth, below which it was not seen. In thin section it is seen lining walls of vesicles together with other minerals like quartz, smectite, mixed layered clays (MLC) or calcite. It sometimes has transformed into quartz but is recognized by its constant thickness on the wall of the vesicle.

Quartz. Quartz was rarely found as groundmass alteration but is rather abundant as open space filling, often with other minerals like calcite and dark clays (e.g. at 122 and 237 m depth). In XRD, quartz also occurs from top to bottom and shows typical peaks at 3.35, 4.25, 3.34, 4.24, 2.46 and 1.82 Å. In thin section it is seen as a replacement for plagioclases. Quartz replaces chalcedony at high temperatures. This can be seen at 1093 m depth, where chalcedony (quartz) appears together with wairakite and green fine-grained clays. Quartz forms at higher temperatures than chalcedony, or above 180°C.

Zeolite. The zeolite group includes hydrous calcium aluminium silicates that commonly occur as secondary minerals in the rock cavities, especially basalt (Kerr, 1959). The zeolite group has been identified by binocular, petrographic microscope and XRD, and commonly indicates low-temperature conditions (< 100-120°C), except laumontite (120-200°C) and wairakite (180-300°C). In well KR-2, zeolites identified are stilbite, thomsonite, chabacite, natrolite, phillipsite, heulandite, laumontite, mesolite, scolecite, and wairakite. The following describes zeolite groups as encountered in the well:

Heulandite. This mineral was detected by XRD with peak values at 2.52 and 2.35 Å at 273 and 348 m depth. It is commonly found in the hyaloclastite series (tuff unit) but is less common in the basaltic lava series.

Chabacite. In XRD it shows typical peak at 3.85 Å and was found at 146 m depth as a filling

in a basaltic lava. In a thin section at 297 m it possibly appears as a tracer with thomsonite.

Laumontite. It has a prismatic and fibrous structure and is mainly found as cavity fills. Laumontite was found at 239 m depth in vesicles within a basaltic breccia unit. In XRD it shows a peak value of 3.77 Å at 348 m depth.

Stilbite/epistilbite. In XRD the mineral shows typical peak values of 9.01, 5.48 and 2.49 Å at 146, 232 and 582 m depth. In thin section it was identified by a sheaf or radial form, and was sometimes difficult to distinguish from thomsonite. It appears at 237, 239 and 297 m depth.

Thomsonite. In XRD it occurs with peak values of 4.55 Å and is found at 582 m depth within a pillow lava unit. In thin section it is radial, sometimes similar to natrolite but natrolite shows much finer radial crystal structure. It appears at 297, 321 and 454 m depth. At 297 m depth thomsonite occurs in vesicles together with quartz and calcite, but it probably was deposited at a late stage.

Natrolite. This mineral was only found at 146 m depth in XRD analysis on grounds of a reflection peak at 1.6 Å.

Mesolite/scolecite. It showed a typical XRD peaks at 3.2 and 2.5 Å and was found at 273, 293 and 348 m depth. This mineral is rare and was not identified in thin section.

Phillipsite. It is a rare mineral and was only identified in XRD by peak values of 2.39, 1.73 and 2.04 Å at 348, 542 and 582 m depth.

Wairakite. It was recognized in cuttings analysis at 1122, 1171 and 1174 m depth together with epidote. In XRD it shows the typical peaks of 5.59, 5.57, 5.53, 3.40, 3.41, and 2.91 Å. In thin section this mineral is first seen at 403 m depth and continues to the bottom of the well.

Epidote. This mineral is famous in high-temperature geothermal systems, because it indicates temperatures above about 250°C. In the cutting samples, it is first seen at 737 m depth as a tracer and is found sporadically down to 810 m depth, but continuously below that. Sometimes it is very abundant and may relate to aquifer zones. In XRD it shows typical peaks of 4.01 and 3.77 Å at 986 m depth. In thin section, it first appears at 966 m depth with characteristic yellow greenish colours in plane-polarized, high pleochroism and high relief, and shows very strong colours in cross-polarized light. This mineral occurs sometimes together with wairakite, chlorite and calcite.

Prehnite. This mineral looks like epidote in thin section except that it has no pleochroism. It indicates high temperatures (> 200°C). In XRD prehnite shows weak reflection peaks at 2.49 and 2.35 Å in samples from 1032 and 1094 m depth. Prehnite was not found in thin section.

Albite. Albite is found in basaltic rock as an alteration product of the Ca-rich plagioclase (labradorite). In thin section albite appears as a replacement of plagioclase (anorthite and labradorite) from 239 to about 966 m depth and absent down to 1217 m. Albite is observed at rock temperatures above 200°C.

Pyrite. Pyrite (FeS₂) is very common from the top to the bottom of the well. Pyrite is by experience one of the many criteria used to identify past or present aquifer zones (see Chapter 6). Pyrite forms as a deposition or a replacement of opaque minerals. It is very easily identified in the binocular stereo microscope.

Limonite. It is included in the iron oxide groups. It usually appears as a replacement product of opaque mineral, like magnetite, but is also found deposited in vesicles. It is red brown in colour. It is first observed at 199 m depth and continues to the bottom.

Sphene. It is generally formed by replacement of opaque minerals, but sometimes also as a replacement of glass, pyroxene and plagioclase. This mineral indicates poor permeability in the Philippines (Reyes, 1990) but this relationship has not been observed in Iceland. Sphene was only identified in the petrographic microscope, where it is seen as red brown and somewhat cloudy coloured crystals. It is first seen at 396 m depth as a replacement of magnetite and replaces plagioclase at 1090-1217 m depth.

Gypsum. Gypsum was only identified by XRD as an accessory mineral with a peak value of 7.6 Å together with swelling chlorite at 275-403 m depth.

Chlorite. In the cuttings it starts to appear at 527 m depth, typically light green in colour, and sometimes appears together with fine and coarse grained clays. Chlorite is divided into two species on ground of XRD i.e. swelling chlorite and chlorite. Chlorite in XRD has reflection peak values constant at about 14 Å (chlorite in iron-rich or in magnesian) and never changes in three conditions, i.e. untreated (air-dried), after glycolation or after heating to 500-550°C (Brown and Brindley, 1980). Swelling chlorite on the other hand shows 14 Å in the air-dried, expands to 16-17 Å in glycolation but collapses to less than or 14 Å after heating to 500-550°C. Swelling chlorite appears at 223 m depth with peak values at 14.48 Å (untreated), expanding to 14.60 Å (ethylene glycol) and collapsing to 13.63 Å on heating to 500-550°C. Swelling chlorite is first observed at 157 m and is found to 1217 m depth, sometimes together with MLC (194 m depth), and together with chlorite at 525, 740 and 821 m depth, but from there to 1217 m depth, the presence of swelling chlorite is rare. In thin section, chlorite start to occur at 396 m depth in the vesicles together with calcite, quartz (in chalcedony wall linings) and fine grained clays. Chlorite replaces pyroxene at 807 m depth and replaces plagioclase at 1217 m depth.

Clays minerals. The clays are the most voluminous alteration minerals. They alter basaltic glass, olivine, plagioclase, and partly pyroxene. The clays in the rocks of well KR-2 are both fine grained clays (smectite) and coarse grained clays (MLC) as observed in vesicle and vein fillings:

Smectite. Smectite (fine grained clays) is green to yellow brownish and is found in vesicles like thin linings. In thin section it has light green colours in plane-polarized light. In XRD it shows reflection peaks of 15.02 Å (untreated), 16.74 Å (ethylene glycol) and 10.04 Å (heated 500-550°C) as analysed at 122 and 275 m depths.

Mixed layered clays (MLC). Evidence of MLC occurrence in this well was based on standard Icelandic references for MLC calibration on XRD. Peaks of 12.8 to 14.6 Å occurred at constant humidity or air-dried, expanded to 16 Å after treatment with ethylene glycol and collapsed to 12.07 Å after heating to 500-550°C. In thin section MLC starts to appear at 199 m and is relatively abundant to 439 m depth. It commonly forms in vesicles and shows radial needles and yellow brownish colours. Sometimes it appears on thinly lined walls in vesicles. In several cavities, it is associated with calcite and quartz. It shows light green colours in plane-polarized light but in cross-polarized light it shows radial needles of yellow brownish colours.

5.2.2 Veins and vesicles

Petrological and binocular stereo microscopes are used to identify veins and vesicles. The presence of veins and vesicles in the lithological formations indicates the past or present hydrothermal activity. Minerals form in the veins and vesicles by deposition. Thirty five veins have been identified from top to bottom in well KR-2, Krýsuvík. Table 2 shows the depth locations of these.

TABLE 2: Veins depth locations and quantities in well KR-2, Krýsuvík.

Depth (m)	Quantity	Mineral fills	Rocks series	Explanations
208-221	5	Qz, Ca, Py, Stb	Hyaloclastite	Low alteration
293-351	7	Ca, Qz, MLC, Py, Io	Basaltic lava + hyaloclastite	Med-high alteration
439-454	2	Ca, Fcc	Basaltic lava	Med-high alteration
948-1093	8	Ca, Py, Cl, Qz	Basaltic lava	High alteration
Widespread	15	Ca, Io, Py, Qz, Cl	Comm. basaltic lavas	Low-high alteration

The intensity of veins varies with depth. Veins are most common in basaltic lavas and less in hyaloclastites (tuff). At 208-321 m depth in the hyaloclastite series, five veins appear filled with calcite and pyrite, while others are filled with calcite, quartz and stilbite. In the basaltic lava series (293-351 m depth) about seven veins appear filled by calcite, quartz, MLC, pyrite and iron oxides. At 439-454 m depth two veins were seen in thin sections filled with calcite and finely crystallized clays (smectite). The surrounding rock has been altered from medium to high intensity. In the basaltic lava at 948-1093 m depth, eight veins appear dominantly filled with calcite or calcite together with pyrite, quartz and clays. Fifteen more veins were found outside the above depth intervals, and these are filled with calcite, quartz, pyrite, iron oxide and clays.

Veins are more common in basaltic lava than hyaloclastites as mentioned previously, which indicate that hydrothermal fluids were flowing more actively through basaltic lava series, mainly at 293-351 m depth and 948-1093 m depth. The temperature at 293-351 m depth is higher than at the other locations, as indicated by the presence of MLC (200-230°C). In veins at 208-221 m depth in hyaloclastite, a lower temperature is indicated by the presence of zeolite (stilbite) which may indicate a past or present temperature of < 100°C.

5.3 Alteration mineral zonation

Many hydrothermal minerals in Iceland are highly temperature dependent where definite mineralogical changes are seen to take place with increasing temperature (Kristmannsdóttir, 1978; Malapitan, 1995). Figure 10 shows that zeolites are found at temperatures up to 200°C where they are transformed to wairakite. Quartz forms at temperatures above 180°C and calcite may form up to temperatures around 270-290°C. Epidote forms at temperatures above 240-260°C. Smectite is the dominant clay up to temperatures of about 200°C

Rock Temperature °C	Alteration zones	Index minerals	Mineralogical Characteristics	Regional Metamorphic Facies
50	I	Smectite Zeolites	Low temperature zeolites and smectite forms	Zeolite Facies
100			Low temperature zeolites → laumontite	
150			Smectite interlayered	
200	II	Mixed-layer clay minerals	Laumontite → wairakite Smectite → mixed-layer clay minerals	Greenschist Facies
250	III	Chlorite Epidote	Mixed-layer clay minerals → chlorite Epidote-continuous occurrence	
300	IV	Chlorite Actinolite	Actinolite forms Plagioclase commonly albited	

FIGURE 10: Correlation of alteration zone in high-temperature geothermal areas in Iceland to rock alteration and methamorphic facies (Kristmannsdóttir, 1978)

where mixed layered clays start to form and chlorite starts forming at temperatures above 230°C.

Alteration minerals zones in well KR-2 are divided into a smectite-zeolite zone, a mixed layered clay zone, a chlorite zone and a chlorite-epidote zone (see Figures 9 and 11). The following is a description of the alteration zonation with temperature approximations.

Smectite-zeolite zone. This zonation is marked by the presence of smectite, chabazite, natrolite and stilbite, supported by quartz. Temperature is less than 200°C. This zone extends from top to about 140 m depth.

Mixed layered clays (MLC) zone. It is marked by the presence of coarse grained clays and supported

by wairakite, albite, and swelling chlorite. Temperature zonation is about 200-230°C. In Icelandic geothermal fields MLC is present where measured temperatures are in the range of 200-230°C (Kristmannsdóttir, 1978). This zonation extends from 140 to 380 m depth.

Chlorite zone. This zone is indicated by the presence of chlorite and swelling chlorite and supported also by wairakite and albite. The top of the chlorite zone was found at 380 m depth and it extends down to 737 m depth. The temperature range of this zone extends from 230°C to about 240°C.

Chlorite-epidote zone. It is clearly marked by the presence of epidote and chlorite. It is also supported by wairakite, albite, sphene and calcite. Temperature in this zone is above 240°C and it extends at least to the bottom of the well at 1217 m depth.

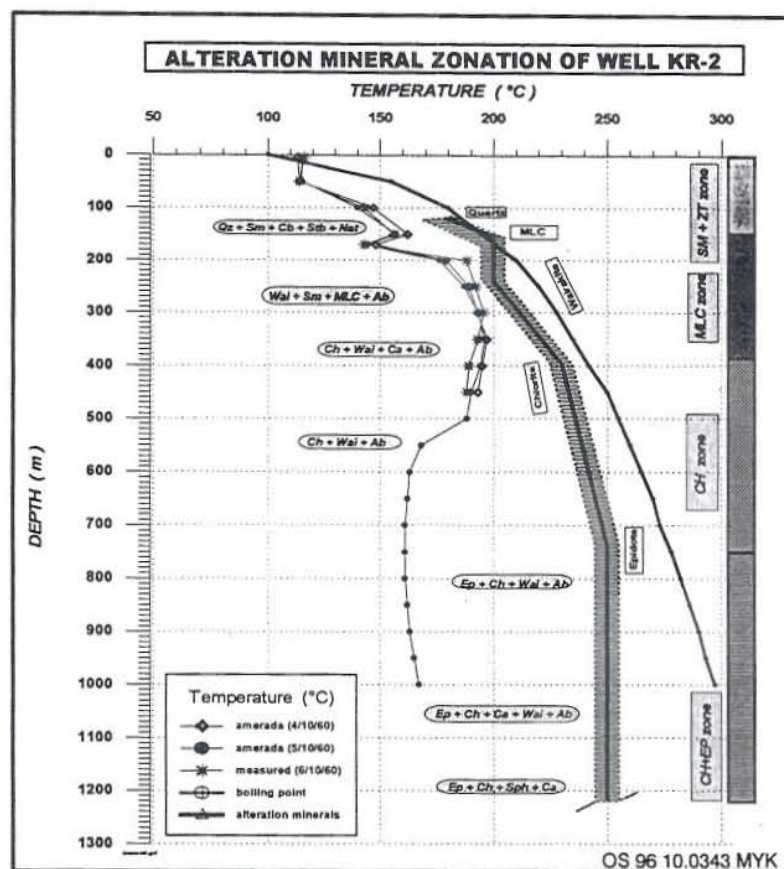


FIGURE 11: Alteration mineral zonation, alteration and measured temperature in well KR-2

5.4 Deposition sequence

Deposition is found to occur as full, partial or rare in cavities and fractures. Clay is the major hydrothermal alteration lining walls of the vesicles and fractures. Table 3 shows the sequences of deposition minerals in vesicles in well KR-2.

The sequence from the upper zone to 237 m depth is characterized by the initial deposition of fine grained clays followed by coarse grained clays, calcite and quartz, but other sequences show fine grained clays followed by coarse grained clays, zeolite (stilbite), calcite and fine grained clays. Stilbite in the sequence indicates a late deposition stage and only fills the space between coarse grained clays and calcite. At 396 m depth sequences are characterized by chalcedony or quartz followed by fine grained clays, chlorite and then calcite. "Spherulitic" structure is typical for chalcedony but has later been pseudomorphed to quartz, so the sequences indicate an evolution from low temperature (< 100°C) to medium temperature (200-230°C) and later to high-temperature (> 230°C). A similar condition occurs with mineral sequences at similar depth; chalcedony (quartz) is followed by albite, wairakite and at the end calcite. Into the chlorite-epidote zone (240-260°C) at 1093 m depth, the mineral sequences consist of fine grained clays followed by chlorite, and at the end wairakite. There are fine grained clays followed by calcite and at the end wairakite. The temperature mineral evolution goes from 200°C up to 270°C, then to less than 300°C.

TABLE 3: Deposition sequences of secondary minerals of well KR-2

Depth (m)	Rocks	Ia	Sequences in time Early ---> Late	Depth (m)	Rocks	Ia	Sequences in time Early ---> Late
199	Tuff	low	fgc--cgc--Ca--Qz	454	Basaltic rocks	high	fgc-gfgc-Ca-Qz
212	Tuff	low	Ca-Qc(Qz)-Ca-fgc-Ca-Qz-Li	536	Basaltic rocks	high	fcc-gfgc-Wai-Qz
237	Basaltic rocks	low	(1) fgc-Ca-Qc-Qz-Ca (2) fgc-cgc-Stb-Ca-fgc	570	Basaltic rocks	high	Qc(Qz)-fcc-Ch / gfgc-Qz-Ch
239	Basaltic rocks	low	fgc-cgc-Ca-Qc-Ca-- Qc-Ca-Qc-Ca-Qc-Ca	594	Basaltic rocks	med.	gfgc-Qz-Ca
255	Basaltic rocks	med.	Qc-fgc-cgc / Qc-fgc-Ca	648	Basaltic rocks	med.	gfgc-Ch-Ca / Qc(Qz)-Ca-cgc
269	Basaltic rocks	low	(1) Qc-Qz-fgc(Li)-Qz (2) fgc-Qc-Li(Ca)-Qz(Li)-- Ca-Qz-fgc-Ca	666	Basaltic rocks	med.	fcc-gfgc-Qz-Ca
289	Tuff sediment	med.	Ca-cgc-fgc-Ca	690	Basaltic rocks	med.	gfgc-Ch-Ca / Pg-Ca-Qz
297	Basaltic rocks	high	Qc-fgc-cgc-Ca / Th-Qz-Ca	703	Basaltic rocks	high	Qc(Qz)-Ca-Wai
321	Basaltic rocks	high	Qc-fgc-cgc-fgc	745	Basaltic rocks	high	
330	Basaltic rocks	med.	fgc-cgc-Ca	807	Basaltic rocks	med.	
351	Basaltic rocks	med.	Qc-Qz / fgc-cgc-Ca	845	Basaltic rocks	high	fcc-Qc(Qz)-Ca-Fgc
396	Basaltic rocks	med.	Qc(Qz)-fgc-Ch-Ca / Qc(Qz)-gfgc-Qz-Ca / Qc(Qz)-Ab-Wai-Ca	854	Basaltic rocks	med.	gfgc-Ch-Wai / Qc(Qz)-fcc-(Li)-Ca
412	Basaltic rocks	med.	fgc-gfgc-Qz / Qc-gfgc-Wai	948	Basaltic rocks	high	gfgc-Ca-Qz
439	Basaltic rocks	med.		966	Basaltic rocks	high	gfgc-Ch
				988	Basaltic rocks	high	
				998	Basaltic rocks	high	cgc-fgc
				1090	Basaltic rocks	high	Qc(Qz)-fcc-gfgc / gfgc-fcc-Qz
				1093	Basaltic rocks	high	fgc-gfgc-Ch / fgc-gfgc-Ca-Wai
				1217	Basaltic rocks	med.	gfgc-Qz

LEGEND

fcc: finely crystallized clay	Qc: Chalcedony	Ch: Chlorite
cgc: coarse grained clay	Qz: Quartz	Wai: Wairakite
fgc: fine grained clay	Ca: Calcite	Stb: Stilbite
gfgc: green fine grained clay	Li: Limonite	Th: Thomsonite
cfp: clays fracture in Pg.	Ab: Albite	Ia: Intensity of alt.

6. AQUIFER ZONES

Determination of aquifers is vital in the geothermal reservoir. Aquifers in the geothermal environment are characterized by the presence of permeable rock formation, feed zone or geological structures and natural recharge areas. Diagnostically their presence is directly determined from records of circulation losses during drilling and logs, such as penetration rate, temperature, caliper and gamma ray log. An aquifer zone may also be recognized from anomalous hydrothermal alteration as a function of permeability such as an abundance of anhydrite, pyrite, epidote, abundant oxidation and presence of adularia. In Iceland, the presence of dust-wood in cuttings may indicate an aquifer zone because dust-wood is used to reduce circulation losses.

Well KR-2 is a very old well, drilled in 1960. Until today, there has been little speculation concerning the aquifer zones in the well. To predict possible aquifer zones, the data used included dust-wood contamination in cutting samples, circulation losses, temperature profiles and the abundance of pyrite and epidote. Figure 12 shows some indicators of aquifer zones, locations where they appear and a correlation with lithology.

Pyrite and sometimes epidote, by experience in Iceland, is a good indicator for past and present permeability (Franzson, pers. comm.). Aquifer locations are divided into two categories, the first containing known aquifers, and the other based on more speculative data.

In the first category, four aquifer zones could be identified:

Aquifer zone 1. At 130 m depth a loss of circulation of about 5 l/s occurred. The surrounding lithology is fresh basaltic lava, so if the aquifer is there it could be in a fracture; it is not seen in the cuttings. It would certainly be a very small aquifer.

Aquifer zone 2. At 160-166 m depth a loss of circulation was reported in the drilling report, with the presence of dust-wood in cuttings, abundant pyrite, and a cooling point in the temperature log. The surrounding lithology is pillow basalt with medium to high alteration and abundant clays. The exact location is probably at 160 m depth, indicated mainly by the cooling point and circulation loss.

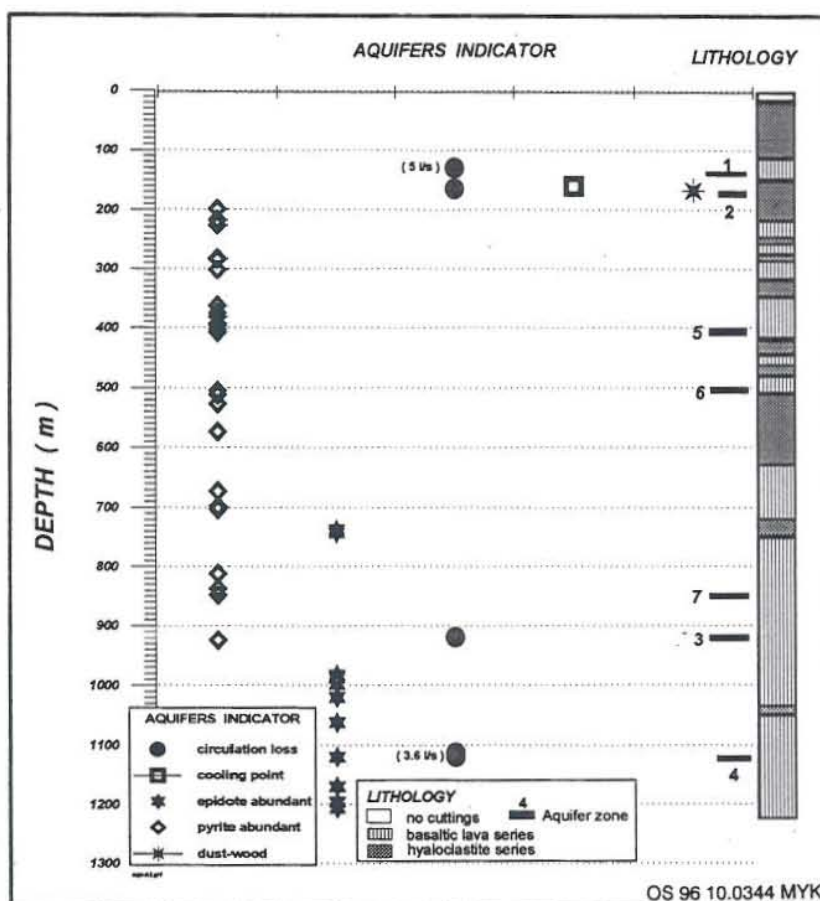


FIGURE 12: Aquifer indicators and their zonation in well KR-2

Aquifer zone 3. At 920-924 m depth, indicated by loss circulation and abundant pyrite. The surrounding rock is highly altered basaltic lava.

Aquifer zone 4. At 1120 m depth a circulation loss of 3.6 l/s was reported which is supported by the presence of abundant epidote. Lithology at that depth is highly altered basaltic lava.

In the second or speculative category, there are three possible aquifer zones:

Aquifer zone 5. At 400-402 m depth an abundance of pyrite and a minor possible cooling point was found (see Figure 8). The rock there is pillow basalt (hyaloclastite). High alteration is directly underlying the possible aquifer. Vesicles are abundant as well as abundant oxidation and quartz.

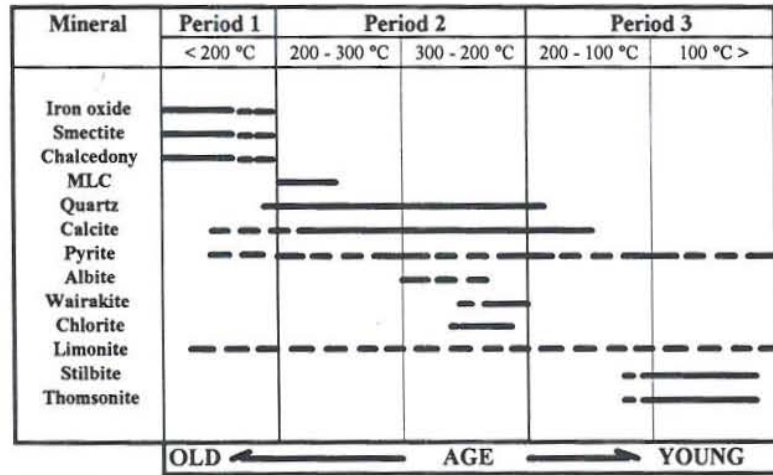
Aquifer zone 6. At 505-515 m depth is a zone of abundant pyrite and dark clays which has also anomalous oxidation. Lithology, there is hyaloclastite (pillow lavas) which has suffered high intensity alteration.

Aquifer zone 7. At about 850 m depth is a zone characterized by abundant pyrite and oxidation along with abundant calcite. Lithology, there are basaltic lavas with medium alteration.

7. TEMPERATURE EVOLUTION

In well KR-2, three distinct stages of alteration and mineralization are recognized. They are recognized on grounds of deposition sequence within vesicles and veins. Figure 13 shows the secondary mineral evolution in well KR-2 from early to late deposition.

The first period is characterized by deposition of chalcedony, fine grained clays (smectite) and iron oxide. This period indicates a fossil system which was formed soon after volcanic deposition and a rise in the



LEGEND
 — Secondary minerals growing
 - - - Secondary minerals possible growing
 OS 96 10.0345 MYK

FIGURE 13: The secondary minerals evolution in well KR-2

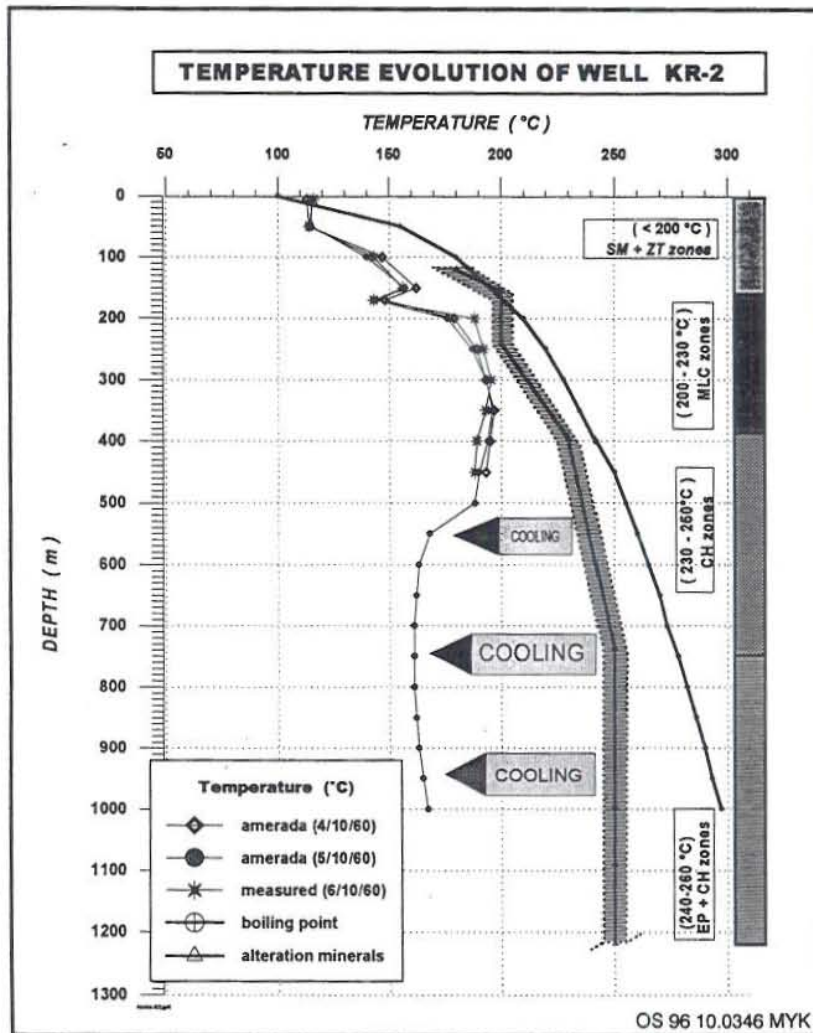


FIGURE 14: Temperature evolution from past to present deduced from mineral deposition sequences in well KR-2

geothermal gradient. This argument is in accordance with Ganda (1987). The temperature is low, < 200°C.

The second period involves prograde alteration of minerals and open space mineralization. This period is represented by mixed layered clays (MLC), chlorite, and wairakite. In the mixed layered clay zone it infers > 200°C, while in the chlorite and chlorite-epidote zones it infers > 240-270°C.

The third period. In this period, the system suffers cooling, indicated by the presence of low-temperature zeolites (stilbite and thomsonite) indicating cooling to well below 200°C.

Today as well as henceforth (?), temperature may be cooling to a low-temperature condition. Figure 14 shows temperature evolution from the distinct alteration temperature (mineral

temperature) in the past to the present temperature represented by temperature curves (measured during completion of the well). A dramatic temperature cooling has occurred from 240°C-260°C (in the chlorite-epidote zone) to 160°C (measured October 5 1960).

The presence of a mushroom-shaped inverse temperature gradient indicates a possible influx of cool water into the system. This phenomena is possibly represented by the presence of abundant oxidation seen in the cuttings (binocular analysis), and a few limonites identified on thin sections may indicate cold water influx (Reyes, 1990). High magnesium concentration suggests that water-rock interaction may have occurred at low temperature (Reyes, 1990).

8. RESERVOIR ASSESSMENT

Figure 15 shows the temperature profiles of wells in the Krýsuvík high-temperature area. The highest temperature is represented by well KR-6 at about 260°C (at 500 m depth) followed by well KR-1 at about 220°C (320 m depth) and KR-9 at 225°C (150 m depth). All wells indicate inverse temperatures at various depths except well KR-7. Temperature correlation along a NE-SW cross-section with wells KR-5, KR-1, KR-2 and KR-9 is shown in Figure 16. KR-5 has an inverse temperature at shallow depth (about 150 m), followed by well KR-1 (400 m depth) and well KR-2 (550 m depth). Well KR-9 is a shallow well and shows an insignificant inverse temperature (at 250 m depth). This figure implies that the reservoir below is controlled by two fluids, possibly moving in opposite directions. Wells KR-5, KR-1, KR-2 and KR-9 are drilled in a reservoir which is controlled by permeable lithologic contacts and fractures possibly related to the Krýsuvík fissure. Figure 17 shows a hydrothermal reservoir model around well KR-2. The hot upflow (about 200°C) ascends from the southwest to well KR-9 and then to wells KR-1, 2 and 5 with temperature decreasing in that direction. Cooler water is envisaged to flow downwards into the hydrothermal system from the opposite direction (northeast).

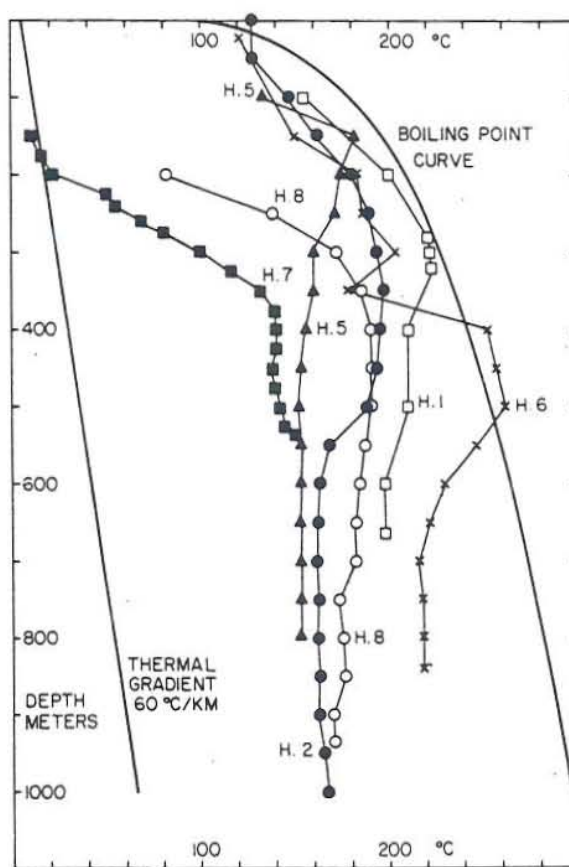


FIGURE 15: Temperature logs of wells in the Krýsuvík area

9. DISCUSSION

The sequence above 550 m depth in well KR-2 shows a repetitive stratification. This feature is commonly observed in the Icelandic volcanic zone. Hyaloclastite series are conspicuous down to 850 m depth, but basaltic lava series are dominant below that. Hyaloclastite formations usually consist of

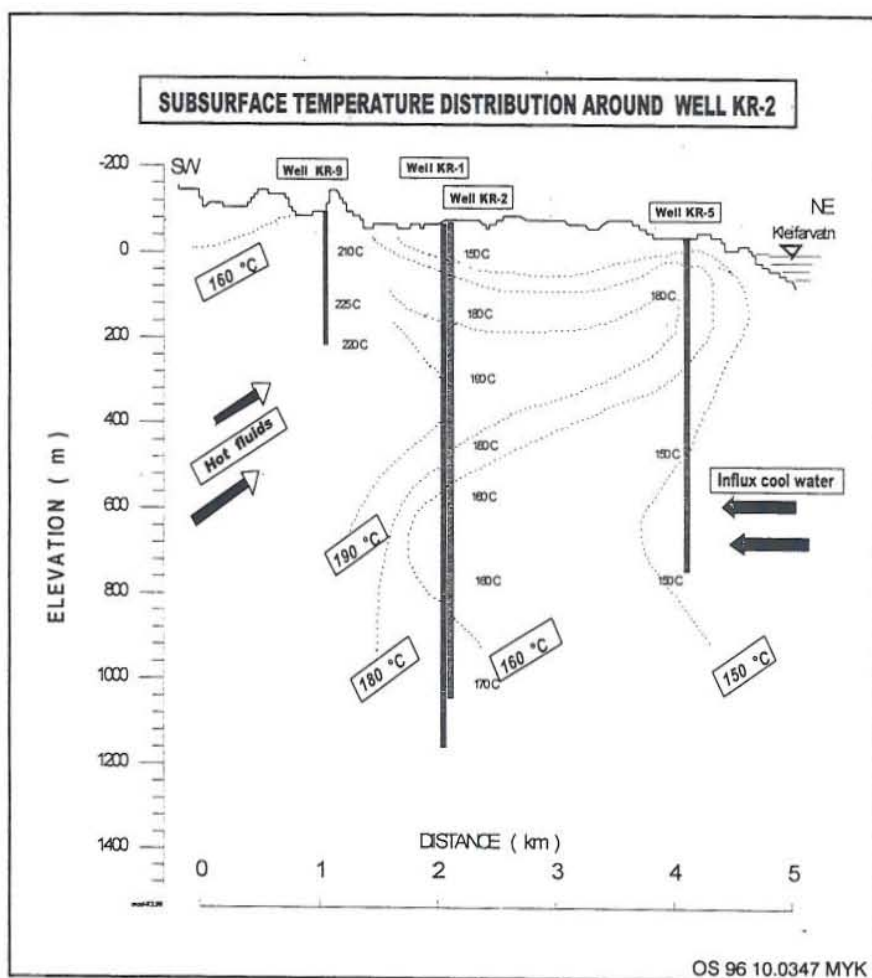


FIGURE 16: Correlation of temperatures in wells KR-9, KR-1, KR-2 and KR-5 in the Krýsuvík area

tuff in the upper part and a base of pillow basalt. Basaltic lava series consist of individual lavas with thicknesses ranging between 2 and 10 m. Intrusive rocks direct the accumulative volcanic succession below about 600 m depth. This condition is due to magma travelling through dilational rifting fissures and/or as sills along weak stratigraphic boundaries. The age of the stratigraphic sequence can be roughly assessed by comparison with ages of the glacial and interglacial periods. Thus it is likely that the rock series to 258 m depth formed during the last glacial period (12,000-115,000 years), the basaltic lava series at 258-329 m depth formed possibly during the last inter-glacial period (115,000-125,000 years) and the repetition of hyaloclastite series 5 to 9 and basaltic lava series 5 to 10 approximately formed during earlier glacial to interglacial periods.

Hydrothermal alteration is indicated by rock alteration and deposition in small veins with amygdalae fillings. There are four mineral zonation in this well including smectite-zeolite, mixed layered clay, chlorite and chlorite-epidote zones. The smectite-zeolite zone to 140 m depth is characterized by the presence of smectite and low-temperature zeolites (< 200°C) and supported by quartz and chalcedony. Similarly, the mixed layered clay zone (200-230°C) is supported by the presence of wairakite, albite and swelling chlorite. The general alteration mineralogy of chlorite and chlorite-epidote zones is similar, except that epidote is thought to start forming at slightly higher temperatures (> 240°C). Veins appear to be more common in basaltic lava series, indicating higher permeability there.

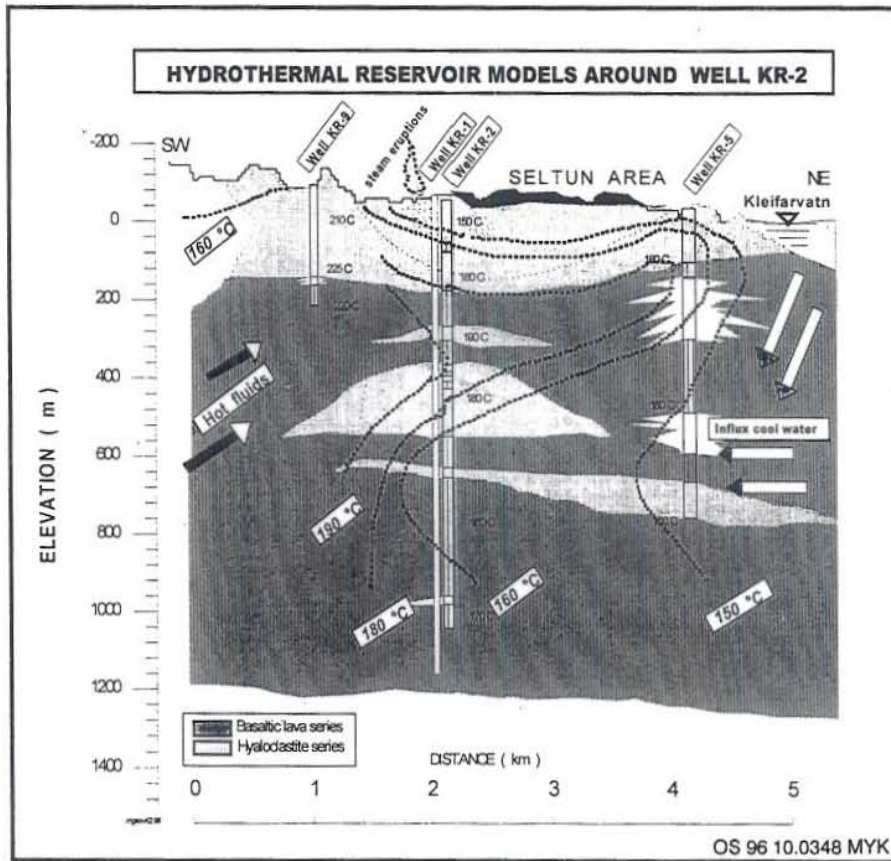


FIGURE 17: Hydrothermal reservoir model around well KR-2, Krýsuvík area

Depositional sequences of hydrothermal minerals start with low-temperature smectite and/or chalcedony, followed by medium- to high-temperature conditions. Sometimes low-temperature conditions are followed by high-temperature ones and then turn back to low-temperature again, as seen at 237 m depth where stilbite comes in late after MLC. In the chlorite-epidote zone (240-270°C), chalcedony (quartz) is followed by chlorite and wairakite. Quartz chalcedony indicates low-temperature conditions followed by high-temperature ones.

There are seven possible aquifer zones identified in the well, separated into two categories. In the first category are confirmed aquifers while the aquifers in the second category are based on more circumstantial evidence.

Temperature is assessed through two data sources, i.e. temperature estimates based on alteration assemblages on one hand and measured temperature on the other. The former can be separated into three time stages, an early stage of relatively low temperature conditions (< 200°C) formed by a high-temperature conditions ($\leq 270^\circ\text{C}$) and then a stage of cooling to < 200°C. The latter source (measured temperature) when compared to the overall alteration temperature estimates, indicates that the hydrothermal system has suffered cooling of up to 80-100°C. The general temperature distribution (alteration and measured) in the Krýsuvík high-temperature field indicates that inflow of hot fluid may ascend from the southwest while an influx of cooler fluids enters the system from the northeast.

10. CONCLUSIONS

The following conclusions can be stated based on geothermal evidence from the study of well KR-2:

1. The lithology of well KR-2 is a repetitive sequence of lava series and hyaloclastite series down to 850 m depth as deduced from the microscopic analyses of the cutting samples, while below that it is dominated by a basalt lava sequence. The sequence down to 258 m depth is believed to have formed during the last glacial period (12,000-115,000 years ago), the underlying basaltic series extending down to 329 m depth was formed during the last interglacial period (~115,000-125,000 years). The underlying lava and hyaloclastite series were formed during earlier interglacial and glacial periods.
2. Formations alter from low to high intensities. The presence of zeolite groups and chalcedony indicates low-temperature (< 200°C) in the smectite-zeolite zones. The other mineral zonations are MLC (200-230°C), chlorite (230-240°C) and chlorite-epidote (240-270°C).
3. There are up to seven aquifer zones in well KR-2. Four of them are confirmed while the presence of the others is more speculative.
4. Temperature evolution from past to present, as seen in deposition sequences, indicates cooling of the geothermal system. And an inverse temperature gradient indicates that there are two kinds of fluid entering the system, hot fluids flowing from the southwest into the system and an influx of cooler water from the a northeasterly direction. Cold water is possibly percolating from lake Kleifarvatn.

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APPENDIX I: Preparation of sample minerals for analyses 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 analyses

1. Under the binocular microscope, hand pick grain fillings either vesicles or veins from the cuttings contained in the rectangular plastic box. The sample depth is dependant 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. Aceton 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 lid against the sample in a slot to make it firm, flat and level.
4. Run samples from 3 to 60 θ on XRD.

Procedure 2: For clay mineral analyses

1. Place approximately two teaspoons of cuttings into a test tube, wash out dust with distilled water. Fill the tube 2/3 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 (more or less three samples) and let dry at room temperature overnight.
3. Place one set of samples in a desiccator containing Ethylene glycol ($C_2H_6O_2$) solution and the other in a desiccator containing $CaCl_2 \cdot 2H_2O$, store at room temperature for at least 24 hours. A thick sample will need a longer time in the desiccator, at least 48 hours.
4. Run both sets of samples from 2 to 14 θ on the XRD.
5. Place one set of samples another on an asbestos plate and heat in a preheated oven at 500-550°C. The exact location of individual samples on the asbestos plate must be known before heating because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment, but do not forget the labelling of the samples.
6. Run samples from 2 to 14 θ on the XRD.

TABLE 2: Results of X-ray diffractometry for deposition minerals in well KR-2

Depth (m)	Lithology	ALTERATION MINERALS															
		Calcite	Quartz	Epidote	Chlorite	Prehnite	Chabazite	Thomsonite	Stilbite	Natrolite	Phillipsite	Heulandite	Laumontite	Wairakite	Mesolite	Albite	Scolecite
146	Basaltic la.	3.03,2.28, 1.87	3.35,1.87				3.85		2.49	1.6							
210	Basaltic la.	3.04,2.28, 1.87	4.25,3.35, 2.46 1.67, 1.54														
232	Basaltic la.	3.02,2.28, 1.87	4.25,3.34,2.45 2.13,1.82,1.54						9.01								
273	Tuff	3.02,2.28, 1.87	4.24,3.34,2.46 2.14,1.82									2.52, 2.35			3.2		
293	Basaltic la.	3.01,2.28	4.24,3.34,1.82 1.67,1.54												3.2		
348	Basaltic la.	3.03,2.28, 1.87	4.27,3.34,2.45 2.13,1.82,1.54								2.04	2.35	3.77				2.5
403	Breccia	3.03,2.28, 1.87	4.25,3.34,2.14 1.82,1.54		4.83									5.59 3.39		3.19	
451	Basaltic la.	3.03,2.28, 2.09	4.24,3.34,2.46 2.12,1.81,1.67 1.54											3.41			
542	Basaltic la.	3.03,2.09	4.25,3.34,2.28 1.81,1.54									1.73			3.4	3.19	
582	Pillow la.		1.67					4.55	5.48			2.39		5.53 3.41			
633	Basaltic la.	3.03,2.09 1.87	4.25,3.34,2.28 2.12,1.81,1.54											5.57, 3.4		3.19	
746	Breccia	3.03,1.90	4.25,3.34,2.28 1.54											5.57, 3.4		3.19	
847	Basaltic la.	3.03	4.24,3.34,2.28 1.82,1.67,1.54											5.57, 3.4		3.19	
927	Breccia	3.03,2.09, 1.87	4.26,3.34,2.46 2.28,2.12,1.82 1.67,1.54		4.82									3.41			
963	Basaltic la.	3.03,1.87	3.35,4.25,2.46 2.13,1.82,1.67 1.54												3.39		
986	Basaltic la.	3.03,1.87	3.34,1.82,2.45	3.77, 4.01											3.41	3.19	
1032	Basaltic la.	3.04,	3.36,2.46,4.27 1.82,1.67,1.54 2.28			2.49								3.42, 2.91			
1094	Basaltic la.	3.03	3.33,1.67			2.35								5.6 3.41, 5.57		3.19	
1217	Basaltic la.	3.02,	3.33,4.23,2.28											3.41			

TABLE 3: The X-ray diffractometry for clay samples in well KR-2

Depth (m)	Alteration intensity	Air-dried d (Å)	Ethylene glycol d (Å)	Heated 500-550°C d (Å)	Probable clay minerals + assesorory
122	Unaltered	15.02,	16.74	10.04	Smectite
146	Weak alt.	12.44, 7.05	16.92, 7.10,	12.07, 7.19	Mixed layer clays, smectite
157	Unaltered	14.92, 7.13	14.99, 7.33	14.49	Swelling-chlorite
194	Weak alt.	13.59, 12.15, 7.65	13.63, 12.18, 7.67	No reflection	Swelling-chlorite and Mixed layer clays
223	Unaltered	29.41, 14.48, 7.61, 7.13	32.1, 14.60, 7.79, 7.21	13.63, 7.13	Swelling chlorite
275	Weak alt.	14.72, 7.63	16.60, 7.64	No reflection	Smectite + gypsum
327	Medium alt.	14.13, 7.12	14.60, 7.25	13.18	Swelling chlorite
357	Medium alt.	14.44, 7.62, 7.17	14.48, 7.62, 7.18	14.02	Swelling-chlorite + gypsum
403	Medium alt.	14.24, 12.41, 7.62, 7.12	14.60, 7.64, 7.19	14.24	Swelling-chlorite + gypsum
457	Medium alt.	14.60, 7.63, 7.18	14.99, 7.81, 7.26	14.60, 7.18	Swelling-chlorite
525	High alt.	14.36, 7.62	15.02, 7.62	14.49, 14.24, 7.19	Swelling chlorite + chlorite
624	Medium alt.	14.24, 7.61	14.97, 7.64	No reflection	Swelling chlorite
694	Medium alt.	14.66, 14.29, 7.62	15.41, 7.64	13.8	Swelling chlorite + gypsum ?
746	High alt.	29.42, 14.36, 7.19	30.44, 14.48,	14.29	Chlorite, swelling chlorite
821	Medium alt.	29.42, 14.48, 7.09	30.65, 14.97, 7.19	14.41	Chlorite, swelling chlorite
938	Medium alt.	14.60, 7.08	14.60, 7.25	14.57	Chlorite
1020	Medium alt.	14.27, 7.13	14.97, 7.24	14.2	Chlorite, (swelling chlorite)
1085	High alt.	14.24, 7.08	14.72, 7.19	14.36, 7.10	(Swelling chlorite), chlorite
1217	Medium alt.	14.48, 7.13	14.77, 7.37	14.31, 7.13	Chlorite, (swelling chlorite)