UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Report 2012
Number 13

OCCURRENCE AND SIGNIFICANCE OF HYDROTHERMAL ALTERATION IN ACTIVE GEOTHERMAL SYSTEMS: A CASE STUDY OF WELL HN-7, HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND AND SURFACE EXPLORATION AT KARISIMBI GEOTHERMAL SYSTEM, NW-RWANDA

Sancta Marie Providence Isimbi
Ministry of Infrastructure
Energy Water and Sanitation Authority
Geothermal Development Division
P.O. Box 537, Kigali
RWANDA
isantap@yahoo.fr

ABSTRACT

Various methods and techniques are used in geothermal exploration to evaluate geothermal systems and understand geothermal reservoir zones. Investigating hydrothermal alteration is one of these methods which can provide direct information about geothermal reservoirs because geothermal fluids, by interaction, can change the composition and properties of rocks. This results in the formation of hydrothermal alteration minerals, some of which are known to form at specific and stable temperature regimes. Thus, they can provide a base for mapping the temperature regimes of a geothermal system. Analysis of hydrothermal alteration can start during surface exploration where hydrothermal deposits are found. Generally, however, this method is more commonly used during exploration/production drilling of geothermal wells.

Petrographic analysis of drill cuttings from well HN-7, Hellisheidi high-temperature field, SW Iceland, was conducted to analyse the hydrothermal alteration in the uppermost 1200 m of the well. Identification and interpretation of hydrothermal alteration is an important part of geothermal exploration, either on the surface or the subsurface, as it gives insight into the present and past conditions of geothermal reservoirs. Based on the petrographic analysis of samples from rock formations drilled through in the uppermost 1200 m of well HN-7, the rocks consist of fine- to medium-grained basalt, overlaying consecutive layers of basaltic breccia and tuff, referred to as hyaloclastite, and pillow basalt. The study of hydrothermal alteration minerals revealed a medium temperature environment (maximum 140°C) for the upper 700 m. The alteration minerals in this zone are mainly zeolites like chabazite, thomsonite, mesolite and scolecite along with fine-grained clay, evaluated in XRD as being smectite. Fine-grained clay changes to coarse-grained clay with depth, and certainly with increased temperature, and along with other minerals like laumontite, the clay constitutes a transition to a high-temperature environment which is evidenced by high-temperature hydrothermal alteration minerals such as quartz (>180°C), wairakite (>200°C), prehnite (>240°C) and epidote (~250°C).

1. INTRODUCTION

Investigations of geothermal resources are often divided into surface and sub-surface exploration. Early investigations are generally concerned with exploration on the surface; later sub-surface exploration takes over when drilling into the geothermal system starts. Direct measurements can be carried out for further exploration and the evaluation of the geothermal system through log analysis of sub-surface geology (Steingrímsson, 2011). This report is the result of a 6 month period of training in borehole geology at the UNU Geothermal Training Programme in Reykjavik, Iceland, where a practical study was carried out on cuttings from well HN-7, situated in the Gráuhnúkar sector, Hellisheidi high-temperature field.

The aim of the project is to gain knowledge and experience in methodology for use in sub-surface exploration of a geothermal system. This is advisable since geothermal exploration in Rwanda is in its early stages with exploration drilling starting in 2013. The study is mainly concerned with:

- Analysis using binocular stereo-microscope of drill cuttings taken every 2 m in the well;
- Petrographic analysis of 24 thin sections from the drill hole;
- XRD analysis of clay minerals;
- Comparative analysis of geophysical logs and sub-surface geological analysis.

The topic of the occurrence and significance of hydrothermal alteration minerals was chosen because of their principal role in understanding and evaluating geothermal systems. Commonly, fluid and reservoir rocks in an active geothermal system react together, resulting in changes in the composition of both rocks and fluids, consequently, hydrothermal minerals form, which can be used to gain insight into the present and past conditions in geothermal reservoirs (Browne, 1984a). Analysis of hydrothermal alteration for geothermal exploration could start during surface exploration in areas with geothermal manifestations, i.e. hydrothermal deposits (e.g. travertine) and hydrothermal eruption breccia, where lithology and hydrothermal alteration serve as guides to the nature of the reservoir rocks and physicochemical conditions in the sub-surface. This is because geothermal systems can exist for several hundred thousand years and an exploitable reservoir can persist at depth long after thermal activity ceases at the surface (Browne, 2011a). Further investigations of hydrothermal alteration continue in drill holes using cuttings of the geological formations that were drilled through. When brought to the surface, they are analysed to determine the lithology and alteration of the rock, caused by thermal fluid passing through, as hydrothermal minerals are known to form at specific and stable temperature regimes therefore they can be used to map the temperature regimes of geothermal systems (Frolova et al., 2010).

The identity and abundance of hydrothermal minerals produced during the fluid/rock interactions depend upon several factors: the composition of primary rocks; temperature; pressure and composition of thermal fluids; duration of fluid-rock interaction; fluid phase; and whether or not boiling occurs (Frolova et al., 2010 and Browne, 1984a). Therefore, mineralogical estimates of sub-surface formations can be used to measure various parameters in order to estimate the reservoir´s natural conditions, pressure and temperature being the most important in geothermal systems. Hydrothermal minerals could also be used to deduce permeability within a system as one of the important parameters which drive a system.

The objective of this study is to comprehend the importance of hydrothermal alteration mineral analysis in estimating: the natural geothermal conditions of a geothermal system via the type, extent and relative amount of the overall alteration within the geological formations of well HN-7; the relative amount and mineralogy of veins and open space fillings and; the methodologies to identify alteration.

1.1 Scope of study

The case study, well HN-7, is a reinjection well situated in the Gráuhnúkar sector, Hellisheidi high-temperature field which is one of the biggest high-temperature geothermal fields in Iceland within the

Hengill volcanic system, SW Iceland. This practical study aims at getting an overview of the methodology of hydrothermal alteration identification, the significance of hydrothermal alteration minerals in a geothermal system, and how they could be used to reach a more thorough geological understanding of geothermal reservoirs. Geothermal drilling is scheduled to start in the Karisimbi prospect in NW-Rwanda in 2013, and these methods are expected to be used there for the same purpose.

Physical and chemical analyses of cuttings are frequently imperative in locating and characterizing a sub-surface resource as well as giving useful insights on sub-surface geology (Doveton, 1984). The methodology used here for determining the lithology and alteration of the rocks is:

1. The stereo- (or binocular) microscope;
2. The petrographic microscope;
3. The X-ray diffraction.

However, accurate identification of lithology, alteration minerals, and faults and fractures from cuttings is sometimes limited by different barriers. Some of the rocks encountered in geothermal and mineral exploration boreholes (such as gneisses and granitic rocks) can resemble one another closely in cuttings even though they are dissimilar in outcrops or core samples. In such cases, the actual rock type(s) in a cutting sample generally can be determined by using various geophysical and other well logs. Faults and fractures, which are commonly the dominant physical controls on geothermal and mineral resources, often produce no apparent direct evidence in the cuttings. They are, therefore, best recognized indirectly by responses on appropriate geophysical well logs (Hulen and Sibbet, 1981). Thus, additional complementary measurements are used:

4. Temperature logs;
5. Resistivity logs;
6. Natural gamma ray logs;
7. Neutron-Neutron porosity logs.

The application of this methodology in geothermal investigation will be discussed later in Section 4.

2. KARISIMBI GEOTHERMAL PROSPECT, NW-RWANDA

2.1 Brief description regional geology of Rwanda

Rwanda is located at the western branch of the East African Rift System (EARS) which is considered to be a developing divergent, tectonic plate boundary dividing the African plate into two new plates, namely the Nubian and Somalian sub-plates or proto-plates. The Rift extends 6,000 km from northern Syria to central Mozambique and splits into two main branches - the Eastern Rift Valley and the Western Rift Valley. The latter, also referred to as the Albertine Rift, is confined by some of the highest mountains in Africa (Virunga Mountains, Mitumba Mountains, and Ruwenzori Range) and contains the Rift Valley lakes, among which is the world's deepest lake (e.g. Lake Tanganyika, -1.470 m), formed as a result of the rifting. There is an indication that oceanic crust generation has begun. The current situation of the EARS shows a rifting phase, which is the first step of a sea opening, and the intrusion of alkaline magma (Jolie et al., 2009).

The oldest rocks of Rwanda are migmatites, gneisses and mica schists of the Paleoproterozoic Ruzizian basement overlain by the Mesoproterozoic Kibaran Belt. The Kibaran, composed of folded and metamorphosed sediments, mainly schists and quartzites intruded by granites, covers most of Rwanda. Cenozoic to Recent volcanic rocks occur in the northwest and west. Some of these volcanics are highly alkaline (Figure 1) and are extensions from the Birunga volcanic area of southwestern Uganda. Tertiary and Quaternary sediments fill parts of the Western Rift in the western part of the country. In addition to the acidic intrusions, the geology of Rwanda shows a lot of intrusive mafic and / or ultra-mafic rocks

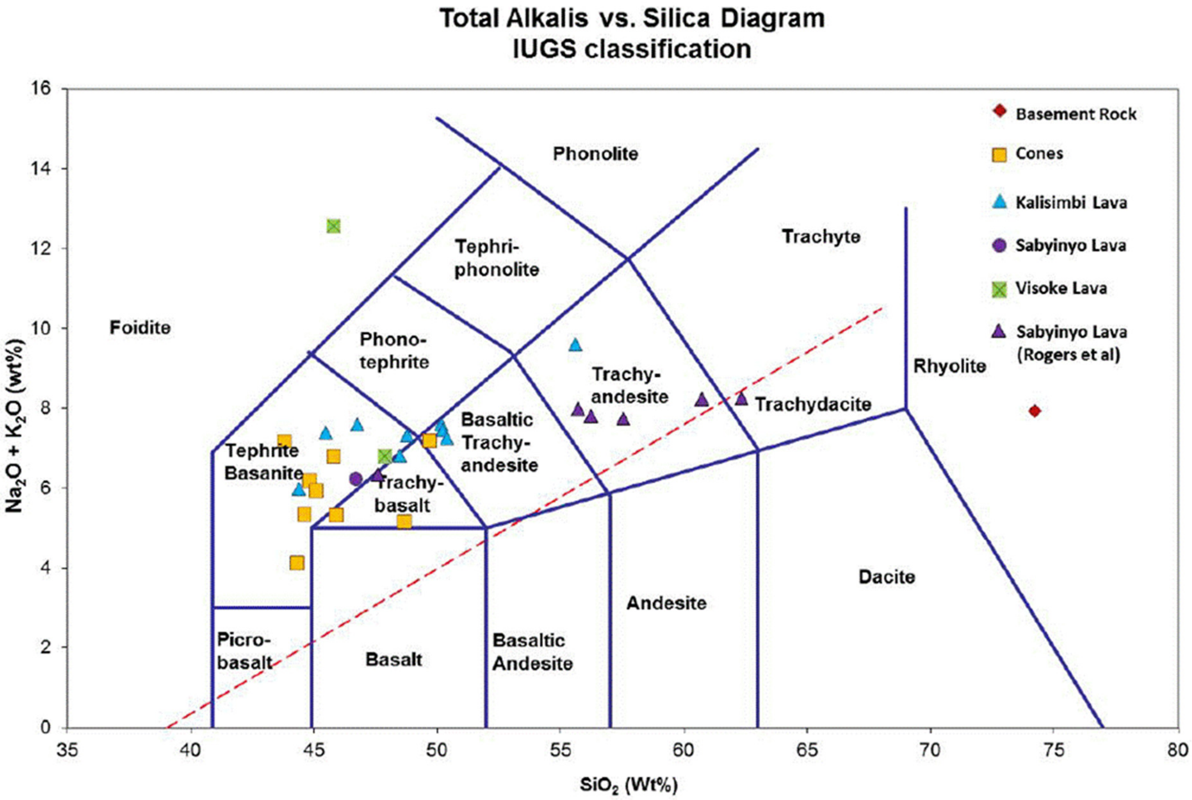


FIGURE 1: Chemical analysis of volcanic rocks in Northwest Rwanda, where the northern geothermal prospect is located (Shalev et al., 2012)

i.e. metadolerites, diorites and amphibolites (sills and dykes). These are especially located in Nyamiyaga and Musaza (southeast of Rwanda) not far from the Tanzanian border and disseminated throughout the country.

Two main recent volcanic areas appear in the southwest and northwest areas bordering Lake Kivu:

- The southern part covers about 5,500 km^2. Its topography does not show volcanic cones. The volcanism in this area occurred entirely through fissures.
- In the northern part, however, appears an east to west row of eight volcanic cones which extends to 80 km as shown in Figure 2. They are perpendicular to the Bufumbira depression and cover 3,500 km^2. Nyamuragira (3,058 m a.s.l.) and Nyiragongo (3,425 m) inside the rift valley axis; Mikeno (4,437 m) in the Democratic Republic of Congo (DRC); Karisimbi (4,507 m) and Bisoke (3,711 m) which serve as a natural border between Rwanda and DRC; Sabyinyo (3,674 m) common to Rwanda, DRC and Uganda; and both Gahinga (3,474 m) and Muhabura (4,127 m) on the border between Rwanda and the Republic of Uganda.

Nyiragongo and Nyamuragira in DRC are the only volcanoes still active in this range. That activity is confirmed by recent respective eruptions (Figure 2); earthquakes are known to occur in areas of Rwanda and other parts of East Africa with apparent association with the major rifts. The highest magnitudes recorded during the last 10 years from1988 to 2008 are the April 2003 earthquake (5.4 Richter) which destroyed houses southwest of Rwanda and the February 3rd, 2008 (6.0 Richter) which caused a lot of damage in the southwest where the Mashyuza geothermal field is located. As shown on the map of 1963-1976 seismic records, the depth of the hypocenters varies between 4 and 40 km. Tectonic movements, magmatic intrusion, and transform zones are the most important causes of earthquakes in the great lakes region (source: various monthly reports of Rwanda geology and mining authority, OGMR, 2009).

2.2 Current situation on geothermal exploration in Rwanda

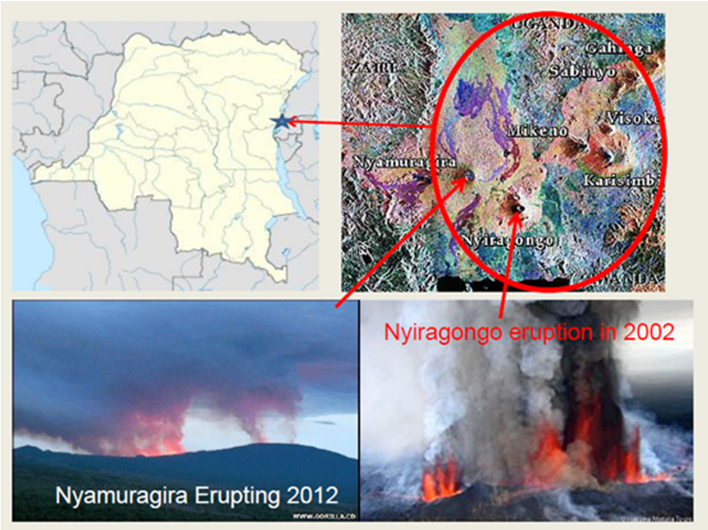


FIGURE 2: The Western Africa Rift valley Birunga volcanic range (Maps and photos from Wikipedia, 2012; NASA, 1999, Airlines and Destinations, 2012; Scienceblogs, 2012)

Rwanda is one of the African countries with potential prospects for geothermal resource utilization. In order to exploit the resources, the Rwandan Government, in partnership with the German Government through the Federal Institute for Geosciences and Natural Resources (BGR), made plans to assess the geothermal resource in the Northern volcanic zone. In the frame of the joint project, a remote sensing survey, a geochemical analysis and a geophysical reconnaissance survey were carried out (Jolie et al., 2009). The surveys covered an area of about 600 km^2, providing information on a regional scale and dividing the geothermal prospect into two prospects. The northern prospect associated with volcanoes includes three areas, namely Gisenyi, Karisimbi and Kinigi; the southern prospect is associated with faults in the East African Rift. Preliminary results indicated that a medium-temperature geothermal system might exist southwest of Karisimbi Volcano. Some geochemical studies expected the reservoir temperature to be in the range of 180-220°C, whereas other detailed studies suggested lower temperatures of 105-140°C.

Later in 2011, geological and geochemical studies were required to comment on several aspects of the geology that related to geothermal mineral alteration and likely reservoir conditions in the sub-surface of the two prospects. The geothermal prospects in Rwanda have many of the attributes needed to host exploitable geothermal reservoirs. The Western Rift Valley is tectonically and volcanically active and faulting is of the type (normal) that creates permeable channels. The areas have high rainfall implying that recharge water would be available to sustain a geothermal system. But the puzzle was why there were so few thermal manifestations. The only surface manifestations are hot springs, a travertine deposit, and vein fillings in eroded granite. The survey came up with the information that the geological regime in northwest Rwanda is favourable for the presence of a geothermal resource, as are the southwest prospects in the Bugarama graben which also occur in a tectonically active location. Analyses of lavas from Karisimbi suggest they may derive from a magma that differentiated at depth in the crust; if so, the magma there may provide heat energy for a convecting geothermal system (Browne, 2011a).

However volcanic rocks derived from Karisimbi volcano have not been hydrothermally altered and temperatures interpreted by silica and cation geothermometry may be misleading, as the volcanic rocks do not contain quartz, and fluids in the plutonic rocks may have re-equilibrated while they ascended too slowly to retain temperatures from greater depths. The next step was then to make additional geophysical measurements, as geophysical techniques were considered the most effective exploration method for evaluating geothermal conditions. These should be aimed at locating a reservoir as well as its up- and outflow zones. They should also seek to identify the presence of magma in the crust near Karisimbi.

Consequently, in 2012, detailed geoscientific surveys in the Karisimbi, Gisenyi and Kinigi geothermal prospects were carried out, concluded by drilling three exploration wells to evaluate potential geothermal reservoirs and to better understand the geothermal prospects (Figure 3). These should reach the potential rocks and provide temperature, and rock and fluid samples that could expand the understanding of the geothermal potential of the prospects (Shalev et al., 2012). The scope of the geoscientific studies included geology, geochemistry, hydrogeology, environmental and geophysical studies (including magnetotelluric (AMT and MT), transient electromagnetic (TEM), controlled source audio magnetotelluric (CSAMT), heat flow, gravity and magnetics and microearthquake (MEQ) data acquisition).

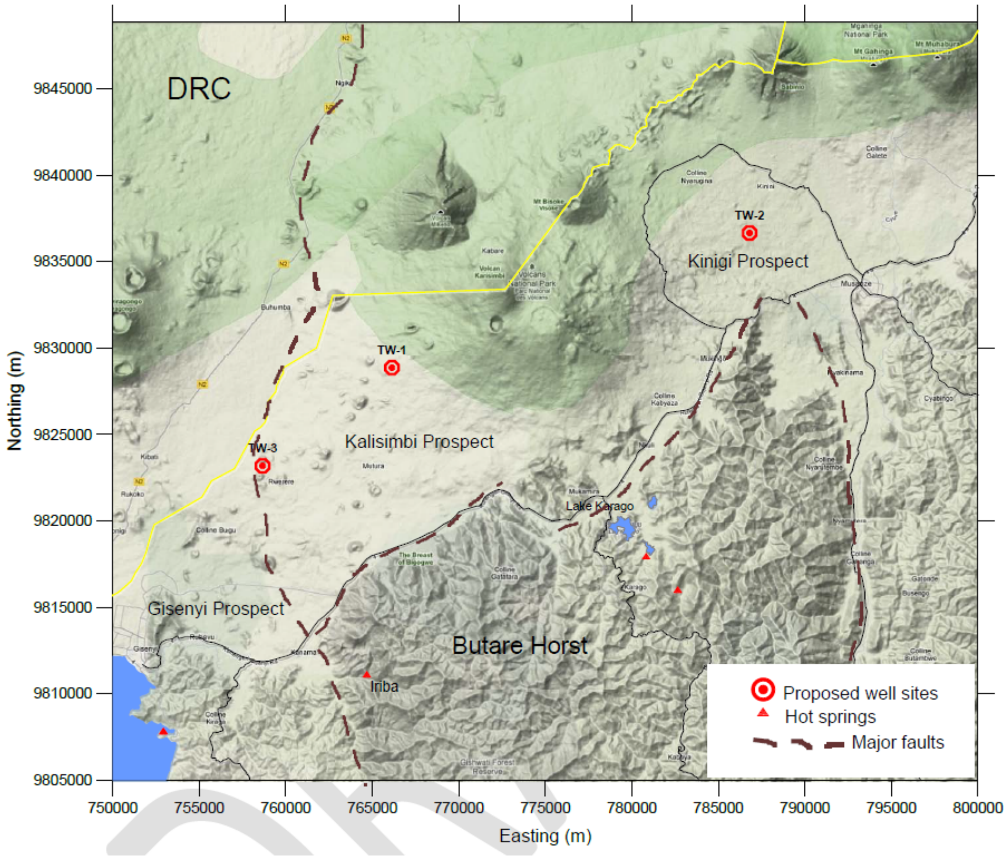


FIGURE 3: Proposed target well sites in the northern geothermal prospect, Virunga geothermal system (Shalev et al., 2012)

2.3 Application of hydrothermal alteration mineralisation for geothermal exploration at Karisimbi prospect, Rwanda

Several geothermal reconnaissance surveys have been undertaken during the last 30 years to investigate whether any geothermal power potential was associated with the chain of Quaternary volcanoes, i.e. Karisimbi, Bisoke, Sabyinyo, Gahinga and Muhabura along the Rwanda-Uganda-Congo border in the western branch of the East African Rift (EARV), in comparison with a similar volcanic geothermal system in the EARV, where production of geothermal power already occurs such as Olkaria in Kenya and Aluto in Ethiopia and where it has been inferred that the sub-volcanic strata, like granites, of the East Virunga range could host intrusive bodies which could be associated with a convective geothermal system. Therefore, in 2011, a geological survey was conducted in the area with the expectation of comments on several aspects of the geology that related to geothermal mineral alteration and likely reservoir conditions in the sub-surface. The methodology used was to examine clasts ejected in hydrothermal, phreatic or phreato-magmatic eruptions. These events ejected material derived from a geothermal reservoir where the lithology and hydrothermal alteration serve as guides to the nature of the reservoir rocks and the physicochemical conditions in the sub-surface. Volcanic eruptions may also bring to the surface rock fragments (called xenoliths) derived from the walls of host rocks by the ascending magma. Their identity is likewise a guide to sub-surface conditions. Products from these eruptions yield information that is obtained very cheaply and can aid in making a geological prognosis of a well, for example (Browne, 2011a).

FIGURE 4: Ancient granite showing steeply dipping veins of at least two different ages; the white vein (mainly quartz) is offset by a micro-fault and is cut by a younger and narrow vein containing biotite (Browne, 2011a)

However, the relative scarcity of hydrothermally altered rocks did not allow for any correlation with sub-surface conditions. This was attributed to the fact that the young basalts covering the prospect are much too permeable to allow any thermal waters that may exist in the sub-surface to reach the ground's surface. However, the underlying granites, pegmatites and schists, are permeable and fluids are able to move through them via interconnected joints (cracks in the rocks) as evidenced at outcrops of granites in Figure 4, and by veins up to several centimetres wide hosting secondary kaolin, quartz and unknown black minerals, thus showing that they once conducted magmatic and hydrothermal fluids (Browne, 2011). This granite is impermeable except along channels; in other words there is no intergranular porosity or permeability.

Feldspars show incipient alteration to sericite (well crystallized); illite (clay with a lower birefringence), which formed later, was also present. More detailed analyses were required and several samples of lava and representative granites were examined petrographically. The purpose for doing so was three-fold: 1) to see if any of these rocks had reacted with thermal fluids; 2) if not, to provide a mineralogical and chemical data, a base with which to compare samples recovered from future drill holes to estimate the magnitude of any mass transfer resulting from fluid/rock interactions; 3) to see if they contained a chemical and/or mineralogical signature at the depths from which they derived (applicable only to lavas). This is important, as it should indicate whether or not the source magma differentiated within the shallow or deep crust or else ascended more directly from the mantle. The rocks examined for these purposes comprised:

- Volcanic lavas derived from Karisimbi volcano;
- Xenoliths, erupted from small cones southwest of Karisimbi: examined to reveal the identity of the basement rocks underlying the cones; their hydrothermal alteration might indicate the presence of a geothermal reservoir;
- Proterozoic granitic and metamorphic basement rocks.

The petrographic analysis revealed the major minerals present in the Karisimbi volcanic rocks which are: calcic-plagioclase, olivine, augite, sanidine, biotite, iron oxides, apatite and volcanic glass; some lavas also contain leucite, analcime or nepheline and the proportions of all these minerals differ markedly between lava flows, nevertheless the volcanic rocks derived from Karisimbi volcano are not hydrothermally altered. Some of the xenoliths are slightly altered with secondary calcite, illite and sericite; an example is a granite xenolith in basalt lava from Mufumba cone. However, only the calcite is likely to have formed as a result of modern geothermal activity (Browne, 2011b).

3. HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND

3.1 Regional geology and tectonic setting of Iceland

Iceland is a plate form of dimensions 300×500 km situated astride a divergent plate boundary and on top of a hotspot presumed to be fed by a deep mantle plume (Einarsson, 2008). Its regional geology is basically the product of the relative movement of this mantle plume and the Mid-Atlantic divergent plate boundary. The mantle plume is migrating eastward relative to the plate boundary and the rifting, followed by continuous volcanic eruptions along the divergent plates, forms new crust predominantly of basaltic composition (Figure 5). Thus, the older rocks in the east and west of the country spread away from each other at a rate of 2 cm/year, as evidenced in Figure 6, leading to a complicated and changing pattern of rift zones and transform fault zones (Wolfe et al., 1997). The surface of Iceland is almost entirely made up of volcanic rocks with basalts being 80-85% of the volcanic pile, and acid and intermediate rocks 10%. The amount of sediments of volcanic origin is 5-10% in a typical Tertiary lava pile, but may locally be higher in Quaternary rocks. Quaternary formations are found along the margins of the rift zone while Tertiary basalts predominate away from the rift zone to the east and west (Figure 6) (Saemundsson, 1979).

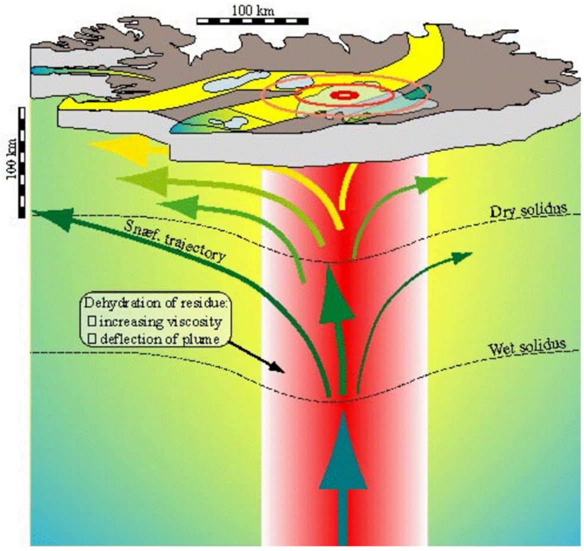


FIGURE 5: Schematic illustration of flow trajectories and melting regime of the Iceland plume in relation to the volcanic rift zones (yellow) and off-rift zones (brown) (Trönnes, 2002)

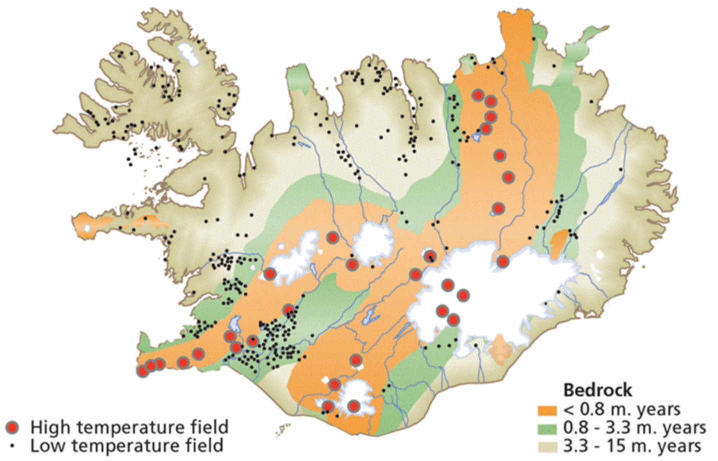


FIGURE 6: Iceland rocks age and geothermal map; white areas are glaciers (from Árnason et al., 2010)

3.2 Geology and tectonic setting of the study area

The Hellisheidi high-temperature field, where the geothermal well HN-7 (the subject of this study) is located, is part of the Hengill volcanic system, which lies within the western volcanic zone of Iceland, as shown in Figure 7. It is located where the South Iceland Seismic Zone (SISZ) intersects the Reykjanes and Langjökull volcanic rift zones, forming a triple junction area which is very seismically active as would be expected from the dense fissure swarm and recent eruptions. This volcanic system includes about a 40-60 km long NNE-trending fissure swarm with normal faults, fissures, frequent magma intrusions and a central volcano (Árnason et al., 2010). Two kinds of tectonic activity seem to prevail in the Hengill area: dilationary rifting, as exemplified by the fissure zone, and a transform component concentrated in the eastern part of Hengill and related to the SISZ (Franzson et al., 2010). The Hellisheidi area is one of the biggest high-temperature geothermal fields in Iceland, containing several economically promising geothermal prospects, and comprises four potential geothermal fields: Skardsmýrarfjall, Hverahlíd, Gráuhnúkar and Reykjafell. Well HN-7 is situated in the Gráuhnúkar sector which is located on the western fringe of the Hengill central volcanic system.

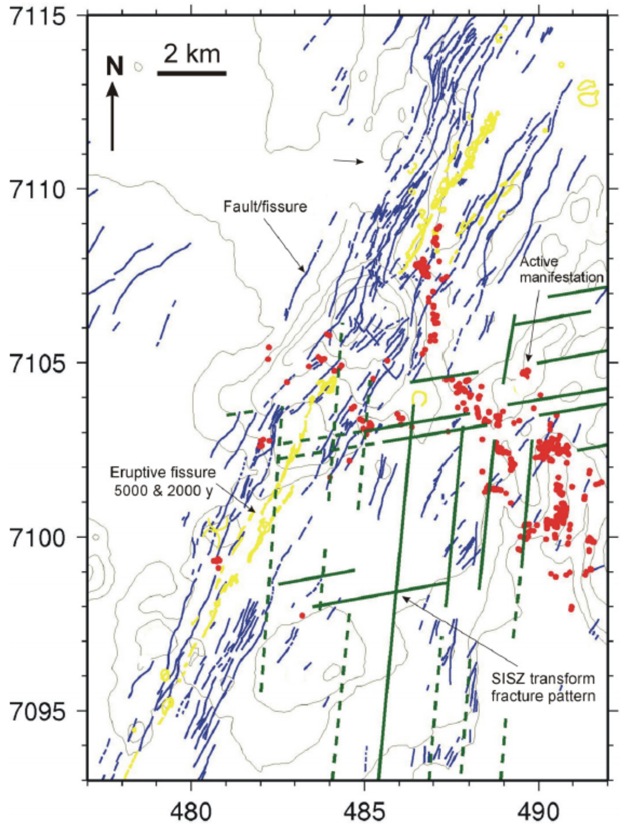


FIGURE 7: Map of the Hellisheidi geothermal field; the inset shows the location of the field in SW-Iceland: blue dots depict well heads; green lines are tracks of directionally drilled wells; hot springs and fumaroles with red dots; faults with combed lines; and volcanic fissures and craters with yellow/red areas; Gráuhnúkar sector is shown by the red circle (Gunnarsson, 2011)

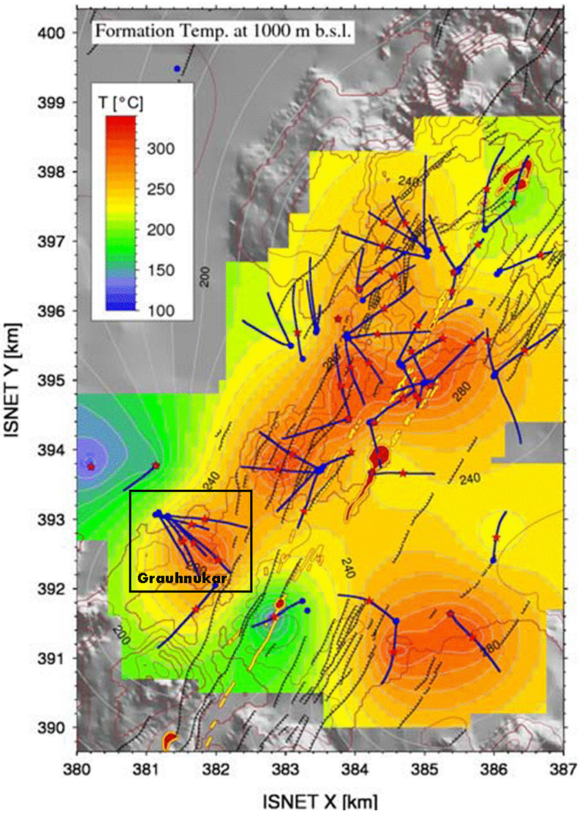


FIGURE 8: Formation temperature at a depth of 1000 m below sea level in the Hellisheidi field. The intersection of the wells at 1000 m b.s.l. is depicted as red stars; formation temperature between data points was calculated using the surface interpolation scheme of the GMT software package (Gunnarsson, 2011)

3.3 Previous studies of the Gráuhnúkar area

Originally, the Gráuhnúkar area was planned as the reinjection zone for the power plant. No manifestations of geothermal surface activity is present and the area was believed to be at the edge of the thermal anomaly in Hellisheidi. Resistivity measurements (TEM and MT) gave no indications that this area could be hot (Árnason et al., 2010). Resistivity anomalies that are known as fingerprints of high geothermal activity were found 1.5-2 km east of Gráuhnúkar. Thus, it came as a surprise that temperature higher than 300°C was measured in reinjection wells that were drilled in the area. The high formation temperature in the Gráuhnúkar area is connected to the hottest parts of the Hellisheidi field (Figure 8) and makes the Gráuhnúkar area promising for production. Wells in the area northwest of Gráuhnúkar yield high enthalpy fluid (> 2000 kJ/kg) in high quantities (Haraldsdóttir et al., 2012).

Due to time constraints in the construction and operation plans of the Hellisheidi Power Plant, the area had to be used as a reinjection zone. No time was available to change those plans and no other reinjection zone was available for reinjecting the excess geothermal fluid from the power plant. The area has been in use since the commission of the plant in 2006. It is not clear what long term effects the injection has on the possibility of using the area for production (Gunnarsson, 2011).

4. SAMPLING AND ANALYTICAL METHODS

Drill cuttings, generally because of their low cost and ease of recovery relative to the core, are standard borehole rock samples. They are commonly the only source of the direct downhole geological information essential for a successful sub-surface investigation. However, drill cuttings from geothermal and mineral exploration boreholes, in contrast with those from most petroleum wells, are often highly fractured and faulted, hydrothermally altered igneous and metamorphic rock sequences. Characterization of a sub-surface resource from cuttings, thus, requires not only especially careful sample collection, preparation, storage (Figure 9) and examination, but also a thorough knowledge of the local geology and the full range of potential borehole contaminants for a successful sub-surface investigation. Cuttings samples should be as representative as possible of an entire drilled interval. Since the geology of geothermal systems and mineralized terrains can be very complex and can change abruptly, cuttings should be collected at relatively short intervals to minimize or avoid homogenization of multiple lithologies or alteration types in a single sample (Hulen and Sibbet, 1981).

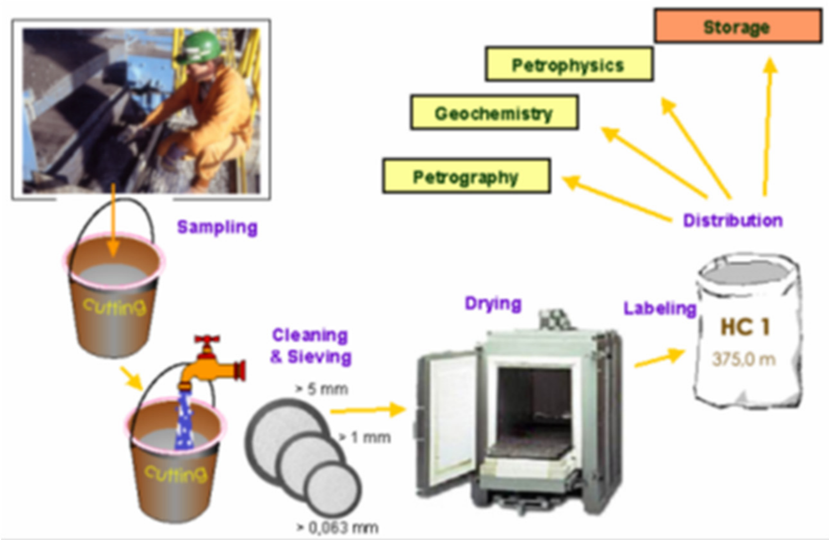


FIGURE 9: Handling and preparation of cutting samples (Wöhrl and de Wall, 2003)

4.1 Sampling methods

During drilling, cuttings from the rock formations were collected every 2 m and were analysed using a binocular microscope for rock classification and preparation of lithological and alteration logs.

Generally, drill cuttings are analysed immediately on site to assist rig personnel and management in deciding the depths at which to set the production casing shoe, when to change the well track or the well drift angle, and when to stop drilling, and also to assist them in anticipating or defining drilling problems such as stuck pipes caused by swelling clays or sloughing of rock formations. Later, the same cuttings are prepared to be taken to the laboratory for petrographic microscope analysis (thin section) for further identification and interpretation; and for XRD analysis, mainly to identify and classify clay minerals, but can also be used to identify other alteration minerals, such as secondary amphiboles.

4.2 Analytical methods for hydrothermal alteration mineralisation

The principle reasons for analysing the drill cuttings from well HN-7 are to provide information about the geological formation drilled into, prepare lithological logs and to map the distribution of the hydrothermal alteration minerals. The instrument used to examine cuttings is a binocular microscope to describe the rock samples and the distribution of hydrothermal minerals in order to estimate the temperature of the fluid that has passed through the formation, thus giving information about the geothermal system. However, the binocular microscope has its own limitations and should be supplemented by other methods, such as the petrographic microscope for further detailed mineralogy description, and XRD which supplies necessary information for the identification of the different phases of clay minerals.

As mentioned above, accurate identification of the lithology, alteration minerals, and faults and fractures from cuttings is sometimes limited. Other geological and geophysical logging, i.e. lowering instruments into boreholes and carrying out in situ measurements, can be used to gain information on the physical properties of the rock formation surrounding the well, as well as about the temperature and pressure within the well.

4.3 Geophysical logs methods

Geophysical logs are highly advanced techniques where complex electronics and sensors are placed inside a logging probe which is lowered on a wireline into a well to carry out continuous measurements or at discrete depth intervals as the probe is moved down or up the well. The aim of well logging is to study the well, its geometry and completion, to study the rock formation and fractures intersected by the borehole, to determine the reservoir temperature and fluid pressures, and to locate feed points connecting the well to the geothermal reservoir.

4.3.1 Resistivity as a function of alteration

Knowledge about the resistivity of rocks is of great importance in geothermal exploration. Geothermal activity influences the formation‘s resistivity through hydrothermal alteration of the rocks where the alteration minerals have different resistivity (Steingrímsson, 2011). Figure 10 shows a cross-section where resistivity, temperature and alteration are compared based on alteration minerals found in wells drilled in the Nesjavellir high-temperature field, illustrating how resistivity change can be related to the occurrence of different alteration minerals.

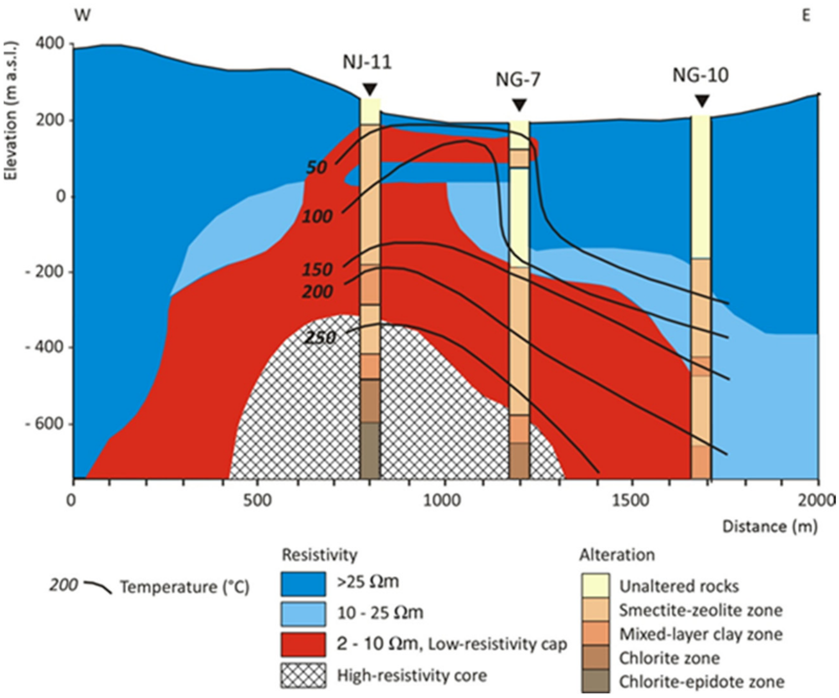


FIGURE 10: The relationship between resistivity, temperature and alteration (Árnason et al., 1987)

Previous studies with electromagnetic soun-dings in high-temperature areas (>200°C) in Iceland have shown high resistivity at the top of a low resistivity cap, underlain by a high-resistivity core (Árnason et al., 1987). It was found that the resistivity lowers in the smectite-zeolite zone and that the resistivity increases again in the chlorite-epidote zone, as shown in Figure 10. The changes in resistivity were explained by different conduction of alteration minerals. The clay alteration is progressive and assumed to be largely irreversible, especially when a high alteration state is reached. The differences in resistivity are caused by loosely bound cations in the smectite and zeolite minerals which make them conductive, but in chlorite the cations are bound in the crystal lattice, hence increasing the resistivity. Because of the very high cation exchange capacity of smectite and mixed layer illite-smectite clays, rocks containing them have very low electrical resistivity.

Nevertheless, care should be taken in deducing alteration from resistivity as the specific electric resistivity of the reservoir formations is the result of two different factors: the resistivity of the rock matrix and the formation fluid. The electric resistivity of rock formations will, therefore, vary with the rock type, the water content, the salinity of the water and the temperature. The most common rock types in geothermal reservoirs are of volcanic origin but sedimentary reservoir rock formations are also found. An igneous rock matrix is generally a poor electric conductor with specific resistivity values of 10^4-10^6 Ωm, whereas the resistivity in a sedimentary rock matrix is a few orders of magnitude lower. The matrix resistivity can, however, be considerably lower if it has undergone medium temperature hydrothermal alteration. The geothermal fluids, even of low salinity, are generally much more conductive (<10 Ωm) than the rock matrix and, therefore, the fluid resistivity will define the resistivity of the reservoir formations except in very low porosity (<<1%) rocks or very conductive rocks (Steingrímsson, 2011).

The formation resistivity value depends, in general, on the porosity (water content) as well as temperature and water salinity (Steingrímsson, 2011). Observations of various rock types lead to an empirical law of the form: $R_o = F \times R_w$, where F is called the formation factor and R_o and R_w are the formation resistivity, and the pore fluid resistivity, respectively. Several empirical relationships between the formation factor F and the porosity have been suggested. The most famous is Archie´s formula:

$$F = a\,\Phi^{-m} \tag{1}$$

where a = Constant;
Φ = The porosity; and
m = A constant called the cementation factor.

The constants a and m in Equation 1 are found to be approximately fixed numbers for rocks of similar type and of similar intergranular and intercrystalline porosity. For sandstone, which is the common rock type in oil reservoirs, the typical values for a and m, based on measurements of core samples, resistivity logs and empirical studies are $a \sim 1$ and $m \sim 2$. Fractured igneous rocks are, however, the most common rock type in geothermal reservoirs. Resistivity-porosity relationships have been determined for fractured basaltic formations in Iceland. A cementation factor, $m \sim 1$ has been found in most cases. A cementation factor of 2 has, however, been found for sedimentary interbeds in the basaltic lava pile (Stefánsson et al., 1982). The constant a seems, however, to be variable in igneous rock formations and values ranging from 1 to 15 have been reported (Steingrímsson, 2011).

Resistivity structures in Iceland can presently be connected to geological variables, such as rock types, alteration and to temperatures to some extent. A direct transfer of such interpretations to geological formations, such as those expected in the geothermal prospects in Rwanda, is perhaps problematic. Metamorphic gneisses to granitic rocks may have quite different resistivity backgrounds which could make interpretation of a prospective geothermal system difficult.

4.3.2 Other geophysical logs

Temperature logs: Temperature logging in boreholes provides a wide variety of information on, for example, the geothermal gradient and heat flow, the effect of aquifer flow on subsurface temperatures, and the mechanics of fault zones (Helm-Clark et al., 2004). The effects of a hot or cold flow into or out of the well from the formation can cause a sudden increase or decrease in the temperature, providing important clues to the position of aquifers in the borehole.

The natural gamma ray logs: Rock formations and minerals contain radioactive isotopes that decay continuously, emitting radioactive particles and radiation into the surroundings. The radioactive isotopes that are mainly found in the Earth's crust are potassium (^{40}K) and those involved in the decay series of uranium and thorium. In igneous rocks, the concentrations of all three radioactive isotopes are ten times greater in acidic rocks than in ultra basic rocks and the concentration of each isotope is generally proportional to the SiO_2 concentrations (Stefánsson and Steingrímsson, 1990).

The neutron-neutron porosity logs: Neutron logs are used in porosity investigation. The log records the ability of the geological formation material to slow down fast neutrons. From the collision theory, the slowing down effectively has a prominent maximum when particles of equal masses collide. The slowing down of neutrons is, therefore, primarily controlled by the abundance of hydrogen; in rock formations, most of the hydrogen is in the formation fluid. Thus, this slowing down effect of formation water on fast neutrons is a basic physical principle, upon which the logging technique for evaluating the "porosity" of rock formations is based (Stefánsson and Steingrímsson, 1990).

5. HYDROTHERMAL ALTERATION IN GEOTHERMAL SYSTEMS

5.1 Geothermometers

During drilling, it is important to simultaneously evaluate the formation temperature by identifying index minerals which form at specific temperatures and are stable at a certain range of temperatures. The first appearance or disappearance of a certain mineral gives a specific temperature range. Table 1 shows some of the most common index minerals, but the list is not exhaustive. The temperature values are mostly based on geothermal empirical work in Iceland from 1970 up to the present (e.g. Kristmannsdóttir, 1979) and on work concerning minerals like illite and albite from Olkaria- Kenya (Browne, 1984b). This temperature dependence of minerals in Iceland is based on long experience of formation temperature and mineral occurrences in a predominantly basaltic environment. This relationship may be somewhat different in the andesitic regimes in the Pacific (e.g. Reyes, 1990). Care should be taken in those relationships when drilling starts in Rwanda.

TABLE 1: Specific secondary temperature dependent minerals, or index minerals, observed in Iceland (e.g. Kristmannsdóttir, 1979) and Kenya (Browne, 1984b)

Minerals	Min. temp. (°C)	Max. temp. (°C)
Zeolites	(40)	(200)
▪ Levyne		60
▪ Chabazite		70
▪ Gimsonite		80
▪ Phyllipsite		100
▪ Thomsonite		120
▪ Mesolite-scolecite	(60)	140
▪ Heulandite		150
▪ Stilbite	(60)	140
▪ Epistilbite	(80)	150
▪ Mordenite	(80)	260
▪ Laumontite	(120)	230
▪ Analcime		170
▪ Wairakite	(200)	300
Chalcedony	30	180
Calcite	50-100	280-300
Pyrite	50	>300
Smectite		<200
MLC (Mixed-layer clays)	220	230
Chlorite	230	>300
Illite	120-200	320
Albite	170	320
Adularia	200	300
Quartz	180	>300
Sphene	200	>300
Prehnite	240	>300
Epidote	230-250	>300
Wollastonite	260	>300
Actinolite	280	>300
Garnet	260-300	>300

According to Browne (1984a), the minerals commonly used as geothermometers are the zeolites, clays, epidote and amphiboles. In well HN-7, the zeolites, which start to appear at around 30-100°C and disappear before 200°C, revealed a medium temperature environment (maximum 140°C) for the upper 700 m. The alteration minerals found in this zone are mainly zeolites like chabazite, thomsonite, mesolite and scolecite along with fine-grained clay evaluated in XRD as being smectite. The smectite changes to coarse-grained clay with depth and temperature and, along with other zeolite minerals like laumontite, constitutes a transition to a high-temperature environment, evidenced by high-temperature hydrothermal alteration minerals such as quartz (>180°C), wairakite (>200°C), prehnite (> 240°C), and epidote (~250°C). Among minerals that occur at high temperatures, i.e. ≥250, epidote seems to be the most reliable and consistent temperature guide. Epidote first appears in many fields at 250°C and the lithology does not influence its formation.

5.2 Permeability indicators

The intensity and type of alteration usually reveals the degree of permeability, past or present. It is the permeability of the rocks that controls the access of thermal fluids which cause hydrothermal alteration. In Olkaria field, Kenya (Lagat, 2010), minerals like illite, adularia, abundant calcite and abundant pyrite are commonly found in or adjacent to aquifers penetrated by wells, and occur as alteration of the rock and in veins, often as well formed crystals. Apart from low alteration intensity, indicators of low permeability can be alteration minerals like prehnite, pyrrhotite, abundant laumontite, and abundant sphene instead of epidote, occurring as rock alterations or tight veins. Other minerals like adularia and albite are often related to permeable zones, especially if they are individually associated with quartz and calcite. This is experienced in New Zealand geothermal fields (Browne, 1984a). However, this relationship is only valid if these minerals occur in veins and fractures (Browne, 1984a). But identification of the original minerals must be made. If the source is the alteration of plagioclase, this relationship does not hold.

In general, the relative high quantity of fracture fillings is a good indicator of past or present permeability. High abundance of the secondary mineral pyrite is good evidence of good permeability. Pyrite and calcite are more abundant between 800-1200 m in well HN-7, where the variance in temperatures, past or present, is from 100-250°C (according to alteration minerals).

5.3 Thermal history and fluid composition

The mineral anomalies, where low- or medium temperature minerals appear with others that are stable at high temperatures, are sometimes observed in mineral assemblages. This can be evidence of transient or long term cooling in the geothermal reservoir. Overprinting of calcite is the most common indication of a cooling event. On the other hand, if calcite disappears it is evidence of temperatures exceeding 290°C.

The thermal history of a geothermal field can also be obtained by studying the fluid inclusion homogenization temperatures (T_h), which are reliable predictors of past to present subsurface temperatures. These temperatures are correlated with the measured stable formation temperatures and interpreted hydrothermal alteration temperatures. Interpreted alteration mineral temperatures and fluid homogenization temperatures (T_h) that are above their stability and measured temperatures, respectively, indicate that the geothermal system has undergone some heating, whereas those that are below indicate that a geothermal system has undergone some cooling (Lagat, 2010).

5.4 Fluid composition

It is the pH and the composition of the fluid that determine the rate and types of hydrothermal minerals to be formed (Browne, 1984a).

5.5 Setting the production casing

The appearance of certain secondary minerals, especially those that start to form at 230-250°C, is often the main criterion in deciding casing points in wells during drilling, especially in exploration wells. This ensures that the cold zones or unwanted aquifers are cased off during drilling; hence, there is no incursion of cold fluids into the well.

6. RESULTS AND DISCUSSION

6.1 Stratigraphy

The properties of primary rocks control the speed, intensity and character of petrophysical alterations, as the chemical composition of the host rock (Figure 11) determines the availability of components to form alteration minerals. It is, therefore, important to examine the rock type in order to understand the alteration process to which the area may have been subjected to.

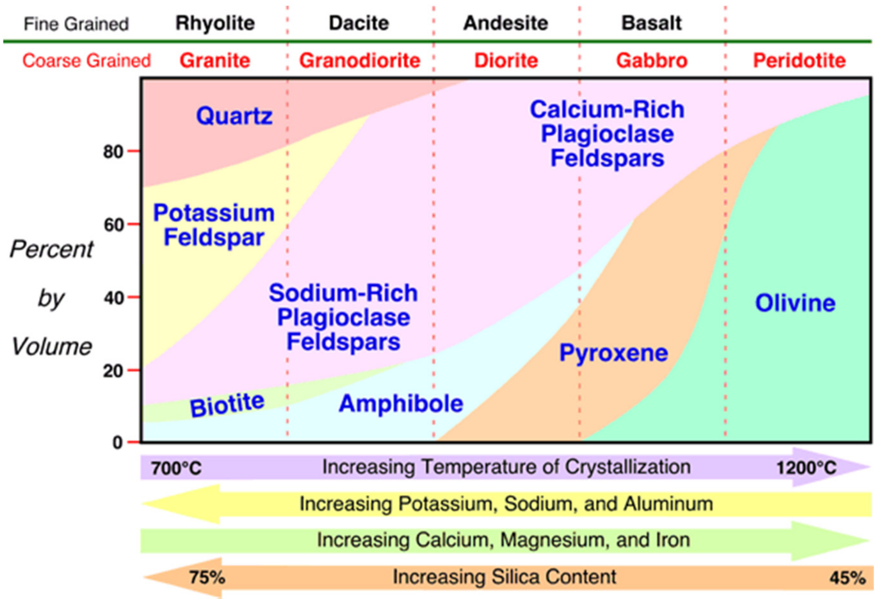


FIGURE 11: Primary minerals of igneous rocks; the first to be formed are more susceptible to alteration (Pidwirny, 2006)

From dissected drill cuttings by binocular microscope or petrographic analysis of thin sections, the geological formation in well HN-7 was classified into 3 groups:

1) Hyaloclastite formations. The rock types within these hyaloclastite units are basaltic breccia and basaltic tuffs;
2) Pillow basalts;
3) Eleven thin-, fine- to medium-grained basaltic lava flows of olivine tholeiite composition.

The descriptions in Table 2 are based on analyses by binocular microscope, 24 petrographic thin sections and 16 XRD analyses of clay minerals.

6.2 Distribution of hydrothermal alteration minerals in well HN-7

The second purpose of the analyses was to identify and characterize the distribution of the secondary minerals that formed when hydrothermal fluids migrated through rock formations; an attempt was made to estimate formation temperature and permeability in well HN-7, for they play the most important roles in the stability of most hydrothermal minerals. The factors usually controlling alteration in geothermal systems are:

- *Temperature,* which is the most significant factor in hydrothermal alteration as chemical reactions between rocks and fluid require elevated temperatures
- *Permeability* of the rocks which controls the access of thermal fluids which cause hydrothermal alteration
- *Initial rock composition*

TABLE 2: HN-7 lithology succession from analyses of the cuttings

Depth (m)	Description
10-12	No cuttings
12-30	Fresh basaltic tuff
30-50	Fresh highly porous basaltic breccia with olivine and plagioclase phenocrysts
50-52	Oxidized scoria between hyaloclastite formation and lava flows
50- 206	A succession of 11 olivine tholeiite lava flows separated by oxidized scoria. High porosity from 100-142 m and a total circulation loss was encountered between 92-102 m. Low-temperature zeolites start to appear, but mostly it is minerals which are related to oxidation like siderite and limonite.
206-244	Vesicular tuff along with some fragments of porous medium-grained basalt with plagioclase and olivine crystals. The rock is highly oxidized and minerals associated with oxidation like siderite are found in pores.
244-310	A mixture of vesicular tuff and fine- to medium-grained basalt with plagioclase and olivine crystals. Secondary minerals are mostly low-temperature zeolites and fine-grained clays; scolecite and chabazite are found at 244 m, thomsonite at 254 m, stilbite at 270 m and philipsite at 296 m.
310-350	Fresh, fine- to medium-grained basalt with variable amount of glass. No vesicles in the formation. Glass is moderately altered.
350-430	The unit is predominantly tuffs along with some fine- to medium-grained basalt fragments. Alteration minerals like heulandite and chalcedony appear
430-462	Fine- to medium-grained basalt fragments with some minor amounts of altered glass and some brown tuffs, making it tuff-rich breccia. Alteration minerals in the formation are mesolite, scolecite, heulandite and stilbite
462-490	The unit is predominantly tuffs along with some fine- to medium-grained basalt fragments.
490-528	A mixture of fresh fine-grained olivine tholeiite basalt, along with some glass. Pyrite and calcite are common and glass is moderately altered.
528-532	Some dark fresh fine-grained basalt, possibly an intrusion or a dyke.
532-564	A mixture of tuff, and fine- to medium-grained tholeiite in variable proportions. The tuff is fine-grained and green in colour. The rock in general is partially altered and has pores which are filled with clay. Mesolite and scolecite are common.
564-650	Fine- to medium-grained tholeiite basalt, mixed with fragments of glass. No vesicles in the formation and glass is moderately altered. Olivine has been completely replaced by dark green clay minerals.
650-668	The unit is predominantly tuff, green in colour, along with some fine- to medium-grained basalt fragments.
668-724	Composed mostly of medium-grained glassy basalt, highly altered with olivine replaced by dark clay minerals oxidized at the edges. Minor amounts of fine-grained basalt are included with pores filled with dark clay minerals. Alteration minerals include scolecite, smectite, calcite, pyrite, chabazite and siderite.
724-816	Composed mostly of highly altered glass with some minor amounts of fine-grained basalt with pores filled with dark clay minerals. Olivine is replaced also by dark clay minerals. First occurrence of laumontite occurs at around 740 m.
816-844	Formation consisting of highly altered fine- to medium-grained basalt, and a minor amount of basaltic glass. All olivine has been replaced by dark clay minerals. The rock is also highly oxidized. There is plenty of calcite and pyrite.
844-1008	Light grey highly vesicular glassy basalt. The colour is probably due to the concentration of calcite in the formation.
1008-1130	A mixture of highly altered tuff and fine to medium basalt. High-temperature alteration minerals are found, like wairakite, quartz and chlorite. High intensity of chalcopyrite is also noted which is indicative of veins close to the margins of large intrusions.
1130-1136	Fine- to medium-grained relatively fresh basalt, probably a dyke
1136-1200	Highly altered tuff with high-temperature alteration minerals such as prehnite and epidote. There is also an abundance of calcite and chalcopyrite.

Alteration is evidenced by the occurrence of hydrothermal alteration minerals formed via devitrification (glass alteration), recrystallization of primary minerals or deposition of new minerals in vugs and fractures. Basaltic glass is the first to be altered in the upper part of the well, at around 100 m. Hydrothermal alteration is also seen as the precipitation of secondary minerals in open cavities, vesicles and fractures in the rock formations, mainly by zeolites changing from low-temperature zeolites to high-temperature zeolite with depth. Another type of hydrothermal alteration is the replacement of primary minerals by secondary minerals. Generally, the primary minerals formed at the highest temperature have the least stability when exposed to hydrothermal alteration, as is the case of olivine which is usually replaced by clay minerals.

The hydrothermal alteration mineral zones in HN-7 were defined based on the presence of one or more index minerals; their distribution zonation has been categorized based on the first appearance of the most common index minerals (Figure 12 and Table 2). Zeolites are the most dominant alteration minerals down to just over 1000 m depth. But the first alteration minerals to occur at 100 m in the well are siderite and limonite. Chabazite and thomsonite are first found at around 250 m, followed by mesolite, scolecite and heulandite at around 420 m. At 780 m depth, laumontite is first found (~120°C). At around 1000 m, there is a sudden appearance of quartz (180°C) and chlorite (230°C), almost at the same depth (Figures 12 and 13) (quartz at 1030 m and chlorite at 1036 m). These are followed by prehnite (240°C) at 1124 m and epidote (250°C), which first appears at 1160 m. From XRD analysis of the clay minerals, it is evident that smectite is dominant for the first 1000 m of the well and is mixed with chlorite with increasing depth. The first appearance of chlorite, according to XRD, is at 1034 m, which signifies the top of the chlorite zone (Figures 12 and 13).

6.2.1 Recrystallization of primary minerals

Primary minerals in igneous rocks are minerals that form during the original solidification/crystallization of the rock (Figure 11). They are important for classification of the rock type drilled through. In contrast are secondary minerals which form at a later time after the host rock has gone through other processes which could change its chemical composition, processes such as metamorphism, weathering and hydrothermal alteration (Lapidus and Winstanley, 1987).

In a geothermal environment, where there are elevated temperatures, high permeability and intense geothermal fluid activity, the primary rocks become unstable. Due to the interaction between hydrothermal fluids and the rocks through which they migrate, the rock's primary minerals undergo chemical reactions and readily alter into secondary minerals to become stable under the newly created natural conditions (Table 3). The order of alteration depends on the Bowen reaction series (Figure 11) so that the first to be formed is also the first to be altered.

TABLE 3: Order of replacement of primary minerals by alteration products in well HN-7

Susceptibility to alteration	Primary minerals	Alteration products
Increasing ↑	Volcanic glass	Palagonite, zeolite, clays, quartz, calcite
	Olivine	Clay minerals, iddingsite, chlorite
	Pyroxene	Chlorite, quartz, pyrite, calcite
	Plagioclase	Calcite, quartz, epidote
	Magnetite	Pyrite, chalcopyrite

Volcanic glass which is a constituent of basaltic rocks, especially hyaloclastite basalt and pillow basalt, cannot be classified as a mineral but is relevant to this discussion as its replacement products are quite relevant as hydrothermal alteration minerals. Volcanic glass is formed when eruption materials cool rapidly and minerals do not have time to form. Examples of this are hyaloclastites and pillow basalts which erupt beneath glaciers. Basaltic glass was the first to be altered and replaced by palagonite in the 200 m upper part of well HN-7. Palagonite is unstable, however, and in general the replacement

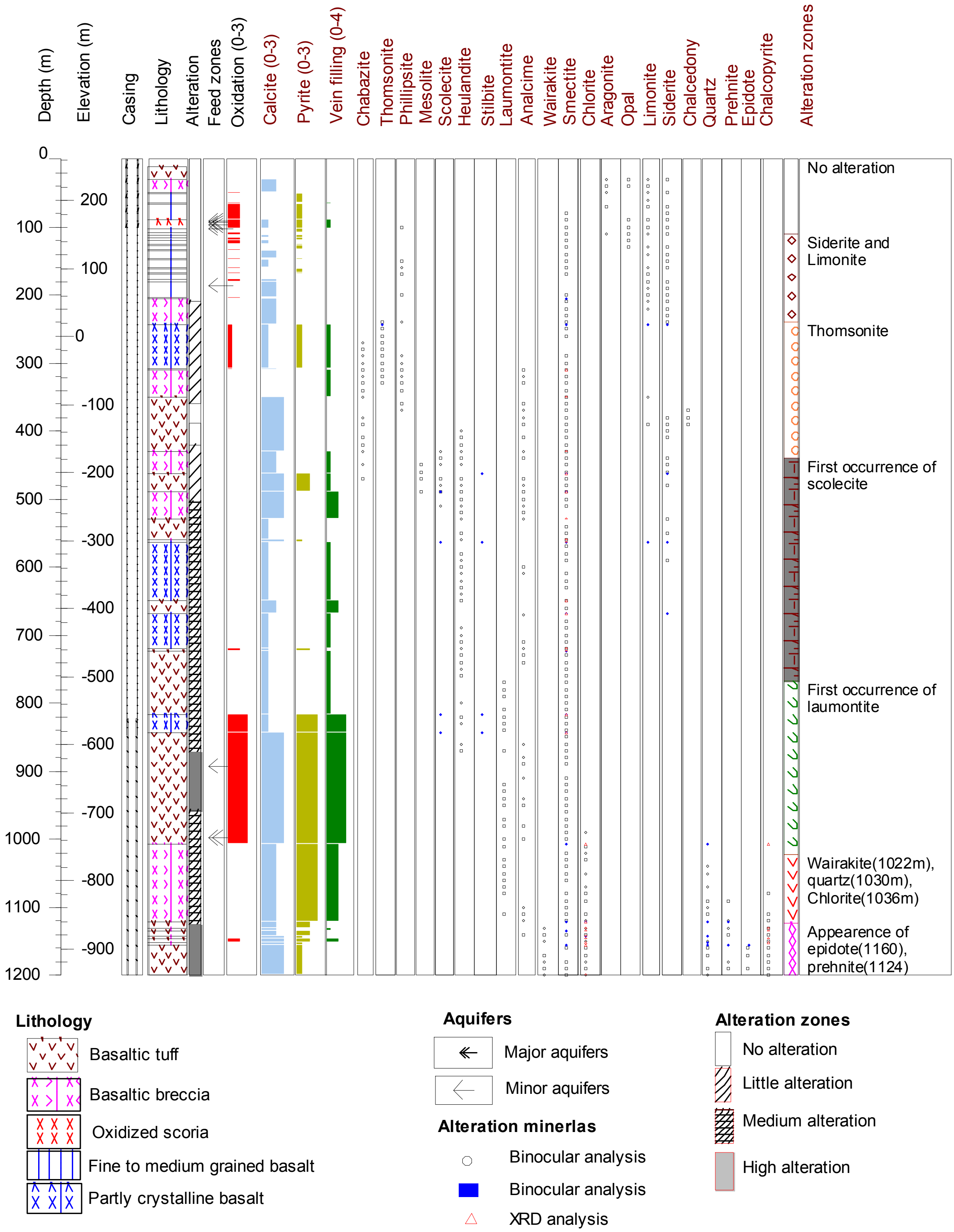


FIGURE 12: Lithology and alteration minerals in well HN-7

products of volcanic glass are clays, zeolites (mordenite, laumontite), cristobalite, quartz and calcite (Browne, 1984a).

Olivine. Basaltic rocks are classified depending on the amount of olivine content. Raymond (1995) classified basaltic rocks based on olivine content as alkali olivine basalt or olivine basalt, containing common to abundant olivine (and a Ca-pyroxene, augite), and tholeiitic basalt which contains little or no olivine (and a Ca-poor pyroxene, orthopyroxene or pigeonite).The basaltic rocks in well HN-7 are of olivine tholeiite composition; the olivine observed in the rock formation gradually alters and at around 500 m it is completely replaced by calcite and clay mineral (smectite).

Plagioclase is the most abundant mineral occurring in most igneous rocks and a major mineral in basalt. In well HN-7, plagioclase was observed to be progressively altered as temperature increased with depth and was finally partially replaced by calcite, zeolites, wairakite, and chlorite.

Pyroxene resembles olivine but differs by the presence of better cleavage and inclined extinction. In well HN-7, it was observed to alter to clay. Generally, at higher temperature, pyroxene changes into actinolite.

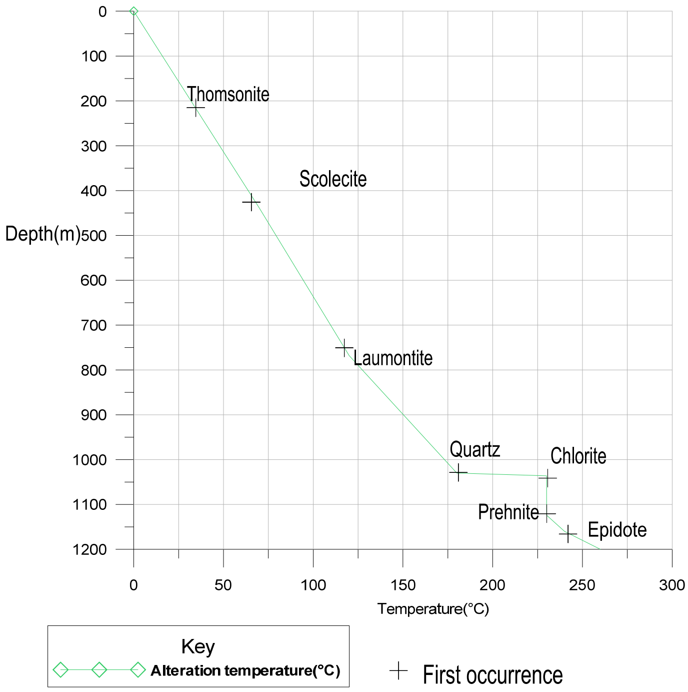


FIGURE 13: Estimated temperature curve based on alteration minerals occurring in well HN-7

Opaque minerals. The iron oxides that occur as constituents of igneous rocks are magnetite, titano-magnetite, ilmenite, pyrite and, rarely, pyrrhotite (Hatch et al., 1972). In Icelandic basalts opaque minerals are mostly magnetite. Some ilmenite is also present and appears as opaque in both plane and crossed polarized light in the petrographic microscope. In well HN-7, the opaque alteration minerals identified are abundant pyrite at around 800 m and chalcopyrite, found with an assemblage of high-temperature minerals above 1000 m.

6.2.2 Vein and vesicle fillings

Fresh volcanic rocks near the surface are generally porous and permeable as tectonic fractures add considerably to the permeability of the rock, but this permeability decreases where geothermal fluid flows through and deposits alteration minerals (Figures 14 and 15).

Below the water table, all cavities and fissures in the rock are saturated with water. These tend to close by mineral precipitation with time; therefore the permeability decreases and heat transfer by water circulation gives way to conduction through the rocks. As the rock is heated water reacts with the rock, dissolving it and causing the deposition of new alteration minerals in fissures and cavities called amygdules, in accordance with the different thermal environment. The formation of amygdule fillings depends upon temperature, the type of rock and the composition of the water it contains. Generally, alteration of rock and the formation of amygdules in the accessible part of the rock strata takes place at temperatures of approximately 30-350°C. Olivine basalt begins to alter at lower temperatures than tholeiite and rocks richer in silica. Following minerals are deposited in vesicles or veins in well HN-7

Minerals associated with cold water in the 100 m uppermost part:
Aragonite is associated with cold circulation as this zone has one of the major aquifers in the well. Aragonite often occurs in the shells of marine organisms. It is also found in amygdules in igneous rock, especially andesite and basalt. It is unstable at standard state temperature and pressure. It was found above 100 m depth in the well.

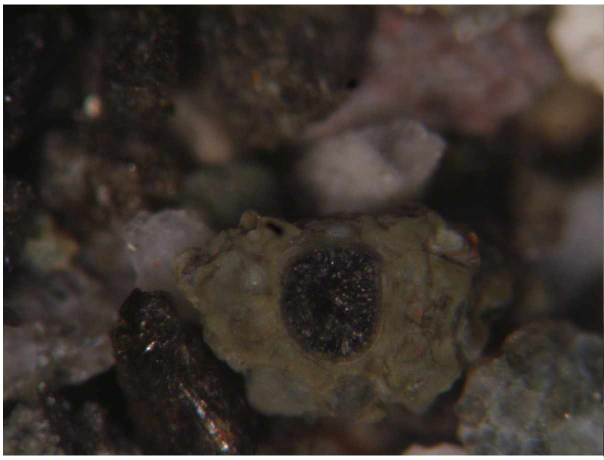


FIGURE 14: Vesicle fillings of clay minerals and calcite amygdules in cuttings

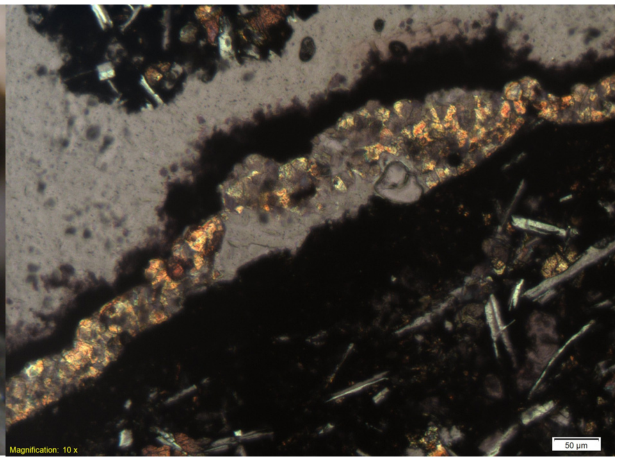


FIGURE 15: Vesicle fillings of clay minerals and calcite vein fillings in thin section (252 m)

Opal is a silica mineral that is almost amorphous with 3-13% water content. The most common variety is pale or milky white, and opaque or translucent, although transparent opal may occur. It has a vitreous or greasy lustre and fractures are irregular and conchoidal. It forms at a low temperature, hence, one of the amygdules is found in the upper parts of the lava. It is a common mineral in active low-temperature geothermal systems. Opal was found above 140 m depth in the well.

Limonite is one of the minerals that form in cold groundwater systems above the geothermal system. It is a spherical mineral in shape and reddish in colour. It occurred from near the surface down to about 250 m, but only sporadically at three locations below that depth.

Siderite occurs most commonly as yellowish, brown or reddish-brown small spherules, showing a radiating pattern when broken up. It also occurs as tabular crystals, which may be curved. The streak is white or pale brown and the lustre is normally vitreous, but is sometimes pearly. Siderite is mainly found in fissures in basalts where hot water has flowed or at the margins of intrusions along with various ore minerals. It may be an important iron ore. It occurred here along with other minerals associated with oxidation. It was found at two depth intervals, firstly above 260 m depth and secondly between 370 and 600 m depth.

The zeolite minerals:
The zone is associated with the first occurrence of zeolite minerals formed by the chemical reactions between the different types of volcanic rocks and alkaline groundwater. The formation temperature of these minerals, with the exception of wairakite, ranges from about 30°C to about 200°C. They include chabazite, thomsonite, scolecite, mesolite, stilbite, laumontite. This zone includes low-temperature zeolites:

Chabazite is characterised by its euhedral rhombohedral crystal that approaches a cube in shape. These minerals are colourless or white. It is the mineral in the zeolite group with the lowest formation temperature (30°C). It is commonly recognized in voids and amygdales between 250 and about 480 m depth.

Thomsonite is a member of the zeolite group with radiating crystals. Spherical aggregates filling vesicles were seen through the binocular microscope as a whitish mineral, first identified at a depth of 280 m. Thomsonite crystallizes at low temperatures from about 30°C and appears in vesicles together with other low-temperature minerals. It was found at 240-340 m depth.

Analcime is a white, grey, or colourless mineral in cubic crystalline form. It occurs as cavity and vesicle fillings associated with calcite and other zeolites. Analcime has a minimum temperature of about 50°C.

Distinguishing analcime from wairakite is difficult in binocular analysis. The occurrence of a mineral with the characteristics of analcime in the mixed-layer clay zone would indeed be wairakite rather than analcime as wairakite forms above 200°C, as do mixed-layer clays. The mineral was first observed at 320 m. Its lower boundary is more uncertain and seems to grade into wairakite below 1100 m. This has to be checked further.

Heulandite is colourless or white with a platy tabular sheet-like appearance. Crystals are monoclinic. They may have a characteristic coffin-shaped habit and perfect cleavage parallel to the plane of symmetry. It is most common in lower parts of the lava pile. Heulandite appeared at about 400 m and disappeared at about 860 m depth.

Stilbite crystals are white and transparent to translucent, either colourless or white. It is an indicator of a minimum formation temperature of about 80°C. It is a common amygdule in geothermal systems and is most abundant in tholeiite low down in the lava pile. It may be difficult to differentiate sometimes between heulandite and stilbite, but they occur within a similar temperature range. It was found sporadically within the same depth interval as heulandite.

Scolecite/Mesolite. Scolecite is structurally similar to mesolite and is characterised by a radial texture. These minerals are taken as a group as they form at a similar temperature range from about 70°C. These minerals usually precipitate in vesicles as threads or hairs and are colourless and transparent. Generally, they occur at similar temperature and depth intervals as other zeolite group minerals such as stilbite, thomsonite and chabasite. These minerals were found between about 400 and 560 m depth.

Laumontite has a prismatic and fibrous structure and is mainly found as cavity fillings. It was found from about 760 m down to 1100 m depth. It occurred in an unstable form in vesicles, subsequently replaced by wairakite, epidote and quartz. According to theory, it becomes unstable above 200°C. When pure, laumontite is colourless or white and transparent. It has perfect cleavage and is very fragile (easily broken). It is frequently associated with other zeolites.

Wairakite is characterised under the petrographic microscope by a very low relief, a dull dark grey colour and crosshatched twinning. Fluid inclusions in its crystal structure usually give wairakite a typically cloudy look. It was first seen at about 1150 m depth and probably continues to below the 1200 m depth that the author worked on. It might have been encountered above, there analysed as analcime. It precipitates in veins or in the core of vesicles, usually succeeding the high-temperature minerals of epidote, quartz and prehnite, but is sometimes found prior to the appearance of platy calcite. It commonly replaces plagioclase and is observed to replace lower temperature zeolites. Wairakite is the only high-temperature zeolite, forming above 200°C (Saemundsson and Gunnlaugsson, 2002).

Clay minerals:
Clay minerals are widely used as the best tool in geothermal exploration as temperature indicators (Kristmannsdóttir, 1979). Clay minerals can be identified using a binocular microscope but, in some cases, it may be difficult to distinguish between them. Petrographically, these minerals can be distinguished as smectite, mixed-layer clays and chlorite based on their optical characteristics. X- ray diffraction (XRD) is, however, considered the best overall method to distinguish between the three types of clay minerals (Figure 16 and Appendix I).

Smectite is the clay mineral with the lowest formation temperature. It is formed from the alteration of glass or primary minerals like olivine and also forms directly from water rock interaction, precipitating into voids and veins. It is fine-grained, greenish to dark in the cuttings and started to appear at 80 m. In thin sections, it was identified first at 212 m and at 344 m in XRD. It has brownish colours in plane-polarized light and is found as vesicular linings and alteration of glass (palagonite). Smectite is an indicator of temperatures lower than 200ºC. It was found all the way down to 1200 m.

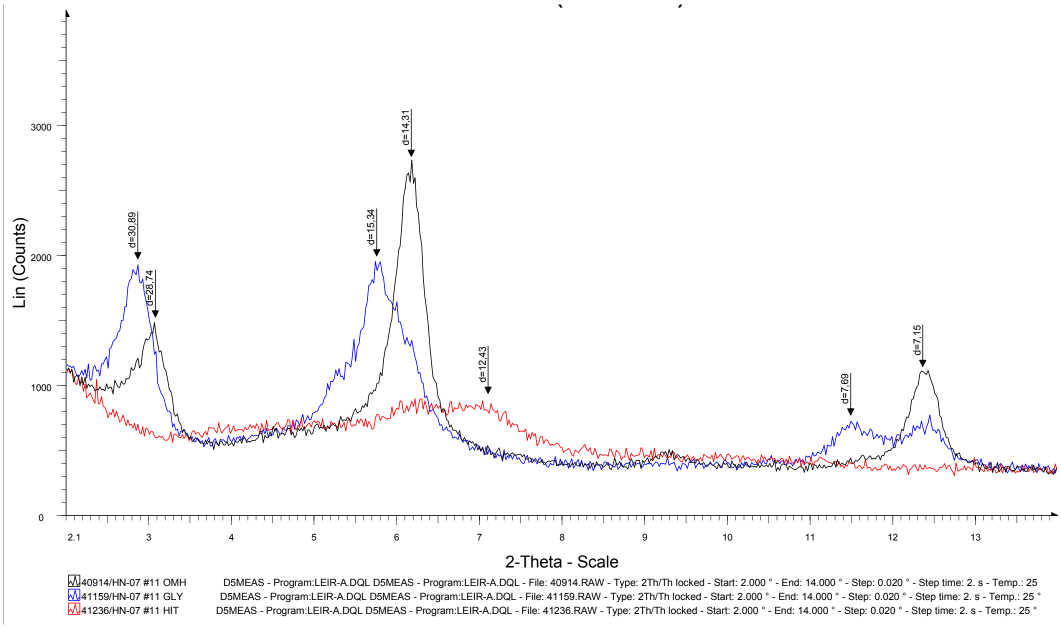


FIGURE 16: XRD analyses at 1068 m depth in HN-7

Mixed-layer clays (MLC) are basically an inter-layering of smectite and chlorite (fine-grained – coarse grained) indicating temperatures between 200 and 230°C. It was detected throughout the cuttings at around 998 m and in thin sections at around 950 m and at 1036 m in XRD. It shows pronounced pleochroism, light to darker green colours in plane-polarized light, and in cross-polarized light shows as high order strong yellow to brown colours. It often appears in voids as a coarse-grained clay mineral, coarser than smectite. The mineral is not shown in Figure 12.

Chlorite was not identified by binocular microscope analysis nor by petrographic analysis. It was identified only in XRD as a mixed layer with smectite at 1036 m. Chlorite is generally characterised by fine- to coarse-grained textures and petrographically chlorite is light greenish in colour in plane polarized light, has a fibrous cleavage and sometimes slight pleochroism. It is characterised in the binocular microscope by a fine- to coarse-grained radial texture in voids. Chlorite occurs both as a replacement of primary minerals in the rock and as void fillings. Chlorite is an indicator of temperatures exceeding 230°C (Kristmannsdóttir, 1979). Chlorite was first analysed at 1036 m and continued to below 1200 m.

Other minerals:
Calcite is a common and widespread mineral filling veins and vesicles in well HN-7. It is white to colourless in the binocular microscope, but transparent to translucent with perfect cleavage in the petrographic microscope. It is easily recognized by its obvious cleavage, extreme birefringence (Figure 17), change of relief with rotation in thin section, and its reaction with weak acid in cuttings. Calcite is associated with pyrite in the whole well and was concentrated from almost the top down to the bottom of the upper 1000 m of the well (Figure 12). It is relatively difficult to determine the temperature of calcite deposition but, as a rule of thumb, this mineral disappears at temperatures above 300°C (Kristmannsdóttir, 1979).

Pyrite is a brassy yellow, cubic, euhedral mineral readily identified by its golden colour and its cubic shape. It was identified in HN-7 mostly from around 840 m but only sporadically above that. It is often associated with calcite. This mineral is sometimes used as a permeability indicator, as may be seen in the aquifers at 880 and 1000 m. The temperature range of pyrite is from around 120 to 260°C (Reyes, 2000).

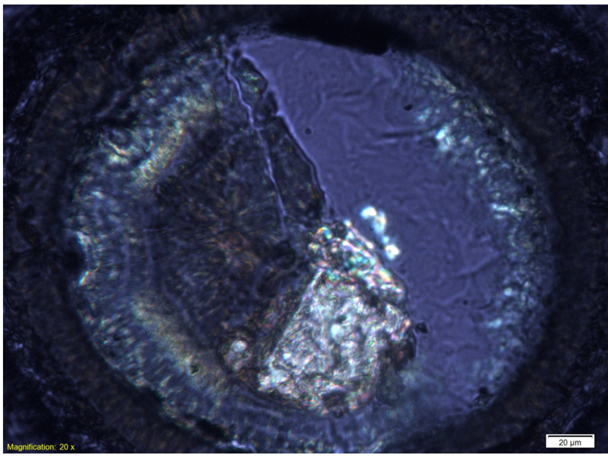


FIGURE 17: Petrographic analyses of thin sections; Calcite deposited in well HN-7 after smectite at 392 m.

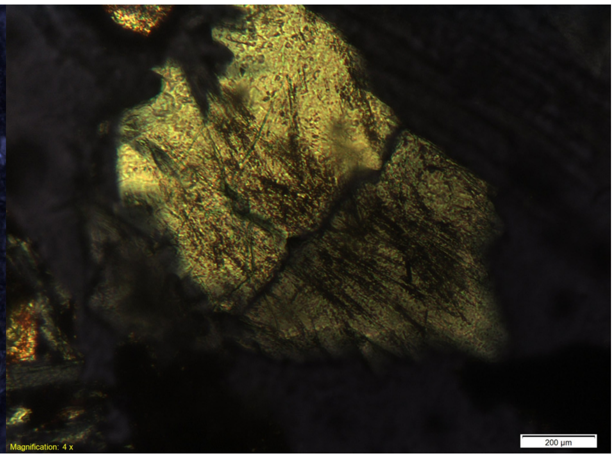


FIGURE 18: Petrographic analyses of thin sections; Quartz succeeding laumontite at 866 m in well HN-7

Quartz belongs to the trigonal crystal system. It is a colourless to white or cloudy (milky) and transparent to translucent mineral. Quartz occurs either as an alteration product of opal or chalcedony or as a vesicle or vein filling mineral. It is generally associated with epidote, prehnite, pyrite and calcite (Gebrehiwot, 2010). Low relief, low birefringence and a lack of cleavage or twinning are the main characteristics of quartz in thin section. In well HN-7, this mineral first appeared at 1058 m. It has a temperature stability of ≥ 180°C. The appearance of euhedral and anhedral crystals of quartz in voids was seen in both thin sections and the cutting samples. It was also seen as a replacement of laumontite in this well at 866 m (Figure 18).

Prehnite is brittle with an uneven fracture, has a vitreous to pearly lustre, and is white to colourless in the binocular microscope. Prehnite occurs mainly as vesicle and vein fillings but also as a replacement of primary minerals. It has a round to nearly spherical shape in binocular microscope but in thin section its strong birefringence can be readily distinguished by a bow tie texture. "The low stability of prehnite is not precise; it appears to be able to form at temperatures above 200°C, and in some instances at about 250°C, and it is present in the geothermal systems to more than 300°C" (Saemundsson and Gunnlaugsson, 2002). It was found below 1100 m in association with epidote, quartz and wairakite.

Epidote has a distinctive yellowish to greenish colour in cuttings. It displays strong pleochroic green colours in thin sections. It occurs as individual grains and crystal intergrowths. It was observed to be associated with quartz, wairakite and chlorite. The occurrence of epidote in significant quantities indicates temperatures above 240-250ºC (Kristmannsdóttir, 1979). It was found as a partial replacement of plagioclase phenocrysts at around 1160 m depth in well HN-7.

Chalcopyrite forms from late magmatic gas-rich liquids and occurs mainly in veins close to the margins of large intrusions. It is yellow in colour, forming octahedrons which are, however, usually distorted. The streak is slightly greenish black. In well HN-7 it occurred along the high-temperature minerals below about 1040 m.

6.2.3 Mineral deposition sequences

Paragenesis is a petrological concept meaning an equilibrium assemblage of mineral phases. The paragenetic sequence in mineral formation is an important concept in deciphering the detailed geological history of a geothermal system.

In hydrothermal systems, mineral sequences are identified from crosscutting veins and amygdale infilling sequences through detailed microscopic studies of petrologic thin section as well as macroscopic field relations and, at times, fluid inclusions (Lugaizi, 2011). Chemical composition analysis and petrographic characteristics of the minerals being deposited lead to an assessment of the chemical changes that have taken place. The mineral anomalies, where low- or medium temperature minerals appear with others which are stable at high temperatures are sometimes observed in mineral assemblages, possible transient or long term evidence of cooling in the geothermal reservoir. The time sequences in which fissures and voids are filled by minerals deposits permit us to evaluate changes in geothermal systems over time.

In the amygdules and fractures, the generation of minerals was visible in thin section. An attempt to reconstruct the paragenetic sequences of hydrothermal alteration minerals using thin section analysis from various depths in a well shows that the hydrothermal system has evolved from low to high-temperature conditions. Generally, in well HN-7, the sheet silicates appear first in the well, followed by zeolites and finally calcite appears. At a deeper level, below 1000 m, quartz followed calcite.

6.3 Aquifers / feed zones

Identification of aquifers in well HN-7 was done by using: circulation losses monitored during drilling (Table 4); the temperature log performed during and after drilling for formation temperature (Appendix II); the geological structure penetrated by the drillhole; the alteration mineral assemblage in a well; and a comparison of temperatures based on alteration minerals and the measured formation temperature, to establish whether equilibrium exists between the two temperatures (Figure 19). Where differences exist, they may indicate recent changes in the geothermal system, whether it be heating or cooling.

TABLE 4: Circulation losses during drilling of HN-7

Depth (m)	**69.5**	**71**	**91**	**94**	**98**	**103**	**102**	**186**	**532**	**~700**
Circulation losses	Total	15-20	Total	Total	Total	13.5	Total	9	3	1
Remarks	May coincide with ground water table		Total loss for 1 hr.	Total loss for a short period of time	Total loss for a short period of time	Circulation loss after installation of casing.	Total loss for a short period of time			

6.4 Comparison of alteration and formation temperatures

Figure 20 shows a comparison between the alteration and formation temperatures in well HN-7. The former shows a gradual temperature increase with depth until about 1000 m where high-temperature alteration suddenly appears with quartz (180°C), chlorite (230°C), prehnite (~240°C) and lastly epidote at 1158 m. This is also presented in Figure 11. The temperature log, on the other hand, shows a different picture where the curve follows the boiling point curve up to 700 m where it rapidly lowers to a temperature akin to alteration curve. Unfortunately, this is considered to reflect boiling conditions within the well from an aquifer at still deeper levels. In this case it is believed that the alteration temperature curve is a better approximation of the formation temperatures than the temperature log. This really emphasizes that logs have to be interpreted with care.

7. CONCLUSIONS AND RECOMMENDATIONS

Various methods and techniques are used in geothermal exploration to evaluate geothermal systems and understand geothermal reservoir zones. It has become apparent that geothermal reservoirs and their immediate environments have certain specific physical characteristics which are susceptible to detection. Investigation of hydrothermal alteration is one of the methods which can provide direct

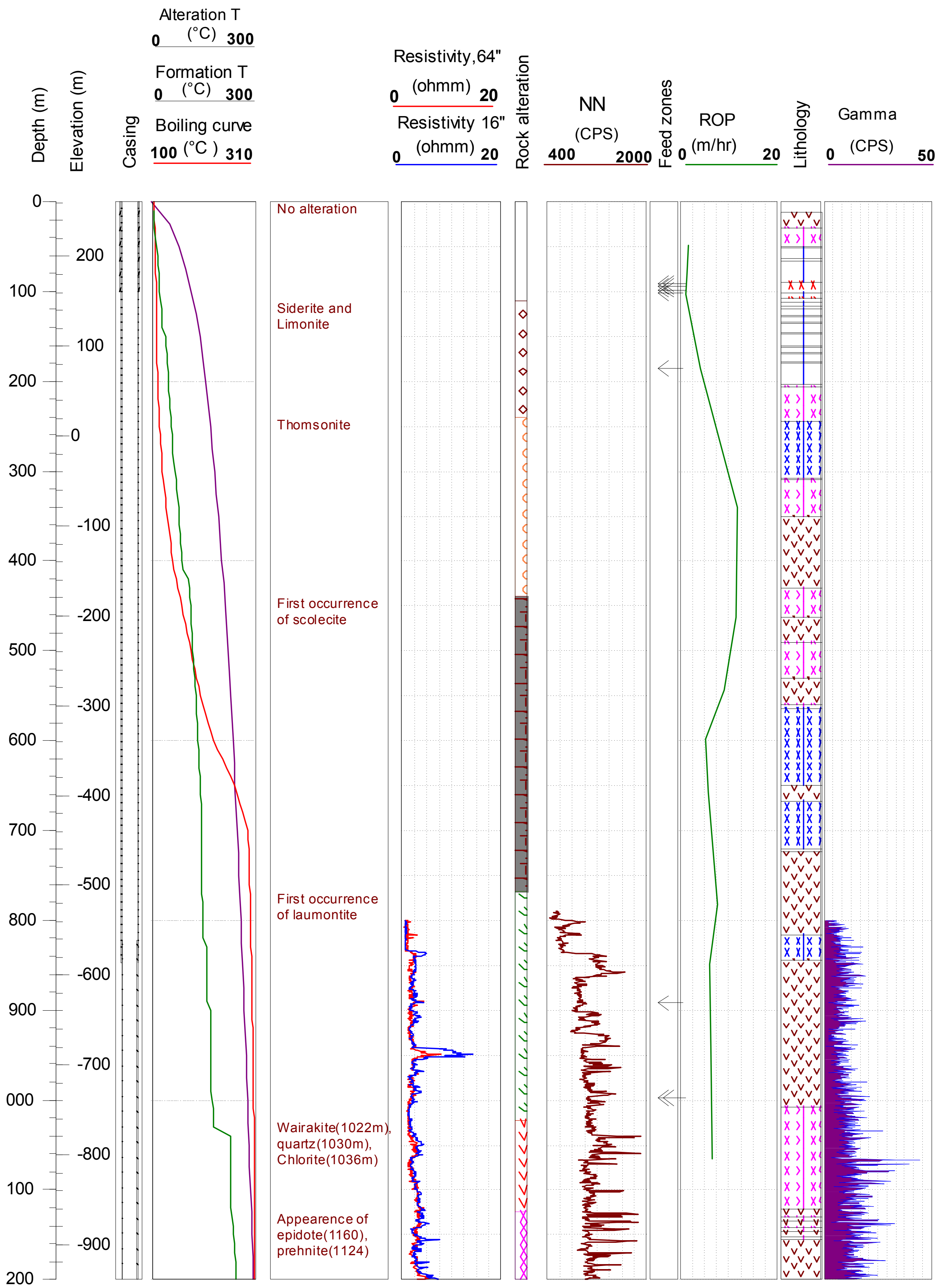


FIGURE 19: Lithology, possible formation temperatures and geophysical logging in well HN-7

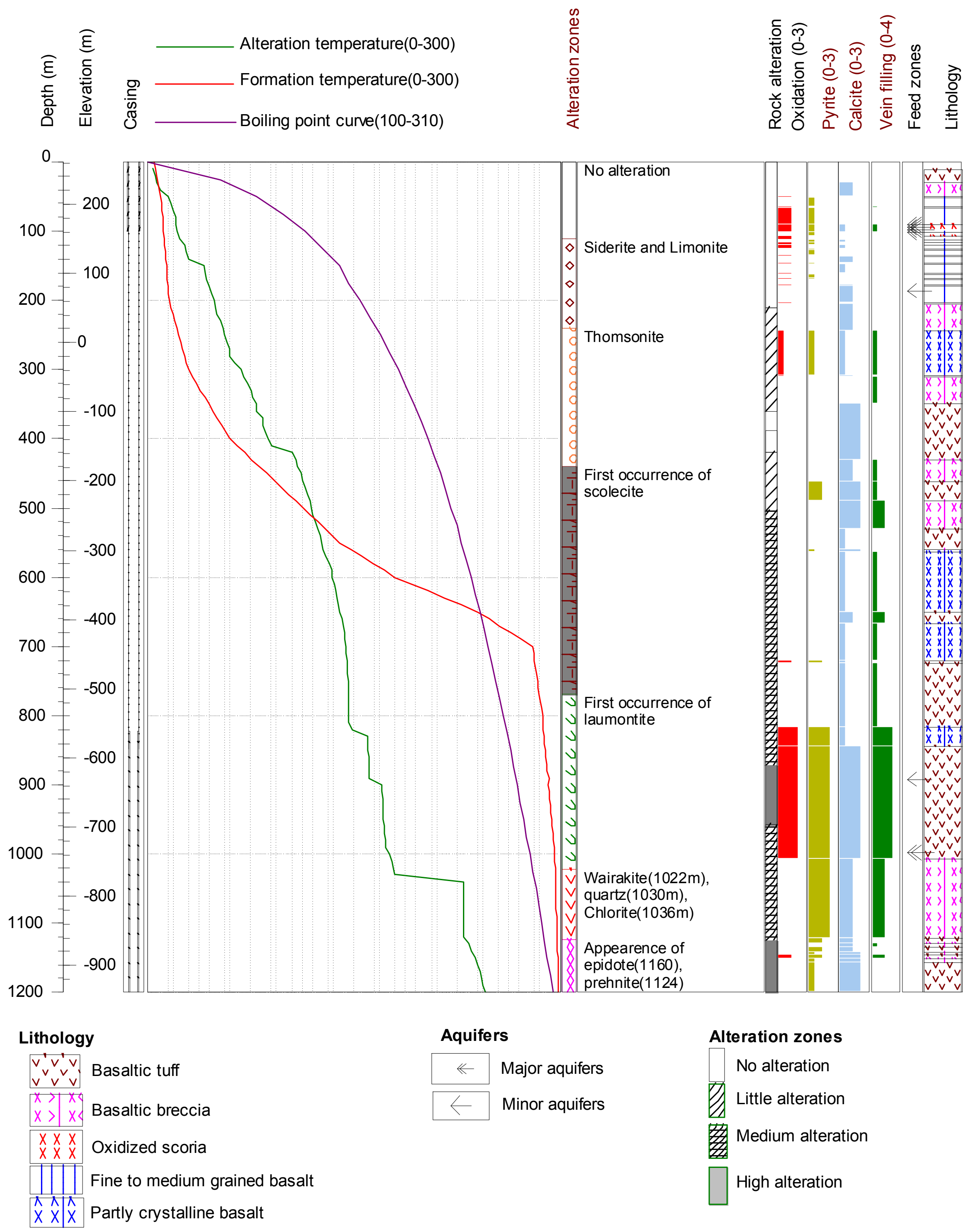


FIGURE 20: Correlation of alteration temperature, formation temperature and boiling point curve in well HN-7

information about geothermal reservoirs. During surface exploration of geothermal investigation, hydrothermal deposits (e.g. travertine) or hydrothermal eruption breccia can serve as guides to the nature of the reservoir rocks and the physicochemical conditions in the sub-surface. Later, when drilling exploration starts, hydrothermal alteration minerals can be identified in the cuttings of the rocks that were drilled through. Comprehension of the newly formed minerals may lead to understanding the characteristics of the thermal fluid. Furthermore, their genetic sequence elucidates on the changes taking place in the thermal system, thus relating geothermal alteration to the past and present conditions of the hydrothermal system. Applications of hydrothermal alteration in geothermal systems are mainly:

- Geothermometers and setting of the production casing;
- Permeability indicators;
- Chemical components of the geothermal fluid;
- Thermal history;
- Predicting scaling and corrosion tendencies of a well.

The study of hydrothermal alteration of the formations penetrated by drill hole HN-7 involved three main techniques, namely:

- *Binocular microscope* with which a number of hydrothermal alteration minerals were found, permitting the estimation of particular formation temperatures.
- *Petrographic microscope* is technologically more advanced for mineralogical analysis of cuttings. Some minerals are too small to be seen in cuttings using a binocular microscope, either primary minerals or secondary minerals, thus leading to misunderstandings. Thin section analyses give more refined results.
- *XRD*. Most alteration minerals can be identified using XRD with appropriate sample preparation. In geothermal analyses, it is mainly used for clay minerals and amphiboles.

Geophysical logs, in addition to the analysis of cuttings, are quite useful in mapping geothermal aquifers and alteration zones. Resistivity logs, for example, show low resistivity in the smectite-zeolite zone, but increased resistivity when entering the chlorite zone.

The degree of hydrothermal alteration and amount of hydrothermal minerals formed in a geothermal reservoir depend largely on the following parameters:

1. The type and permeability of the rock;
2. The temperature and chemical composition of the fluid; and
3. The duration of geothermal activity.

The study of the secondary minerals formed in the rocks by the action of hydrothermal fluids, their distribution and their interrelation gave the temperature characteristics of the geothermal system in Gráuhnúkar sector of the Hellisheidi high-temperature field. When compared to the formation temperature, the system in Gráuhnúkar appears to be heating up or almost in equilibrium.

In all geothermal fields, proper understanding of hydrothermal alteration is important as it is this information that gives a general picture of the geothermal system, its history and possibly its future. Hydrothermal minerals can be useful as geothermometers and, therefore, assist in determining the depth of the production casing while drilling. Additionally, these minerals are used in estimating fluid pH and other chemical parameters, as well as predicting scaling and corrosion tendencies of fluids, measuring permeability, possible cold-water influx and as a guide to the hydrology. The minerals commonly used as geothermometers are the zeolites, clays, epidote and amphiboles. In well HN-7, the zeolites which started to appear above 30°C and disappeared before 200°C revealed a medium temperature environment (maximum 140°C) for the upper 700 m. The alteration minerals in this zone are mainly zeolites like chabazite, thomsonite, mesolite and scolecite along with fine-grained clay evaluated in XRD as being smectite. The smectite changed to coarse-grained clay with depth and temperature and, along with other zeolite minerals like laumontite, they constituted a transition to a high-temperature environment, evidenced by high-temperature hydrothermal alteration minerals such as quartz (>180°C), wairakite (>200°C), prehnite (>240°C) and epidote (~250°C). Among the minerals that occur at high temperatures i.e. ≥250, epidote seems to be the most reliable and consistent temperature guide. According to Browne (1984a), epidote first appears in many fields at 250°C and the lithology does not influence its formation.

Most faults and fractures, commonly the dominant physical controls on geothermal and mineral resources, are identified by associated hydrothermal alteration, especially where there is abundant calcite and pyrite, as is the case in HN-7 from 892 to 1200 m. Nevertheless, at times no indications are seen in the cuttings, although indications may be seen in the appropriate geophysical logs. Interpretations concerning permeability and temperature deduced from alteration minerals in well HN-7 give a broader outlook on the geothermal system in Gráuhnúkar.

Subsurface investigation in geothermal systems involves different methods which have to supplement each other during exploration; a microscopic study of cuttings is part of the geological and mineralogical research which aims towards a more thorough geological understanding of a geothermal reservoir but alone it could lead to more limited information. Additional measurements like temperature logging, resistivity logging etc., are necessary to confirm details of the geothermal system. One must appreciate that alteration portrays the long term condition of the geothermal system, while the present formation temperature shows only the last stage. Therefore, a comparison between the two gives good evidence of the evolution of the geothermal system.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to the Government of Iceland and the United Nations University - Geothermal Training Programme (UNU-GTP) for awarding me the fellowship to take part in the UNU-GTP 2012 programme. Many thanks go to all the UNU-GTP staffs under the leadership of the Director, Dr Ingvar B. Fridleifsson and Deputy Director, Mr Lúdvík S. Georgsson. Not to forget Ms Thórhildur Ísberg, Mr Ingimar G. Haraldsson, Mr Markús A.G. Wilde and Ms Málfrídur Ómarsdóttir, for their assistance and support during my stay in Iceland. Intense gratitude also goes to all lecturers. Thanks to my supervisors, Mr Hjalti Franzson and Mr Steinthór Níelsson, for their guidance and for sharing their knowledge and experience during my project and throughout the course. I would also like to sincerely thank Mr Björn S. Hardarson, Ms Anette K. Mortensen and Ms Helga Margrét Helgadóttir for dedicating their time to helping me during my project. Many thanks go to my colleagues, the 2012 fellows, especially my roommates, for their collaboration, encouragement and nice times during the six months together in Iceland.

I am also grateful to my employer, the Energy Water Sanitation Authority (EWSA) for granting me the permission to attend this training. Special thanks go to my family for their prayers, love and patience while I was away from home. Most important, I would like to thank the Almighty God for His love, care and guidance during the whole period in Iceland.

REFERENCES

Airlines and Destinations, 2012: *Nyiragongo eruption of 2002.* Airlines and Destinations, webpage: *www.airlinesanddestination.com.*

Árnason, K., Eysteinsson, H., Hersir, G.P., 2010: Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. *Geothermics*, *39*, 13-34.

Árnason, K., Haraldsson, G.I., Johnsen, G.V., Thorbergsson, G., Hersir, G.P., Saemundsson, K., Georgsson, L.S., Rögnvaldsson, S.Th., and Snorrason, S.P., 1987: *Nesjavellir-Ölkelduháls, surface exploration 1986*. Orkustofnun, report OS-87018/JHD-02 (in Icelandic), 112 pp+maps.

Browne, P.R.L., 1984a: *Lectures on geothermal geology and petrology*. UNU-GTP, Iceland, report 2, 92 pp.

Browne, P.R.L., 1984b: Subsurface stratigraphy and hydrothermal alteration of the eastern section of the Olkaria geothermal field, Kenya. *Proceedings of the 5th New Zealand Geothermal workshop, Geothermal Institute, Auckland,* 33-41.

Browne, P., 2011a: *Geothermal prospects in Rwanda.* University of Auckland, Institute of Earth Science and Engineering IESE), report.

Browne, P., 2011b: *Petrographic report: Samples from geothermal prospects in Rwanda*. University of Auckland, Institute of Earth Science and Engineering IESE), report.

Doveton, J.H., 1984: *Log analysis of subsurface geology*. John Wiley & Sons, NY, 273 pp

Einarsson, P., 2008: Plate boundaries, rifts and transform in Iceland. *Jökull, 58*, 35-58.

Franzson, H., Árnason, K., Saemundsson, K., Steingrímsson B., and Gunnlaugsson E., 2010: The Hengill geothermal system, conceptual model and thermal evolution. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 9 pp.

Frolova, J.V., Ladygin, V.M., and Rychagov, S.N., 2010: Petrophysical alteration of volcanic rocks in hydrothermal systems of the Kuril-Kamchatka Island Arc. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 4 pp.

Gebrehiwot M., K.., 2010. *Subsurface geology, hydrothermal alteration and geothermal model of Northern Skarðsmýrarfjall, Hellisheiði geothermal field, SW Iceland.* University of Iceland, Faculty of Geosciences, UNU-GTP, Iceland, report 5, 65 pp.

Gunnarsson, G., 2011: A story of success and failures, mastering reinjection in the Hellisheidi field, SW-Iceland. *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca*, 8 pp.

Haraldsdóttir, S.H., Franzson, H., and Árnason, K., 2012: Preliminary study of down-hole resistivity from 72 boreholes in the S-Hengill geothermal field, SW-Iceland, with respect to surface resistivity data and alteration minerals. *Proceedings of the 37thWorkshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca,* 2-8 pp.

Hatch, F.H., Wells, A.K., and Wells, M.K., 1972: *Petrology of igneous rocks* (13thedition). George Allen and Unwin Ltd., London, 551 pp.

Helm-Clark, C.M., Rodgers, D.W., Smith, R.P., 2004: Borehole geophysical techniques to define stratigraphy, alteration and aquifers in basalt. *J. Applied Geophys., 55,* 3-38.

Hulen, J.B, and Sibbet, B.S., 1981: Sampling and interpretation of drill cuttings from geothermal wells. In: *Geothermal log interpretation handbook* (2nd ed.). Society of Professional Well Log Analysts, Utah.

Jolie, E., Gloaguen, R., Wameyo, P., Ármannsson, H., Hernández Pérez, P.A., 2009: *Geothermal potential assessment in the Virunga geothermal prospect, Northern Rwanda*. Federal Institute for Geosciences and Natural Resources (BGR). Geozentrum, Hannover, Germany.

Kristmannsdóttir, H., 1979: Alteration of basaltic rocks by hydrothermal activity at 100-300°C. In: Mortland, M.M., and Farmer, V.C. (editors), *International Clay Conference 1978*. Elsevier Scientific Publishing Co., Amsterdam, 359-367.

Lagat, J., 2010: Hydrothermal alteration mineralogy in geothermal fields with case examples from Olkaria domes. *Presented at Short Course V on Exploration for Geothermal Resources, organized by UNU-GTP, KenGen and GDC, Naivasha, Kenya*, 24 pp.

Lapidus, D.F., and Winstanley, I., 1987: *Collins dictionary of geology*. Harper Collins Publishers, London and Glasgow, 565 pp.

Lugaizi, I., 2011: Borehole geology and hydrothermal mineralisation of well HE-32, Hellisheidi geothermal field, SW-Iceland. Report 20 in: *Geothermal Training in Iceland 2011.* UNU-GTP, Iceland, 433-436.

OGMR, 2009: *Geology of Rwanda.* Rwanda Geology and Mining Authority, reports.

NASA, 1999: *Space radar image of Karisoke and Virunga volcanoes.* NASA, PIA01736.

Pidwirny, M., 2006: *Characteristics of Igneous Rocks. Fundamentals of Physical Geography* (2nd ed.). PhysicalGeography.net, webpage: www.physicalgeography.net/fundamentals/10e.html.

Raymond, L.A., 1995: *Petrology, the study of igneous, sedimentary and metamorphic rocks* (2nd ed.). McGraw-Hill Co., Inc., NY, 720 pp.

Reyes, A.G., 1990: Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment*.* *J. Volc. Geoth. Res., 43,* 279-309.

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

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

Scienceblogs, 2012: *Nyamuragira eruption of 2012*. Scienceblogs, webpage: *scienceblogs.com*.

Shalev, E., Browne, P., Wameyo, P., Hochstein, M., Palmer, J., and Fenton, R., 2012: *Geoscientific survey of the Rwandan Karisimbi, Gisenyi and Kinigi geothermal prospects*. University of Auckland, Institute of Earth science and engineering (IESE), report.

Stefánsson, V., Axelsson, G., and Sigurdsson, Ó., 1982: Resistivity logging of fractured basalt. *Proceedings of the 8th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca,* 189-195.

Stefánsson, V., and Steingrímsson, B.S., 1990: *Geothermal logging I, an introduction to techniques and interpretation* (3rd edition). Orkustofnun, Reykjavík, report OS-80017/JHD-09, 117 pp.

Steingrímsson, B., 2011: Geothermal well logging: geological wireline logs and fracture imaging. *Presented at Short Course on Geothermal Drilling, Resource Development and Power Plants, organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 11 pp.

Trønnes, R.G. 2002: Geology and geodynamics of Iceland. In: Planke, S., (ed.) *Iceland 2002 – Petroloeum geology field trip guide (prepared for Statoil Faroes licence groups by Volcanic Basin Petroleum Research).* Nordic Volcanological Insititute and Orkustofnun, Reykjavik, 23-43.

Wikipedia, 2012: *Democratic Republic of Congo*. Wikipedia, webpage: *en.wikipedia.org/wiki/Democratic_Republic_of_the_Congo*

Wöhrl, T., and de Wall, H., 2003: Sampling of cuttings. ICDP Training Course in Shimabara, Japan, website: *www.icdp-online.org/news/training/Shimabara/Woehrl/7c_Sampling-Cuttings.pdf.*

Wolfe, C.J., Bjarnason, I.Th., Van Decar, J.C., and Solomon S.C., 1997: Seismic structure of the Iceland plume. *Nature, 385*, 245-247.

APPENDIX I: XRD clay mineral results from well HN-7

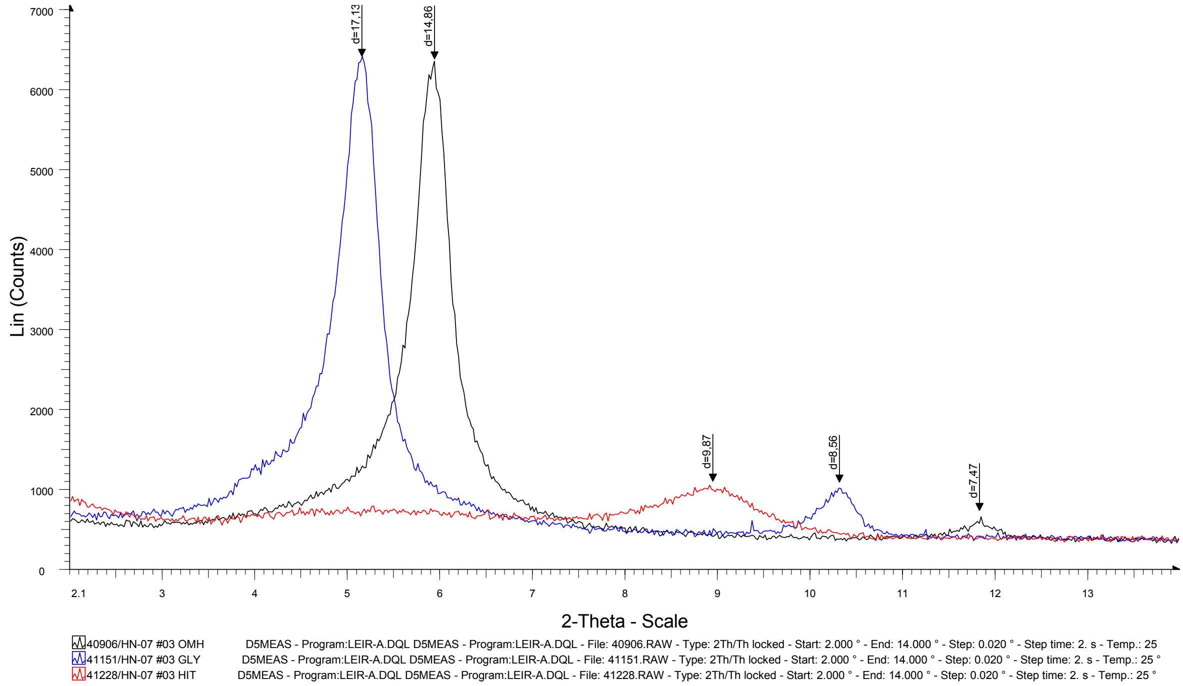


FIGURE 1: Smectite from well HN-7, sample 3 at 614 m

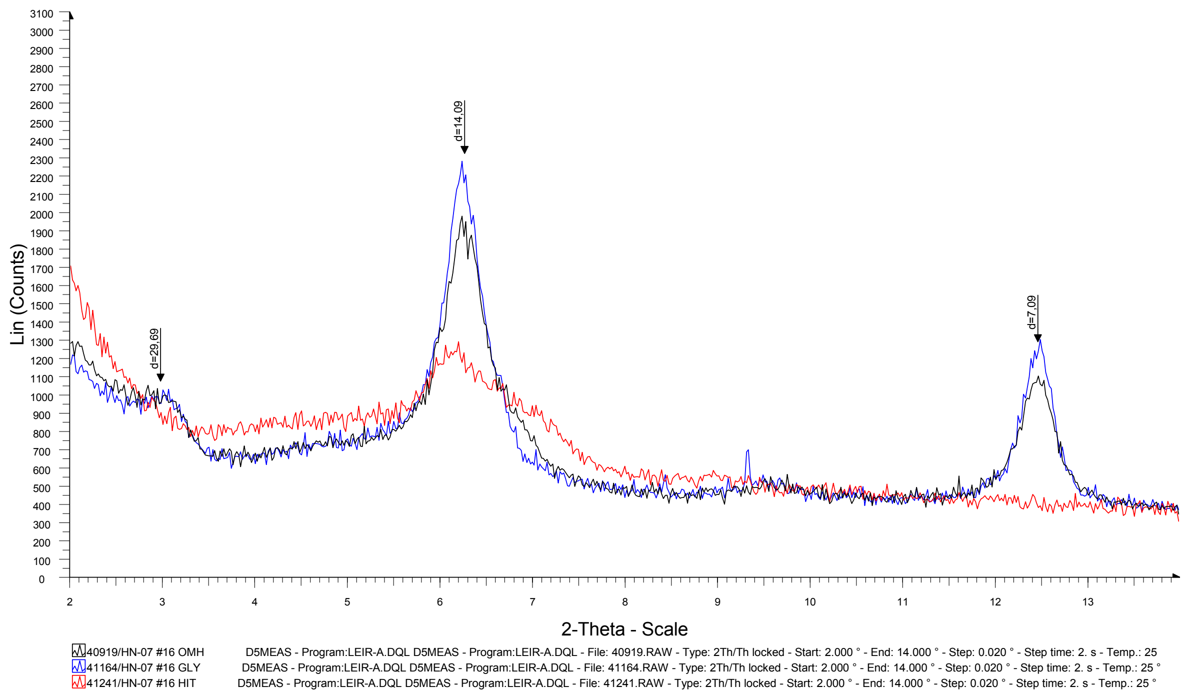
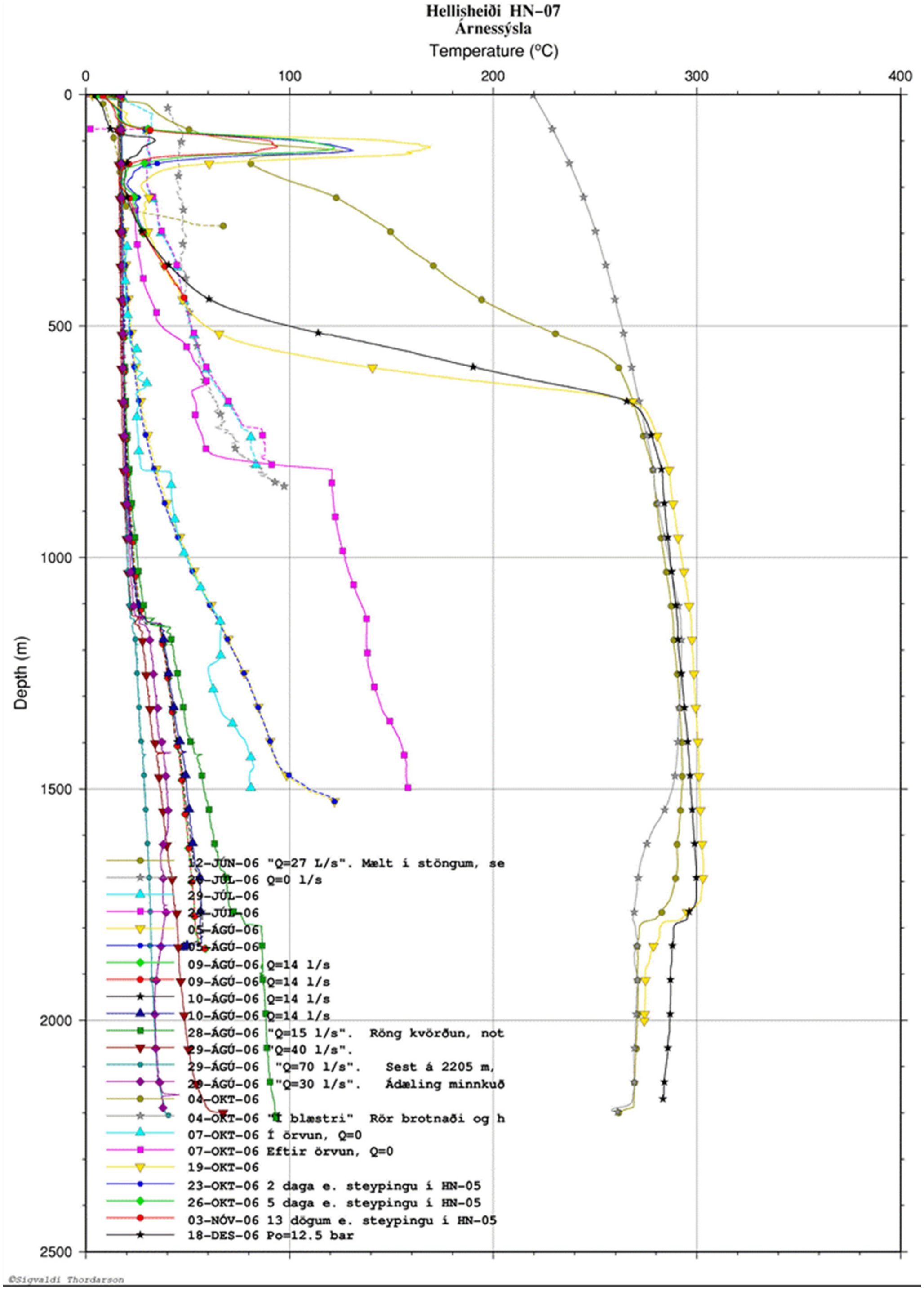


FIGURE 2: Smectite mixed-layer clay smectite and chlorite from well HN-7, sample 16 at 1200 m

APPENDIX II: Temperature graphs measured during and after drilling of well HN-7



Information on the temperature logs:

- Temperature logging tools were lowered on a wireline into a well during drilling to carry out temperature measurements.
- From the temperature logs the formation temperature can be calculated which shows the present temperature of the rock formations.
- In HN-7 a hot feed zone was cut at about 1800 m depth causing boiling in the well and therefore a distorted temperature measurement.