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BOREHOLE GEOLOGY AND HYDROTHERMAL MINERALISATION OF WELL HN-08, HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

Well HN-08 is located in the Hellisheidi high-temperature field, within the Hengill geothermal area in SW-Iceland. It is a directional reinjection well reaching a total depth of 2580 m. The uppermost 1000 m are analysed here. The well was drilled in May 2007 targeting a series of large faults at the western margin of the Hengill graben. The lithology of well HN-08 comprises basaltic hyaloclastite formations, basaltic lavas flows and dyke intrusions. Six alteration zones were identified: a zone of no alteration at <210 m depth, smectite-zeolite zone (<200°C) from 210-1004 m, mixed-layer clay zone (200-230°C) from 1004 to 1264 m, chlorite zone (230-240°C) from 1264 to1410 m, chlorite-epidote zone (>240°C) from 1410 to 1700 m and the epidote-amphibole zone (>260°C) from 1700 to the bottom. The alteration zones correlate with measured formation temperature, indicating that the geothermal system at this location is not affected by cooling. Just five insignificant circulation losses were identified in the production part and two very small aquifers above the production part. The correlation of hydrothermal alteration with well HN-05 at Gráuhnúkar shows that the lithology is similar, and the hydrothermal alteration indicated by epidote-wairakite and prehnite appears almost at the same depth. In addition, the intensity of hydrothermal alteration increases moderately with depth in the two wells.

1. INTRODUCTION

The Hengill high-temperature geothermal field rates as one of the largest in Iceland. It is geographically located in SW-Iceland, approximately 30 km east of Reykjavík. Well HN-08 is the eighth reinjection well drilled in the southwest part of the Hengill central volcanic complex, and the sixth well drilled in the Gráuhnúkar sector. Gráuhnúkar is located on the western fringe of the Hengill central volcanic system. HN-08 is a directional well, reaching a depth of 2580 m. This geological research is based on the upper 1000 m of the well, and involves the characterisation of the lithology, hydrothermal mineralisation, and sequences of mineral deposition and aquifers. A comparison is done with well HN-05 located on the same platform. The methods used are binocular stereo-microscope, petrography microscope and lastly X-ray diffraction (XRD) to identify the types of clay and other minerals. This report is a completion of the six-month training at the United Nations University Geothermal Training Programme (UNU-GTP) in 2008.

2. TECTONIC AND GEOLOGICAL STRUCTURE OF THE HENGILL AREA

2.1 Main aspects of tectonics and geology of Iceland

Iceland is a product of a unique tectonic and geological combination of divergent oceanic plate boundaries and a hot spot. The island is geologically located on the sea floor spreading boundary of the Mid-Atlantic Oceanic Ridge, where the tectonic plates of the North American and Eurasian plates are diverging at an average rate of 2 cm per year. It is a site where the mid-oceanic ridge is exposed above sea level. The exposure lies between the Kolbeinsey Ridge to the north and the Reykjanes Ridge to the south. The west-northwest motion of the mid-oceanic ridge relative to the hot spot has resulted in repeated southeastward ridge jumps since ~23 Ma and the formation of overlapping spreading centres (Garcia et al., 2003; Hardarson et al., 1997). Iceland is divided into various volcanic rift zones namely: northern, middle, western and eastern zones (Figure 1). The magmatic activity is currently represented on land by the volcanic zones (Hardarson et al., 1997). The western and eastern volcanic zones are being offset by a "leaky transform fault" of the Mid-Iceland volcanic zone, also known as the south Iceland seismic zone (LaFemina et al., 2005). The location of the mantle plume or hot spot is thought to be located underneath the southeast portion of the island. It represents the broadest hot spot on the planet**.** The volcanic zones are the primary settings for intense tectonism, active volcanism and widespread geothermal activity.

The geological history of Iceland is relatively young, undergoing continuous tectonic activity and changes. The oldest rock formations date back to Tertiary basaltic lavas, which are predominantly exposed in the eastern and northwest quadrants of the island. A rock outcrop is dated approximately 16 Ma in the extreme northwest region (Hardarson et al., 1997). The Quaternary rocks are composed of sequences of basalt lavas and hyaloclastites that are exposed in the central, southwest, and east sectors. The volcanic episodes during this period were strongly controlled by climatic conditions. The volcanism is divided into: ice free volcanism and glacial time volcanism. The ice free volcanism is categorized into Interglacial and Postglacial volcanism, and the rock types erupted under these climatic conditions are represented by sub-aerial eruptions forming lava flows, pyroclastic scoria, and lavas. The glacial volcanism is divided into sub- and supra-glacial volcanism, and eruptions are characterised by phreato-magmatic deposits and the formation of hyaloclastites.

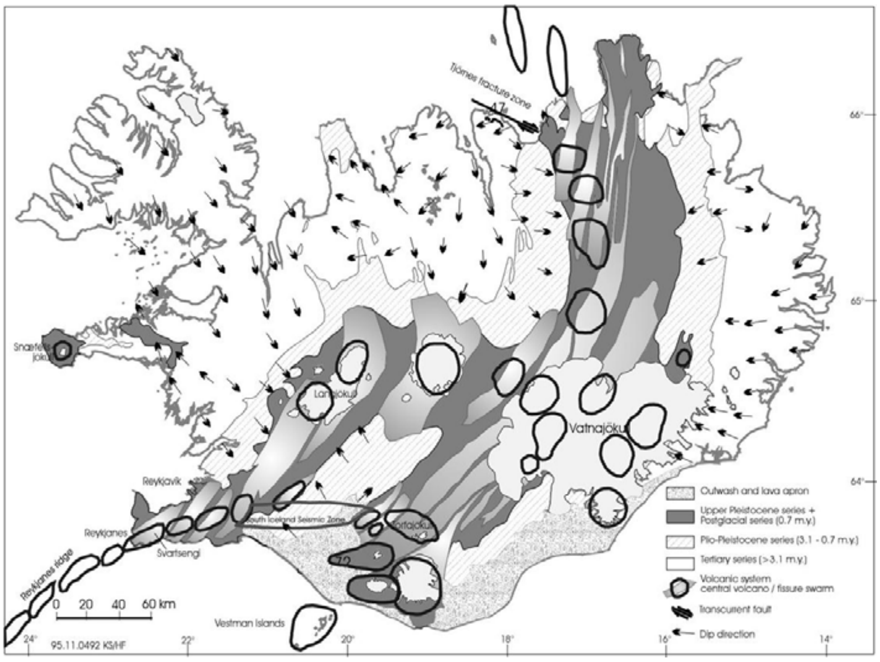

FIGURE 1: Map showing the main geological features of Iceland (Saemundsson, 1979)

2.2 Geological aspects of the Hengill geothermal fields.

Hengill is one of the highest mountains in the region east of Reykjavík, Iceland's capital. It is the symbol of the Hengill central volcano of the Hengill volcanic system, composed of crater rows and a large fissure swarm. It is located on the eastern border of the Reykjanes Peninsula, SW-Iceland (Figure 2). It is set at the continuation of the Mid-Atlantic ridge (Reykjanes Ridge) in Iceland, at the triple junction of the Reykjanes Peninsula volcanic zone, the Western volcanic zone and the South Iceland Seismic Zone. The Hengill volcanic system has a 100 km long NE-SW axis and is 3-16 km wide, extending from Selvogur in the south to Ármannsfell in the north.

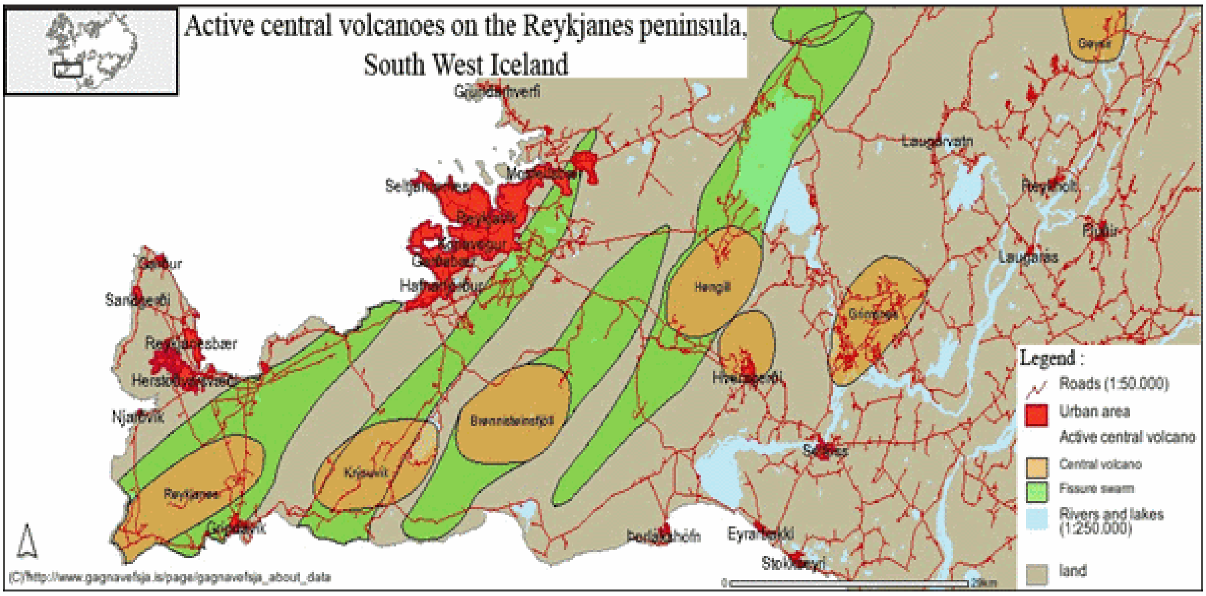

FIGURE 2: Active central volcanoes in SW-Iceland (Gíslason and Gunnlaugsson, 2003)

The Hengill central volcano covers an area of about 40 km² (Björnsson et al., 1986). The Hellisheidi geothermal field is located in the southern part of the Mt. Hengill area, and some 20 km south of the Nesjavellir high-temperature field (Figure 3). The present well field in Hellisheidi covers some 12 km². The first exploration well was drilled in 1985 at Kolvidarhóll (KhG-1) at the western boundary of the Hellisheidi field. A total of 50 high-temperature wells and nine reinjection wells have been drilled in the Hellisheidi area as of September 2008.

Production plans for the Hellisheiði power plant aim at a capacity of 300 MWe electrical generation and 400 MWt thermal energy production. Two steam turbines (45 MWe each; 90 MWe total) have been online since December 2006 and a 33 MWe back-pressure turbine since 2007. The plant's purpose is to meet increasing demand for electricity and hot water for space heating in the industrial and domestic sectors of the greater Reykjavík area (Elmi, 2008).

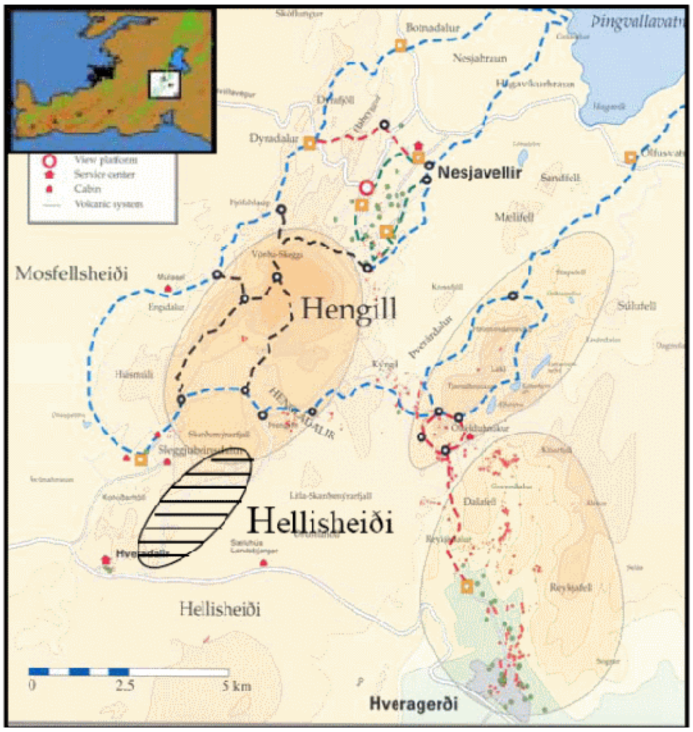

FIGURE 3: The three volcanic systems in the Hengill area (modified from Gíslason and Gunnlaugsson, 2003); the Gráuhnúkar reinjection area is in the southwest corner (a small square)

The Hengill area is one of the largest high-temperature areas in Iceland, extending over some 100-110 km². The geothermal activity is believed to be connected to three volcanic systems (Figure 3). The geothermal area in Reykjadalur and Hveragerdi belongs to the oldest system, called the Grensdalur system. Northwest of this is another volcanic system named after Mt. Hrómundartindur with the last eruption taking place about 10,000 years ago. The geothermal area at Ölkelduháls is connected to this volcanic system. West of these two volcanic systems lies the Hengill volcanic system, with active tectonic and volcanic NE-SW fractures and faults extending from Lake Thingvallavatn to Nesjavellir and further to the southwest through Innstidalur, Kolvidarhóll, Hveradalir (hot spring valleys) and Hellisheidi (Saemundsson, 1979). A geological map of the southern part of Hengill volcano, where the Hellisheidi project lies, is shown in Figure 4.

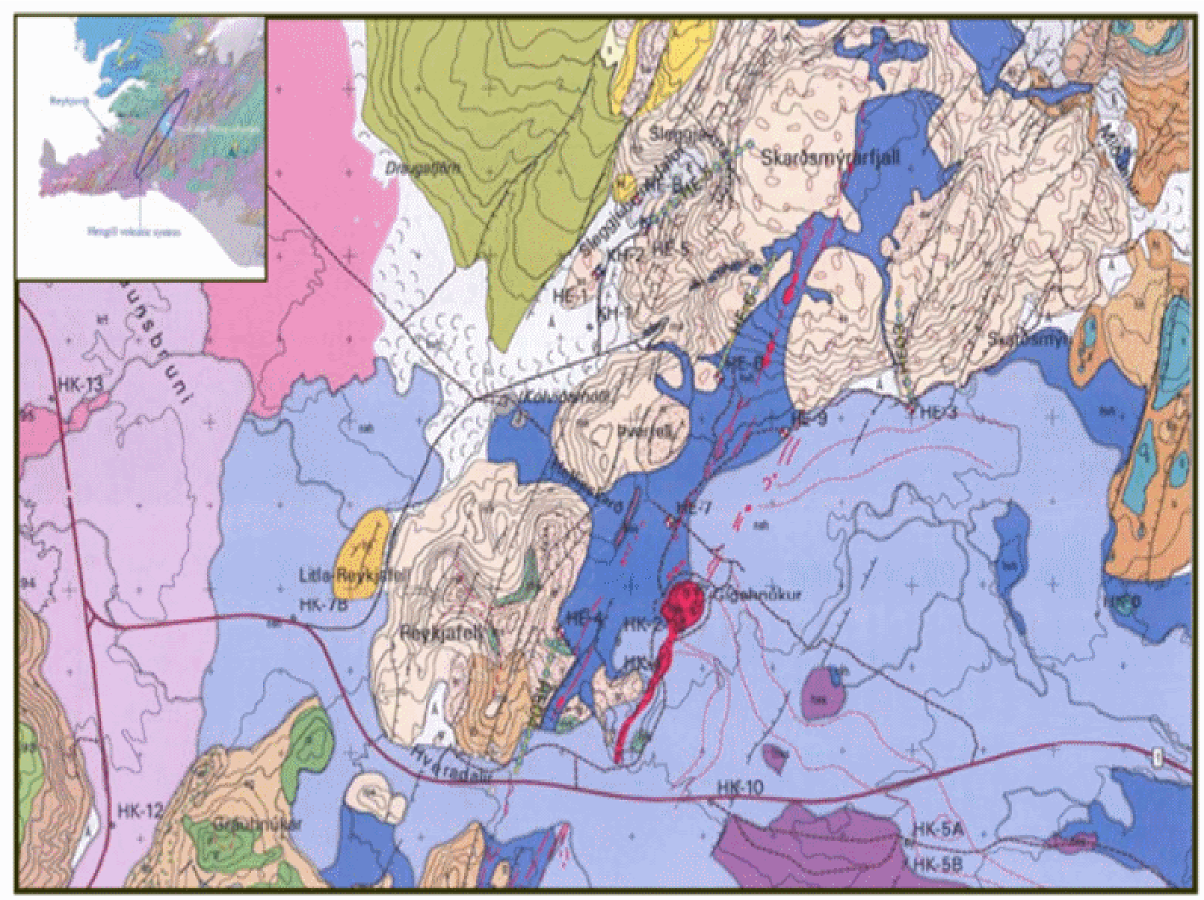

FIGURE 4: Geological map of Hellisheidi area (Saemundsson, 1995), the part shown extends over an area of approx. 9 × 6 km; wells marked with HE are recently drilled high-temperature wells in the Hellisheidi field (Hartanto, 2005). The large gray (blue and pink) areas are composed of lava flows while the light greyish (brown) colour shows hyaloclastite formations. The Gráuhnúkar reinjection area is in the southwest corner

A tensional stress system has developed in the zone of the active Hengill volcanic system. The tensional stress has opened northeast trending vertical fractures, faulting, a graben and geothermal systems that occur along the fissure swarm which provide highly permeable conditions for fluid flow (Björnsson et al., 1986), as shown in Figure 4. The fracture network is periodically activated, providing conduits for the episodic eruptions of basalt and the intrusion of dykes. Magma moves into the shallow crust at temperatures on the order of 1200°C and supplies heat to the hydrothermal system (Bödvarsson et al., 1990). On the surface, the Hengill area is almost entirely built up by volcanic rocks of late Quaternary and Holocene age (Árnason et al., 1967). The rocks are mostly subaerial basaltic flows and hyaloclastites, but small amounts of rocks of intermediate and rhyolitic compositions occur as well.

The Hengill Mountain itself was mostly built-up in one or two large sub-glacial eruptions during the last glacial period. New geological data presented in 2002 suggest that the lower part of the mountain may have formed during the 2nd last glacial period (Fridleifsson et al., 2003). The geology of the Hellisheidi geothermal field is characterised by the presence of two kinds of common hyaloclastite formations and basaltic fissure lavas produced in an active fissure swarm.

Hyaloclastite formations: Sub-glacial fissure eruptions produce elongated ridges that are 1-5 km wide, up to tens of kilometres long, and a few hundred metres thick. The cores of these ridges consist of permeable pillow lavas, but the flanking hyaloclastite deposits can serve as aquitards. Thus subglacial eruptions are remarkable in that they are able to create both the geothermal reservoir rocks and the caprock in one volcano (Wohltz and Heiken, 1992). Commonly, hyaloclastite formations in Iceland are created by the effect of volcanism under glaciers. The sequence of formation is shown in Figure 5. The most recent volcanism of this type was in Bárdarbunga in 1996 in the glacier Vatnajökull, but the most famous episode was formed at the seafloor south of Iceland in 1963-1967, and formed the island Surtsey which belongs to the Vestmannaeyjar archipelago. The morphological structure is named móberg (in Icelandic) or hyaloclastite, and the formation is a table mountain. Hyaloclastite formations characterise the environment in the Hengill region and include mountains such as Mt. Skardsmýrarfjall, Mt. Reykjafell and Mt. Hengill.

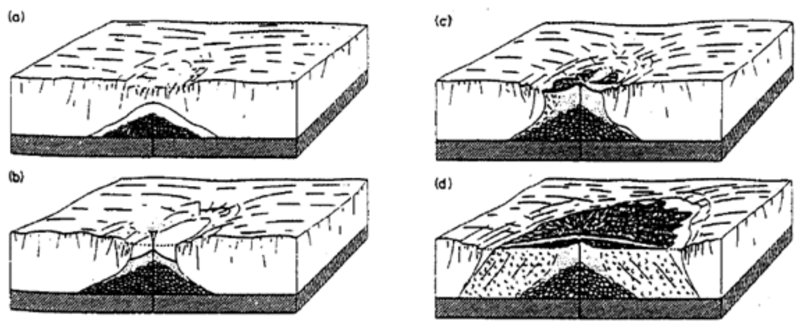

FIGURE 5: Growth of a subglacial, monogenetic volcano; a) A pile of pillow lava forms deep in a melt water lake; b) Slumping on the flanks of the pillow lava pile produces pillow lava breccia; c) Hyaloclastite tuffs are erupted under the shallow water; d) A lava cap propagates across its delta of foreset breccia (Jones, 1969; Saemundsson, 1979)

The fissure swarm: There are two main volcanic fissures of Holocene age trending NE-SW in the Hengill area that have fed the last volcanic eruptions in the area, extending from Lake Thingvallavatn in the northeast part of the Hengill area (Nesjavellir high-temperature field) to about 20 km southwest of the Hengill mountain (Hellisheidi). The age of the older one is about 5500 years and the younger one is about 2000 years old (Saemundsson, 1967). Lava flows from the fissure swarms are widespread and cover a large part of Hellisheidi. These eruptive fissures and parallel faults are believed to control upflow and outflow of hot water and steam from the centre of the Hengill system. Tectonic activity is episodic and accompanied by rifting and major faulting along the fissure swarm that intersects the Hengill central volcano and magma is injected into the fissure swarm (Saemundsson, 1979).

2.3 Geophysical surveys in the Hengill area

Extensive resistivity surveys have been conducted in the Hengill region, including the Hellisheidi geothermal field, such as Schlumberger and TEM resistivity measurements (Björnsson et al., 1986; Árnason and Magnússon, 2001). Aeromagnetic and gravity surveys have, furthermore, been done in the Hengill geothermal area, including Hellisheidi (Björnsson et al., 1986). The DC resistivity surveys delineated 110 km^2 low-resistivity areas at 200 m b.s.l., and the magnetic survey showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds. Recent transient electro-magnetic soundings (TEM) have led to a revision of the resistivity map (Figure 6).

The electrical resistivity also provides information on the degree of alteration and therefore hydrothermal activity, including both fossil and recent alteration. A low-resistivity area covering 110 km^2, measured at a depth of 400 m, indicates roughly the extent of the high-temperature fields. All surface manifestations, like fumaroles and altered ground, are within this area (Hersir et al., 1990). The main resistivity feature is a high-resistivity zone (50-500 Ωm) which is observed beneath the low-resistivity layer.

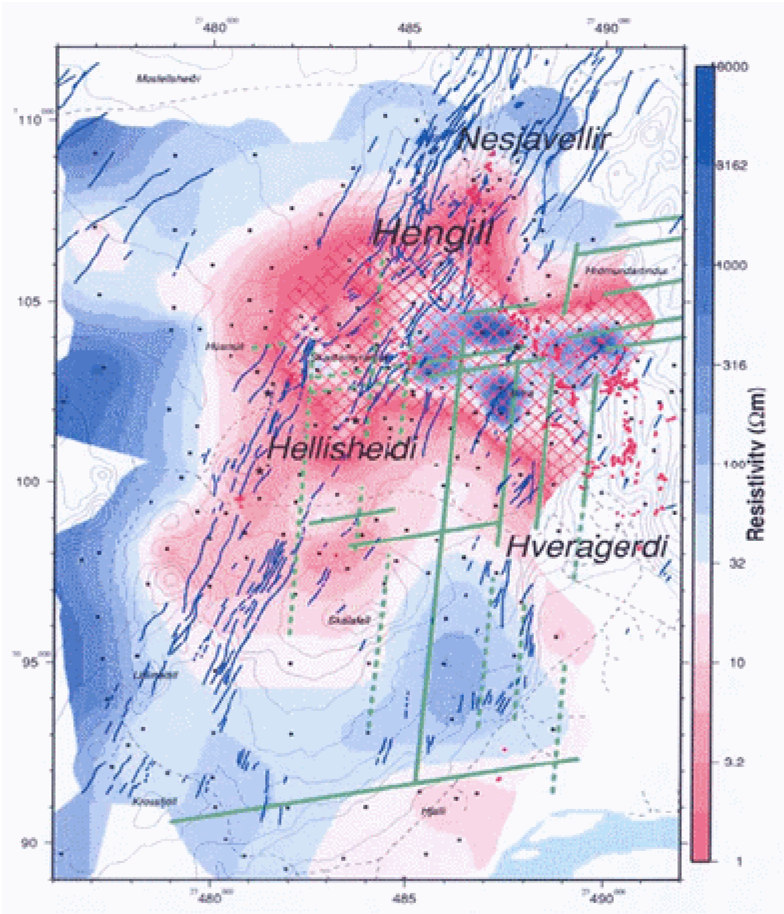

FIGURE 6: Hengill area, resistivity at 100 m b.s.l. according to a recent TEM survey, faults (blue/irregular lines) and interpreted earthquake fractures from recent seismic events (green/straight lines) (Árnason and Magnússon, 2001)

A correlation between resistivity, rock temperature and alteration at Nesjavellir (northeast of Hellisheidi) shows high-resistivity values close to the surface which can be attributed to fresh unaltered rocks. The low-resistivity values (1-5 Ωm) are connected with the smectite-zeolite alteration belt at temperatures between 50 and 200°C. Below the low resistivity there is the high-resistivity core or layer, mentioned above, associated with a high-temperature alteration zone. This high-resistivity core is related to the chlorite–epidote zone, located under a chlorite zone, indicating temperatures of more than 240°C (Árnason et al., 2000).

3. BOREHOLE GEOLOGY

The main reinjection system for the Hellisheiði power plant consists of six wells that were drilled north of Gráuhnúkar, and are located between Hveradalir and Threngsli on Hellisheidi (Figure 7). The injection area is situated in the southwest part of the Hengill volcanic system. Gráuhnúkar forms the northeast segment of a hyaloclastite ridge that extends to Stakihnúkur in the southwest. On the surface the formation consists mainly of fine-grained, layered tuff, but fractured interglacial lava can be found in places on top of the tuff. It is believed that the formation was erupted from a relatively short volcanic fissure early during the last glacial period during a short period of warmer climate,

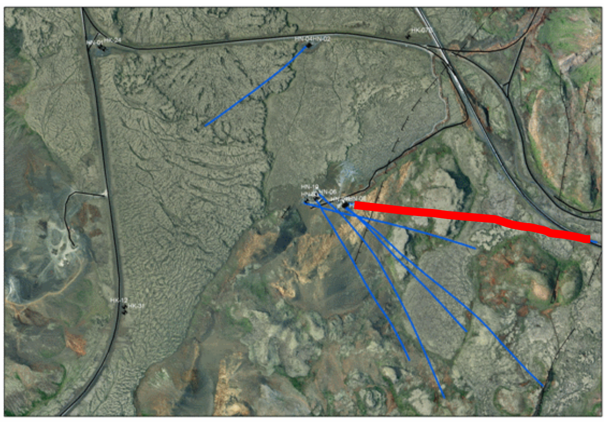

FIGURE 7: Aerial photo of Gráuhnúkar area; the path of the directional well HN-08 is marked with a red/broad line, while other wells are shown with a blue/thin line

possibly some 70,000 years ago (Saemundsson et al., 1990). This is supported by the fact that lava flows are found at only 400 m above sea-level showing that the eruptive product melted their way up through the glacier at that altitude.

The rocks of Gráuhnúkar belong mostly to the olivine tholeiite and olivine basalt series, but picrite is found at a few locations to the southwest. Postglacial lavas surround the Gráuhnúkar formation dating from between 5500 and 2000 years (Saemundsson, 1995). Geothermal alteration is not seen at the surface at Gráuhnúkar but some is found to the east, for example at Hveradalir.

The reinjection wells at Gráuhnúkar are all directional and trend towards the east (Figure 7). They are located west of the extensive NE-SW faults that mark the western boundary of the Hengill volcanic system but these faults are quite permeable. The injection wells cut the faults and thereby extend into the Hengill geothermal system. E-W trending fissures, probably related to the South Iceland seismic zone, which cut the NE-SW faults, may increase the permeability of the injection area (Hardarson et al., 2007). As the injection area was developed, it was discovered that the temperatures in the wells ranged between 270 and 305°C. Consequently, Reykjavik Energy is looking for a new injection field so that the present area can be harnessed for production.

3.1 Drilling of well HN-08

Well HN-8 is a directional well with a total depth of 2580 m. The well pad is located north of Gráuhnúkar at coordinates (according to ÍSN93) X= 381308.49; Y= 393048.38 and Z= 261 m a.s.l. On the same drill pad are wells HN-5 and HN-7. The well, like other wells in the area, was drilled by the Icelandic company Jardboranir Ltd. Drilling started on May 20 and finished on June 23, 2007. Two drill rigs, Saga and Geysir, drilled the well. The drilling was carried out in four stages, a pre-drilling stage for the surface casing, stage 1 for anchor casing, stage 2 for production casing and stage 3 for the production part (Figure 8). The pre-drilling stage was done using a small drill rig (Saga) drilling down to 96 m with a 26" drill bit. The well was then cased and cemented using a 22½" surface casing. The rest of the well was drilled by a large rig (Geysir). The main character of the well design is given in Figure 9.

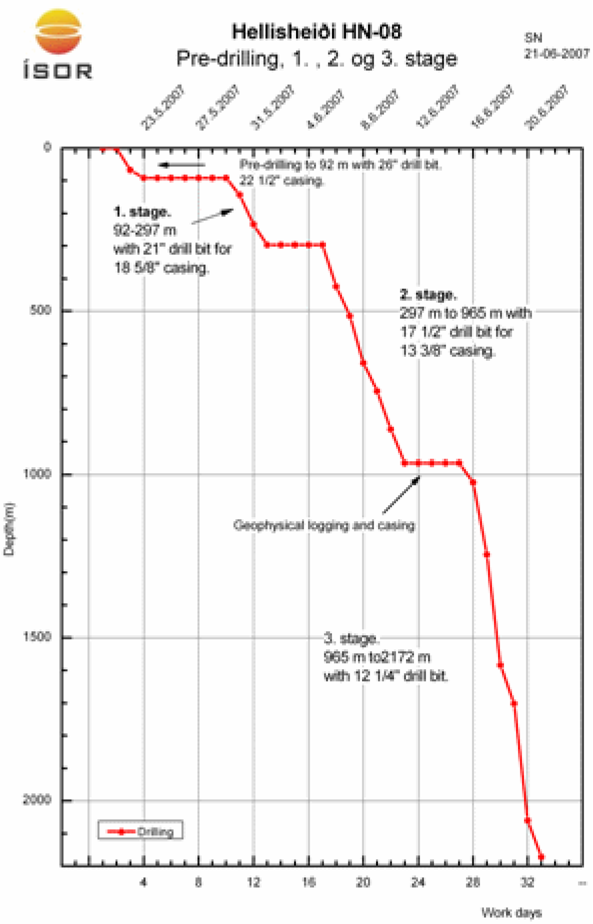

FIGURE 8: Drilling progress of well HN-08 (ISOR data, unpublished)

Drilling with Geysir started on May 29. During drilling, at 93 m depth, olivine basaltic lava layers were intersected and at 102 m depth a complete circulation loss occurred. At 142 m depth, cuttings started resurfacing and showed that the rocks consisted of rather hard, relatively fresh lava series from the last interglacial period. At 206 m depth, the rocks changed into slightly altered basaltic tuff layers that became rather like breccias at about 250 m depth. At 268 m, the drill penetrated a vesicular pillow lava unit where the vesicles were mostly empty. Glassy grains were generally fresh but some vesicles were created with thin clay layers. The rocks were relatively fresh although limonite, analcime and scolecite could be seen. The drilling was stopped at 297 m depth in a pillow lava section, which was considered a good layer for the end of the 18⅝" anchor casing. The casing, however, got stuck at 235 m depth because of a cave-in higher up in the well. This problem was solved by keeping circulation through the casing in order to ease it through the trouble zone and down to 295 m depth where cementing was done.

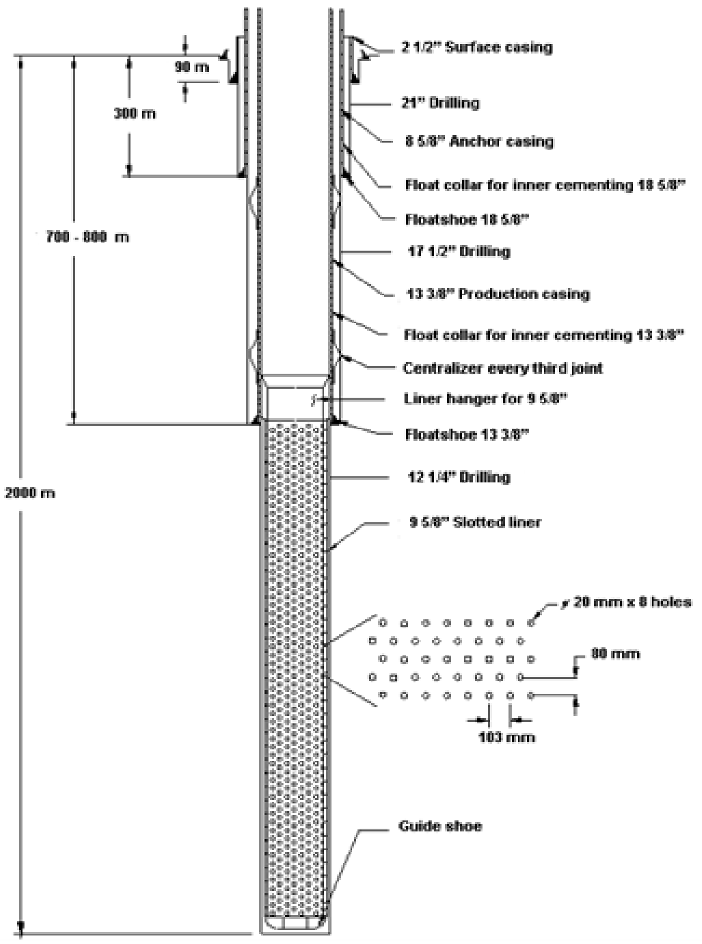

FIGURE 9: The main character of the well design for HN-08; the casing depths do not apply to HN-08 (Mortensen et al., 2006)

Directional drilling for the production casing started on the morning of June 5 with rotation and sliding. The drilling went smoothly with a few pauses for gyro or logging. The rock consisted of pillow lava and basaltic breccias with basaltic tuff layers in between. In the beginning of stage 2, the rocks were still relatively fresh. At 800 m the alteration started to increase, and at 950 m depth the high-temperature minerals quartz and wairakite started to appear. The drilling was stopped at 965 m depth where the well had reached the high-temperature system of the Hengill area; this layer was considered good for stabilizing the end of the 13⅜" casing. The casing almost reached the bottom of the well and cementing was successful.

The final stage, or the production stage, was drilling to 2580 m using a 12¼" triconal bit and a motor. The drilling in the production part went smoothly until, at 2172 m, the torque increased suddenly. The combination of the drill string was changed in order to lower the torque. Temperature and gyro logging was done at that time and showed the inclination of the hole to be 31,9° and the direction 98°. The drilling continued and at 2518 m a total circulation loss occurred; drilling was stopped for good at 2580 m. When the well had been cooled down and cleared of cuttings, the circulation loss was about 2 l/s. Temperature logging was done and it showed that the main aquifer seemed to be at 2350 m depth where tuff met breccias. A few temperature anomalies occurred at 2200 m where intrusions were found. On the evening of June 28, a 9⅝" slotted liner was released into the well. The lowermost 500 m of the line was slotted, but from there every other pipe was slotted. The top 150 m are non-slotted. The liner was hung at 922 m and reached down to 2552.8 m. When the liner had been fitted, procedures for stimulating the well started. The well was closed on June 30 when the stimulation procedures were finished.

3.2 Stratigraphy of well HN-08

The simplified stratigraphic column of well HN-08 down to 2000 m is shown in Figure 10 and consists primarily of alternating sequences of hyaloclastite units, layers of lava, and basaltic intrusive bodies. The data between 1000 and 2000 m were provided by ISOR. The series or units are further subdivided into various sub-series: the hyaloclastite lithology into pillow lavas (glassy basalts), basaltic breccias and basaltic tuff; the lava flows are classified into fine- to medium- and medium- to coarse-grained texture. Overall, six hyaloclastite units, four lava flow series, and two intrusions were recognized. The hyaloclastites and pillow lavas have glassy texture. The interior parts of the pillow lavas have crystallised textures of tholeiite and are sometimes porphyritic. Volcanic breccia is characterised by abundant lithic fragments. The lava flows are tholeiitic and olivine tholeiitic in composition. Tholeiitic basalt is fine-grained and slightly richer in silica but poorer in sodium. It constitutes crystals of calcium-rich plagioclase, clino-pyroxene and magnetite. It also contains minor olivine. Olivine tholeiite is coarser grained with crystals of plagioclase, augite, and some olivine. Intrusive rocks are of more massive and fine to coarse-grained texture. They are relatively unaltered compared to the surrounding rocks. The intrusive bodies were intercepted at various depths. The lithological descriptions are based mostly on binocular microscopic analysis with additional information from petrographic identifications. The descriptions and characteristics of these series/units are as follows:

Hyaloclastite series I (above 48 m):
This volcanic hyaloclastite is divided into two main units: a) basaltic tuff at 4-12 m and 26-32 m depth, and b) basaltic breccias at 12-26 m and 32-48 m. The rock is plagioclase porphyritic, vesicular and very fresh. The voids are empty except for minor amounts of limonite and calcite. This hyaloclastite belongs to the Gráuhnúkar formation.

Basalt lava series I (48-106 m and 146-206 m):
This series includes sub-aerial lavas which lie below the Gráuhnúkar formation. It consists mainly of thick fine- to medium-grained basaltic lava flows. Between 106 and 146 m, there are not any cuttings. The entire unit is approximately 118 m thick. The flow unit consists of porphyritic olivine tholeiite lavas with phenocrysts of plagioclase and pyroxene, and with olivine and opaque minerals in the groundmass. Textural variation is interstitial to subophitic. A skeletal pattern is seen in a few phenocrysts of plagioclase and microcrystals of olivine. The basalt lava flows are moderately oxidized from the top to 206 m. The lava unit has oxidation colours of reddish cream to yellowish. This series is fresh.

Hyaloclastite series II (206-766 m):
This hyaloclastite is a predominantly glassy-basalt with basaltic breccias near the top. This series is composed of glassy basalt layers with a thickness of 177 m in all (at 268-297 m, 306-366 m, 396-472 m and 754-766 m); of basaltic breccia, in all 334 m thick (at 252-268 m, 300-366 m, 366-396 m and 472-754 m) and of basaltic tuff (between 206 and 252 m), i.e. 46 m thick.

Basalt lava series II (766-776 m):
This basalt layer is 10 m thick olivine tholeiite. It is assumed to be a sub-aerial lava flow. The alteration minerals are clay, limonite, thomsonite, analcime and heulandite.

Hyaloclastite series III (776-1178 m):
This series is a 402 m thick olivine tholeiite and is characterized by an alternating basaltic tuff, basaltic breccias and glassy basalt. The primary minerals are olivine, plagioclase, pyroxene and glass. The unit shows minor alteration in the upper segment but becomes moderately altered in the lowest segment where it has a bleached greenish colour. Olivine micro-crystals are partially to almost completely altered into clay. Micro-laths of plagioclase and glass are little to partially altered into clay, while the pyroxene and opaques are totally fresh. Mesolite, scolecite, heulandite, stilbite, laumonite, wairakite, chalcedony, quartz, clay, fine-grained clay, coarse-grained clay, prehnite, epidote, siderite, limonite and calcite are common. Mineral successions are typically clay, followed by zeolites or calcite, with calcite as the end-member.

Basalt lava series III (1178-1192 m):
This basalt layer is 14 m thick. It is composed of an aphyric fine- to medium-grained basalt. The basalt is moderately altered to greenish and brownish colours. Coarse-grained clay, wairakite,

laumonite and quartz are common. Calcite and pyrite veins are absent in this series and the vesicles are rare. The vesicles are partially or totally filled with calcite or clay.

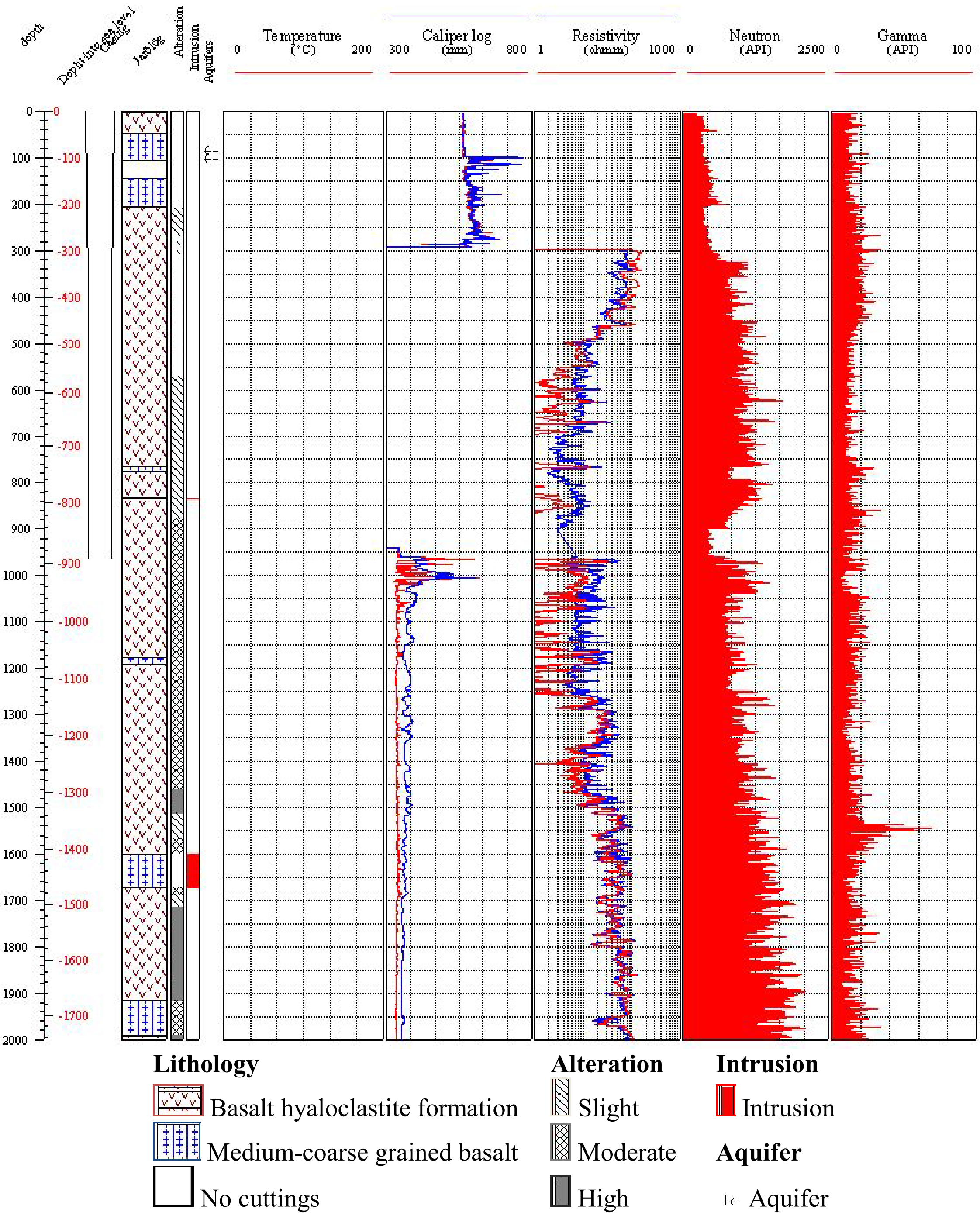

FIGURE 10: Simplified lithology and geophysical logs of well HN-08 (unpublished ISOR data)

Hyaloclastite series IV (1192-1916 m):
This series is aphyric and consists of alternating layers of basaltic tuff, basaltic breccias and glassy basalt. The sequence has a total thickness of about 724 m. The unit is moderately altered in the upper segment but becomes highly altered in the lowest segment where it has a bleached colour, greenish and creamy. Between 1508 and 1568 m, we have an acidic fine-grained rock which is moderately altered with abundant calcite. The basaltic tuff (206-252 m) is aphyric and totally fresh. The glassy

basalt (pillow basalt) is aphyric and the primary minerals are olivine, pyroxene, plagioclase and opaques. The basaltic breccia is also aphyric.

The unit is little altered in the upper segment but becomes moderately altered in the lowest segment. Olivine micro-crystals are altered into clay, the glass shows minor clay alteration and the plagioclase is totally fresh. Calcite, fine-grained clay (smectite), thomsonite, clay, stilbite, heulandite, mesolite (scolecite) are common. Mineral successions are typically of clay followed by calcite or zeolites, with zeolites as the end-member.

Petrographic interpretation of these layers indicates glassy to hypocrystalline and cryptocrystalline nature. It is made up of olivine, plagioclase, pyroxene, and opaque. The sequence is moderately altered with greenish-creamy and brownish colours. The secondary assemblage consists of clay, pyrite, epidote, magnetite, wairakite, quartz and wollastonite. Olivine micro-crystals are partially to totally altered into clay. Plagioclase crystals are slightly affected by calcite and clay alteration. Pyroxenes and opaques are relatively fresh. The alteration sequences in the upper portion are quartz → wairakite and fine grained clay → calcite → quartz.

Basalt lava series IV (1916-1990 m):
The series has a total thickness of about 74 m. The series has fine- to medium-grained textured basaltic lava flows with plagioclase, pyroxene and opaque. The basalt is moderately altered to greenish and brownish colours. Pyrite and calcite are moderately abundant but decrease with depth. The alteration mineralisation is typically calcite, clay, epidote, wairakite, and quartz. Large plagioclase phenocrysts are replaced mostly by clay. In the entire sub-unit, pyroxenes are very resistant to alteration, while opaques are altered to sphene. Epidote sometimes forms a radial-acicular habit but is not as common as quartz. The voids are partially or completely filled by quartz, epidote, calcite, or clay. Calcite, pyrite, and open vesicles appear. The mineral assemblages consist of simple sequences of epidote → quartz, epidote → clay, and epidote → wairakite.

Hyaloclastite series V (1990-2000 m):
Between 1990 and 2000 m, this series has basaltic breccias. The sequence is highly altered with greenish-creamy colours. The secondary assemblage consists of clay, epidote, wairakite and quartz.

3.3 Intrusive rocks

Generally, the intrusive rocks are identified as being massive, relatively low in alteration, and with coarser-grained texture than the surrounding wall rocks. Geophysical logs show intrusions in association with high neutron-neutron peaks and resistive anomalies. As mentioned earlier, the intrusions encountered in the Hengill-Hellisheidi geothermal field are made up of two types: fine-grained basaltic and andesitic-rhyolitic dykes/sills.

Intrusive unit (832-836 m):
This is a 4 m thick fine- to medium-grained basalt dyke intrusion. It consists of olivine tholeiite and is almost fresh.

Intrusive unit (1600-1674 m):
This is coarse-grained olivine tholeiite basalt with an apparent thickness of approximately 74 m, with plagioclase, phenocrysts, opaque and pyroxene. Epidote and quartz are abundant. This intrusive dyke is fresh to slightly altered.

4. HYDROTHERMAL ALTERATION

Hydrothermal alteration is a change in the textural, mineralogical, and chemical composition of the host rocks brought about by the action of hydrothermal fluids, steam and/or gas (Henley and Ellis, 1983; Hochstein and Browne, 2000). The hydrothermal fluids carry dissolved solids, either from a nearby igneous source or from leaching out of some nearby country rocks. The primary minerals are replaced by secondary minerals due to changes in the environmental conditions. Secondary minerals precipitate along open cavities, vesicular structures, and fracture zones in the wall rock formations.
The mineralogical alteration suites provide in-depth information on past and present characteristics, and an assessment of the characteristics of the geothermal system. The intensity or degree of alteration depends on several factors such as: permeability (related to gas content and hydrology of a system), temperature, duration of activity (immature or mature), rock composition, pressure, hydrothermal fluid composition (pH value, gas concentration, vapour- or water-dominated, magmatic, meteoric), a number of superimposed hydrothermal regimes (overprinting of alteration), and hydrology (Browne, 1978; Reyes, 2000; Franzson, 2008). Permeability and temperature play an important role in the stability of most hydrothermal minerals. Temperatures vary from <100 to >300°C. The degree of permeability is directly related to the intensity of the rock. The source of permeability may be faults and fractures zones, lithological contacts, formation permeability (clasts and breccia fragments), and paleosols (Reyes, 2000). The composition of fluids and gasses are extremely variable. These factors are comparatively interconnected to one another. The mineralogical and alteration signatures may vary from one geothermal system to another. The temperature vs. rock-mineral scale relationships of Icelandic geothermal systems are illustrated in Figure 11. The principal components, glass and olivine, are the first to alter at low temperature, followed by plagioclase and pyroxene at much higher degrees, and, finally, the ore and high-temperature minerals above 200°C (Pendon, 2006).

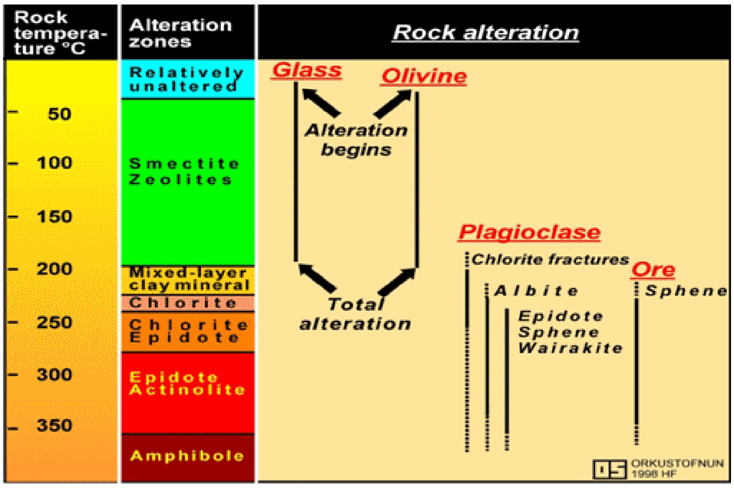

FIGURE 11: Mineral alteration vs. temperature diagram (Franzson, 1998)

4.1 Primary rock minerals

Most rocks in geothermal areas contain some primary minerals which are unstable in a geothermal environment. These have a tendency to be replaced by new minerals that are stable, or at least meta-stable, under the new conditions. The replacement hydrothermal minerals record the interactions between the wall rocks and the hydrothermal fluids, while space-fill minerals reflect the processes that affected the circulating fluids (Browne, 1978). The primary minerals in the rocks penetrated by well HN-08 (Table 1) are characterized by glass, olivine, plagioclase, pyroxene and opaques. The replacement of the minerals can best be studied by petrographic thin-section analysis. The primary minerals first began to alter intensively in this well below 892 m depth.

Glass: The most common replacement minerals of glass are clay minerals and calcite. It starts to alter to clay at approximately at 220 m depth, to calcite at 1122 m, and to quartz at 1178 m.

Olivine is the most unstable mineral. It was easily identified where the rock is olivine tholeiite basalt and in intrusions below 1600 m. The mineral starts to alter into clay at 380 m.

Plagioclase is common in the microcrystalline ground-mass and as phenocrysts in basalt. This is seen throughout the well where crystallisation has taken place. Plagioclase starts to alter commonly into clay below 946 m.

Pyroxene was observed as phenocrysts and in the ground-mass in this well. The pyroxene shows limited alteration.

Opaque minerals are slightly altered.

TABLE 1: Primary mineral alteration in well HN-08

Fresh/unaltered	Alteration products
Olivine	clay, calcite, quartz, wairakite, epidote
Plagioclase	Clay
Pyroxene	no alteration
Opaque	slightly altered
Glass	clay, calcite, quartz

4.2 Distribution of hydrothermal minerals

The distribution of hydrothermal alteration minerals of well HN-08 is shown in Figure 12. Results of XRD analysis of clay minerals on samples from well HN-08 are given in Appendix 1, with some examples from individual XRD runs also shown. The secondary mineralisation in the lithological successions is similar to other areas in the Hengill geothermal system. The minerals are calcite, quartz, zeolites, epidote, and a few other less abundant minerals. Below is a summary of the alteration products:

*Calcite***:** It is one of the most abundant and widely distributed secondary mineral. It occurs almost continuously in the entire upper 712 m starting at 216 m. It is very common in the pores of hyaloclastites and lava flows but less in the more compact intrusions. Calcite either occurs as a replacement of primary minerals or as a direct deposition mineral. The former type is commonly associated with plagioclase and glass with the presence or absence of other secondary minerals. An early generation of dog-tooth shaped calcite was observed underlying thin linings of clay and chalcedony in a thin section (1122 m). Calcite formation can be linked to boiling dilution and condensation of carbon dioxide in the geothermal system. It can also form during the heating of cooler peripheral fluids (Simmons and Christenson, 1994).

*Chalcedony***:** Chalcedony is one of the varieties of silica polymorph that have temperature equilibrium of less than 180°C (Fournier, 1985). It occurs in an interval depth from above 720 to about 966 m but below this depth chalcedony was replaced by quartz. In thin sections, it can be seen as a thin-layered lining in vesicles.

*Quartz***:** In well HN-08, quartz was first seen at a depth of about 536 m depth. It reappeared at about 876 m, and continued to 2000 m. Quartz has a temperature stability of >180°C. Quartz appears as euhedral to anhederal crystals, and crystallises in the form of mineral replacements. It is patchy, pervasive to total replacement of the glass matrix, and large olivine minerals are widespread. Short prismatic euhedral faces are very typical in amygdule, crystallising either in the outer rim or nucleus, as mono-mineral or with complex amalgamation of other secondary mineralisation. These associations of crystals consist usually of epidote, calcite, wairakite, and clay.

*Zeolites***:** Zeolites are a group of hydrated alumina-silicate minerals that have framework structures enclosing interconnected cavities occupied by large positively charged ions, generally of sodium, potassium, magnesium, calcium, barium and water molecules. It commonly and naturally forms in cavities of porous rocks during the alteration processes (Saemundsson and Gunnlaugsson, 2002). This group is temperature dependent and is used as geothermometer indicators of geothermal formations at temperatures below 200°C. The highest-temperature zeolites are laumontite (120-200°C) and wairakite (200-300°C). In well HN-08, quartz is widely seen as a pseudomorph from zeolites, indicating a temperature increase in the geothermal system. The following zeolites have been identified under the binocular and petrographic microscopes in well HN-08:

Thomsonite: This member of the zeolite family was observed in the thin section and binocular microscope at 380-768 m depth. It has radiating, elongated and slightly flattening crystal habits. Thomsonite crystallises at around 50°C.

Analcime: This mineral has a whitish-grey colour and is characterised by trapezohedron-sided crystal faces. It was observed at the depth between 270 and 752 m. Analcime has a temperature formation of about 50-70°C.

Scolecite: It was found in the thin section at 276-428 m with the last appearance at 892 m, being partially replaced by quartz, but the crystal figure/habit could still be recognised. Scolecite precipitates between ~80 and 120°C.

Mesolite: It was found in thin sections at a depth of 220-946 m. It is characterised by fibrous radiating clusters. Mesolite is finer and fainter in colour when compared to scolecite in a petrographic microscope. It forms at approximately 60°C.

Heulandite: This mineral was recognised in the binocular at the depth between ~876 and ~902 m and in the thin sections at the depth between 1318 and 1972 m; it has a platy tabular sheet-like and whitish-colour appearance. It has a crystallisation temperature of 90-120°C (Franzson, 1998).

Stilbite: Under the microscope, stilbite is characteristically radial and with fan-like aggregates, and shows good cleavage. Stilbite has been found at the depth interval 408-1178 m, and is indicative of the temperature range 90-120°C.

Wairakite: This mineral was found from the depth of ~800 m to the base of the analysed section at 1570 m. It has the petrographic distinguishing features of being colourless, low-birefringence, with recognisable perpendicular polysynthetic sets of twin lamella, comparable to the characteristics of microcline (Thomson and Thomson, 1996). The occurrence of wairakite represents a high-temperature environment of 200-300°C (Saemundsson, and Gunnlaugsson, 2002).

Epidote: Epidote is a common mineral in hydrothermal processes. It is a high-temperature mineral that has a lower temperature stability formation between 230 and 260°C in volcanic rocks (Browne, 1978), but in Iceland it forms at temperatures >240° (Franzson, 1998). In well HN-08, it appeared continuously from ~1392 m and down to 2000 m, showing as euhedral to subhedral minute prismatic and radiating needle-liked crystals. It is frequently observed associated with other alteration mineral assemblages such as quartz, calcite, clay or wairakite.

Prehnite: Prehnite begins to crystallise at temperatures above 200°C. Commonly, it is found in veins or vesicles, as seen in HN-08. The first appearance of prehnite was observed at 1066 m but it became more persistent below 1674 m. Normally, prehnite occurs along with epidote and other high temperature minerals and as a part of simple to complex mineral assemblages.

Wollastonite: This mineral is a hairy-like high-temperature mineral, first seen at 1438 m and continued to 2000 m. In the thin sections, wollastonite seemed to crystallise after epidote. The upper boundary of wollastonite indicates a temperature of around 270°C.

Limonite: This hydrated iron oxide mineral forms mostly due to the oxidation of iron and other metal minerals to cold meteoric water-rock interaction at a shallow depth, and with temperatures usually <80°C. In well HN-08, it started to appear and is common between 272 and 1002 m. It has a physical habit showing oolitic, spheroidal, and concentric patterns, which were deposited along the surface of the fragments, inside the vugs, and along the fracture zones.

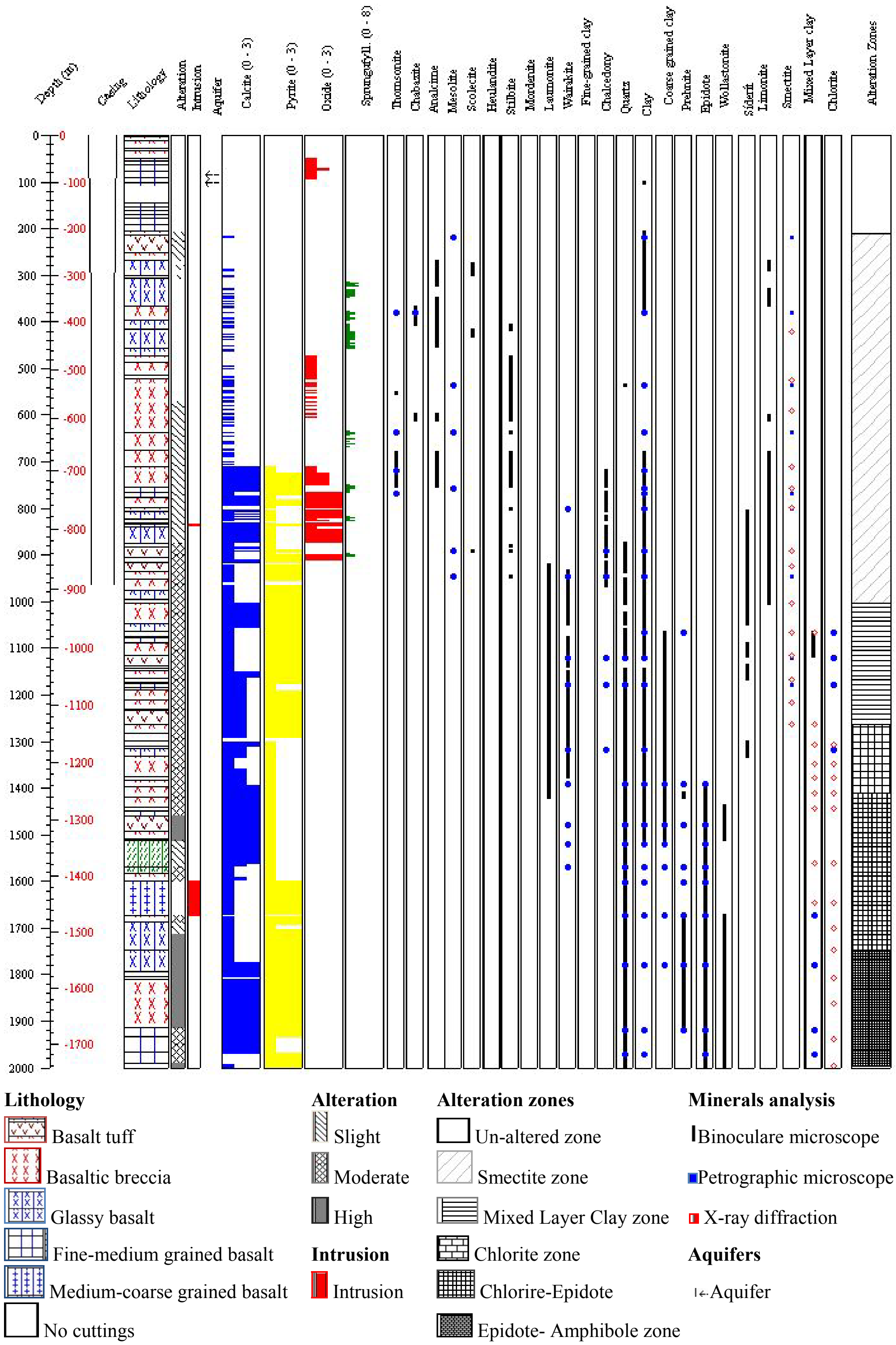

FIGURE 12: Distribution of hydrothermal alteration minerals in the top 2000 m of well HN-08; lithology and alteration below 1000 m is from ISOR (unpublished), except petrographic and XRD-analysis which are from this study

Clay minerals: Clay minerals are common and abundant alteration products in the hydrothermal system. It is the dominant mineral in both high- and low-temperature fields in Iceland (Kristmannsdóttir, 1977). These crystals are finely crystalline or meta-colloidal and occur in flake-like or dense aggregates of varying types. Primary minerals like olivine and plagioclase are altered to different types of clay. Volcanic glass transforms directly to clay. Clays precipitate as a direct replacement of earlier crystallised minerals, and as infillings in vesicles in the nucleus. The typical clay alteration products in Iceland consist of three types: smectite, mixed-layered clays, and chlorite. XRD analysis of the samples in well HN-08 showed smectite, mixed layered clays and chlorite (stable and unstable).

> *Smectite*: Smectite in well HN-08 has a thin-layer zone at about ~270 m depth. Under the microscope, smectite is fine-grained with a greenish-brown colour. It is deposited as a thin lining layer in vesicles and as a mineral replacement. In XRD it has a peak between 13.3 and 15.53 Å for untreated, 13.7 and 15.55 Å for glycolated, and 10.2 and 10 Å for a heated sample. Smectite forms at temperatures below 200°C (Franzson, 1998).
>
> *Mixed-layer clays:* Mixed-layer clay minerals are intermediate products of pure end-members of clays (Sradon, 1999). This type of clay was identified through the binocular microscope at 1066 m depth; from analysis of thin sections, it also appeared at depths of 1066 m, and in the XRD at 1044 m depth. Under plane polarized light, the clay showed strong pleochroism.
>
> *Chlorite*: Chlorite is the most extensive alteration product in HN-08. It appears immediately after the disintegration of mixed-layer clays at around 1392 m, and all the way down to 1780 m. Based on XRD analysis, chlorite is divided into a stable and an unstable type. In the upper layer, the first to crystallise is the unstable chlorite (~1306-1748 m). This chlorite has re-appearing reflection peaks at ~14.8 Å for air-dried, ~14.8 Å for ethylene glycolated, and collapses after being heated to 550°C. The collapse may be caused by the absence of Fe and Mg. Stable chlorite had re-appearing peak values of 14.8-15 Å in all treatments. Chlorite is characterised by fine- to coarse-grained textures, and petrographically with dull light green-greyish non-pleochroic colour. In the thin sections, it was observed that some of the unstable type had more dynamic pleochroic colours which resembled mixed-layer clays. The presence of chlorite is usually associated with other hydrothermal minerals in veins and vesicles. Chlorite has a crystallisation temperature above 230°C (Franzson, 1998).

4.3 Alteration mineral zonation

Some of the secondary minerals are good geothermometer indicators, being temperature dependent and crystallising at specific temperature ranges (Reyes, 2000). Minerals like clays, zeolites, prehnite, garnet, and amphibole contain OH or nx-H2O in their crystal lattices (Browne, 1978). In the Icelandic geothermal settings, low-temperature zeolites and amorphous silica form below 100°C, chalcedony below 180°C, quartz above 180°C, wairakite above 200°C, epidote above 240°C, and garnet and amphibole above 280°C (Saemundsson and Gunnlaugsson, 2002; Franzson, 1998). The clay minerals crystallise below 200°C for smectite, at 200-230°C for mixed layer clays, and above 230°C for chlorite (Kristmannsdóttir, 1977). In the uppermost 2000 m of HN-08, six mineralisation zones were recognized based on mineral-indice temperatures, crystallinity and abundance (Figure 12). These alteration zones are as follows:

Unaltered- zone, 0-210 m:
The formations down to 210 m depth contain no alteration that is related to hydrothermal activity.

Smectite-zeolite zone (<200°C), 210-1004 m:
This alteration zone is characterised by the presence of smectite coupled by low-temperature silica and some members of the zeolite group. This alteration assemblage covers the interval ~ 210-1004 m.

Mixed-layer clay zone (200-230°C), 1004-1264 m:
The mixed layer clay zone was identified only through the petrographic microscope at a depth of about 1100 m. The zone interval is probably approximately from 1004 to 1264 m. Under petrographic microscope, the clay is medium- to coarse-grained and has vibrant greenish-brownish pleochroic colours. The XRD results indicate more smectite type clay characteristics than chlorite. In this layer, quartz was becoming widespread. The mixed-layer clays have a temperature range between 200 and 230°C.

Chlorite zone (230-240°C), 1264-1410 m:
This zone is marked by the appearance of chlorite (unstable) together with abundant quartz and wairakite and extends from ~1264 to 1410 m. Under the petrographic microscope, some of the unstable chlorite crystals have almost the same characteristics as stable chlorite such as a dull green colour but, in some instances, with a faint pleochroic behaviour resembling the mixed-layer clays.

Chlorite - epidote zone (>240°C), 1410-1700 m:
This zone ranges between 1410 and 1700 m. It consists of chlorite with the appearance of abundant epidote coupled with wairakite and quartz at the upper level. The XRD analyses and interpretations show that chlorite has an unstable behaviour from 1410 to 1700 m depth, and then transforms into stable chlorite beyond 1562 m.

Epidote-amphibole zone (>260°C), 1700-1996 m:
This zone ranges between 1700 and 1996 m. It consists of epidote with the appearance of amphibole coupled with phrenite and quartz. The XRD analyses identified the apparition of amphibole at 1884 m depth.

4.4 Mineral deposition sequences and paragenesis

The hydrothermal mineralisation assemblages depend on the specific evolution and reactions with various factors such as temperature, fluid composition, rock types, the interaction between the hydrothermal fluids and the country rock, porosity and permeability of the rock, and duration of the interactions. Successive stages of mineralisation reflect the paleo-geothermal and present hydrothermal activities and environmental situations. The sequences may vary from simple to highly complex. The secondary mineralisation sequences may be reversed, repeated or parts may be missing entirely, depending on the specific evolution and its reactions to the precedent sealing mineral and/or minerals, and the host rock as a whole. In addition, precipitation of single mineral or mineral assemblages may be sealed at any point in the sequence and remain sealed, until being reactivated at a certain time and event in the geothermal system.

The study of the direct depositions and replacement of secondary mineralisation were analysed under the petrographic microscope. These mineral suites varied from low- to high-temperature environments but overprinting cannot be disregarded. The observed sequences range from simple bi-mineral assemblages to more complex mineral associations. It is also common to distinguish a single mineral with precipitation behaviour of multiple layers, particularly clay minerals. The secondary hydrothermal mineralisation sequences observed in well HN-08 are presented in Table 2.

Clays are seen forming as thin linings in the walls of the vesicles and veins or thicker and coarser-grained clays, usually with platy calcite as the dominant end-member of assemblages. Calcite and clays are present in the entire sequence. The appearance of calcite is relatively complicated. It crystallised mostly at the end of the sequence but also appeared in the beginning and middle of the assemblages. The presence of calcite at the end of the high-temperature mineral sequences may imply cooling. In the upper zone at ~720 m, fine-grained smectite prevailed, coupled with zeolites and chalcedony. A thin zone of mixed-layer clays appeared from the lower limit of smectite down to ~1066 m; below this zone, fine- and coarse-grained chlorite started to precipitate. Coarse-grained clay commonly succeeded the fine-grained clay. At a depth of 936 m, wairakite and quartz became part of the sequence down to 1150 m. They replaced the low-temperature zeolites, while chalcedony became pseudo-morphs of quartz. Epidote becomes common at 1392 m, and at a much deeper level, it succeeds wollastonite (Pendon 2006).

TABLE 2: Results of XRD analysis for the well HN-08 (unpublished ISOR data)

Sample	Depth m	d(001) OMH	d(001) GLY	d(001) HIT	d(002)	Mineral	Type	Remarks	Other minerals	Depth m
#01	210							no clay		
#02	422	13.3	13.7	10.2	0	Sm:sm	sm			
#03	526	15.3	15,4/16,3	10.2	0	Sm:sm	sm			
#04	590	13.05	13.9	10.2	0	Sm:sm	sm			
#05	712	15.4	17.2	10.5	0	Sm:sm	sm			
#06	758	12.97	13.54	10.1	0	Sm:sm	sm			
#07	798	13/14	13/14	10	0	Sm:sm	sm			
#08	892	15.2	15,2+	10	0	Sm:sm	sm			
#09	924	15.3	15,3+	10	0	Sm:sm	sm			
#10	978	15.27	15.55	10 vague	0	Sm:sm	sm			
#11	1004	15.09	15.29	10	0	Sm:sm	sm			
#12	1066	15.23	15.25	10	~small hump	Sm/ML: sm/ill/chl.	sm/MLC	signs of MLC		
#13	1116	15.6	15.6	10	0	Sm:sm	sm			
#14	1166	15.3	15.5	10	0	Sm:sm	sm			
#15	1216	15.3	15.5	10 vague	0	Sm:sm	sm			
#16	1264	15.53	15.55	10	~small hump	Sm/ML: sm/ill/chl.	sm/MLC	signs of MLC		
#17	1306	14.8	14.8	14/~12	7,27 HIT=0	Chl. +MLC.	Chl.+ MLC	unst. chlorite and MLC		
#18	1348	14.8	14.8	14/~12	7,27 HIT=0	Chl. +MLC.	Chl.+ MLC	unst. chlorite and MLC		
#19	1378	14.8	14.8	14/~12	7,27 HIT=0	Chl. +MLC.	Chl.+ MLC	unst. chlorite and MLC		
#20	1410	14.9	14.9	14.9	7,23 weak HIT=0	Chl. +MLC.	Chl.+ MLC			
#21	1444	31/14,9	31/14,9	14/~12	7,2 HIT=0	Chl. +MLC.	Chl.+ MLC	unst. chlorite and MLC		
#22	1562	31/14,9	31/14,9	14/~12	7,2 HIT=0	Chl. +MLC.	Chl.+ MLC	sam, but very little clay		
#23	1646	14.8	14.8	15	7,2 str. HIT=small	Chl. +MLC.	Chl.+ MLC			
#24	1700	14.8	14.8	15	7,2 st. HIT~0	Chl. unst.	Chl. unst.			
#25	1748	14.8	14.8	15	7,2 st. HIT~0	Chl. unst.	Chl. unst.			
#26	1808	14.8	14.8	15	7,2 st. HIT =med	Chl	Chl	amphibol 8.5Å	amphibol 8.5Å	
#27	1862	14.8	14.8	15	7,2 st. HIT=med	Chl	Chl	amphibol 8.5Å	amphibol 8.5Å	
#28	1938	14.8	14.8	15	7,2 str. HIT=small	Chl	Chl	amphibol 8.5Å	amphibol 8.5Å	
#29	1996	14.8	14.8	15	7,2 str. HIT=small	Chl	Chl	amphibol 8.5Å	amphibol 8.5Å	

4.5 Mineral deposition sequence

The mineral sequences deposited from the geothermal system into vesicles were studied petrographically. The results of that study are shown in Table 2. The depositional minerals were found mostly in vesicles. The alteration mineral assemblages change from low-temperature minerals such as zeolites to moderate- to high-temperature minerals with increasing depth, such as quartz, wairakite, and prehnite. Clay and calcite are the most common minerals participating in the mineral sequence in this well. The fine-grained clay is mostly found as thin linings in the walls of vesicles, associated or deposited after chalcedony, which is also found near the boundary of vesicles.

5. AQUIFERS

Aquifers are typically water-saturated regions in the subsurface which produce an economically feasible quantity of water to a well. The movement of sub-surface water is controlled by the type of rock formations, the characteristics of its permeability and porosity, the temperature and pressure of the sub-surface environment, natural recharge, and the hydraulic gradient. The presence of structural formations such as faults, fractures, and joints, lithological contacts, clasts and fragmented matrixes, and paleosols are positive indications of geothermal feed zones (Reyes, 2000). The formation of strong and good aquifers is very important in geothermal systems for the extraction of hydrothermal fluids and steam. The methods for determining the presence of aquifers include direct observation of circulation loss/gains, sudden changes in the rate of drilling penetration, and from geophysical measurements of temperature and calliper logging. Examination of rock cuttings is an indirect approach in determining aquifers. The presence of numerous shredded rocks (mylonites), abundant vein networks, drusy and a high concentration of alteration minerals are indications of the presence of a strong sub-surface hydrological circulation. Alteration minerals such as the crystallisation of quartz, adularia, anhydrite, wairakite, illite, hyalophane, abundant pyrite and calcite are also positive signs of good permeability. However, the absence of these alteration minerals, a low degree of alteration, the precipitation of prehnite, pumpellyite, pyrrhotite, and large quantities of laumontite and titanite can be attributed to a low-permeability zone (Reyes, 2000). Loss of circulation may vary from minor or weak loss, due to tight characteristics of the formation, to total circulation loss that is characterised by highly permeable formations. In the geothermal settings of Iceland, the highest permeable zones intercepted are associated with dykes and faults (Arnórsson, 1995; Pendon, 2006)

Two very small aquifers were identified at 85 and 102 m depth. Below that, just five feed zones were encountered at 446, 534, 832, 1115 and 1995 m depth. These were associated with circulation losses with a range of 2-3 l/s. The circulation losses ranged from very small to insignificant losses where a moderately permeable zone was encountered.

6. DISCUSSION

Generally, the stratigraphy of the upper 2000 m of well HN-08 consists mainly of hyaloclastites, with some basaltic lava flows and basaltic intrusions. The volcanic sequence is divided into four main units based on the textural differences and the intensity of alteration. The distinction of the volcanic sequences in the well is, though, predominantly based on whether they are aphyric or porphyritic. Thus, five hyaloclastite units (separate sub-glacial eruptions), one basalt unit and an intrusion could be identified in the well.

In well HN-08, the geological and hydrothermal alteration studies show that the degree and the intensity of rock alteration and the distribution of mineral alteration generally increase with depth. Below about 800 m depth, the degree of alteration increases rapidly both in temperature-dependent minerals and alteration intensity. The temperature can be been defined based on the hydrothermal alteration mineral temperature, with an assessment according to the first appearance of the alteration minerals. Table 3 shows the deposition sequence of secondary minerals in well HN-08.

Beside well HN-08, five wells were previously drilled in the Gráuhnúkar area, i.e. HN-03, HN-05, HN-06, HN-07, and HN-10 (Figure 7). HN-08 is a directional well drilled to the east like the others, with a total depth of 2576 m. The lithological formations encountered in the wells consist primarily of unaltered basaltic lava flows above almost 200 m depth but basaltic hyaloclastic rocks of breccia and tuff with intercalated fresh or altered basaltic lava flows at deeper levels. The rocks intercepted in the wells were almost the same sequences. However, in wells HN-08 and HN-05, the formations were intruded by some basaltic dykes of fine- to coarse-grained olivine tholeiite with an aphyric texture.

A comparison of common secondary minerals in wells HN-05 (ISOR, unpublished data) and HN-08 down to 1300 m depth is given in Figure 13, while Tables 4 and 5 show the results of XRD analysis from the two wells.

- Secondary mineralization starts with clay alteration at ~190 m in well HN-08 but at 90 m for well HN-05.
- Laumontite appears at ~930 m in well HN-08 but at ~880 m for well HN-05.
- Quartz appears at ~876 m in well HN-08 and at ~1060 m for well HN-05.
- Epidote appears at ~1392 m in well HN-08 but at ~1250 m in well HN-05.
- Finally, prehnite appears below 1300 m depth in both wells.

The secondary minerals observed with the binocular microscope are almost the same for the two wells, and the lithology is also almost same.
Comparison of the alteration zones in wells HN-08 and HN-05 gives the following comparisons:

- Smectite-zeolite zone (<200°C) is between 210 and 1004 depth in HN-08, but between 320 and 1194 m depth in well HN-05.
- The mixed-layer clay zone (200-230°C) is between 1004 m and 1264 m depth in well HN-08 but is not represented in well HN-05.
- The chlorite zone (230-240°C) appeared between 1264 and 1410 m in well HN-08 but between 1194 and 1242 m in well HN-05.
- The chlorite-epidote zone (>240°C) is between 1410 and 1700 m in well HN-08 and between 1256 and 1852 m for well HN-05.
- Finally, the epidote-amphibole zone (>260°C) is between 1700 and 1996 m for well HN-08 but between 1852 and 2010 m in well HN-05.

TABLE 3: Deposition sequence of secondary minerals in well HN-08

Depth (m)	**Mineral assemblages Early stage ⟶ Late stage**						**Degree of alteration**	**Rock types**
200							No alteration	Glassy basalt
220	Smec		Zeo			Cc	Slight	Breccias
380	Smec		Zeo			Cc	Slight	Breccia and pillow
536	Smec		Zeo			Cc	Slight	Pillow basalt
636	Smec		Zeo			Cc	Slight	Glassy basalt
720	Smec	Cc	Zeo			Cc	Slight	Breccia and pillow
756	Smec	Cc	Zeo			Cc	Slight	Breccia and pillow
768	Smec		Zeo			Cc	Slight	Pillow basalt
800	Smec		Zeo			Cc	Slight	Breccias
834	Chal	Cc	Zeo			Cc	Moderate	Glassy basalt
892	Chal	Fgc	Zeo			Cc	Moderate	Tuff and pillow
946	Chal	Fgc	Zeo			Cc	Moderate	Tuff and pillow
1066	Smec	Cc	Zeo			Cc	Moderate	Breccia
1122	Smec	Cc	Zeo			Cc	Moderate	Breccia
1178	Smec	Cc	Zeo	Qtz		Cc	Moderate	Breccia
1318	Chal	Fgc		Qtz			Moderate	Glassy basalt
1392		Fgc		Qtz	Wai		Moderate	Tuff and pillow
1478				Qtz	Wai	Cc	High	Breccia
1520				Qtz	Wai	Cc	High	Breccias
1570		Fgc				Cc	Slight	Intrusion
1602		Fgc				Cc	Slight	Intrusion
1674		Fgc		Qtz	Wai	Cc	Moderate	Pillow basalt
1780				Qtz	Wai	Cc	High	Glassy basalt
1918			Preh			Cc	Moderate	Breccia and lava
1972			Preh			Cc	Moderate	Breccias and lava

Explanation: Smec = smectite, Zeo = zeolite, Fgc = fine-grained clay, Cc = calcite, Qtz = quartz, Wai =wairakite, Preh = prehnite, Chal= chalcedony.

As can be seen from the comparison above, the alteration zones are almost the same for the two wells, except for the non-presence of the mixed-layer clay zone (200-230°C) in well HN-05. The amphibole appeared at 1808 m depth in well HN-08 and at 1884 m in well HN-05. In well HN-05, the aquifers are small and few, as in well HN-08.

7. CONCLUSIONS

The following conclusions can be deduced from the geological study of well HN-08:

1. The stratigraphy of the first 2000 m depth of well HN-08 consists of sub-glacial hyaloclastite formations, basaltic lava flows and a basaltic intrusion.
2. According to the distribution of alteration minerals, the following alteration zones were identified: a) a zone of no alteration above 210 m; b) the smectite-zeolite zone (<200°C) from 210 to 1004 m; c) the mixed-layer clay zone (200-230°C) from 1004 to 1264 m; d) the chlorite zone (230-240°C) from 1264 to1410 m; e) the chlorite-epidote zone (>240°C) from 1410 to 1700 m; and f) the epidote-amphibole zone (>260°C) from 1700 to 1996 m.

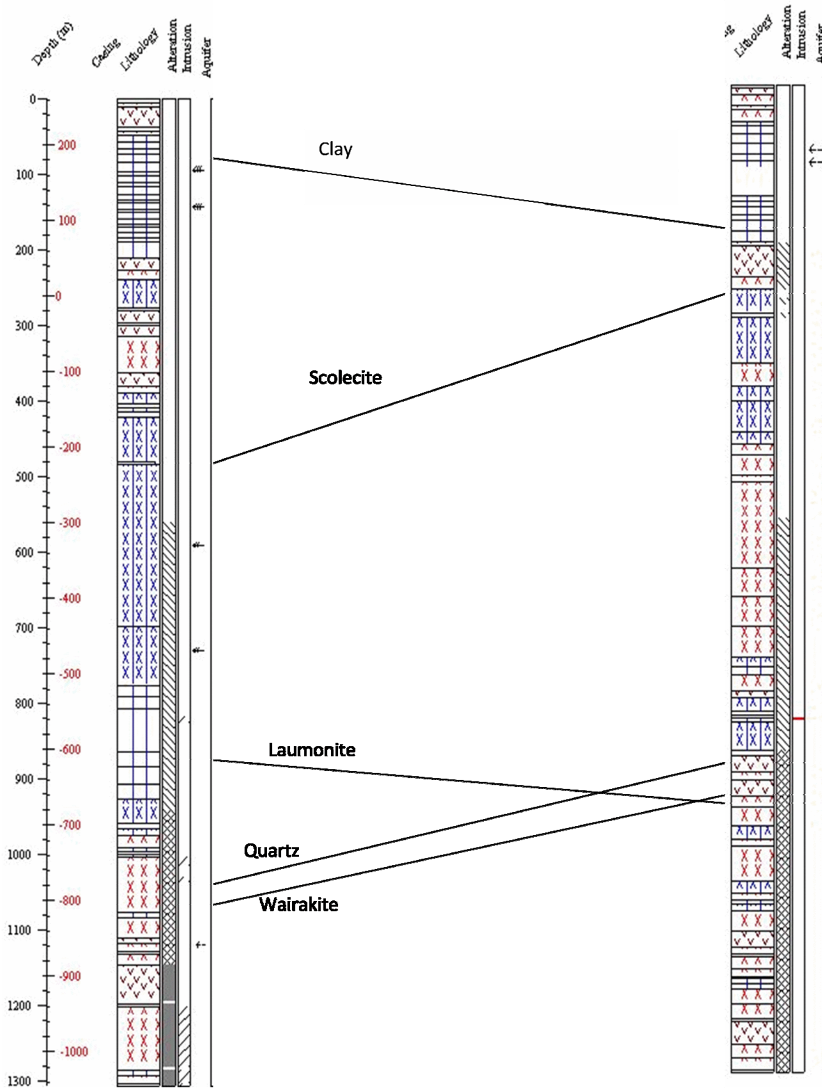

FIGURE 13: Comparison of some minerals of wells HN-08 and HN-05 (from ISOR, unpublished)

3. According to circulation loss data, temperature logs, and the intensity of alteration, two small aquifers were distinguished, located in the uppermost part of the well, but five minor feed zones were found at deeper levels.

4. By studying the hydrothermal alteration minerals, it was found that the temperature rises moderately but steadily from about ~230 to 940 m depth with the appearance of zeolites, quartz and wairakite. And generally, temperature as defined by the appearance of different alteration minerals, increases moderately in this well with the appearance of epidote and prehnite at 1392 m depth and wollastonite at 1438 m depth.

5. The correlation of the common secondary mineralogy and the alteration zones for the two wells HN-08 and HN-05 in the Gráuhnúkar geothermal field demonstrates similarity and moderately progressive alteration with increasing depth.

TABLE 4: Results of XRD analysis for well HN-05 (unpublished ISOR data)

Depth (m)	Type of clay	Alteration zones
320	Smectite	Smectite zone
358	Smectite	Smectite zone
406	Smectite	Smectite zone
466	Smectite	Smectite zone
490	Smectite	Smectite zone
512	Smectite	Smectite zone
574	Smectite	Smectite zone
668	Smectite	Smectite zone
844	Smectite	Smectite zone
890	Smectite	Smectite zone
922	Smectite	Smectite zone
972	Smectite	Smectite zone
1030	Smectite	Smectite zone
1050	Smectite	Smectite zone
1080	Smectite	Smectite zone
1100	Smectite	Smectite zone
1156	Smectite	Smectite zone
1194	Smectite	Smectite zone
1220	Chlorite- unstable	Chlorite-zone
1230	Chlorite- unstable.	Chlorite-zone
1242	Chlorite	Chlorite-zone
1256		
1310	Chlorite+ Epidote	Chlorite-Epidote zone
1336	Chlorite.+ Mixed-Layer-Clay+ Epidote	Chlorite-Epidote zone
1390	Chlorite.+ Mixed-Layer-Clay+ Epidote	Chlorite-Epidote zone
1432	Chlorite.+ Mixed-Layer-Clay+ Epidote	Chlorite-Epidote zone
1460	Chlorite.+ Mixed-Layer-Clay+ Epidote	Chlorite-Epidote zone
1502	Chlorite.+ Mixed-Layer-Clay+ Epidote	Chlorite-Epidote zone
1534	Chl. ill+ Epidote+ Epidote	Chlorite-Epidote zone
1550	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1602	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1648	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1690	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1800	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1852	Chlorite- unstable+ Epidote	Chlorite-Epidote zone
1884	Epidote+Amphibole	Epidote-Amphibole zone
1972	Epidote+Amphibole	Epidote-Amphibole zone
2010	Epidote+Amphibole	Epidote-Amphibole zone

TABLE 5: Results of XRD analysis for well HN-08

Depth (m)	**Type of clay**	**Alteration zones**
210		
422	Smectite	Smectite zone
526	Smectite	Smectite zone
590	Smectite	Smectite zone
712	Smectite	Smectite zone
758	Smectite	Smectite zone
798	Smectite	Smectite zone
892	Smectite	Smectite zone
924	Smectite	Smectite zone
978	Smectite	Smectite zone
1004	Smectite	Smectite zone
1066	Smectite/Mixed Layer Clay	Mixed Layer Clay zone
1116	Smectite	Mixed Layer Clay zone
1166	Smectite	Mixed Layer Clay zone
1216	Smectite	Mixed Layer Clay zone
1264	Smectite/Mixed Layer Clay	Mixed Layer Clay zone
1306	Chlorite.+ Mixed Layer Clay	Chlorite zone
1348	Chlorite.+ Mixed Layer Clay	Chlorite zone
1378	Chlorite.+ Mixed Layer Clay+ Epidote	Chlorite zone
1410	Chlorite.+ Mixed Layer Clay+ Epidote	Chlorite zone
1444	Chlorite + Epidote	Chlorite-Epidote zone
1562	Chlorite.+ Mixed Layer Clay+ Epidote	Chlorite-Epidote zone
1646	Chlorite.+ Mixed Layer Clay+ Epidote	Chlorite-Epidote zone
1700	Chlorite. Unstable+ Epidote	Chlorite-Epidote zone
1748	Epidote+Amphibole.	Epidote-Amphibole zone
1808	Epidote+Amphibole	Epidote-Amphibole zone
1862	Epidote+Amphibole	Epidote-Amphibole zone
1938	Epidote+Amphibole	Epidote-Amphibole zone
1996	Epidote+Amphibole	Epidote-Amphibole zone

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REFERENCES

Árnason, B., Theodórsson, P., Björnsson, S., and Saemundsson, K., 1967: Hengill, a high-temperature thermal area in Iceland. *Bull. Volcanologique, XXXIII-1*, 245-260.

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Th., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000*, *Kyushu-Tohoku, Japan,* 923-928.

Árnason, K., and Magnússon, I.Th., 2001: *Geothermal activity in the Hengill area. Results from resistivity mapping.* Orkustofnun, Reykjavik, report, OS-2001/091 (in Icelandic with English abstract), 250 pp.

Arnórsson, S., 1995: Geothermal systems in Iceland; structures and conceptual models; I, high-temperature areas. *Geothermics, 24,* 561-602.

Björnsson, A., Hersir, G.P., and Björnsson, G., 1986: The Hengill high-temperature area SW-Iceland: Regional geophysical survey. *Geoth. Res. Council, Transactions, 10,* 205-210.

Bödvarsson, G.S., Björnsson, S., Gunnarsson, Á., Gunnlaugsson, E., Sigurdsson, Ó., Stefánsson V., and Steingrímsson, B., 1990: The Nesjavellir geothermal field, Iceland. Part 1. Field characteristics and development of a three-dimensional numerical model. *J. Geotherm. Sci. and Tech., 2-3,* 189-228.

Browne, P.R.L., 1978: Hydrothermal alteration in active geothermal fields. *Annual Reviews of Earth and Planetary Science, 6,* 229-250.

Elmi H., D., 2008: *Geothermal resource assessment through well testing and production response.* University of Iceland, MSc thesis, UNU-GTP, report 1, in print.

Fournier, R.O., 1985: The behaviour of silica in hydrothermal solutions. *Rev. Econ. Geology, 2,* 45-61.

Franzson, H., 1998: Reservoir geology of the Nesjavellir high-temperature field in SW-Iceland. *Proceedings of the 19th Annual PNOC-EDC Geothermal Conference, Manila*, 13-20.

Franzson, H., 2008: *Borehole geology.* UNU-GTP, Iceland, unpubl. lecture notes.

Fridleifsson, G.Ó, Ármannsson, H., Árnason, K., Bjarnason, I.Th., and Gíslason, G., 2003: Part I: Geosciences and site selection. In: Fridleifsson, G.Ó. (ed.), *Iceland Deep Drilling Project, feasibility report.* Orkustofnun, Reykjavik, report OS-2003-007, 104 pp.

Garcia, S., Aranaud, N.O., Angelier, J., Bergerat, F., and Homber C., 2003: Rift jump process in Northern Iceland since 10 Ma from $^{40}Ar/^{39}Ar$ geochronology. *Earth Planet Sci. Lett., 214,* 529-544.

Gíslason, G., and Gunnlaugsson, E., 2003: Preparation for a new power plant in the Hengill geothermal area. *IGA News, 51*, 4-5.

Hardarson, B.S., Fitton, J.G., and Pringle, M.S., 1997: Rift relocation - a geochemical and geochronological investigation of a paleo-rift in northwest Iceland. *Earth Planet Sci. Lett., 153,* 181-196.

Harðarson, B.S., Helgadóttir, H.M., and Franzson, H., 2007: Hellisheidi power plant – the downflow area at Gráuhnúkar. ÍSOR, Reykjavík, report ÍSOR-2007/001 (in Icelandic), 29 pp.

Hartanto, D.B., 2005: Borehole geology and alteration mineralogy of the well HE-11, Hellisheidi geothermal field SW-Iceland, Report 8 in: *Geothermal training in Iceland 2005*. UNU-GTP, Iceland, 83-109.

Henley, R.W., and Ellis, A.J., 1983: Geothermal systems ancient and modern: a geochemical review. *Earth Science and Reviews, 19*, 1-50.

Hersir, G.P., Björnsson, G., Björnsson, A., 1990: *Volcanoes and geothermal systems in the Hengil area, geophysical exploration*. Orkustofnun, Reykjavik, report OS-90031/JHD-06 (in Icelandic), 92 pp.

Hochstein, M.P., and Browne, P.R.L., 2000: Surface manifestations of geothermal systems with volcanic heat sources. In: Sigurdsson, H. (editor), *Encyclopedia of volcanoes*. Academic Press, San Diego, California, 835-855.

Jones, J.G., 1969: Intraglacial volcanoes of the Laugarvatn region, Southwest Iceland, I. *Q.J. Geol. Soc. Lond., 124,* 197-211.

Kristmannsdóttir, H., 1977: Types of clay minerals in altered basaltic rocks, Reykjanes, Iceland (in Icelandic). *Jökull, 26,* 3-39.

LaFemina, P.C., Dixon, T.H., Malservisi, R., and Árnadóttir, T., 2005: Geodetic GPS measurement in South Iceland: Strain accumulation and partitioning in a propagating ridge system. *J. Geophy. Res. 110-B11405.*

Mortensen, A.K., Hardarson, B.S., Danielsen, P.F., Sigurdsson, Ó., and Kristinsson, B., 2006: *Ölkelduháls, well HE-22. Drilling for 22½" surface casing to 87 m and 18⅝" safety casing to 311 m depth.* ÍSOR, Reykjavík, report 2006/023, 46 pp.

Pendon R.R., 2006: Borehole geology and hydrothermal mineralisation of well HE-22. Ölkelduhals field, Hengill area SW-Iceland. Report 17 in: *Geothermal training in Iceland 2006*. UNU-GTP, Iceland, 357-390.

Reyes, A.G., 2000: *Petrology and mineral alteration in hydrothermal systems: from diagenesis to volcanic catastrophes.* UNU-GTP, Iceland, report 18-1998, 77 pp.

Saemundsson, K., 1967: *Vulkanismus und Tektonik des Hengill-Gebietes in Sudwest-Island*. Acta Nat. Isl., II-7 (in German), 195 pp.

Saemundsson, K., 1979: Outline of the geology of Iceland. *Jökull, 29,* 7-28.

Saemundsson, K., 1995: *Geological map of the Hengill area 1:50,000.* Orkustofnun, Reykjavík.

Saemundsson, K. and Gunnlaugsson, E., 2002: *Icelandic rocks and minerals*. Edda and Media Publishing, Reykjavík, Iceland, 233 pp.

Saemundsson, K., Snorrason, S.P., and Fridleifsson, G.Ó., 1990: *Geological map of the southern Hengill area, between Hengladalir and Krossfjöll*. Orkustofnun, Reykjavík, report OS-90008/JHD-02 B, 15 pp.

Simmons, S.F., and Christenson, B.W., 1994: Origin of calcite in a boiling geothermal system*. Am. Jour. Sci., 294,* 361-400.

Sradon, J., 1999: Nature of mixed-layer clays and mechanisms of their formation and alteration. *Annu.Rev. Earth Planet. Sci., 27,* 19-53.

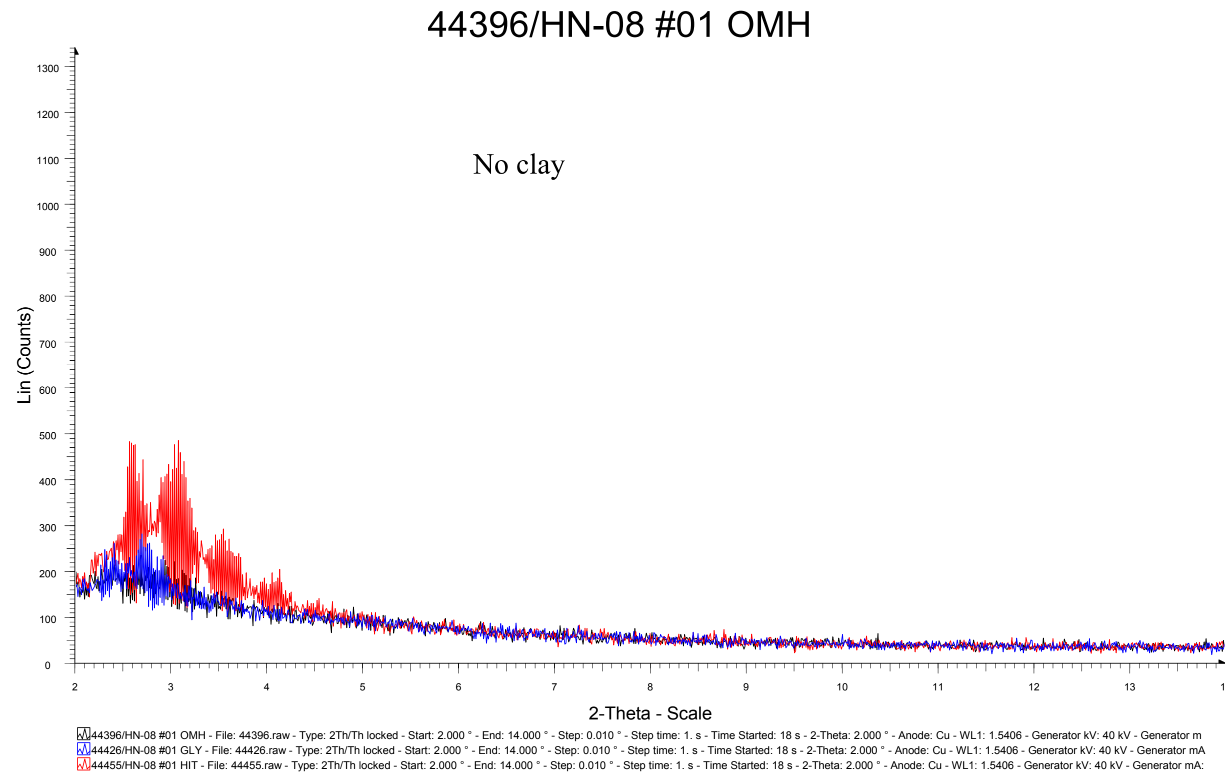
Thomson, A.J.B., and Thomson, J.F.H., 1996: *Atlas of alteration: A field and petrographic guide to hydrothermal alteration minerals.* Alphine Press Ltd., Vancouver, British Columbia, 119 pp.

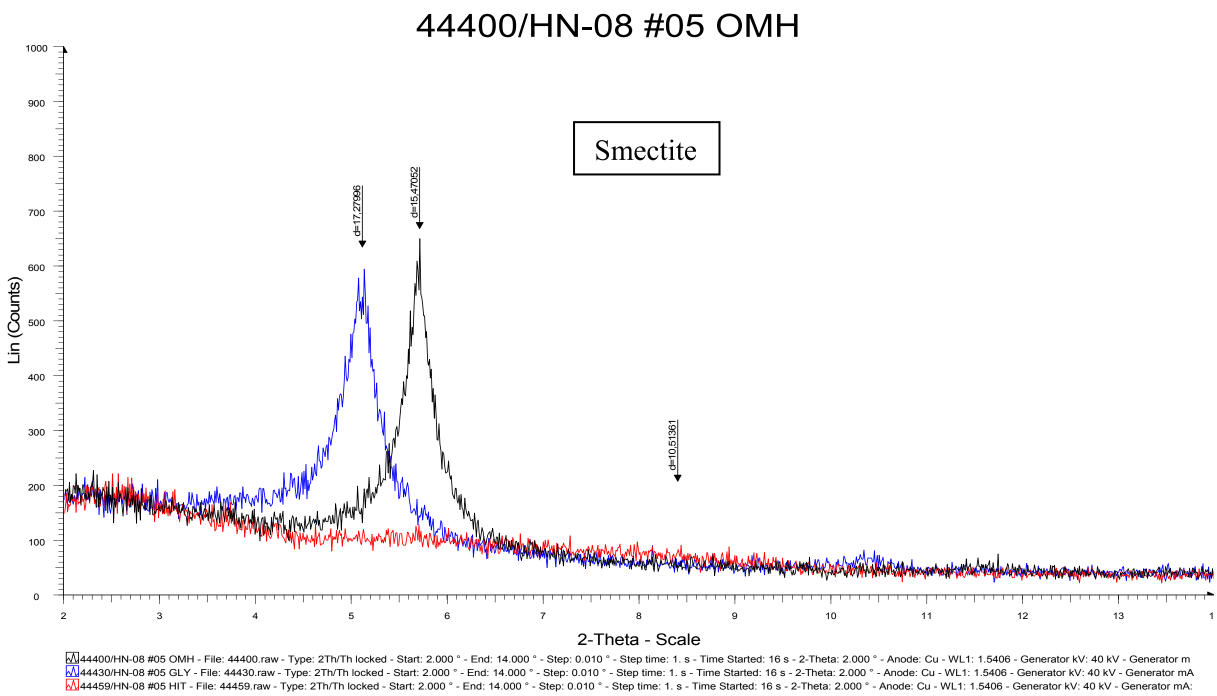
Vargas, J.R.M., 1992: *Geology and geothermal considerations of Krísuvik valley, Reykjanes, Iceland.* UNU-GTP, Iceland, report 13, 35 pp.

Wohltz, K., and Heiken, G., 1992: *Volcanology and geothermal energy.* University of California Press, Ca, 432 pp.

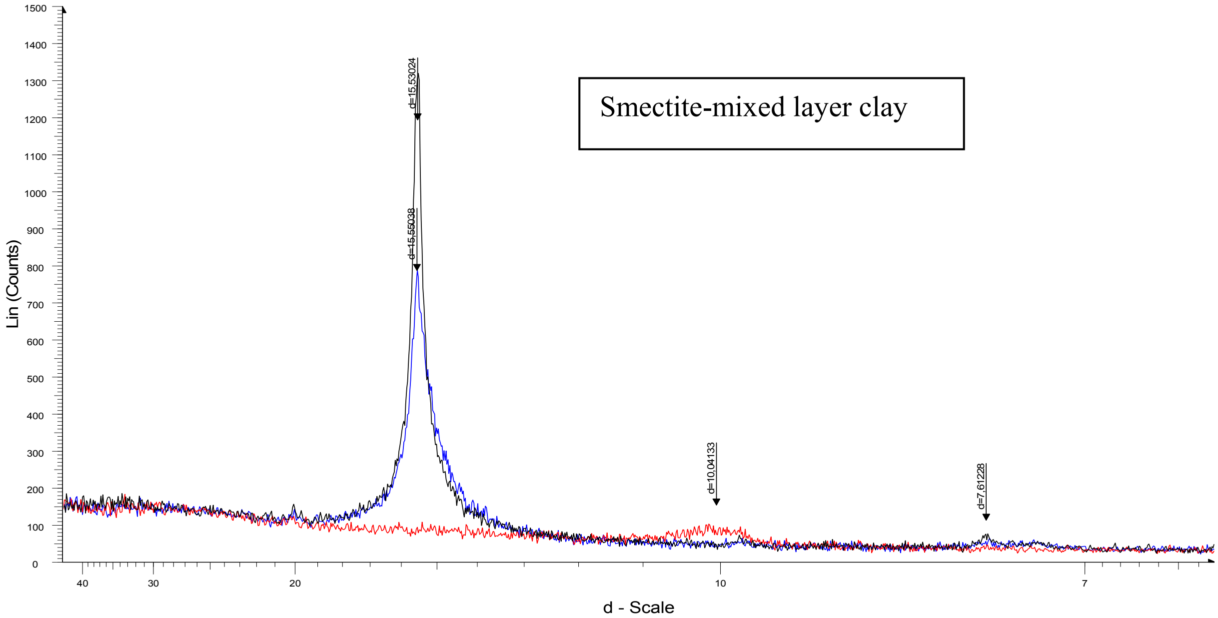
APPENDIX I: X-ray diffraction analyses of clay minerals of well HN-08

Depth (m)	Untreated (Å)	Glycolated (Å)	Heated (Å)	Type of clay
210				No clay
422	13.3	13.7	10.2	Smectite
526	15.3	15.4/16.3	10.2	Smectite
590	13.05	13.9	10.2	Smectite
712	15.4	17.2	10.5	Smectite
758	12.97	13.54	10.1	Smectite
798	13/14	13/14	10	Smectite
892	15.2	15.2+	10	Smectite
924	15.3	15.3+	10	Smectite
978	15.27	15.55	~10	Smectite
1004	15.09	15.29	10	Smectite
1066	15.23	15.25	10	Smectite-Mixed Layer Clay
1116	15.6	15.6	10	Smectite
1166	15.3	15.5	10	Smectite
1216	15.3	15.5	~10	Smectite
1264	15.53	15.55	10	Smectite- Mixed Layer Clay
1306	14.8	14.8	14/~12	Chlorite- Mixed Layer Clay
1348	14.8	14.8	14/~12	Chlorite- Mixed Layer Clay
1378	14.8	14.8	14/~12	Chlorite- Mixed Layer Clay
1410	14.9	14.9	14.9	Chlorite- Mixed Layer Clay
1444	31/14.9	31/14.9	14/~12	Chlorite- Mixed Layer Clay
1562	31/14.9	31/14.9	14/~12	Chlorite- Mixed Layer Clay
1646	14.8	14.8	15	Chlorite- Mixed Layer Clay
1700	14.8	14.8	15	Unstable Chlorite
1748	14.8	14.8	15	Unstable Chlorite
1808	14.8	14.8	15	Chlorite
1862	14.8	14.8	15	Chlorite
1938	14.8	14.8	15	Chlorite
1996	14.8	14.8	15	Chlorite


44396/HN-08 #01 OMH
No clay
Lin (Counts)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
2
3
4
5
6
7
8
9
10
11
12
13
1
2-Theta - Scale
44396/HN-08 #01 OMH - File: 44396.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 18 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator m
44426/HN-08 #01 GLY - File: 44426.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 18 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA
44455/HN-08 #01 HIT - File: 44455.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 18 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA:

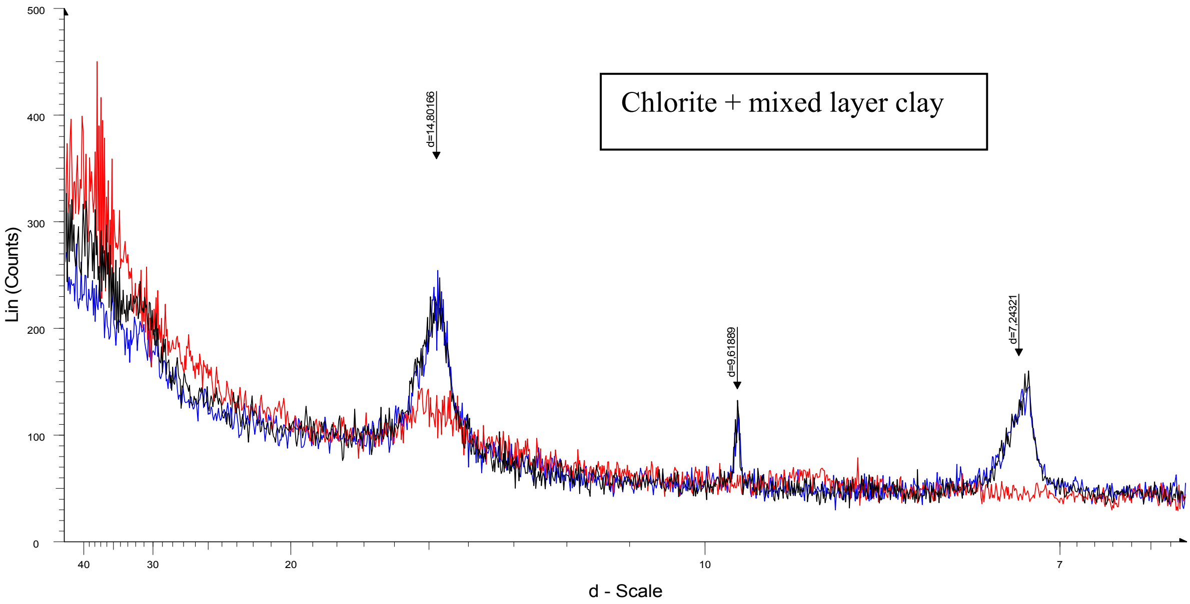

44400/HN-08 #05 OMH
Smectite
d=17,27996
d=15,47052
d=10,51361
Lin (Counts)
1000
900
800
700
600
500
400
300
200
100
0
2
3
4
5
6
7
8
9
10
11
12
13
1
2-Theta - Scale
44400/HN-08 #05 OMH - File: 44400.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator m
44430/HN-08 #05 GLY - File: 44430.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA
44459/HN-08 #05 HIT - File: 44459.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA:

44411/HN-08 #16 OMH

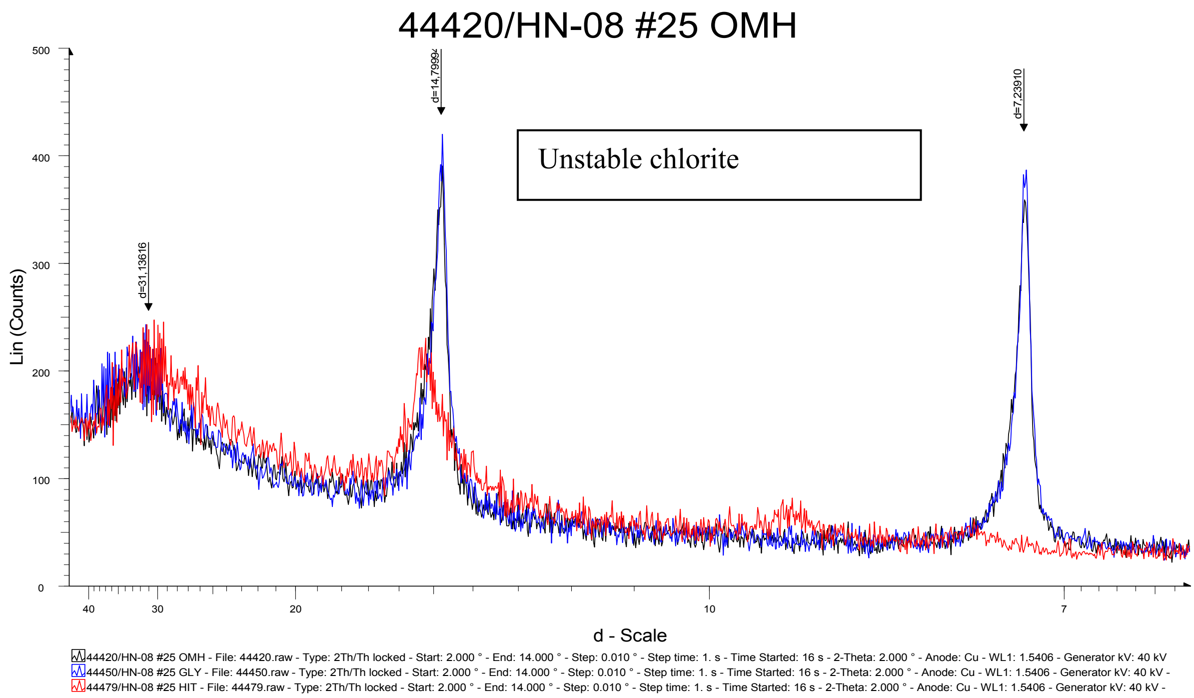


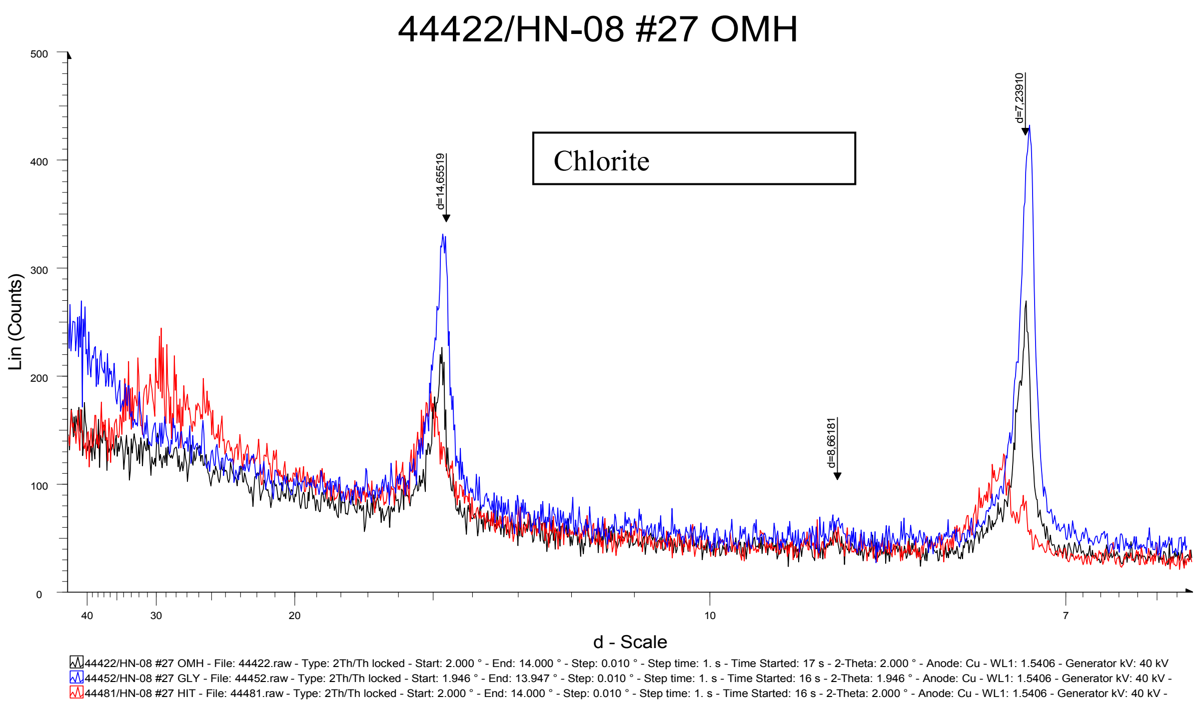
44411/HN-08 #16 OMH - File: 44411.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator m
44441/HN-08 #16 GLY - File: 44441.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 15 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA
44470/HN-08 #16 HIT - File: 44470.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV - Generator mA:

44413/HN-08 #18 OMH



44413/HN-08 #18 OMH - File: 44413.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV
44443/HN-08 #18 GLY - File: 44443.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -
44472/HN-08 #18 HIT - File: 44472.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -


44420/HN-08 #25 OMH
Unstable chlorite
d=31.13616
d=14.7999
d=7.23910
Lin (Counts)
500
400
300
200
100
0
40
30
20
10
7
d - Scale
44420/HN-08 #25 OMH - File: 44420.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV
44450/HN-08 #25 GLY - File: 44450.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -
44479/HN-08 #25 HIT - File: 44479.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -


44422/HN-08 #27 OMH
Chlorite
d=14.65519
d=8.66181
d=7.23910
Lin (Counts)
500
400
300
200
100
0
40
30
20
10
7
d - Scale
44422/HN-08 #27 OMH - File: 44422.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 17 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV
44452/HN-08 #27 GLY - File: 44452.raw - Type: 2Th/Th locked - Start: 1.946 ° - End: 13.947 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 1.946 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -
44481/HN-08 #27 HIT - File: 44481.raw - Type: 2Th/Th locked - Start: 2.000 ° - End: 14.000 ° - Step: 0.010 ° - Step time: 1. s - Time Started: 16 s - 2-Theta: 2.000 ° - Anode: Cu - WL1: 1.5406 - Generator kV: 40 kV -