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BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF WELL RN-12, REYKJANES GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

The current study focuses on high temperature geothermal well RN-12, which is located in the seawater-dominated geothermal system at Reykjanes field in SW Iceland. This is a vertical well, drilled in 2002 and reaching a total depth of 2506 m. The uppermost 1024 m are presented in this report. The well was kept offline until it was brought online for production in May, 2006 to feed the then-new 100 MW power plant. Drill cuttings were used to gather data from binocular and petrographic microscopes, and XRD and fluid inclusions analyses. Geophysical logs were used to corroborate conclusions derived from the cuttings. The lithology of well RN-12 contains hyaloclastite formations, such as tuff, breccia, tuff-rich sediments and pillow basalts in addition to basaltic lava flows and intrusions. The rock texture within these units range from fine-grained to medium-grained, even coarse-grained in some cases. Basalt intrusions were found at 360-396, 416-452, 460, 480-484, 500-510, 524-538, 542-576, 622-654, 708-752, 768-772 and 920-932 m. Two alteration groups were identified in the well, one based on the clay mineralogy zones, the other on the alteration mineral distribution zones. These sequences are: smectite-zeolite zone from 10 to 702 m; mixed-layer clay zone from 702 to 782 m; chlorite zone from 782 to 1024 m. The alteration mineral zones are: quartz zone from 70 to 260 m; prehnite zone from 260 to 610 m; epidote zone from 610 to 694 m; garnet zone from 694 to 762 m; and wollastonite zone from 762 to 1024 m. Thirteen small aquifers were identified in the well, all cased off, but three main feed zones were inferred at depths of 1000, 1300 and 2200 m. A fluid inclusion study from secondary quartz showed a homogenization temperature which ranges from 265 to 295°C. This temperature range correlates with the alteration and formation temperatures, which indicates that the well is in equilibrium with the geothermal system around well RN-12.

1. INTRODUCTION

This project report is a partial fulfilment of a six months training course at the United Nations University Geothermal Training Programme (UNU-GTP). The report focuses on the geological and geothermal aspects of well RN-12 which is one of the production/exploration wells in the Reykjanes geothermal field, SW-Iceland. Well RN-12 was drilled vertically down to 2506 m in the year 2002. Cuttings were sampled at 2 m interval for analysis and identification of subsurface formations and an

analysis of temperature dependent alteration minerals. The main analytical techniques used in this study were binocular and petrographic microscopic analyses, X-ray diffraction and a fluid inclusion analysis.

1.1 Purpose of the study

The main purpose of borehole geology is to analyse the various rock formations in order to understand the lithology, detect porosity and permeability, and estimate the alteration temperature by analysing alteration mineralogy, which gives indications on the conditions in the well and aids in deciding casing depths. This allows us to grasp the nature of the sub-surface and structural geology. The relationship between geology and permeability and knowing the hydrothermal alteration is a step towards predicting the shape of the geothermal system, its evolution and present state. These principles were applied to analyse well RN-12 in the Reykjanes geothermal system, in detail, by using drill cuttings and all available data collected during drilling, including geophysical logging.

2. OUTLINE OF GEOLOGY

2.1 Regional geology of Iceland

In a global view, Iceland is a unique geological system set on an active mid-oceanic spreading ridge. It is considered one of few places in the world where we can observe the evolution and mechanism of rifting above sea level. Iceland is located on the Mid-Atlantic Ridge, separating the plate boundary of the Eurasian- and North American plates which spread approximately 18 mm per year to the ESE and WSW (Saemundsson, 1979) (Figure 1), and situated on a top of a hotspot presumed to be fed by a deep mantle plume (e.g. Einarsson, 2008). Iceland's regional geology is the product of the relative movement of the Mid-Atlantic divergent plate boundary across the mantle plume (e.g. Hardarson et al., 1997). The exposed Iceland crust contains evidence of major ridge-jumps over the last 16 million years and this relocation of the magmatic focus has been a prominent process in the evolution of the

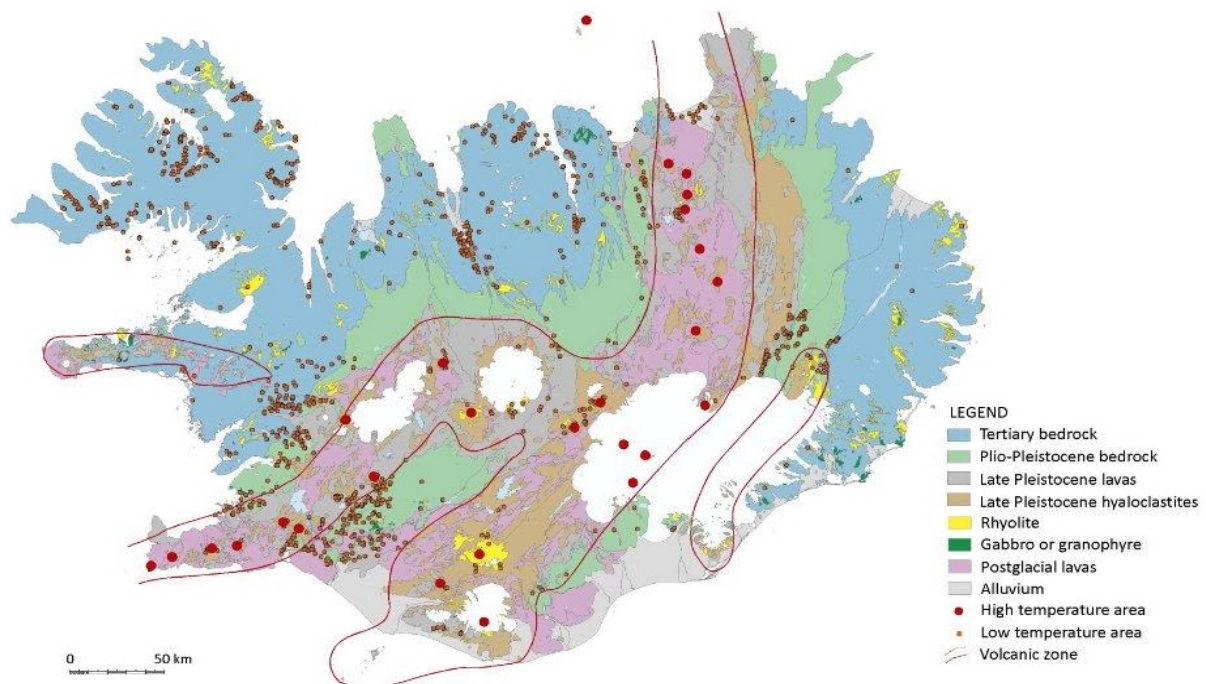


FIGURE 1: Geological map of Iceland (Jóhannesson and Saemundsson, 1999)

island (e.g. Saemundsson, 1979; Hardarson et al., 1997). On average, the spreading of the plates is 18 mm/year leading to a complex form of rift zones and transform fault zones (Figure 1). Iceland is almost entirely made up of volcanic rocks with basalts being 80-85% of the volcanic pile and evolved rocks constituting ~10%. Sediments of volcanic origin are 5-10% in a typical Tertiary lava pile but may be locally higher in Quaternary rocks. Quaternary formations are found along the margins of the rift zone while Tertiary basalts predominate to the east and west, away from the rift zone (Saemundsson, 1979).

2.2 Reykjanes high-temperature field

The Reykjanes peninsula is the south westernmost part of Iceland (Figure 2) and it is the landward extension of the sub-marine Reykjanes Ridge. Geologically, on the surface, the Reykjanes peninsula consists of hyaloclastites formed during the last glacial periods and of post-glacial basaltic lava flows. The volcanic activity in this area was intense during postglacial times; the number of eruptions is not known but estimated to be a few hundred (Höskuldsson et al., 2006). The peninsula hosts four volcanic centres and several geothermal fields: Reykjanes, Eldvörp and Svartsengi fields in the western part; the Krýsuvík field in the middle of the peninsula; and Brennisteinsfjöll and Hengill fields in the east (Figure 2).

The Reykjanes geothermal field is situated at the tip of the Reykjanes peninsula (Figures 1 and 2). Exploration of the Reykjanes geothermal field started in the early 1950s and a well was drilled there in 1956. Geological maps and surface exploration surveys were done in the 1960s (Lindal and Lúdvíksson, 1969). In the late 1960s, seven wells were drilled in the area to explore the extent of the field. In late 2002, the regional district heating company, Hitaveita Suðurnesja (HS Orka), decided to increase steam production in order to accommodate the demand for the power plant. A new drill site

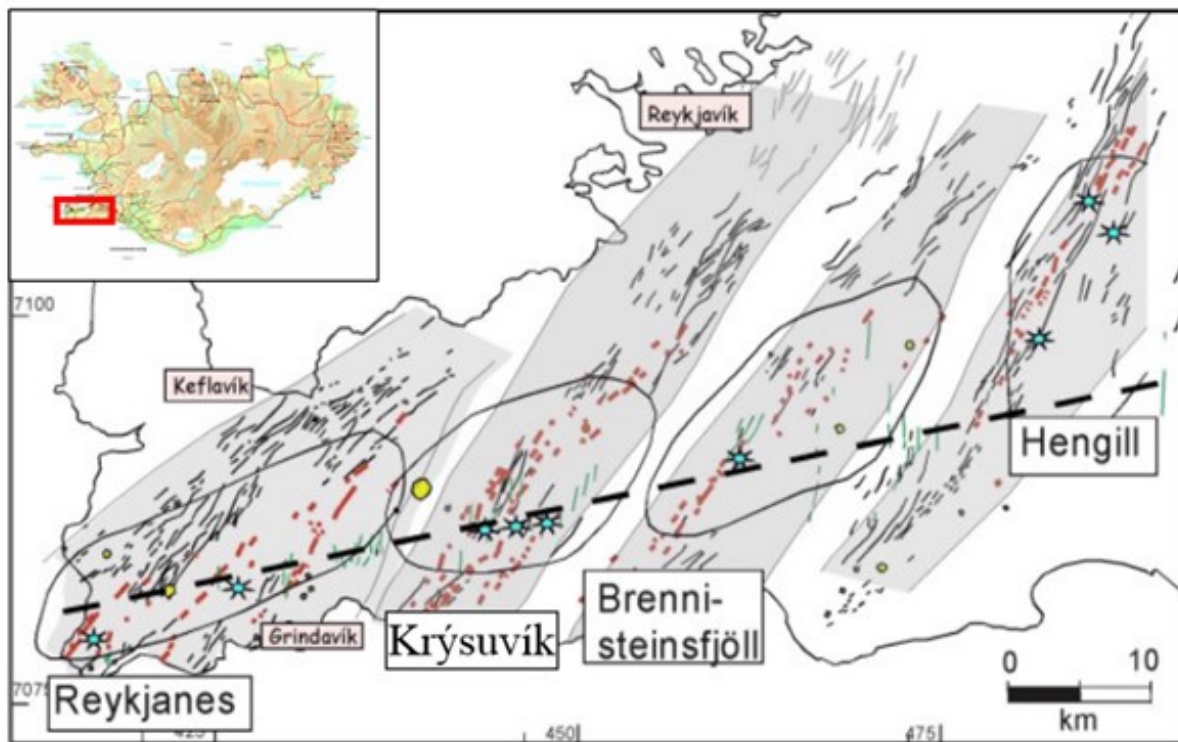


FIGURE 2: Map of the Reykjanes Peninsula showing fissure swarms as black lines, eruptive fissures as red lines, faults as green lines, geothermal fields as blue stars; four volcanic zones are circled, and the location of the plate boundary is shown as a dashed line (Jakobsson et al., 1978); Data from Árnason et al., 1986; Einarsson et al., 1991; Eyólfsson 1998; Hreinsdóttir et al., 2001; Sigurdsson, 1985; Saemundsson and Einarsson, 1980; Mawejje, 2007

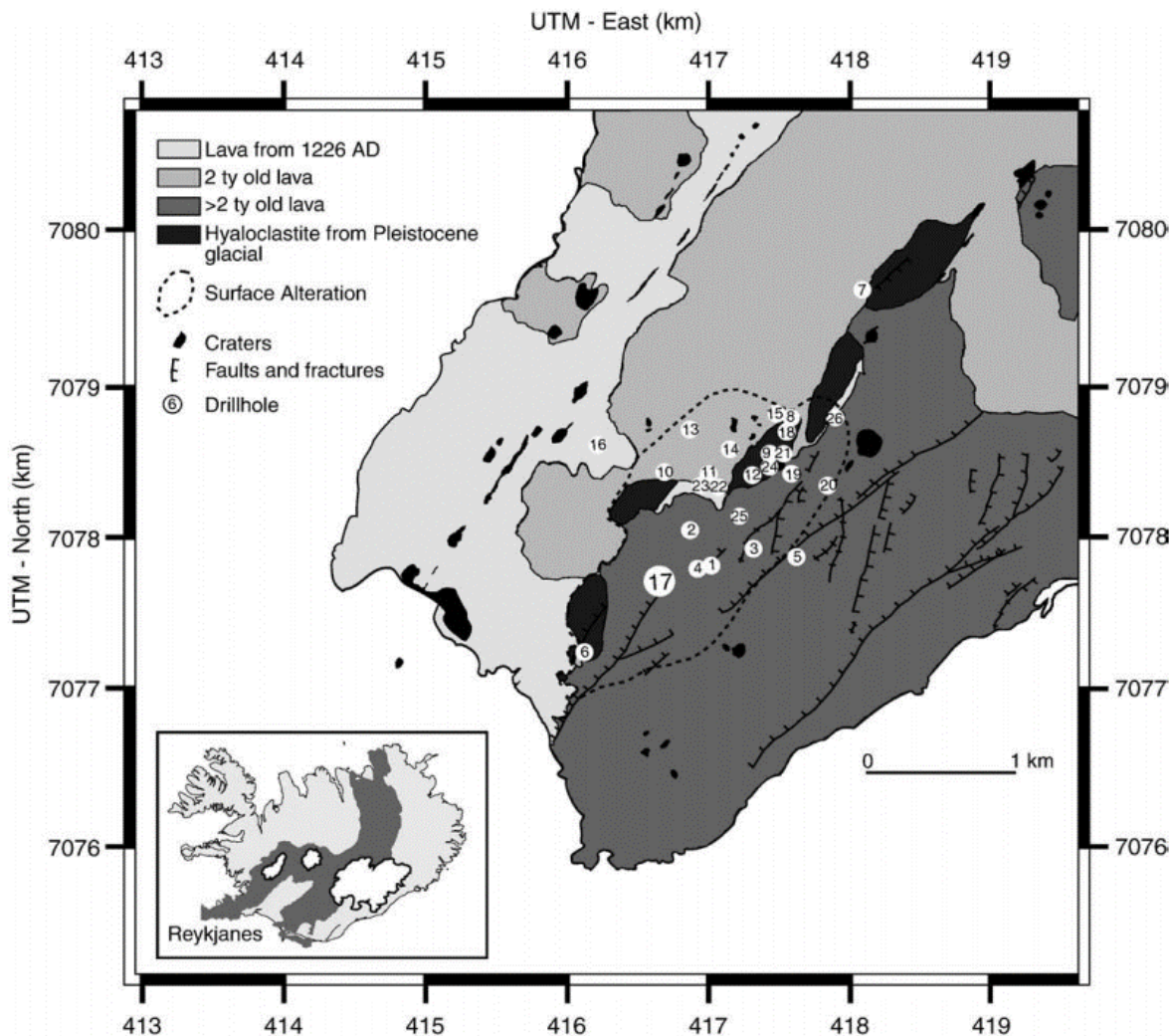


FIGURE 3: Map of the Reykjanes Peninsula showing major faults, fractures, lava flows, surface alteration and location of well RN-12 (map adapted from Saemundsson and Einarsson, 1980; Franzson et al., 2002; Fridleifsson et al., 2003; Marks et al., 2010)

for well RN-12 (Figure 3) was selected between wells RN-9 and RN-11 at Reykjanes at 63.82382°N, 22.68128°E and 18.13 m a.s.l. The number of the well is 18912 in the National Energy database. The drilling started on 22.10.2002 and ended on 17.12.2002 at 2506 m depth.

2.3 Geophysical studies in the Reykjanes area

Surface resistivity surveys in the Reykjanes area have been carried out since 1970 with continuous updating, including applying MT surveys. Early resistivity was measured by (DC) methods with a Schlumberger configuration, followed by TEM (transient electromagnetic) and subsequently MT surveys (Fridleifsson et al., 2011). Low resistivity was showing in the upper part of the field at 800 m depth with an extensional delimitation zone of around 10 km². The main up-flow zone was located by surface resistivity and conceded with the NE-SW eruptive fissure zone (Figure 4) with an intersection of a N-S trending up-flow zone in the central part of the field (Karlisdóttir, 2005). Recently, in 2010, MT surveys found that resistivity reached down to 20-30 km or more, revealing a low-resistivity body at 10 km depth under Reykjanes, consisting of a heat source seated below or a large magma body (gabbroic) that is cooling (Figure 4) (Fridleifsson et al., 2011).

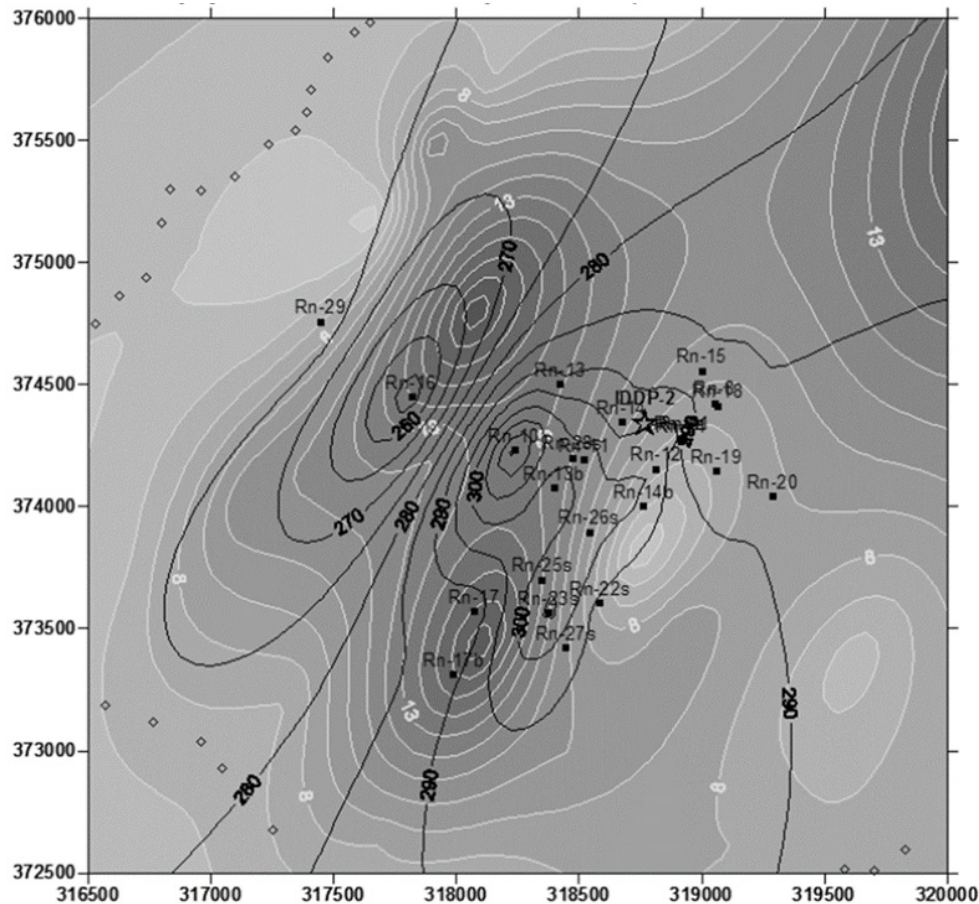


FIGURE 4: A map showing drill hole locations (RN-numbers and apparent location of inclined wells at 1600 m depth, e.g. well RN-22). The isotherms drawn are based on well temperature logs and evaluation of the formation temperatures at 1600 m depth; the isotherms show a cooling “pond” at well RN-16 (~255°C) and a thermal peak at well RN-10 (~310°C); the grayscale shades show MT-resistivity contours from <5 to ~18 ohmm (Fridleifsson et al., 2011)

2.4 Drilling of well RN-12

Well RN-12 has the same design as wells RN-10 and RN-11; the wells are vertical without slotted liners and the drilling stages were set up into three phases in addition to the preliminary drilling (Figure 5). The preliminary drill phase was executed with a 26” air hammer pipe down to 82 m depth and cased with a 22½” surface casing down to 79 m. Subsequently, the first and second phases were drilled with gel and few bags of soda to maintain the pH of the mud (Richter et al., 2003). The 1st phase was drilled with a 21” drill bit down to 300 m and cased with an 18⅝” anchor casing down to 291.4 m. The second phase was drilled with a 17½” bit down to 854 m and cased with a 13⅜” production casing down to 841.7 m (Figure 5). Finally, the production part was drilled with a 12¼” bit down to 2506 m, with the possibility of putting in a 9 5/8” slotted liner, but it was decided to go without the liner (Jónsson et al., 2003). The design is shown in Figure 5 and the drilling progress is shown in Figure 6.

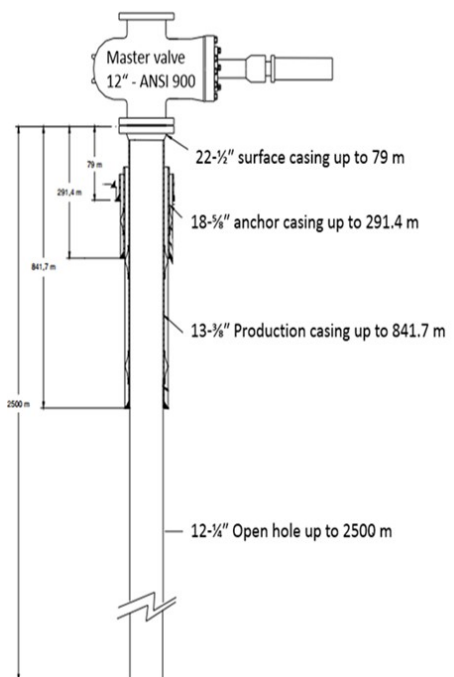


FIGURE 5: Design of well RN-12 (Richter et al., 2003)

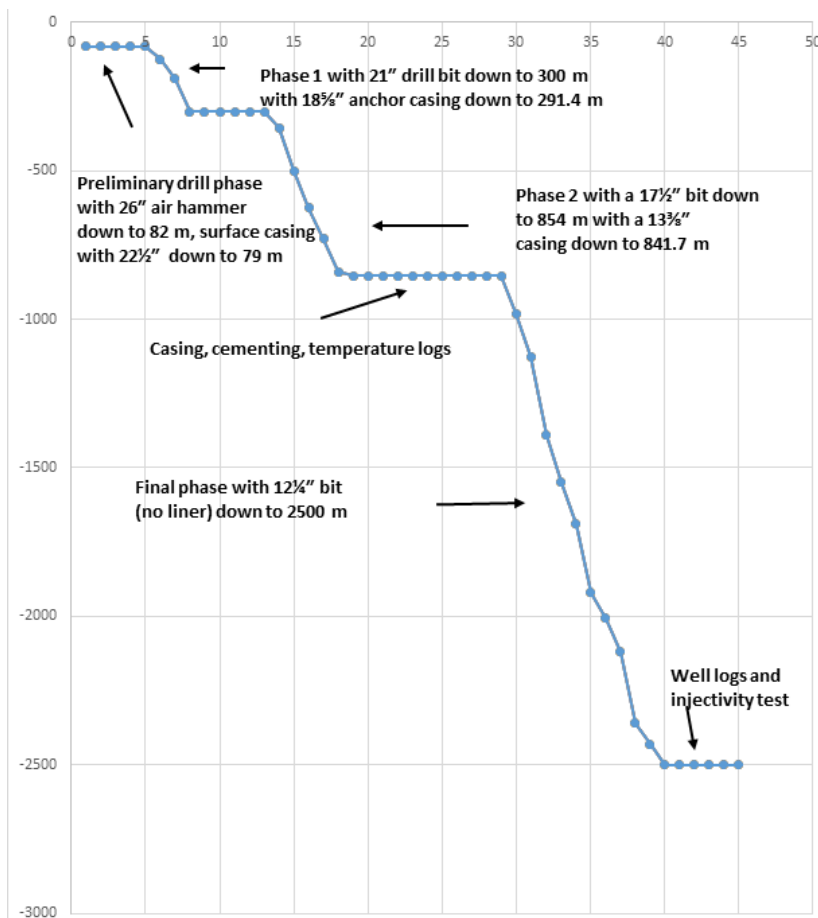


FIGURE 6: Drilling progress of well RN-12 (Jónsson et al., 2003; Richter et al., 2003)

Remark: all the depths mentioned and appearing on all figures in this paper are based on the distance from the rotary table. The rotary table is, in this case, 6.86 m from the top of the cellar.

3. SAMPLING AND ANALYTICAL METHODS

3.1 Analytical representation methods

Sampling and analytical methods

Drill cuttings from well RN-12 were sampled at 2 m intervals during the drilling operations. In this study, drill cuttings from well RN-12 are from 10 m down to 1024 m and were analysed at the ISOR geological laboratories, a total of 494 samples. Usually drill cuttings are analysed at the drill site by the use of a binocular microscope to enable the geologists to understand the sub-surface geological formations and conditions which help in applying the right drilling procedures. Representative samples of different rock units are then selected for further studies based on the formations and/or alteration.

3.2 Analytical methods

Binocular microscope: Drill cuttings from 2 m intervals were used. The samples were washed with clean water to remove impurities. Water was added to the sample box to enhance visibility. The binocular used was an Olympus ZX16. In the binocular microscope different rock formations were analysed, colours of the formations were noted as well as the rock type, grain size, mineralogy, alteration mineralogy and the intensity of the alteration.

Petrographic microscope: Representative samples from selected lithological units were selected and, in this study, 23 thin sections were analysed from 0 to 1240 m depth at: 30, 80, 96, 126, 268, 336, 394, 442, 482, 546, 600, 640, 694, 754, 812, 866, 940, 986, 1030, 1090, 1140, 1210 and 1240 m depth. Thin sections were mounted on a Leica petrographic microscope. The purpose of the petrographic analysis is to confirm the analysis and provide a more detailed study of different formations encountered in the well, study the mineralogical evolution in the well, and the alteration encountered in the well.

X-ray diffraction analysis: Samples were selected from representative lithological units and analysed for clays. Samples from: 24, 38, 68, 92, 104, 148, 158, 248, 280, 320, 356, 400, 456, 490, 542, 660, 672, 702, 782, 866, 924, 970, 998, and 1014 m depths were placed in a test tube, distilled water was added to dissolve the constituents, then the test tube was shaken and left in a rack so that the < 2 microns clay minerals were left in suspension. A few drops were placed on a marked glass slide and left to dry. That way the sample could be analysed using the XRD equipment. Ethylene glycol was added to the air dried sample and then the sample was heated to between 500 and 550°C. The samples were analysed in the XRD equipment after each treatment to identify the different types of clays based on the peak locations and their intensity in the XRD spectra. The results of the clay analyses samples for the well are listed in Appendix I.

Microthermometry and Leica microscope: Fluid inclusions are "bubbles" of fluid trapped within the host mineral during its deposition from its parent hydrothermal fluid. Fluid inclusions can be either primary or secondary. Primary fluid inclusions are trapped in the crystal lattice during growth while secondary fluid inclusions are trapped along healed cracks (Roedder, 1984). Fluid inclusions were identified in the prepared sample by use of a petrographic microscope. Double-polished thin sections (approximately 70 microns) of cuttings from well RN-12, which contained abundant quartz, were prepared for fluid inclusion analysis. The thin sections were mounted on a Linkam THS MG 94 heating stage for analysis. The inclusions were heated slowly until the fluid homogenization temperatures (i.e. the bubble disappears) were obtained. Homogenization temperatures of individual inclusions were measured at least twice and the results were recorded in 5°C intervals.

3.2.1 Use of geophysical logs

Neutron-neutron logs: The main purpose of neutron logs is to capture the quantity of hydrogen scattering and water trapped in the formation, as well as to estimate the formation porosity (Ásmundsson, 2011). Generally, the water content in the formation is a good indicator for porosity or alteration. Neutron logs are consequently used to locate porous formations.

Caliper logs: The main idea for using this tool is to measure the diameter of the well and precisely locate cavities and wash-outs in the well. That will allow predictions for the volume of cement necessary for casing operations. Caliper logs may also be used to locate feed-points or feed zones.

Temperature logs: The main purpose of using the temperature tools is to locate aquifers in a well. The logs also give an idea of the behaviour of the well and the formation temperature. This valuable information will determine and predict any blow-out risks as well of feed zones (Steingrímsson and Gudmundsson, 2005).

Resistivity logs: The contribution of the resistivity matrix and the formation fluid will reflect the rock porosity and hydrothermal alteration. Low alteration is shown as higher resistivity when compared to altered rocks.

Gamma ray logs: This logging tool is sensitive to radioactive isotopes within the rock (K, Th, U). It is used to determine the amount of clay and, therefore, alteration, in the rock formation and also to relate the quantity of SiO₂ in the rock. The logging, therefore, can identify if rocks are of evolved chemical composition (Stefánsson et al., 1982).

4. RESULTS

4.1 Stratigraphy of well RN-12 from surface down to 1024 m

The stratigraphy of well RN-12 consists of two main divisions: hyaloclastite and crystallized basalt. These two main formations are divided into series of rock units that alternate in sequences of hyaloclastites (pillow basalt, breccias and tuff), and crystalline rocks (lava flows, intrusions).

Hyaloclastite: Such formations are hydrated tuffs or breccias, rich in volcanic glass. They are formed during volcanic eruptions under water or ice. Sometimes traces of sideromelane and tachylite, with smaller amounts of minerals are seen. This formation contains some amounts of crystalline and partially crystalline rock fragments and, if unaltered, are characterised as highly porous, promoting circulation for cold water and geothermal fluid. However, when altered, they become less permeable and may form cap rocks (Franzson et al., 2011).

Basalt: This rock formation is a common extrusive igneous volcanic rock that is formed by cooling of magma as basaltic lava. The basalts are usually grey to black in colour, but with oxidation they tend to be brown or rusted. They occur as lava flows or pillow lavas. Generally lavas are formed after an eruption, characterised by the solidification and cooling of the rock. However, pillow lavas are formed during cooling of magma erupted in subglacial or submarine volcanic events.

Intrusives: Intrusive rocks found in this well are characterized by fine- to medium-grained basalt and are mostly unaltered compared to the surrounding rock formations. Most of the intrusive bodies are located at 360 to 396 m; 416 to 452 m; 460 m; 480 to 484 m; 500 to 510 m; 524 to 538 m; 542 to 576 m; 622 to 654 m; 708 to 752 m; 768 to 772 m and 920 to 932 m.

These analyses were carried out using the binocular microscope, with additional information from petrographic analysis in thin sections. Figure 7 shows the simplified lithology of the well along with the geophysical logs.

No cuttings 0-10 m

Basaltic tuff - 10-24 m:

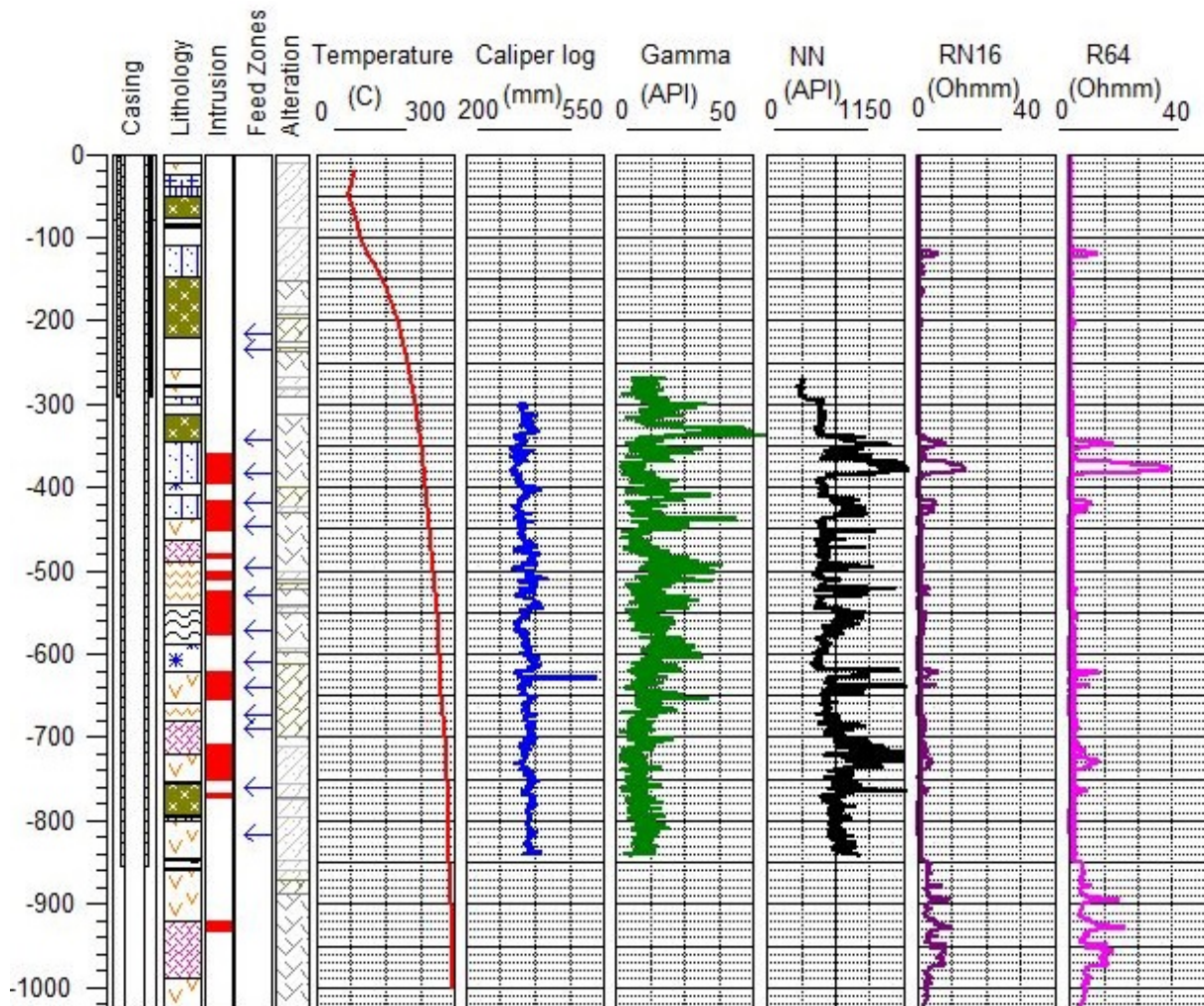
Cuttings at this level are brownish to reddish, fine grained basaltic tuff, with vesicles filled with calcite and partially with clay through the pores. The presence of pyrite and thomsonite was observed in binocular and petrographic microscope.

Basalt - 24-76 m:

This formation can be divided into three layers. The upper part, from 24-40 m, consists of tuffaceous basalt, mostly crystallized, olivine and plagioclase, fine to medium grained, porous and mixed with greenish clay. Some oxidation occurred. Mixed-layer clay and fine to medium grained basalt appear between 40-50 m; this middle section is totally oxidized and crystalline, mostly plagioclase and olivine. The lowest part, from 50-76 m, contains basalt lava comprised mostly of aphyric fine crystalline grains, with a greyish light texture, that are slightly oxidized. Binocular and petrographic analyses show, beside the clay, the occurrence of pyrite, thomsonite, and quartz at 70 m. Also, there is some manifestation of calcite in all samples.

Basaltic tuff - 76-108 m:

This thin layer was trapped between two basaltic lava formations and consisted mostly of fine grained and glassy basalt tuff and clay. The texture is slightly less apparent compared to the formation above, but is commonly reddish with vesicles filled with calcite and pyrite; oxidation is observed. A petrographic microscope analysis shows the presence of anhydrite (90 m), smectite, chalcedony and chabazite.



LEGEND

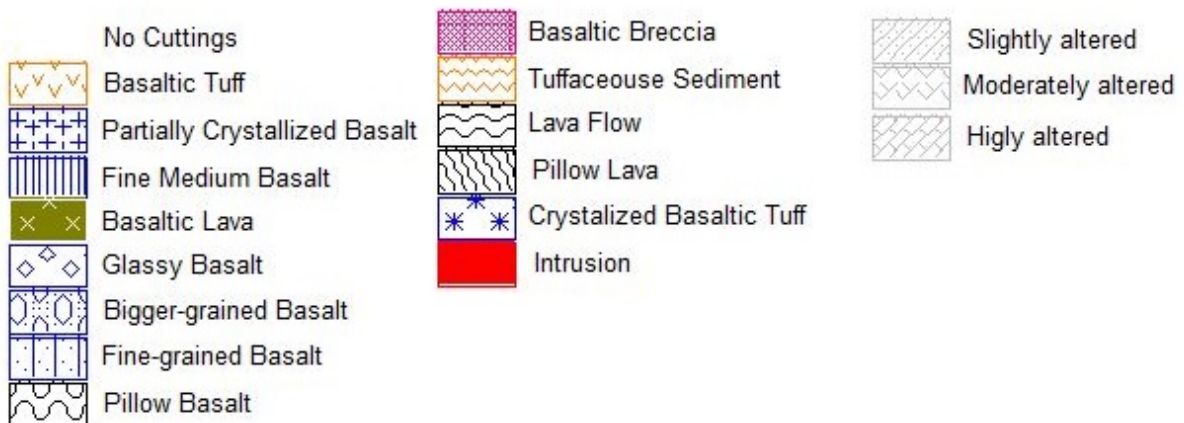


FIGURE 7: Simplified lithology and geophysical logs of well RN-12. Feed zones shown as arrows

Basalt (porphyritic basaltic lava) - 108-148 m:

This section shows two main layers. The top part is mainly of plagioclase porphyritic, sometimes glassy porous basalt, mixed with tuff. Noteworthy is the abundance of oxidation. The presence of clay calcite and pyrite is apparent. The bottom layer has fine grains of basalt lavas that are oxidized, and

calcite fills the pores of the vesicular grain from 110-148 m. Dark clay was also observed. Both petrographic and binocular analysis showed some alteration from glass to clay and also the formation of anhydrite.

Basalt (aphyric basaltic pillow basalt and lava flow) - 148-258 m:

This thick formation is divided into two layers. The upper part is a fine, granular basalt mixture of lava with tuff, and contains plagioclase and olivine crystals of light greyish texture. Pores are filled with clay. This zone has less pyrite and calcite than above and no oxidation. The bottom layer consists mainly of a combination of pillow lava and lava flows and is, fine- to medium-grained, plagioclase and olivine basalt. This zone has more pyrite, and calcite is at times platy; oxidation is abundant in the lower part. The most common alteration minerals are phillipsite, amorphous silica and quartz in the pores and some anhydrite.

Basaltic tuff - 258-346 m:

This section is structured into two layers of basaltic tuff. The upper part is dominated by an amalgam of basalt, clay and tuff. The succession is medium-to coarse-grained and the colour increases from light brown to dark brownish. The formation has abundant fractures and is largely porous and filled by ample calcite, dark clay and sulphites at around 260-290 m. The lower part of the tuff is more altered as the texture changes to dark brown in the bigger grains. There is a significant amount of calcite, sulphite silica and pyrite. The vesicles are totally filled with clay; petrographic analyses of the alteration minerals showed some albitizations of plagioclase, and the pyroxene is starting to alter into clay.

Basalt (porphyritic basaltic) intrusion - 346-396 m:

This formation is underlined by thin mixed sediment and tuff. The main part consists of a fine-grained, compact basalt intrusion mixed with tuff and sediment, changing in colour from greyish to dark. The tuff is partially crystallized. The deposition minerals are calcite, pyrite, and smectite. The lower part consists of a mixture of medium- to coarse-grained dark tuff and a crystalline intrusion. The pores are mostly larger than above and vesicles are filled by clay and calcite at the lower end along with pyrite. The petrographic analysis revealed some clay alteration, and the presence of anhydrite, feldspar, prehnite and quartz.

Basaltic tuff - 396-464 m:

This section is divided into three tuffs intersected by fine basalt. The top part is basaltic tuff, light grey to brownish and coarse-grained, containing some crystalline material. No oxidation is apparent in this part, however, the veins are filled by calcite, clay and prehnite. The middle part is mainly a mixture of tuff and fine-grained basaltic intrusion. The bottom part is partially basalt tuff, and vesicles in this section are filled by mixed-layer clay, calcite, possibly scolecite, anhydrite and quartz.

Porphyritic basaltic breccia - 464-542 m:

In this part of the well we can see the appearance of breccia with a mixture of tuff sediment and this zone is divided into two layers. The upper part is composed of brownish tuff down to 490 m, with some crystalline fragments and the texture is largely coarse-grained and vesicles filled with an abundance of calcite and clay. The lower part is a mixture of breccia and some fine sediment. Their texture is fine- to coarse-grained and largely brownish. The vesicles and fractures are filled with scolecite, quartz, anhydrite, calcite and pyrite. This zone is mixed with basaltic intrusive grains similar to the intrusive above.

Basalt (aphyric basaltic lava flow)-542-588 m:

This formation is mostly a lava flow and breccia, fine- to medium-grained. The grains are all partially glassy and plagioclase crystalline with small vesicles filled with clay, pyrite and calcite. Petrographic analyses revealed some depositions of quartz and clay. In general, there are few occasions where oxidation occurred.

Porphyritic basaltic breccia - 588-760 m:

This section is mainly composed of a mixture of glassy tuff, breccia and crystalline lava, dark to brownish on top. In the middle part, a thin layer of sediment and tuff mixture is found. The pores in this top part are mainly empty. However, the bottom layer that follows consists of a basalt breccia where the colour ranges from brownish to light brown; the breccia is abundantly fractured. The vesicles are filled with clay, pyrite, calcite, chalcopyrite, quartz, and epidote. Several intrusions are seen in this zone, and we observe a rapid increase in hydrothermal alteration with well-formed quartz and the appearance of epidote that followed from 690 m.

Aphyric basaltic pillow basalt - 760-854 m:

This zone is divided into two separate formations. The upper part is an intrusion of fine-grained basalt lava, mixed with tuff and some breccia which are greyish and glassy. The vesicles are filled with calcite, silica, actinolite, chlorite and epidote. From 790 m to the bottom of this zone we observe some pillow basalt mixed with tuff, fine-grained and slightly turning into a darkish colour. This zone ranges from glassy to partially crystalline and the vesicles are filled with mixed-layer clay and calcite. This zone shows slight oxidation.

Basaltic tuff - 854-920 m:

This zone consists of a breccia mixture of pillow basalt, pillow breccia and tuff. It is likely that the basalt fragments in this section are from intrusions. The appearance is light greyish to dark grey in colour with a dispersion of fine- to medium-grained fragments containing few vesicles. No oxidation appears in this zone, but the pores are filled with quartz, pyrite, and epidote. Some mixed-layer clay is apparent from 898-920 m.

Aphyric basaltic breccia - 920-1024 m:

This zone consists of a mixture of breccia and tuff, and is divided into two zones: The upper part is mainly formed of breccia that is light greyish in colour, and partially crystallized to fully crystallized basalt fragments. The most common alteration minerals are actinolite and epidote with fine-grained clay and calcite. The bottom part, from 990 m, contains more tuff, with some medium-to coarse-grained crystalline fragments. The vesicles in this zone are abundant, mostly filled with dark clay; epidote, chlorite and quartz. This zone shows significant alteration down to 1024 m.

4.2 Intrusions

An intrusion can be described as a body of magma that solidifies under Earth's surface. Intrusions usually appear fresh, sometimes with a coarse-grained texture in comparison to the host rock since the concealed subterranean magma cools slowly in concordance to the surrounding rock, giving time for the crystals to grow. However, small intrusions, like dykes, may be fine grained. Intrusive contacts are often associated with permeability as the surrounding host may become fractured as it is intruded into. Therefore, the surrounding boundaries are frequently oxidized as a result of water and heating (Gebrehiwot, 2010). Several intrusions have been identified in well RN-12 at: 360-396 m, 416-452 m, 460 m; 480-484 m; 500-510 m; 524 m- 538 m; 542-576 m; 622-654 m; 708- 752 m; 768-772 m; 920-932 m (Figure 6).

Intrusive unit I (360-396 m):

The section consists of fine- to medium-grained basalt that is greyish to dark in colour. The alteration starts at this level with the deposition of clay, anhydrite and quartz.

Intrusive unit II (416-452 m and 460 m):

This section contains fine- to medium-grained fragments and they are marginally light to dark in colour, plagioclase-phyric with some scolecite deposition.

460 m: This is a small intrusion, formed of basalt, fine- to medium-grained, light brownish and plagioclase porphyritic.

Intrusive unit III (480-484 m):

This thin intrusion is mixed with breccia which is largely brownish fine-medium grained, fractured, and the vesicles are filled by well-formed quartz.

Intrusive unit IV (500-510 m):

This thin layer is also relatively fresh, fine-grained basalt mixed with a breccia mixture and some grains of sediment. The presence of quartz is apparent at this level.

Intrusive unit V (524 m-538 m):

This is 14 m thick medium-grained basalt, with a light brownish colour, partially crystalline with plagioclase phenocrysts.

Intrusive unit VI (542-576 m):

This layer is basalt mixed with breccia, light brown to dark in colour. Veins are filled with quartz and significant oxidation is observed.

Intrusive unit VII (622-654 m):

Crystalline basalt mixed with glassy, brownish tuff comprise this layer. Pores in this range are empty.

Intrusive unit VIII (708-752 m):

This layer is a basalt intrusion, brownish to light brown, fine-medium grained. Epidote appears in the fillings. Some oxidation occurs in this zone.

Intrusive unit IX (768-772 m):

This layer is comprised of fine-medium grained basalt, glassy in places. Some micro-crystals of quartz and epidote are observed.

Intrusive unit X (920-932 m):

This final unit is a relatively fresh, medium-grained plagioclase-phyric basalt.

5. HYDROTHERMAL ALTERATION

When studying hydrothermal mineralogy, the meaning of alteration reflects the rock formations interacting with hot hydrothermal fluids. The science behind hydrothermal alteration interprets the conversion that occurs as a result of changes in the conditions to which the rocks are subject to causing primary minerals to be replaced by secondary minerals. The rocks change their composition either by removing, adding or redistributing their prime elemental components. This transformation can be determined in a chemical way or principally by the natural law of interaction between temperature, pressure and depth. In hydrothermal mineralogy, the alteration of the minerals caused by high temperatures has a predisposition that could define where the primary and secondary minerals will be found in the stratigraphy. This defined disposition also reveals the standard degree of formation of the minerals (Table 1). Temperature plays a key role in mineral alteration. As such, alteration minerals can give important information regarding temperatures to be expected in a well during drilling and is important when deciding casing depths. They are also very important when comparing mineral alteration curves to formation temperatures. A simplified and calibrated scale of hydrothermal alteration minerals is shown in Table 1.

TABLE 1: Index minerals reflected with temperature in high-temperature areas in Iceland (Kristmannsdóttir, 1979, Franzson, 1998)

Minerals	Min. Temperature (°C)	Max. Temperature (°C)
Zeolites	40	120
*Laumontite	120	180
*Wairakite	200	
Smectite		<200
**MLC	200	230
Chlorite	230	>300
Calcite	50-100	280-300
Quartz	180	>300
Prehnite	240	>300
Epidote	230-250	>300
Wollastonite	270	>300
Actinolite	280	>300

Notice: * Appropriate to zeolite, ** Mix Layer Clay

5.1 Distribution of hydrothermal alteration minerals

Hydrothermal alteration minerals form as the result of the alteration of primary minerals. During this evolution many stimuli come into effect like: temperature, permeability, fluid chemistry, rock formation and pressure (Brown, 1978; Kristmannsdóttir, 1979). In the case of well RN-12, the hydrothermal minerals found in the rocks vary from low temperature to high temperature minerals like, pyrite, analcime, calcite, mixed-layer clay, chlorite, prehnite, quartz, epidote and wollastonite. However, they all occur at shallow depths compared to other wells in the area (Figure 8).

The distribution of alteration minerals with depth in well RN-12 is shown in Figure 9, and all the different minerals are described below:

Calcite: This mineral is the most abundant alteration mineral in well RN-12. It is apparent that the deposition of calcite occurred mostly in several distinct zones and at least 8 of them have been clearly identified. These zones are at: 10-40, 90-100, 122-340, 372-398, 406-618, 664-698, 840-888 and 902-946 m. Most of these zones were identified in basalt tuff, breccia, pillow lava and lava flow. However, a lesser amount of calcite deposition was observed in intrusions and at the lower part of the well, between 950 and 1024 m.

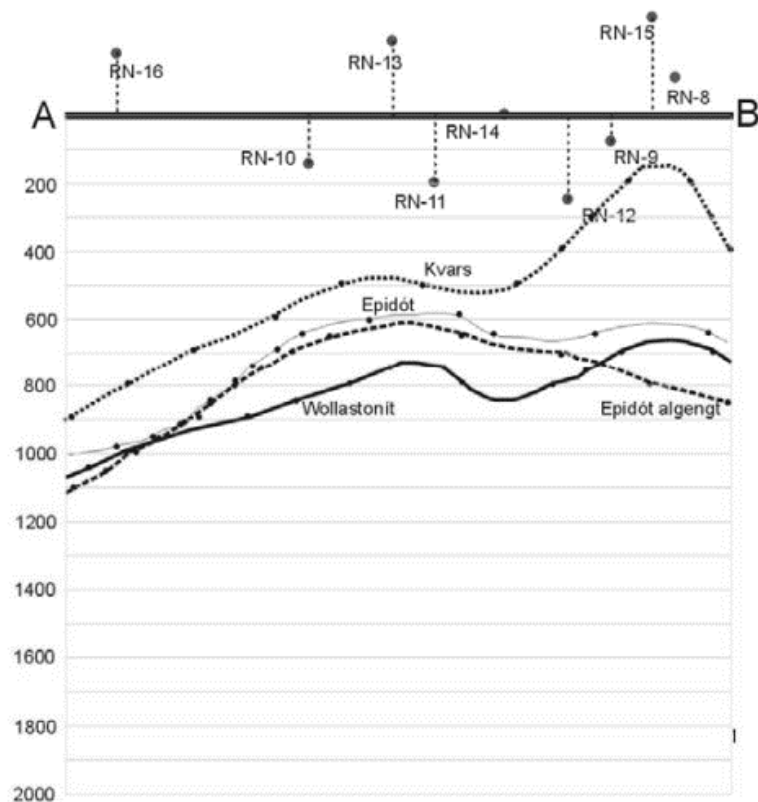
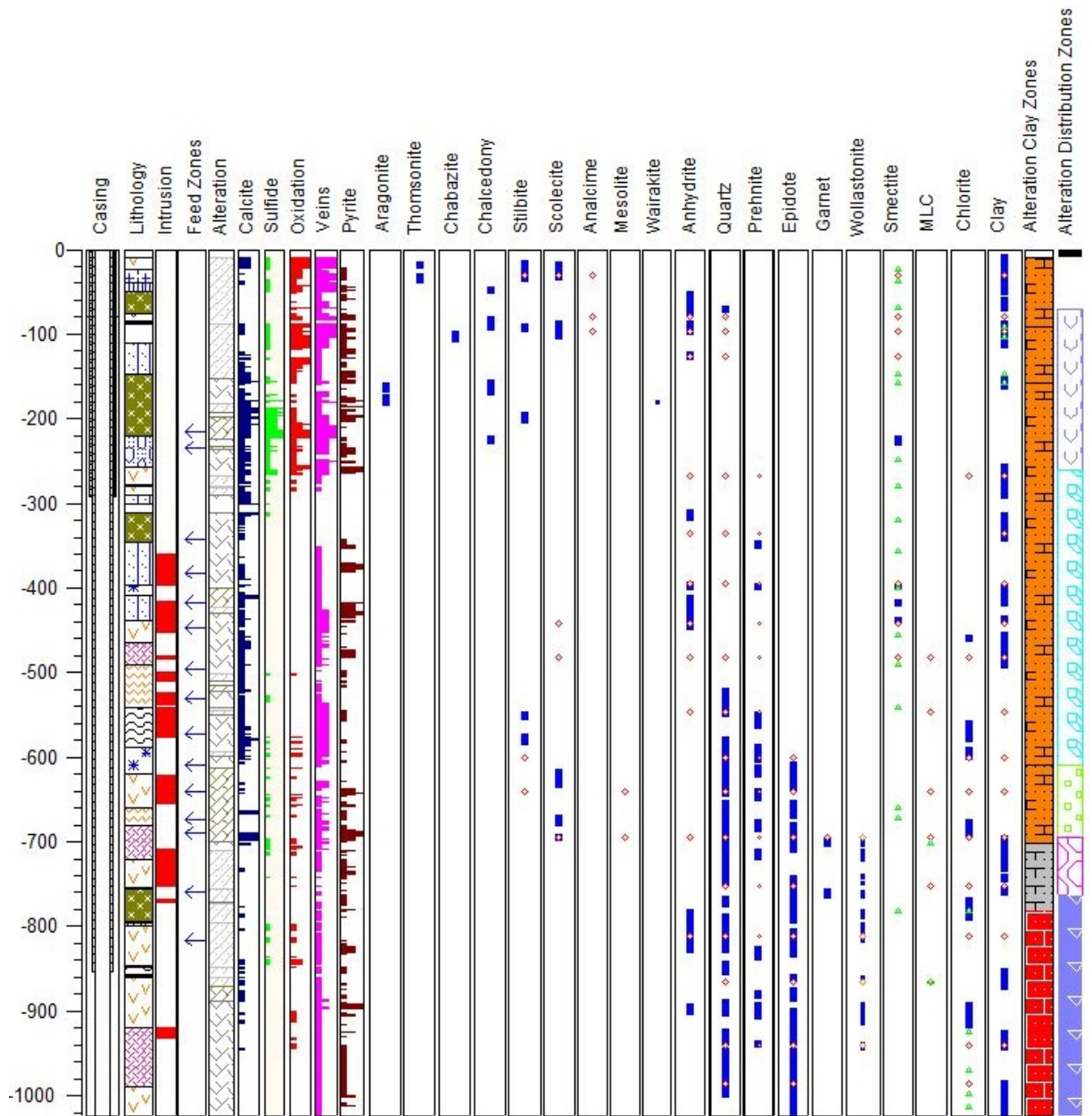


FIGURE 8: Depth to the first appearance of quartz, epidote and wollastonite in the area of well RN-12 (Franzson, 2004)



LEGEND

- | | | | |
|-------------------------------|----------------------------|-----------------------|--------------------|
| No Cuttings | Basaltic Breccia | XRD analysis | Smectite - Zeolite |
| Basaltic Tuff | Tuffaceous Sediment | Petrographic analysis | MLC |
| Partially Crystallized Basalt | Lava Flow | Binocular analysis | Chlorite |
| Fine Medium Basalt | Pillow Lava | | Quartz |
| Basaltic Lava | Crystallized Basaltic Tuff | | Prehnite |
| Glassy Basalt | Intrusion | | Epidote |
| Bigger-grained Basalt | | Slightly altered | Garnet |
| Fine-grained Basalt | | Moderately altered | Wollastonite |
| Pillow Basalt | | Highly altered | |

FIGURE 9: Distribution of hydrothermal alteration minerals, location of aquifers and alteration zones of well RN-12

Anhydrite: Due to salinity, this white, sometimes greyish, mineral was found in well RN-12, but seawater has access to the geothermal system (e.g. Tómasson and Kristmannsdóttir, 1972). The deposition of anhydrite commonly occurs as a vein filling and is most abundant at 60-90, 115-126, 310-320, 402-450 and 792-900 m. These depositions are all associated with hyaloclastite formations.

Pyrite: This mineral is common in most Icelandic wells and it is most abundant in eroded, highly altered rocks of extinct central volcanoes, where it forms shiny coatings on the surface of fissures, or clusters of glittering golden granules in the rocks (Saemundsson and Gunnlaugsson, 2014). In well RN-12, pyrite is most common at: 22-120, 128-202, 222-262, 418-446, 474-512, 544-594, 628-642, 658-798, 824-884, 912-924, and 930-1012 m. It appears that pyrite is more abundant in the upper part of the well and appears as bigger grains, then gradually becomes medium to fine crystal cubes until they get bigger again and more abundant from 658 to 900 m, and finally medium in size all the way to 1012 m. As a result, it appears that pyrite reflects permeability in the well as most of the depositions were concurrent with the feed zones.

Prehnite: Prehnite forms small spherical clusters of crystals with vitreous lustre, often pale green in colour, but sometimes white or greyish. When it is broken up, the crystal clusters appear to be radiating. Prehnite occurs mostly with epidote and other high-temperature minerals in basaltic rocks around and above 250°C. For well RN-12, it first appeared at: 260 and 350 m; and then at 550-720, 840, 880-940, 1090, 1190 and 1210 m.

Garnet: This is a group of minerals of varying composition. In Iceland, garnet is mainly andradite (iron-rich), grossular (calcium-rich) and hydro-grossular, the only form that contains water. It has been found in eroded extinct geothermal areas in the roots of central volcanoes, often with epidote (Saemundsson and Gunnlaugsson, 2014). In well RN-12, it was found in fissures close to and in an intrusion zone at 700-762 m. This mineral forms at 300°C and above.

Zeolites: Zeolites, like mesolite, chabazite, thomsonite and analcime, are generally low-temperature alteration minerals and are usually restricted to the upper parts of basaltic formations in hydrothermal system depositions. They are composed of sodium, calcium and aluminium silicates and tend to precipitate in vesicles. As thermometers, zeolites form at relatively low temperatures and are dependent on the composition of the hydrothermal fluids. For well RN-12, the sequence of deposition is at: 14-180, 442-600, and 810-870 m. Different zeolites are described below:

- A. *Mesolite:* Mesolite is white, translucent or greyish, but may be tinted by impurities, usually pink or red. It forms as small-scale fibrous radiating clusters or tufts. It was found between 616 and 694 m.
- B. *Chabazite:* Chabazite appears white or clear, rarely yellowish brown or slightly reddish. They are near-cubic crystals that are twinned, penetrating each other with corners projecting from their crystal faces. In this well they appeared along with chalcedony between 100 and 106 m.
- C. *Thomsonite:* It is a radiating zeolite, where the crystals are elongated, slightly flattened, rather thin fibres with slanted ends. Mostly they form dense masses of radiating clusters, with mammillary structures whose surface is finely bristled (Saemundsson and Gunnlaugsson, 2014). In well RN-12, thomsonite was relatively rare, appearing at 18, 32 and 36 m.
- D. *Analcime:* Analcime mainly forms colourless, or white, many-sided crystals with a vitreous lustre. It occurs either as individual crystals or as clusters which glitter, as in the case of the colourless crystals. This crystal was found in the well between 88 and 96 m.
- E. *Scolecite:* Scolecite is a typical fibrous zeolite, four-sided, often rather densely packed, flattened crystals which form groups or aggregates. It is colourless, or white, with vitreous or slightly silky lustre. In well RN-12, it appeared in the presence of other minerals like mesolite, analcime, thomsonite and chabazite at: 14-32, 36, 88-96, 100-106 and 616-694 m.
- F. *Stilbite:* This mineral appears in many forms but most commonly as thick, tabular crystals with pointed terminations. It is generally milky-white, but clear and translucent variants exist, and also coloured types, usually reddish-brown but sometimes greenish. Stilbite is mostly found in

basalt in the analcime zone and below. It is most abundant in tholeiite, low down in the lava pile. In well RN-12, stilbite was observed in thin sections and cuttings at around: 14-32, 88-96, 198-204 and 550-600 m.

G. Wairakite: This mineral is a calcium-rich variant of analcime (or a closely related mineral), but forms at higher temperatures than other zeolites, or at more than 200°C. It is well known in Iceland, but small in scale, and has mainly been found in boreholes in high-temperature geothermal areas (Saemundsson and Gunnlaugsson, 2014). In well RN-12, it was found at 180 m and 1090 m (Figure 10).

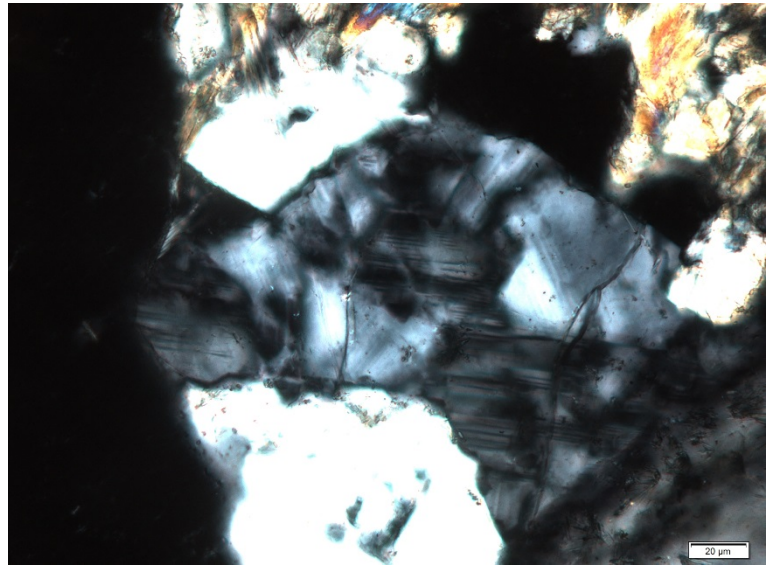


FIGURE 10: Wairakite found at 1090 m in well RN-12

H. Chalcedony: Chalcedony is a silica mineral often regarded as amorphous but, in fact, it forms tiny thread-like crystals which are just distinguishable under a microscope. It is commonly whitish, or greyish, while other colours have been found, such as pale blue, dark-brown to black, yellowish and greenish. It is commonly found as an amygdale in tholeiitic basalt and rhyolite. It was found in well RN-12 in cuttings and thin sections at: 158-162 and 222-226 m

Quartz: This mineral is generally white, milky-white or grey, and translucent or opaque. It forms hexagonal prismatic crystals which end in slanted faces meeting at a point, six-sided pyramid. In evolved igneous rock, it occurs as a primary mineral. In well RN-12, it appeared first at 70 m in an intrusion, and was observed in thin section from 480 m; however, they appeared well formed from 634 to 1024 m in cuttings and down to 1240 m in thin sections.

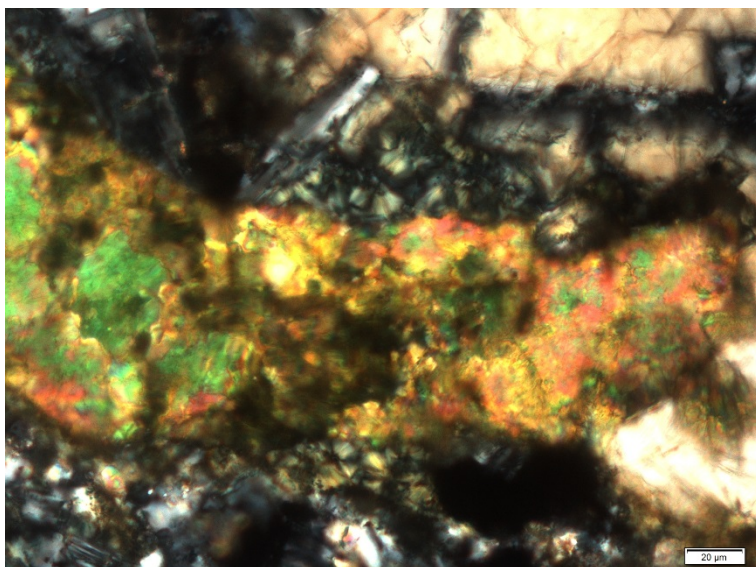


FIGURE 11: Epidote found in vein fillings at 754 m in well RN-12

Epidote: This mineral is generally micro-crystalline, forming a green or yellowish-green coating on the walls of cavities and veins. Its streak is white or slightly grey. Epidote forms in both basaltic and acidic rocks at temperatures around 230°C, and above. In well RN-12, the first appearance of epidote was in cuttings at: 610-638, 654-698, 750-832, 860-936 and 990-1024 m. In thin section, epidote was found fully grown at 754-1240 m (Figure 11).

Wollastonite: This white and fibrous mineral appears at temperatures above 270°C and is stable beyond 300°C. The rock becomes characteristically green, known as propylite. The colour is

mainly due to chlorite and epidote, typical for alteration at 200-300°C. Generally, wollastonite occurs with garnet and epidote in high temperature systems (Saemundsson and Gunnlaugsson, 2014). In Iceland, it is mainly found only in borehole cuttings. In well RN-12, the first appearance of this mineral was at: 698-720, 740-748, 760-764, 782-788, 798-816, 858-864, 892- 896, 900-912 and 938-944 m.

Clay minerals: These minerals are formed by the dissolution of the primary minerals in the basaltic rock formations or as depositions. Several factors govern the degree of alteration such as permeability in concordance with gas, temperature, formation activity, pressure and hydrothermal fluid composition (Marosvölgyi, 2009; Kristmannsdóttir, 1975; Browne, 1978; Reyes, 2000; Franzson, 2006; Franzson, 2008). They are common and abundant in hydrothermal systems. Clays are common alteration products of nearly all rock forming minerals. They are formed in both low and high temperature fields. In general, primary minerals such as plagioclase, pyroxene and olivine are altered into sub-class types of clays:

- A. *Smectite:* This mineral is a low-temperature clay (<200°C), fine-grained, often brownish or greenish, although black varieties occur, with low birefringence. It is found as a coating in altered rocks and distinct crystallisation could be seen under the microscope. Generally, smectite deposition could be found in the upper part of the geothermal field. In well RN-12, this clay was recognized at: 24-126, 148-356, 400-542 and 660-782 m, and under thin section from 30 to 180 m.
- B. *Mixed-layer clays:* This mineral is formed as a derivation from the degradation or aggradation of pre-existing clay minerals; it is a very useful mineral geothermometer (Harvey and Brown, 2000). The mixed-layer clays are, thus, the product of reactions involving clay mineral end members where different kinds of clay layers alternate with each other. In well RN-12, mixed-layer clay was found at: 482, 546, 640, 694, 760-854 and 898-1024 m.
- C. *Chlorite* can be recognized in cuttings by its green, radiating structure. However, it can be difficult to distinguish from smectite except by XRD. It has a greenish to brown colour, and its streak is green with coatings and lumps, often flaky with wavy flakes. It mostly forms at some depth in geothermal areas where temperature has exceeded 200°C (Reyes, 2000). As a result, chlorite is commonly formed with relatively high temperature alteration minerals. In well RN-12, the first appearance of chlorite occurred along with smectite at: 268, 460, 482, 560-580, 590-600, 680-694, 760-790, 893-918 and 940-1014 m.

5.2 Interpretative alteration of primary minerals

The main primary minerals in Icelandic basalt are glass, olivine, plagioclase, pyroxene and opaque minerals, mainly magnetite and ilmenite. Those minerals play a key role when they encounter hot hydrothermal fluids (Gebrehiwot, 2010; Franzson, 1998). In Figure 12, the alteration zones in Iceland are shown along with the alteration of primary minerals with increasing temperature. Table 2 shows the primary minerals in well RN-12 and their alteration products.

Glass: Placed here even though it is homogenous and without any crystal structure. The alteration of glass begins in

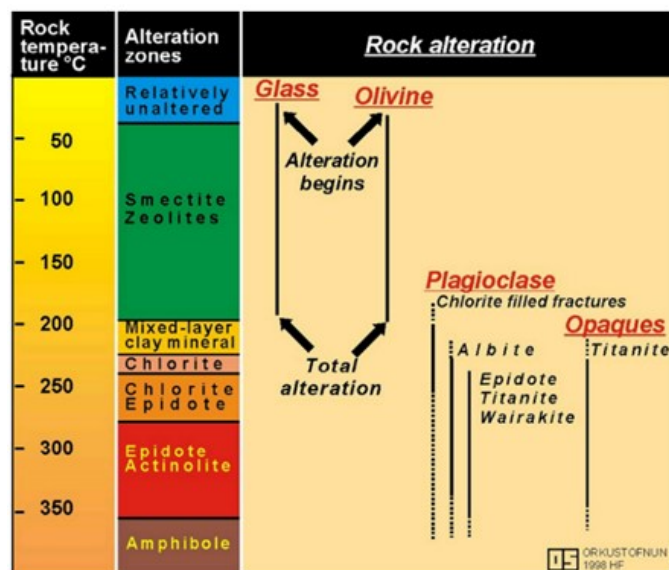


FIGURE 12: Alteration zones in Iceland with temperature and alteration of primary basalt rock (Franzson, 1998)

TABLE 2: Primary alteration minerals in well RN-12

Altered/unaltered	Alteration results
Glass	Clay ⇒ calcite ⇒ zeolite ⇒ quartz
Olivine	Clay ⇒ calcite ⇒ p. calcite ⇒ analcime ⇒ quartz
Plagioclase	Clay ⇒ calcite ⇒ quartz ⇒ wairakite ⇒ chlorite
Pyroxene	Clay ⇒ smectite ⇒ calcite ⇒ actinolite
Opaque	Clay ⇒ limonite ⇒ pyrite ⇒ mixed-layer clay

the upper part of well RN-12 and is radically turned into brownish clay with reddish oxidation down to 300 m, where it turns into mixed-layer clay and calcite. Later on through the depth it gets replaced by quartz from 336 m.

Olivine: Olivine forms a compositional series of minerals, based on the proportion of magnesium to iron. It forms yellowish-green to dark green small granules and is distinguished by its fracturing with indistinct cleavage (Saemundsson and Gunnlaugsson, 2014). In this well, olivine is fresh on top, then becomes oxidized (24 m) and gradually turns into clay. Through the well, olivine has a tendency to transform into calcite at around 200 m and phillipsite at around 280 m, then into platy-calcite at 268 m. At around 650 m, olivine was altered into analcime, followed by quartz.

Plagioclase: Plagioclase is part of the feldspar family and falls into the subdivision that contains the albite-anorthite compositional series. Textures are seen as flat crystals or columnar and granular, with parallel cleavage. Twinning is common and the colour is normally white or greyish-white, while some types are pale yellow or pink (Saemundsson and Gunnlaugsson, 2014). For well RN-12, the plagioclase starts to be transformed into albite from 120 m depth. At around 324 m to 352 m, we observed a transformation into silica. From 700 m to 912 m, plagioclase is altered into albite, chlorite and epidote.

Pyroxene: Commonly, pyroxene is referred to as a compositional series of minerals. It is black or dark green in colour, and forms prismatic crystals, either transparent or with a vitreous lustre, sometimes its streak is grey or green with uneven fractures. It is one of the principal rock-forming minerals in basalt and gabbro (Saemundsson and Gunnlaugsson, 2014). In well RN-12, it appears to be fresh at the beginning, however, it gets oxidized and, at around 90 m to 390 m, it tends to be glassy followed by clay alteration. After 900 m, it becomes altered into actinolite.

Opaque: In well RN-12, the alteration of opaques began with oxidation but, from 92 m, they tended to alter into clay and mixed-layer clay down to 620 m. At around 800 m, it was fresh, then turned into clay.

5.3 Sequence of alteration minerals

In general, the deposition of alteration minerals in geothermal systems occurs mainly in vesicles and fractures. The alteration mineral assemblages usually change from low-temperature to high-temperature with increasing depth, e.g. from quartz and wairakite to epidote, prehnite, wollastonite and actinolite (Koestono, 2007).

The sequence of alteration minerals in well RN-12 was analysed both with binocular and petrographic microscopes and can be seen in Table 3. The deposition of fine-grained clay was found in both vesicles and veins, sometimes seen as coarse-grained. Calcite is seen both before and after clay deposition and, towards the lower part, it is also seen coming after the high temperature mineral, quartz. Otherwise, the overall sequence shows that alteration minerals indicating higher temperature follow minerals indicating lower temperatures.

TABLE 3: Mineral deposition sequence of well RN-12

Depth (m)	Deposition sequence	Degree of alteration
30	Calcite ⇒ zeolite	Small
80	Clay ⇒ quartz	Moderate
96	Calcite ⇒ smectite	High
268	Clay ⇒ calcite	High
336	Prehnite ⇒ anhydrite	No alteration
394	Calcite ⇒ prehnite	Small
442	Zeolite ⇒ calcite	High
480	Clay ⇒ quartz	Moderate
482	Zeolite ⇒ quartz	High
546	Clay ⇒ quartz	High
600	Clay ⇒ quartz	High
640	Clay ⇒ quartz	High
694	Quartz ⇒ prehnite	Small
754	Quartz ⇒ epidote	High
812	Epidote ⇒ wollastonite	Moderate
866	Clay ⇒ quartz ⇒ wollastonite	Moderate
940	Quartz ⇒ epidote	High
986	Clay ⇒ quartz ⇒ epidote	Moderate
1030	Quartz ⇒ epidote	High
1090	Quartz ⇒ epidote ⇒ wairakite	High
1140	Clay ⇒ quartz ⇒ calcite	Moderate
1210	Clay ⇒ epidote ⇒ wollastonite	High
1240	Clay ⇒ epidote	High

5.4 Alteration zones

Geothermal systems are usually defined as either high or low temperature fields according to temperature at 1 km depth. Fields with temperature $<150^{\circ}\text{C}$ at 1 km depth are classified as low temperature while fields with temperature $>200^{\circ}\text{C}$ at 1 km depth are high temperature. This gives an idea of the alteration mineralogy at different depths within the systems (Kristmannsdóttir and Tómasson, 1978) although careful analysing is always necessary since variations in temperature are common. It must be noted that it is possible that alteration minerals in certain areas represent fossil conditions, therefore giving past formation temperatures. In Iceland, the alteration zones have been studied and, in general, agreed upon. It has been recognized that zeolites form below 100°C , quartz above 180°C , mixed-layer clays above 200°C , chlorite above 230°C , prehnite above 240°C , epidote above $230\text{--}250^{\circ}\text{C}$ and actinolite above 280°C (Kristmannsdóttir, 1979; Franzson, 1998; Saemundsson and Gunnlaugsson, 2014).

The alteration zones are based on petrographic, binocular and XRD analyses, and are mainly focused on clays to determine the alteration zones. In well RN-12, it was decided to divide the alteration zones into two parts (since some of the alteration minerals were in contradiction to the dominating clay in specific areas), giving clay alteration zones on one hand and alteration mineral distribution zones on the other because the alteration minerals (other than clays) show much higher temperatures in the well than the clays. It is possible that, due to the geothermal system in Reykjanes, the unconsolidated clay mineral deposition dominates the alteration, given the same results as well RN-17 (Hardardóttir, 2011, Marks et al., 2010). The clay alteration zones are:

Smectite-zeolite zone (10-702 m): This zone is characterized by an abundance of zeolites showing the low temperature of the upper part of the well. The presence of prehnite at 260 m may, however, indicate temperature > 240°C.

Mixed-layer clay zone (702-782 m): This thin zone was identified by XRD analysis and shows mixed-layer clay at this depth.

Chlorite zone (782-1024 m): A zone of chlorite mixed with minor epidote is seen at this depth. That demonstrates temperatures between 230-250°C (Brown, 1978; Franzson, 1987). At the same depth, alteration minerals such as wollastonite are seen, indicating higher temperatures.

Alteration mineral distribution zones are:

Quartz zone (70-260 m): Quartz appears at around 70 m (indicating >180°C) and is seen in thin sections down to around 150 m but then disappears until at 280 m. Zeolites still prevail at this depth and quartz may be showing locally raised temperatures.

Prehnite zone (260-610 m): The presence of prehnite it is noted at about 260 m and becomes abundant at around 600 m, indicating temperature higher than 240°C. The abundance of prehnite at around 600 m coincides with the first appearance of epidote.

Epidote zone (610-694 m): This zone is characterized with the disappearance of zeolites and the appearance of epidote in both fine crystals and as full grown. Epidote is abundant in this part of the well, indicating temperatures around 250°C.

Garnet (694-762 m) and wollastonite zone (762-1024): Garnet appeared in an intrusive zone, indicating localised raised temperatures caused by the intrusions, and is not seen below 762 m. Wollastonite was first seen at 698 m. These minerals indicate temperatures higher than 270-280°C.

To recap the interpretation of the history of alteration in this well, one must consider the alteration mineral assemblages in relation to their relative time of deposition (Table 3). The deposition of alteration minerals is quite complex in this well as there are contradictions between the clays and other alteration minerals. Some minerals may be close to the current formation temperature but some may be recording fossil circumstances.

When the results in Table 3 are compared with the alteration zones, the following depositional sequence may be plausible:

Calcite ⇒ Smectite ⇒ Quartz ⇒ Prehnite ⇒ Epidote ⇒ Wollastonite.

6. FLUID INCLUSIONS

Fluid inclusions are tiny bubbles, known as microscopic vacuoles, which are found in minerals such as quartz and calcite, trapped inside these crystals during crystallisation (primary inclusion) or recrystallization (secondary inclusion). Secondary inclusions are confined, or trapped, along restored cracks in the secondary crystals and provide crucial information about the history and condition of the geothermal system in terms of determining the thermal condition and history of the system, in particular, records of compositional and temperature conditions from the time the inclusions were formed (Roedder, 1984).

6.1 Interpretation of fluid inclusions analysis

Two quartz crystals were collected at different depth intervals, at 690 m and 844 m, from well RN-12; it was not necessary to polish the crystals as they were well formed and clear. In those two quartz crystals, nine fluid inclusions were studied at different temperature sequences (Figure 13 and Table 4). According to the results and the homogenization temperatures from those two depths, the fluid inclusions showed two high temperature groups. The first quartz crystal, from 690 m, had 5 inclusions and was showing temperatures varying between 265 and 280°C. The second quartz crystal, from 844 m, had 4 inclusions with temperatures varying between 270 and 295°C (Table 4). It is noted that the fluid inclusions from both quartz crystals enumerated the normal condition of the well as they were respectively concurrent with the temperature profile shown when the quartz fracture veins healed after crystallization. The precise implication of those fluid inclusions with the temperature in relation to the formation and alteration temperature is discussed in the next chapter.

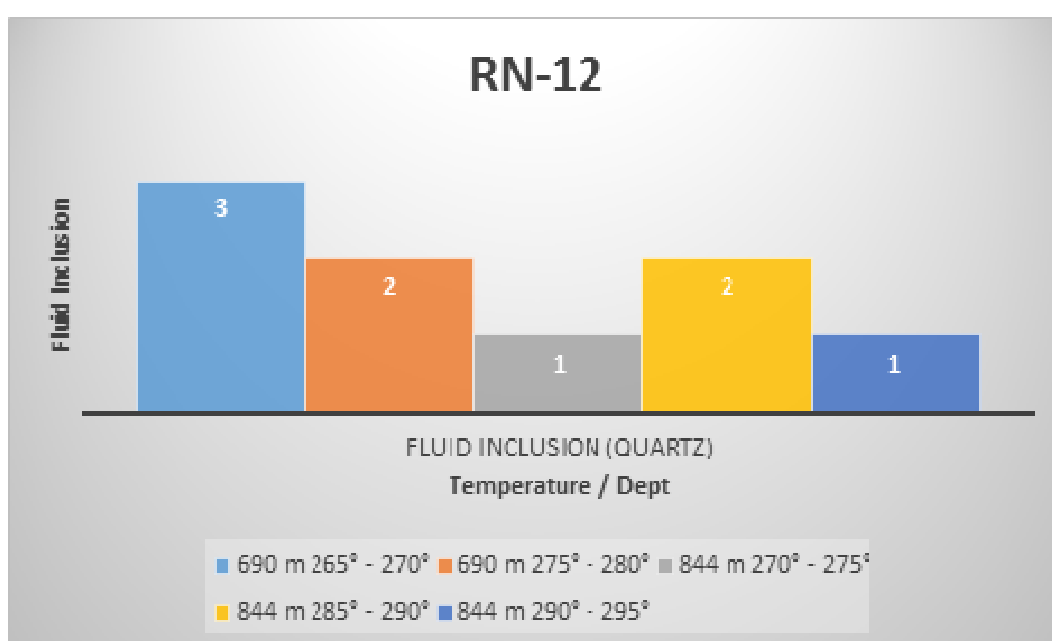


FIGURE 13: Fluid inclusions in quartz crystals at 690-844 m, well RN-12

TABLE 4: Fluid inclusion homogenization temperatures in well RN-12

Depth	Homogenization temp. (Th) ranges (°C)	No of fluid inclusions	Type of crystals
690	265 - 270	3	Quartz
	275 - 280	2	Quartz
844	270 - 275	1	Quartz
	285 - 290	2	Quartz
	290 - 295	1	Quartz

6.2 Temperature and alteration temperature profile of well RN-12

The temperature profile of the well, taken after it had recovered after well completion, shows the formation temperature around the well (Figure 14). From the drill cutting analysis, the alteration temperature can be extracted, as seen in Figure 14. There is consistency between the formation and alteration temperatures, indicating equilibrium in the geothermal system, i.e. it is neither cooling nor

heating up; it is mainly in equilibrium. The homogenization temperatures, derived from the fluid inclusions, further support this conclusion, as they plot in line with both the formation and alteration temperatures (Figure 14).

7. AQUIFERS

Aquifers are typically in underground water-saturated permeable rocks. A geothermal aquifer is a permeable underground formation, or unconsolidated material, such as gravel or sand, which can carry hot fluids, and/or gases, which are subsequently mined, or extracted, for geothermal utilization.

In the case of Reykjanes, which is dominated by basalt and hyaloclastite, the fluid circulation is promoted in both cold groundwater and geothermal fluid but, with an increase in alteration, permeability tends to decrease (Franzson et al., 2011). However, frequently faults and fractures enable the fluids to pass through in higher permeability. The same applies to intrusive contacts, as the host rock is often fractured due to the intrusion. Permeability also occurs at lithological boundaries. Geophysical logs are often used to locate aquifers, in particular temperature logs. Drilling parameters, such as penetration rates and pumping pressure, may also be indicative of feed-zones. Circulation losses can also point to aquifers. A sudden abundance of alteration minerals in drill cuttings may show that an aquifer has been penetrated.

7.1 Study of aquifers in well RN-12

The upper part of the well RN-12 was drilled with mud for safety measures. Even though there were several feed zones identified and blocked by the casing off down to 841 m, it was difficult to identify the feed zones from the circulation losses, as the boundary between the circulation losses and the aquifers was masked by the amount of mud used for drilling. However, several aquifers were identified using temperature logs, circulation losses and abundant mineralization in the cuttings, such as quartz, epidote, pyrite and anhydrite. The aquifers of this well are described below and are shown in Figure 15.

Aquifers 1 and 2: These aquifers are located at the lower part of the anchor casing, at 215 and 235 m, respectively. They were indicated by loss of circulation in the basaltic lava formation.

Aquifers 3 and 4: Were located at 342 and 382 m, respectively. Aquifer 3 is in a basaltic lava formation while the other is in fine-grained basalt. However, both were related to intrusions that were

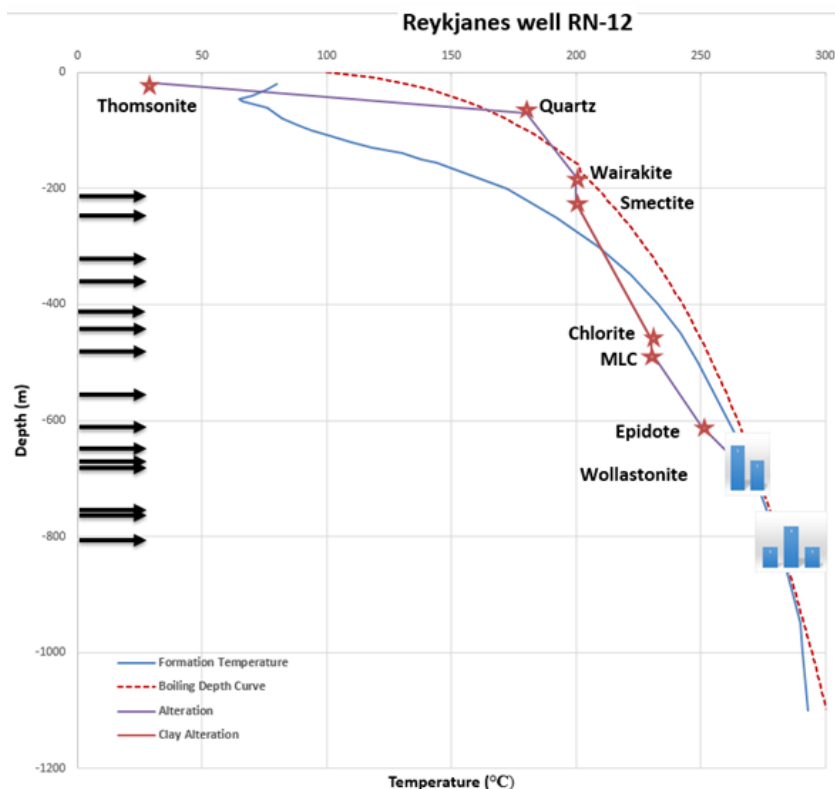


FIGURE 14: Well RN-12, formation temperature (blue line), alteration distribution (purple line, and clay zone (brown line), boiling curve (red broken line) temperature with fluid inclusion temperatures as columns

identified by temperature logs, in the cuttings and by high peaks in the resistivity log, a low peak in neutron- neutron and a higher peak on gamma.

Aquifers 5, 6 and 7: The first two were located in crystalized tuff at 418 and 447 m, respectively, while the last one is located in tuffaceous sediment at 496 m. The first two were identified by temperature logs and by higher resistivity, neutron-neutron and low caliper and gamma, but both are in an intrusion zone that is moderately altered. The last one was identified by low resistivity and higher peaks in gamma, neutron-neutron.

Aquifers 8 and 9: They are located at 530 and 572 m, respectively. They are in tuffaceous sediment and a lava flow, respectively. Both were apparent from temperature logs and showed signs of high peaks in gamma and neutron-neutron, but low in resistivity; however, they were both in an intrusion zone.

Aquifers 10, 11, 12 and 13: They are located at 610, 640, and 673 and 690 m, respectively. All of them are located in basaltic breccia, basaltic tuff and tuffaceous sediment. They can be seen on temperature logs and have low peaks in neutron-neutron, low in resistivity and in gamma.

Aquifers 14, 15 and 16: They appeared at 760, 770 and 816 m, respectively. The first two are found in basaltic lavas and the third in basaltic tuff. They were apparent in temperature logs and the first two showed higher peaks in all the geophysical logs except in the caliper log, while the last one showed a higher peak in gamma and neutron-neutron and a lower peak in resistivity and the caliper.

All of the above aquifers were cased off.

Aquifers 17 and 18: Located at 900 and 968 m, respectively. The first one is in basaltic tuff and the second one is in basaltic breccia. They were both identified by temperature logs and high peak resistivity.

8. DISCUSSION

The main formations observed in well RN-12 were hyaloclastites such as basaltic tuff, breccia and pillow basalt, underlain by partially crystallized basalt and tuffaceous sediment. Crystalline formations include basaltic lavas and intrusions.

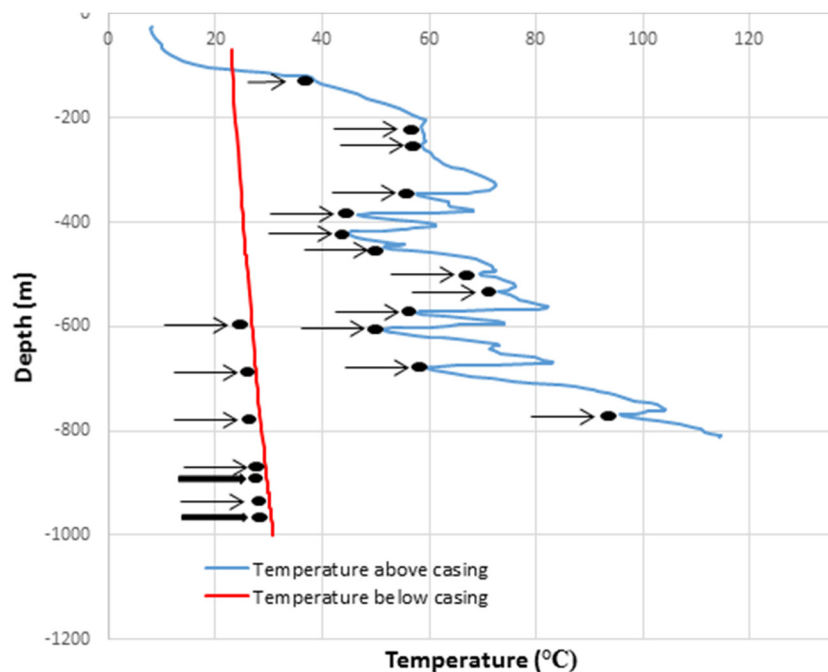


FIGURE 15: Small aquifers identified from temperature log in upper part and below production casing in well RN-12

The deposition of hydrothermal minerals occurred in veins and vesicles and appears early in the well and is in abundance in the lower part of the section analysed for this well. They replaced gradually the primary minerals with increasing depth. It is noteworthy that most of the alteration minerals appeared at shallower depths than that observed in nearby wells like RN-11, RN-13 and RN-14. It appears that the hydrothermal alteration increased progressively from 200 m down to the bottom. The maximum increase was between 600-700 m, where the last of low temperature alteration minerals disappeared and high temperature minerals kicked in (Figure 9). Two classes of alteration zones were identified, one based on the clay analysis, the other on the alteration mineral distribution. The first one consists of a smectite-zeolite zone, a mixed-layer clay zone, and finally a chlorite zone. The second includes a quartz zone, a prehnite zone, an epidote zone, a garnet zone, and finally a wollastonite zone (Figure 9).

It seems as if the geothermal system on the Reykjanes Peninsula is in equilibrium in the immediate area around well RN-12. This can be deduced from, for example, Figure 14 which shows that alteration- homogenization and formation temperatures plot more or less together.

Most of the aquifers encountered in this section of the well are generally shallow and above the bottom of the production casing, which means that they were all cased off. Only two of them are below the production casing, at 900 and 968 m. It seems as though the aquifers correlate with intrusions and lithology. The feed-zones were identified by temperature logs, loss of circulation and geophysical logs, and an increased abundance of alteration minerals was observed in those zones.

9. CONCLUSIONS

The following conclusions can be deduced:

- The stratigraphy of well RN-12 is mainly comprised of hyaloclastite (basaltic tuff, basaltic breccia, and pillow basalt) in addition to basaltic lavas and intrusions;
- Alteration minerals show that most the high temperature minerals appear at relatively shallow levels with a rapid appearance of the minerals starting with quartz followed by prehnite, epidote and wollastonite at around 800 m. The alteration is shallower than that seen in nearby wells;
- Two types of alteration zones were identified, one based on the clay minerals and the other on the alteration mineral assemblages. The first one includes: a smectite-zeolite zone (10 - 702 m), a mixed-layer clay zone (702 – 782 m) and finally a chlorite zone (782 – 1024 m);
- The second type, based on the alteration minerals, includes: a quartz zone (70 – 260 m), a prehnite zone from 260 to 610 m, an epidote zone from 610 to 694 m, a garnet zone from 694 to 762 m and a wollastonite zone from 762 to 1024 m;
- Most of the aquifers encountered in this well were in the upper part of the well, above the lower limit of the production casing. Two feed zones were observed at around 900 and 968 m. Generally, most of the aquifers were related to intrusions, but some with fractures and lithological boundaries. Beyond that, major feed zones were inferred at depths of 1000, 1300 and 2200 m (Jónsson et al., 2003);
- Fluid inclusions show temperatures reaching 300°C. This correlates with the formation temperature and alteration temperature. This indicates that the geothermal system around well RN-12 is in equilibrium, showing no signs of cooling or heating up.

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APPENDIX I: XRD clay analysis results from well RN-12

TABLE 1: Fluid inclusion homogenization temperatures in well RN-12

Sample no.	Depth (m)	D(001) untreated sample	D(001) glycolated sample	D(001) heated sample	D(002)	Minerals
1	24	15.18	0	10.39	0	Smectite
2	38	14.68	0	10.39	0	Smectite
3	68	0	14.24	10.39	0	Smectite
4	92	15.36	0	0	0	Smectite
5	104	13.85	14.45	10.15	7.77	Smectite
6	148	12.81	13.05	10.03	15.07	Smectite
7	158	15.25	13.39	10.03	0	Smectite
8	248	14.97	13.20	10.20	0	Smectite
9	280	15.59	15.09	10.20	0	Smectite
10	320	13.17	13.71	9.99	0	Smectite
11	356	13.71	13.16	9.99	7.24	Smectite
12	400	15.31	17.17	10.05	0	Smectite
13	456	15.65	17.47	10.05	0	Smectite
14	490	15.65	13.56	10.05	0	Smectite
15	542	15.65	0	10.05	0	Smectite
16	660	15.65	13.26	10.05	0	Smectite
17	672	15.38	14.15	10.05	0	Smectite
18	702	30.75	14.47	11.85	0	MLC
19	782	0	14.06	10.21	7.22	Smectite
20	866	15.00	31.50	11.68	7.33	MLC
21	924	0	14.70	0	7.23	Chlorite
22	970	15.09	0	0	0	Chlorite
23	998	14.77	7.74	7.22	0	Chlorite
24	1014	14.84	0	7.78	7.22	Chlorite

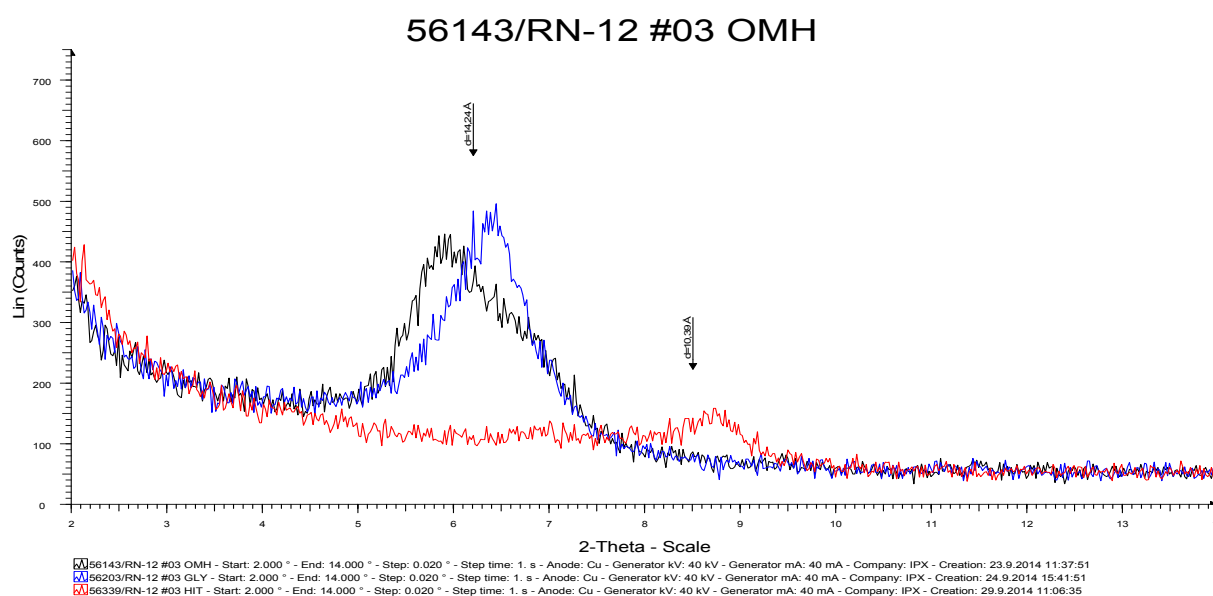


FIGURE 1: Well RN-12, XRD analysis of a sample 3 from 68 m

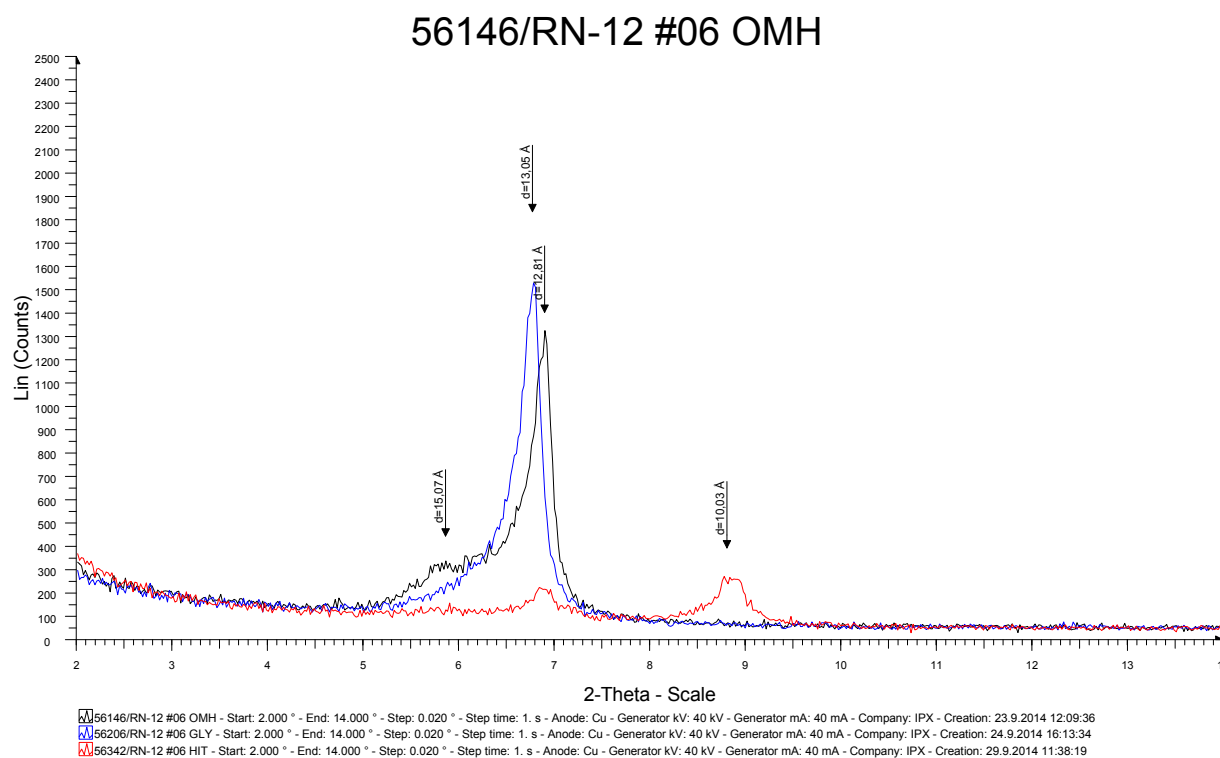


FIGURE 2: Well RN-12, XRD analysis of a sample 6 from 148 m

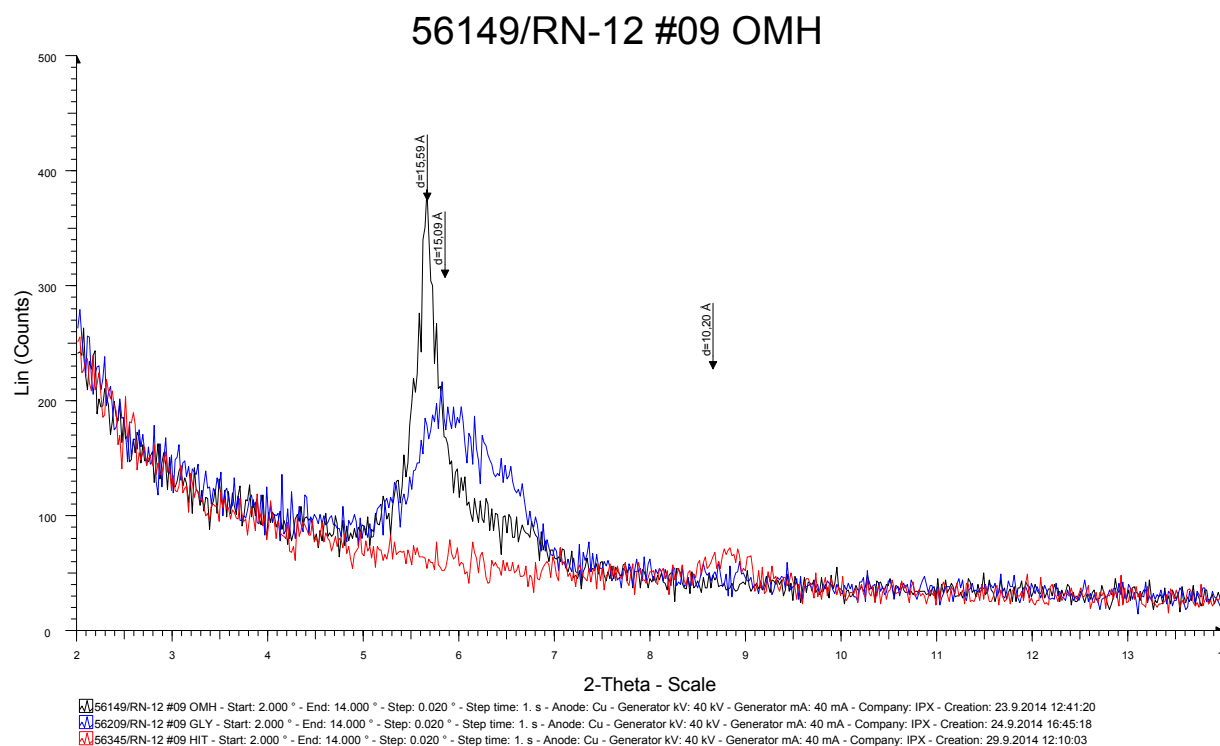


FIGURE 3: Well RN-12, XRD analysis of a sample 9 from 280 m

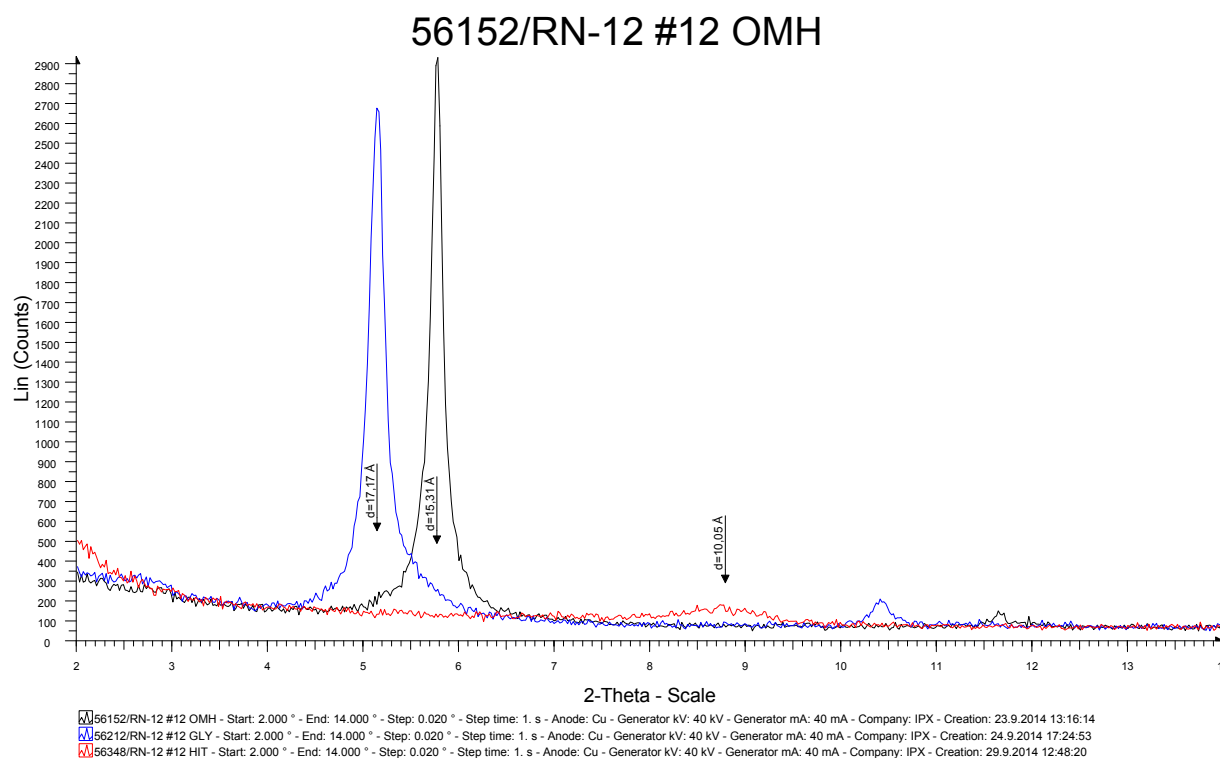


FIGURE 4: Well RN-12, XRD analysis of a sample 12 from 400 m

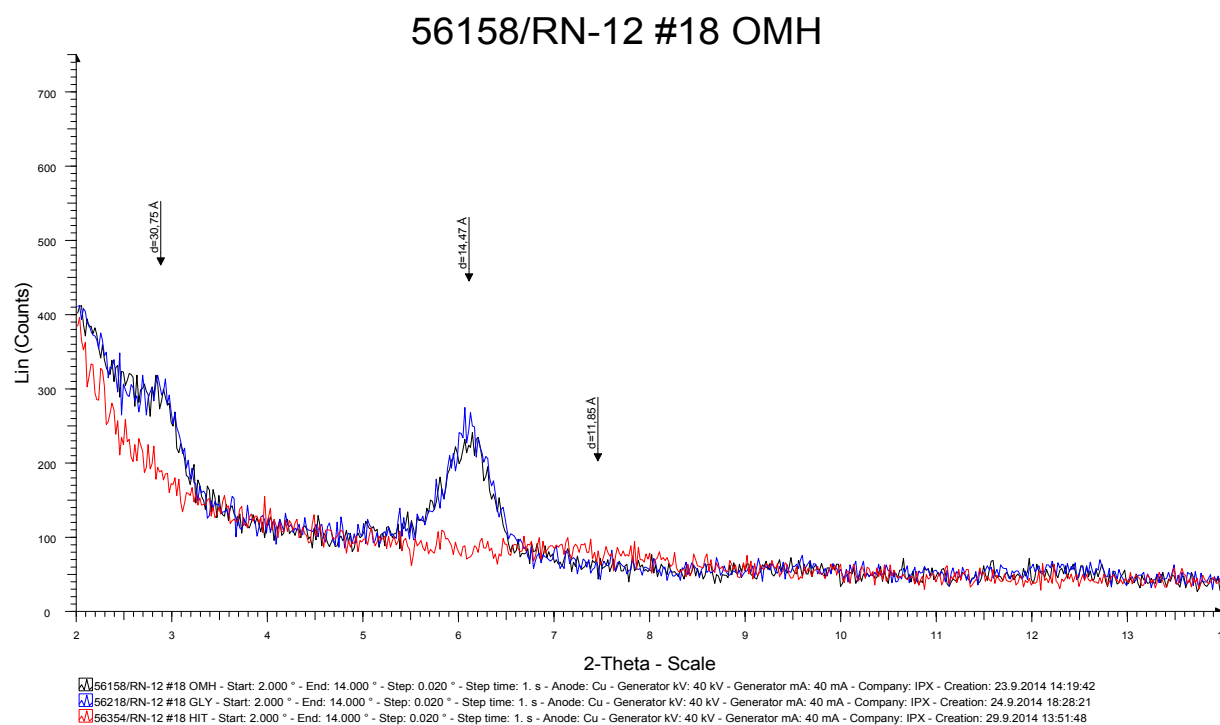


FIGURE 5: Well RN-12, XRD analysis of a sample 18 from 702 m

56160/RN-12 #20 OMH

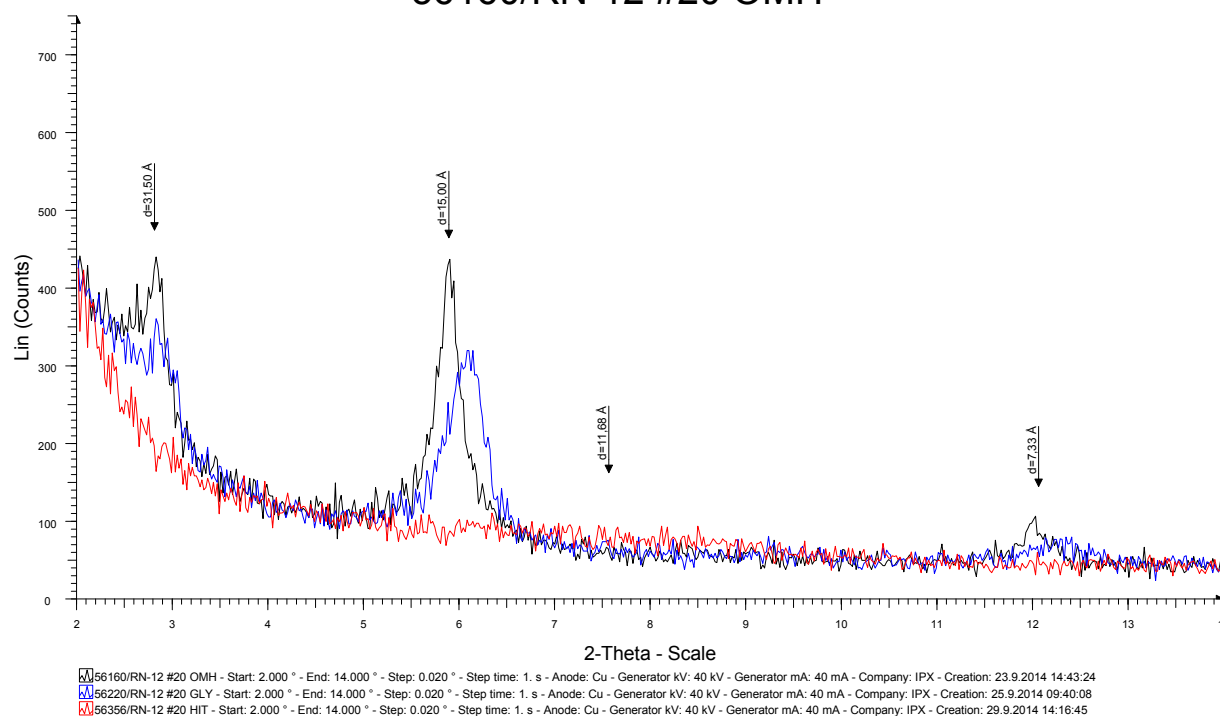


FIGURE 6: Well RN-12, XRD analysis of a sample 20 from 866 m

56161/RN-12 #21 OMH

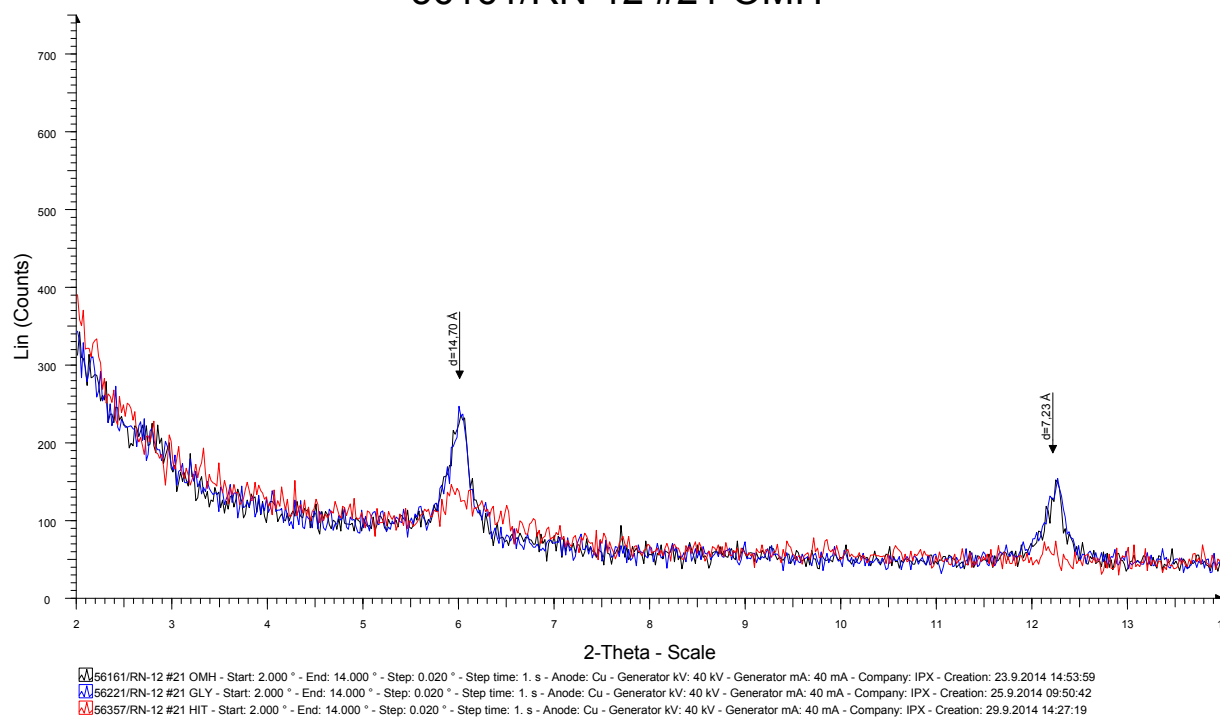


FIGURE 7: Well RN-12, XRD analysis of a sample 21 from 924 m

56163/RN-12 #23 OMH

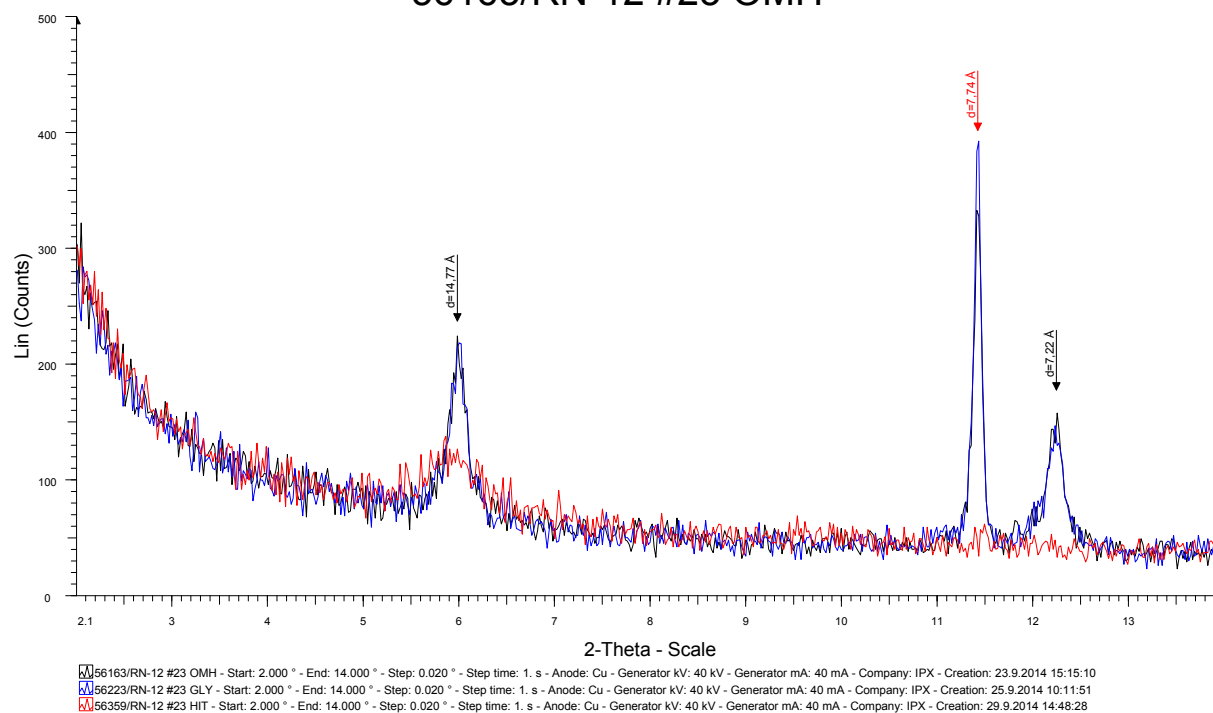


FIGURE 8: Well RN-12, XRD analysis of a sample 23 from 998 m

56164/RN-12 #24 OMH

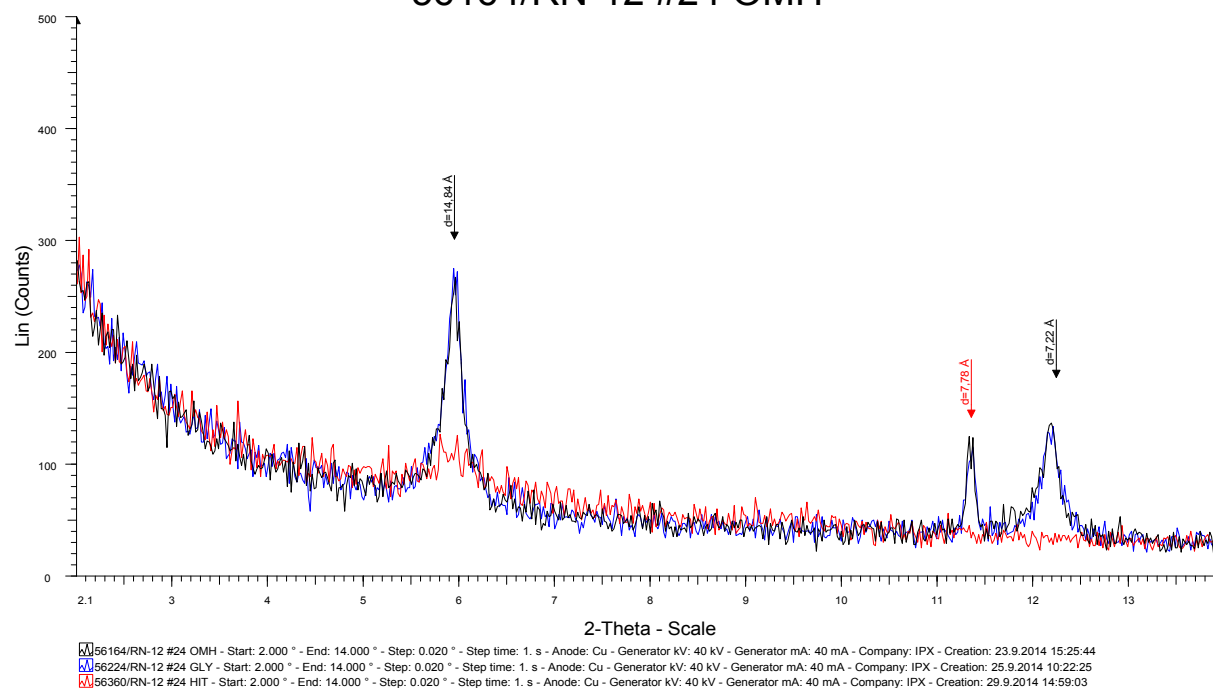


FIGURE 9: Well RN-12, XRD analysis of a sample 24 from 1014 m