UNITED NATIONS
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SUBSURFACE GEOLOGY, HYDROTHERMAL ALTERATION AND GEOTHERMAL MODEL OF NORTHERN SKARDSMÝRARFJALL, HELLISHEIDI GEOTHERMAL FIELD, SW ICELAND

Report 5
December 2010

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2010
Number 5

SUBSURFACE GEOLOGY, HYDROTHERMAL ALTERATION AND GEOTHERMAL MODEL OF NORTHERN SKARDSMÝRARFJALL, HELLISHEIDI GEOTHERMAL FIELD, SW ICELAND

MSc thesis
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by

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United Nations University
Geothermal Training Programme
Reykjavík, Iceland
Published in December 2010

ISBN 978-9979-68-287-5
ISSN 1670-7427

This MSc thesis has also been published in April 2010 by the
School of Engineering and Natural Sciences, Faculty of Earth Sciences
University of Iceland

INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2010, 452 scientists and engineers from 47 countries have completed the six month courses. They have come from Asia (42%), Africa (29%), Central America (15%), and Central and Eastern Europe (14%). There is a steady flow of requests from all over the world for the six month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the UNU and the Government of Iceland.

Candidates for the six month specialized training must have at least a BSc degree and a minimum of one year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but several excellent students who have only BSc degrees have made requests to come again to Iceland for a higher academic degree. In 1999, it was decided to start admitting UNU Fellows to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. The six month studies at the UNU Geothermal Training Programme form a part of the graduate programme.

It is a pleasure to introduce the 25th UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Mr. Kiflom Gebrehiwot, BSc in Geology, of the Ministry of Energy and Mines, Department of Mines, Geological Survey of Eritrea, completed the six month specialized training in Exploration Geology at the UNU Geothermal Training Programme in October 2005. His research report was entitled: "Geothermal mapping in western Ölkelduháls high-temperature field, SW-Iceland". After three years of geothermal research work in Eritrea, he came back to Iceland for MSc studies at the Faculty of Earth Sciences of the University of Iceland in August 2008. In April 2010, he defended his MSc thesis presented here, entitled "Subsurface geology, hydrothermal alteration and geothermal model of Northern Skardsmýrarfjall, Hellisheidi geothermal field, SW-Iceland". His studies in Iceland were financed by the Government of Iceland through a UNU-GTP Fellowship from the UNU Geothermal Training Programme. We congratulate him on his achievements and wish him all the best for the future. We thank the Faculty of Earth Sciences at the School of Engineering and Natural Sciences of the University of Iceland for the co-operation, and his supervisors for the dedication.

Finally, I would like to mention that Kiflom's MSc thesis with the figures in colour is available for downloading on our website *www.unugtp.is* under publications.

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director
United Nations University
Geothermal Training Programme

PREFACE AND ACKNOWLEDGEMENT

Geothermal energy is a proven resource for direct heat and power generation. Iceland is located in a zone of high heat flow as it straddles the Mid-Atlantic Ridge, a constructive plate boundary. Because of its strategic location Iceland is endowed with geothermal resources. One of the high-temperature geothermal fields in Iceland is the Hellisheidi geothermal field, southern sector of the Hengill system currently operating at 213 MWe. To date 57 wells has been drilled since drilling started in 2001. The very intense drilling in this field has resulted in a limited time to do detailed research into the geological factors controlling the geothermal system. Due to this, Reykjavik energy has initiated a recent research work to better understand the subsurface conditions in Hellisheidi and generate a geothermal model, believed to show a clearer and broader view of the field.

A team was organized by Iceland Geosurvey (ISOR) for this task and a research work is being conducted to understand the subsurface conditions on the wells in the different part of the field. The team includes Sandra Ósk Snaebjörnsdóttir, Helga Margrét Helgadóttir, Steinthór Níelsson, Sveinborg Hlíf Gunnarsdóttir and Theódóra Matthíasdóttir all from ISOR and myself. About 20 of the wells have been selected and divided among the team for a thorough and detailed research work in order to develop a comprehensive model of the Hellisheidi geothermal system.

This thesis is done as part of the partial fulfilment of the degree of Master of Science in Geology and submitted to the University of Iceland accounting for 60 ECTS out of the 120 ECTS required for the degree and contributes an additional input to the development of the geothermal model at hand. The author is very much indebted to the team for their constructive discussion and being supportive the whole way, especially Sandra Ósk Snaebjörnsdóttir who is working on the wells close to and west of the studied wells in this thesis.

I would like to express my gratitude to the Government of Iceland and United Nations University Geothermal Training Program (UNU-GTP) for funding my studies at the University of Iceland, and the Department of Mines, Ministry of Energy and Mines, Eritrea for supporting me to attend this study. I am sincerely grateful to Dr. Ingvar Birgir Fridleifsson, the director of UNU-GTP and Mr.Lúdvík S. Georgsson, deputy director of UNU-GTP for the Fellowship, their encouragement and guidance throughout, and special thanks also go to Thórhildur Ísberg, Dorthe H. Holm, and Markús A.G. Wilde for their great help and assistance. Reykjavik Energy is acknowledged for allowing me to use the data from the Hellisheidi geothermal field.

I extend my gratitude and indebtedness to my supervisors: To Dr. Hjalti Franzson for having been there the whole way and providing a very supportive environment for my research along with much guidance. To Prof. Stefán Arnórsson for his help and guidance during the whole period of study and all the lecturers of the University of Iceland for providing a great learning experience. To Dr. Árny Erla Sveinbjörnsdóttir for reviewing the thesis with valuable comments.

My sincere appreciation to Dr. Karl Grönvold and Mr. Níels Óskarsson for their valuable teaching and guidance for the analysis with Electron Microprobe Analysis (EMPA) and Inductively Coupled Plasma (ICP-OES). Special thanks to Gísli Örn Bragason and Ásgeir Einarsson for their assistance and valuable discussions in this aspect. I am grateful to Sigurdur Sveinn Jónsson for the X-ray diffraction (XRD) analysis, to the staff of ISOR with whom interaction was of great help. Special thanks are extended to my fellow students at UNU-GTP and University of Iceland, their fruitful discussions and friendship was very encouraging throughout my study. Thank you all.

ABSTRACT

Skardsmýrarfjall is located in northern part of Hellisheidi, which in turn is situated in the southern sector of the 110 km^2 Hengill low-resistivity anomaly, one of the high-temperature geothermal fields in Iceland containing economically promising geothermal prospects. Two wells drilled in this area with the aim of understanding the geothermal system beneath were studied; HE-24 a vertical well drilled to a depth of 2587 m and HE-37 a directional well having a depth of 3111.5 m. The lithology of the wells comprises hyaloclastites and lavas with intrusions of basaltic and intermediate composition. The hyaloclastite formations have been further classified into seven different formations based on their texture, crystallinity and compositional variation. In addition to these the different hyaloclastite formations have been identified for another two wells HE-39 and HE-27 in Skardsmýrarfjall and correlated with the above wells. Permeability in the wells is related to lithological contacts, intrusive boundaries, major faults and fractures. Aquifers in the top part of the wells are related to stratigraphic boundaries while sources of permeability in the bottom part being mostly along intrusive boundaries. Hydrothermal alteration in the wells is controlled by temperature, rock type and permeability. The mineral assemblage showed the hydrothermal system to have evolved from low- to high-temperature conditions followed by cooling evidenced by the precipitation of calcite at later stages. The mineralogical examination also revealed five zones of hydrothermal alteration beneath a zone of unaltered rocks. These zones are zeolite-smectite, mixed layer clay, chlorite, chlorite-epidote and epidote-actinolite. Fluid inclusion studies have shown three distinct ranges of homogenization temperatures indicating two or a third probable phases of geothermal activity in well HE-37; an earlier one with high rather anomalous temperature up to 320^0C and a lower temperature range of 215-230°C which conforms to present formation temperature at 734 m but is higher than the formation temperature at 1162 m. A third stage may be present, showing temperatures as low as 175°C at 734 m, which is lower than formation temperatures at that depth but conforms to the temperature at 1162 m. In well HE-24 a similar wide range of fluid inclusion temperatures show probable three phases and boiling is proposed at 700 m. A more shallow hydrothermal alteration is found in the northern part of Skardsmýrarfjall which diminishes to the south observed in well HE-37 in the north and well HE-24 in the south. This shallow hydrothermal alteration in this area together with the scanty surface manifestations in the whole of Skardsmýrarfjall on the one hand and the presence of very extensive fossil surface alteration in Hengill mountain on the other could indicate that an upflow channel of the geothermal system may underlie Hengill mountain, which also further indicates that the studied wells are located in the outflow zone of the system. In general the evidences from this study has shown that there are three successive stages within the history of the geothermal system: A progressive heating, a later cooling episode and, finally, a probable renewed heating phase, which may relate to the two Holocene eruptive fissure eruptions.

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1. INTRODUCTION

Surface exploration was the main source of information and was given a greater emphasis in the early days before subsurface exploration started by drilling into geothermal systems. The latter has developed through time giving deeper and detailed information when at first shallow and deep exploratory wells were drilled and later with appraisal and production drilling. When surface exploration of a geothermal system has been carried out, further exploration and evaluation of the geothermal system is mainly based on information gained from wells (exploratory and production wells) drilled into the reservoir. This development has led geologists to measure various parameters directly from borehole and get in-depth information about geothermal systems. Geological samples (cores and drill cuttings) are obtained from wells to determine lithology and alteration of rocks and fluid samples (water, steam and gas) are collected and analysed to determine the fluid chemistry of the reservoir. In addition to these several measuring instruments are sunk into the borehole to measure or estimate reservoir parameters, pressure and temperature being the most important in geothermal systems.

Geothermal systems in Iceland are distinguished as low-temperature and high temperature areas (Bödvarsson and Pálmason, 1961). The low-temperature areas are located outside the volcanic rift zone and have reservoir temperatures lower than 150°C at 1 km depth. High temperature fields, on the other hand, are confined to the active rift zone and characterized by reservoir temperatures of more than 200°C at a depth of 1 km (Figure 1). Shallow reservoirs concentrating heat flow resulting from magmatic intrusions and from the Earth's hot interior are the main targets for drilling production wells, the hot water and/or steam being piped to the surface where it is used either directly or for power generation. Technology enables it to be utilised to generate electricity and provide domestic and industrial heat. Geothermal energy has proven to be reliable, economic, environmentally friendly and renewable.

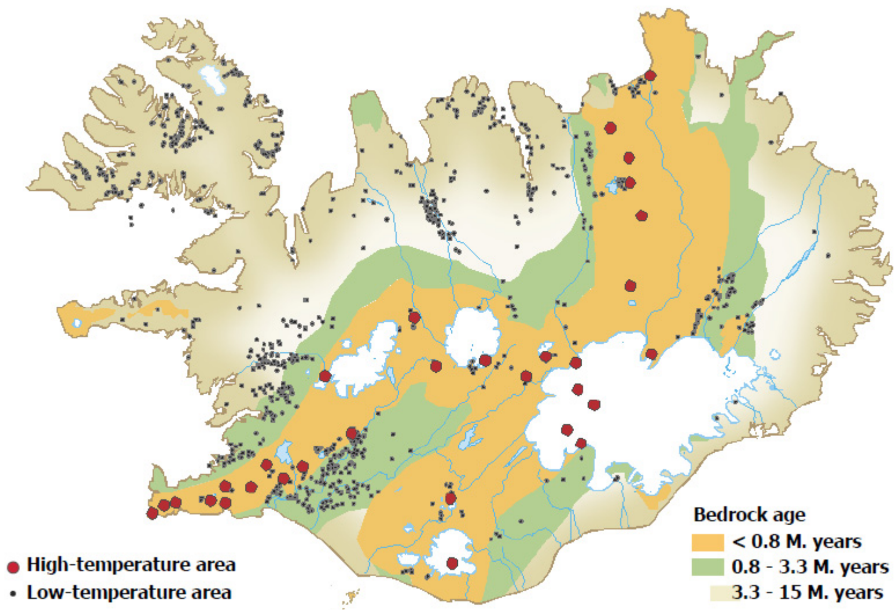


FIGURE 1: High and low temperature fields and bedrock age in Iceland (Orkustofnun database)

The Hengill Hellisheidi, where the geothermal wells in the present study are located is one of the biggest high temperature geothermal fields in Iceland containing several economically promising geothermal prospects. This active volcanic system lies on the plate boundary between the North America and the European crustal plates. These plates are diverging at a relative motion of 2 cm/year opening a NNE trending system of normal faults and frequent magma intrusions. This volcanic system includes about 40-60 km long NNE-trending fissure swarm with normal faults, fissures, frequent magma intrusions and a central volcano. The Hellisheidi high temperature field is part of the Hengill volcanic system. It is situated in the southern sector of the Hengill central volcano south of the Nesjavellir high temperature field. This vast geothermal system is currently operating a 120 MWe and 290 MWt unit in the Nesjavellir field and 210 MWe in the Hellisheidi field.

This extensive high-temperature area containing several economically promising geothermal prospects has been the focus of attention for many decades. Exploration started in the Hellisheidi system in 1985 with a well drilled at Kolvidarhóll and followed by a well at Ölkelduháls in 1995 (Franzson et al., 2005). This was succeeded by a continuous and vital exploration through drilling many productive wells by targeting fractures and graben boundaries. Initial work focused on geological, geophysical and geochemical sampling, which led to the drilling of a few shallow exploratory wells in Hengill. Then, extensive geological, geophysical and geochemical surveys have been carried out in the greater Hengill area in conjunction with the Nesjavellir and Hellisheidi drilling activities to better understand subsurface geothermal settings in the system. Studies have started recently to better understand the subsurface conditions in Hellisheidi and generate a geothermal model using PETREL 3D software which is believed to show a clearer and broader view of the field.

The objective of this study which makes use of two wells (HE-24 and HE-37) in the high temperature Hellisheidi geothermal field is to determine the natural geothermal conditions in the system by obtaining information on the wells i.e. the geological units drilled through (mineralogy and rock type) to better define the stratigraphy and structures within the wells; the type, extent and relative amount of overall alteration within the wells; the relative amounts and mineralogy of the veining and open space filling which leads to the better understanding of the water rock interaction and hydrothermal alteration; locate permeable zones and define the hydrological connection between the well and the reservoir and lastly to assess and visualize the position of the wells with regards to the geothermal system by producing conceptual geothermal model in that part of the area.

1.1 Regional geology and tectonic setting

1.1.1 Regional geology

Iceland straddles the Mid-Atlantic Ridge, a divergent plate boundary between the European and American plates evidenced in a zone of active rifting and volcanism. Its surface 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 (Saemundsson, 1979) (Figure 2). The rifting followed by continuous volcanic eruptions along the divergent plates forms new crust predominantly of basaltic composition as the older rocks in the east and west of the country spread away from each other at a rate of 2 cm/year. Hence, 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.

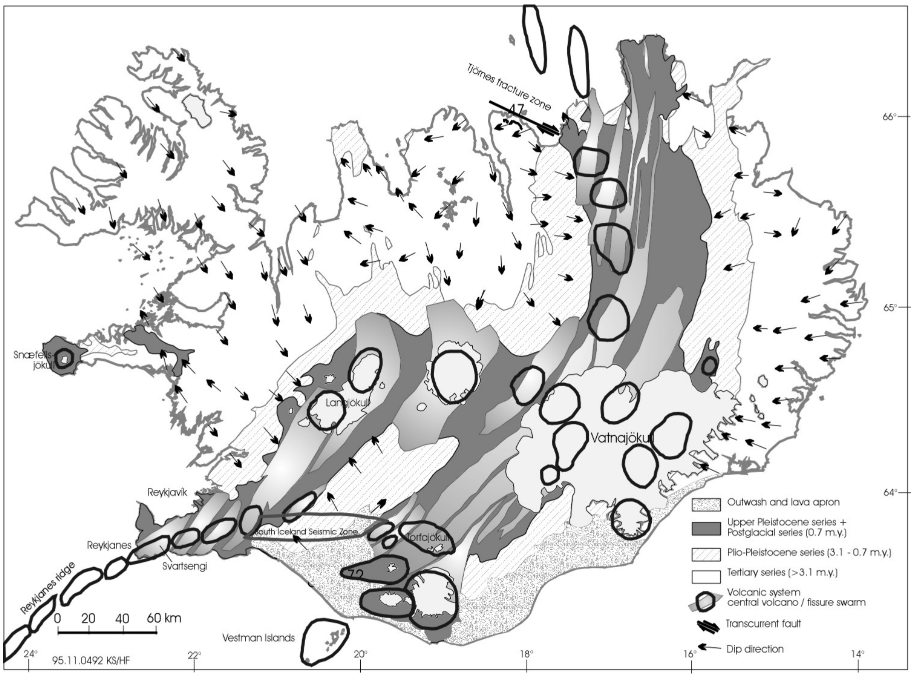


FIGURE 2: Geological map of Iceland with active volcanic systems

The Hengill area is almost entirely built up of volcanic rocks. Subglacially formed hyaloclastites together with pillow basalts constitute the main rock types in the area. Second in extent are

Pleistocene and Postglacial lava flows (Saemundsson, 1967). The sub-surface basaltic strata comprises mostly hyaloclastite volcanic formations down to some 1000 m b.s.l. and underlain by a more dominant lava succession. The Hengill volcano is in the central part of a 40-60 km long volcanic fissure/fault swarm. It is suggested to be divided into three volcanic systems; i.e. the Hveragerdi-Grensdalur (Graendalur) volcanic system (eastern part of the area) that was active between 700,000 and 30,000 years ago, but is now partially eroded down to the chlorite zone; the Hrómundartindur system, whose surface formations are younger than 0.2 Ma; and the currently active Hengill system (Saemundsson and Fridleifsson, 1980). The oldest rocks, about 0.8 my old from the Matuyama epoch, are located in the lowlands southeast of Hveragerdi town, and the youngest are the Holocene lava flows from the fissure swarm cutting Hengill volcano in the west (Fridleifsson G.Ó. pers.comm.).

Hyaloclastites are the dominant rock units in Hengill and are formed in sub-glacial eruptions, while lava series form during interglacials. Basaltic hyaloclastite form when magma quenches during eruption into the base of the glacier, and piles up into a heap mostly as pillow basalts, breccias and tuffs. Although of relatively high porosity, these formations tend to have low permeability, especially when they have been hydrothermally altered. Hellisheidi field is within the Hengill central volcano where volcanism is most intense, and where hyaloclastites have formed highlands. Interglacial lavas, however, when erupting in the highlands will flow downhill and accumulate in the lowlands surrounding the volcano.

1.1.2 Tectonic setting

In the Hengill area, the currently active spreading plate boundary is represented by the Hengill volcanic system, a northeast-southwest striking swarm of normal faults and fissures containing the Hengill central volcano. It is the eastern most of a series of four closely spaced basaltic fissure systems that cut diagonally across the Reykjanes Peninsula (Figure 2). The volcanic rift zone, a zone of active rifting and volcanism, is characterized by well developed extensional structures such as tension fractures, normal faults and grabens and rocks younger than 0.8 million years. It runs mainly NE-SW in southern Iceland with a more northerly trend in N-Iceland (Pálmason and Saemundsson, 1974). The volcano is intersected by a fracture system or fissure swarm that extends for 60-80 km from southwest to northeast (Figure 3). It is traversed by a graben about 10 km broad which runs NE-SW parallel to the hyaloclastite ridges. This graben is part of a greater structure which accompanies the Reykjanes-Langjökull volcanic zone. The western part of the Hengill area is split up by numerous subparallel normal faults. These constitute a 5 km broad inner graben of intense faulting and fissure volcanism.

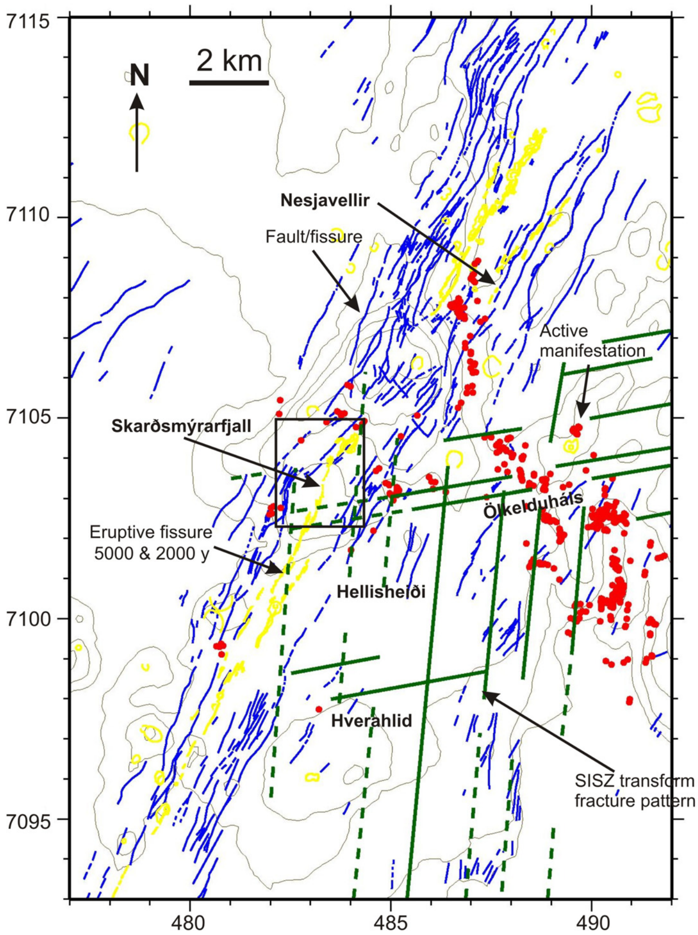


FIGURE 3: The Hengill volcanic system with fissure swarm, and a central volcano. Topography, transform faults, post-glacial eruptive fissures (adapted from Árnason et al 2010). Box shows location of Figure 5

Faults and major fractures strike mostly NE-SW and are conspicuous in the east and west marking the boundaries of the fault and fissure zones of the volcano. Postglacial volcanism includes three fissure eruptions of ages 9000, 5000 and 2000 years. The two younger NE-SW volcanic fissures are believed to provide some of the main geothermal upflow and outflow channels of the system (Franzson et al., 2005; Franzson et al., 2010). These fissures can be traced further to the north, through Nesjavellir field and into Lake Thingvallavatn (Saemundsson, 1995). There are also the South Iceland Seismic Zone strike-slip faults in a N-S direction (Figure 3). Two major NE-SW faults occur in the west part of the field with a total throw of about 260 m. These large faults can be traced to Jórukleif about 15-20 km to the northeast, where throw of the faults approach some 200 m towards SE. They are believed to represent the western margin of the Hengill fissure/fault zone (Sæmundsson 1995).

1.2 Geophysics

DC-resistivity using Schlumberger and dipole-dipole soundings, aeromagnetic, bouger gravity and seismic surveys were carried out in Hengill area between 1975 and 1984. (Hersir, 1980; Hersir et al., 1990; Thorbergsson et al., 1984; Björnsson and Hersir, 1981; Pálmason, 1971; Foulger, 1984). In 1986 a detailed DC resistivity survey was done which delineated a 110 km^2 low resistivity area at 200 m b.s.l. and furthermore showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds. It is assumed to be related to a highly conductive layer which is interpreted as being caused by high porosity, high temperature and ionic conduction in highly thermally altered rocks. Nearly all surface geothermal manifestations in the Hengill area are within the boundaries of the low-resistivity anomaly at sea level (Björnsson et al., 1986; Árnason et al., 1987). In 1987 the central-loop Transient Electro-Magnetic (TEM) method was initially tested in Iceland and a total of 280 TEM soundings have been covered in Hengill area to date (Árnason, 2010). TEM resistivity survey conducted in Hengill and Ölkelduháls areas revealed an extensive low-resistivity layer delineating the geothermal system with a pronounced increase in resistivity below the low-resisitivity layer. The underlying higher resistivity was interpreted to reflect transition in dominant alteration minerals from low temperature clays (smectite and mixed layer clays) to the formation of chlorite and less water-rich alteration assemblage which makes it more resistive (Árnason, 1993; Árnason et al., 2000). Recent Geophysical studies (integrated TEM and MT) in the Hengill area reveals a resistivity structure, consisting of a shallow low resistivity layer, in the uppermost 2 km, underlain by high resistivity (Figure 4). At greater depth a second low resistivity layer is observed in most of the area, again underlain by higher resistivity (Árnason et al., 2010).

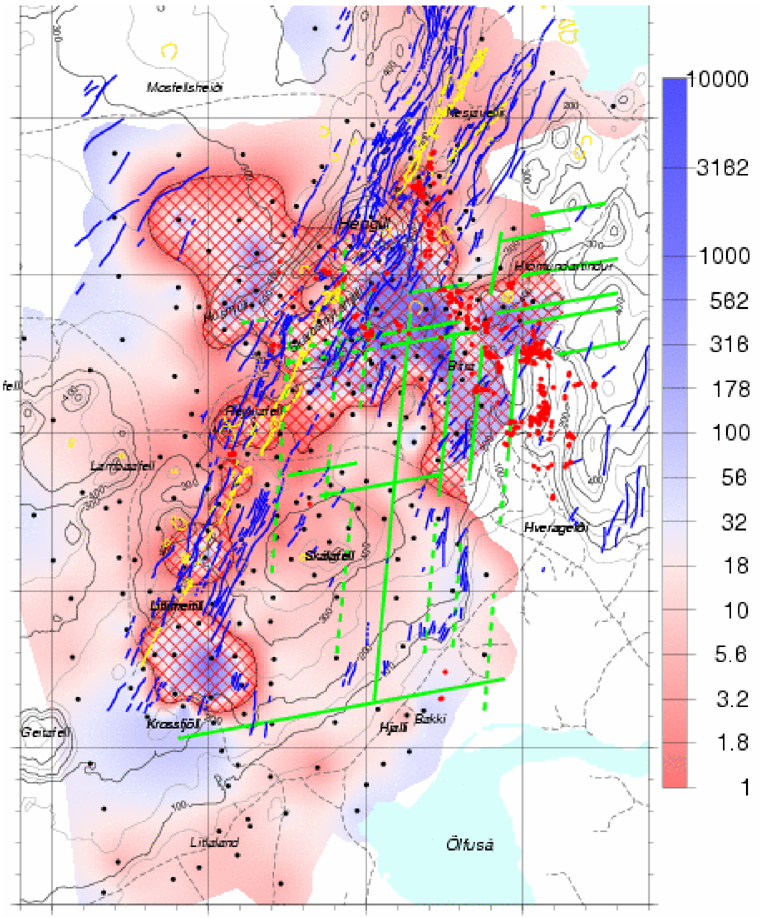


FIGURE 4: A resistivity map of the Hengill central volcano at 850 m b.s.l. showing variations in resistivity. The cross-hatched areas define high resitivity cores below low resistivity, and would indicate alteration temperatures of over 200°C (Árnason et al., 2010)

Earthquake activity is distributed over the whole of the Hengill high temperature geothermal area and some areas peripheral to it. It is situated at a triple junction of a rather complex pattern of three tectonically active zones, the Reykjanes Peninsula, the south western volcanic zone and the South Iceland Seismic Zone. It exhibits continuous microearthquake activity correlated with surface geothermal activity. A seismological study carried out in this area concluded the seismicity in the area could be divided into two parts, infrequent and intense episodes of crustal movement due to the stress release along the plate boundary and secondly, continuous small magnitude earthquakes mostly associated with the extinct Graendalur (Hveragerdi) central volcano (Foulger, 1988). A tectonic event, consisting of approximately 100 thousand micro-earthquakes, vibrated the Hengill area between 1994 and 2000. Most quakes were located at 5 ± 3 km depth, reflecting the locally very thin and hot crust. The quakes group on lines striking either E-W or N-S, but surprisingly not to the NNE as seen in the surface geology (Árnason and Magnússon, 2001).

1.3 Subsurface Geology

Subsurface exploration in Hengill dates back to 1968 with five wells and continued with the drilling of another 13 wells between 1981 and 1985 leading to the start of power production in 1986 at Nesjavellir. The overall stratigraphy in the Nesjavellir and Hellisheidi fields show similar character and has shown that the geology is dominated by hyaloclastites in the top and underlain by lava sequence (Franzson et al., 2010). In Hengill, basaltic dykes or sheets as well as intermediate and acid rocks occur as intrusives which become noticeable below about 800 m depth and increase up to 80-100% below 2000 m depth. Shallow dipping dioritic sheet-like intrusions are also found at various depths and they contribute substantially to the permeability in the field, along with the basaltic intrusions. An age of about 0.4 million years is proposed for the Hengill central volcano which puts a upper age limit on the geothermal system (Franzson et al., 2005, 2010).

1.4 Fluid chemistry and isotope studies

Geology of geothermal systems is complex, with rocks and tectonic structures of variable porosity and permeability. The composition of the high-temparture fluids are chemically different by origin and as they interact with the host rock in variable ways. The geothermal fluid can also undergo phase changes from liquid to steam and vice versa through boiling. The geothermal systems are also dynamic in nature as there is a continuous flow of fluid and heat into the system (natural recharge), within the system (fluid convection) and out of the system as it spits hot springs and fumaroles as surface manifestations. Hence a better understanding of the chemical composition of the reservoir fluid and its chemical properties for utilization (gas content, scaling potential and corrosion) as well as origin of the geothermal water through isotope studies helps utilize and explain better the nature and condition of the geothermal system at hand.

Various geochemical and isotope studies have been carried out in Hengill and Hellisheidi fields. Recent studies conducted by collecting condensate and steam from different wells in the Hengill geothermal field have shown that first, most of the waters in the Hellisheidi field are classified as partially equilibrated waters in the Cl-SO4-HCO3 and Na-K-Mg diagrams with only a few samples above the fully equilibrated water line which could be due to the removal of Mg ions probably due to boiling. Secondly, the water for Hellisheidi field is more of local origin and shows more pronounced boiling compared to the fluid from the Nesjavellir field. It is also suggested that the Nesjavellir field is isotopically and chemically more mature than Hellisheidi which makes the latter a younger field (Mutonga, 2007).

2. SAMPLING AND ANALYTICAL METHODS

2.1 Sampling

The study of subsurface geology of wells involves sampling and measuring at discrete depths, and in situ or laboratory testing. The basic method is to analyse the drill cuttings and prepare lithological and alteration logs. The geological data is mostly based on analysis of drill cutting samples taken at 2 m interval during drilling. Drill cuttings are samples typically collected from geothermal wells and are independent and relatively inexpensive data source of the direct downhole geologic information essential for a successful subsurface investigation. Drill cuttings analysis of rock type is a visual method of semi quantitatively describing rock and pore characterstics from drill cuttings. Unlike core, the interpretation of cutting analysis is far more difficult as there are a lot of problems associated with the collection of the cuttings which has to be accounted for. These are: The composition of cutting samples may not represent the actual rock penetrated as drilling of softer, more brittle, more readily cleaved, or finer grained minerals may result in their depletion in a sample during collection; previously drilled units may be incorporated into a sample; the time required for samples to reach the surface has to be compensated for, otherwise interpretation errors are produced as the drilling depth is likely to be greater than the actual depth from which the sample came (Low, 1977). Interpretation becomes more difficult as cutting size decreases and become finer grained.

The cuttings are analyzed in binocular microscope on site and representative rock and mineral samples are selected from the different rock types penetrated for petrographic, fluid inclusion and XRD analysis as well as microprobe and ICP-OES analyses (see next section). In addition to these analyses, geophysical borehole logs (resistivity, caliper, neutron and natural gamma) which are measured during drilling are used to get information on the physical properties of rocks. Geophysical logs give information on structure, physical properties and performance of the geothermal system penetrated by the well (Stefánsson and Steingrímsson, 1990). Because of the difference in electrical properties between different formations the resistivity log will show lithological variations clearly. The natural gamma log detects the gamma radiation from rocks due to isotopes although these isotopes are found in very small quantities in rocks. The count rate measured by a gamma ray tool at each depth in a borehole is related to the concentration of the radio isotopes ^{40}K, ^{238}U and ^{232}Th in the formation outside the well, and defines a quantity that is called the radioactivity of that formation (Stefánsson and Steingrímsson, 1990). This log is especially helpful in identifying intermediate to acid intrusives as these rocks contain elevated concentrations of the above isotopes as compared to basaltic rocks. The neutron logs are used in porosity investigations and can be related to the porosity of the formation while caliper logs measures the diameter of the well.

2.2 Analytical methods

2.2.1 Binocular microscope analysis

In Binocular analysis of cutting samples a fairly large portion of each sample is analysed to help define the type and relationship of host rock and alteration mineralogy. Samples are analysed after being washed to remove dust particles. Wetting of the samples is essential during analysis as it may enhance the visibility of certain obscured features in the cuttings as finely disseminated sulphides. The analysis has been done using Olympus binocular microscope and data on the lithology, intensity of alteration and type and abundance of alteration minerals is collected.

2.2.2 Petrographic microscope analysis

Analysis of cutting samples by petrographic microscope is one of the most important laboratory procedure of every hydrothermal alteration and lithological studies. These studies were implemented in order to construct the overall geologic framework of the wells and in conjunction with other analyses document and characterize geothermal fluid flow paths. Thin sections were prepared for the different representative samples taken from each rock type in the wells. Studies of these samples provided data including: rock type and mineralogy, relative amount of overall alteration (alteration intensity), relative amounts and mineralogy of the veining and the presence of open-space fillings as a function of depth.

2.2.3 X-ray diffractometer analysis

A standard X-ray diffraction (XRD) analysis technique is concerned primarily with structural aspects of clay minerals and permits quantitative determination of clays and other minerals in the <4 micron fraction. When an X-ray beam travels through a mineral and a certain geometric requirements are met, X-rays scattered from a crystalline solid can constructively interfere, producing a diffracted beam. A diffractometer is used to make a diffraction pattern of these crystalline solids making use of the diffracted beam. A diffraction pattern records the X-ray intensity as a function of 2-theta angle (angle of diffraction of the X-ray) which is characterstic of a specific mineral. Different clay minerals were identified using this method from both wells. Samples have been taken from different depths of the wells showing variable intensities of alteration to analyse the types of clay minerals. After the samples has been diluted with water and placed as thin films on a glass plate it was run in the range of 2 - 14° on the XRD machine. The detailed procedure of prepartion of clay mineral samples for this type of analysis as well as the results with the diffractograms are described and tabulated in the Appendix A.

2.2.4 Fluid inclusion analysis

Fluid inclusion studies were implemented to assist in separating different thermal events, and thus in assembling the thermal history of the system. Fluid inclusions in minerals represent trapped portions of the liquids, gases and melts from which the crystal has grown. It could be used to establish the thermal conditions in which a mineral might have formed. Inclusions formed during primary growth of a mineral (primary) are distinguished from inclusions incorporated in the host mineral during a later process after the crystal has been formed (secondary). The generally accepted mechanism for forming secondary inclusions involves the development of post crystallization fractures initiated during mechanical or thermal stress. These cracks are then sealed by later fluids to form the characterstic trails of secondary inclusions which typically cross-cuts earlier generations (Shepherd et al., 1985).

Microthermometric measurements were performed using a Linkam combined heating-freezing stage. A 40× long working-distance objective lens was used. The accuracy of the homogenization temperatures (Th) is estimated to be ±1°C.

2.2.5 Electron microprobe analysis

Electron Microprobe analysis is a non-destructive method and uses a high-energy finely focused (approx. 1 micron) beam of electrons directed onto a flat polished specimen. These high energy electrons ionize the inner shells of the target elements in the sample to generate X-rays characteristic of the elements. The resulting X-rays are diffracted by analyzing crystals (TAP, PET, LIF) and counted using detectors. Quantitative analysis for determining the chemical composition of the samples is then accomplished by measuring and comparing the intensity of the characteristic wavelengths for each element to intensities measured on standard reference materials of known compositions. Necessary corrections for the effects of absorption and fluorescence in the sample are applied by computer and the results can be displayed as weight % or atomic proportions.

Samples of hydrothermal alteration minerals selected from the two wells at different depths have been analysed by the wavelength dispersive Electron microprobe analysis instrument at the University of Iceland.

2.2.6 ICP analysis

Whole-rock chemical analyses were done for the altered rocks from well 24, at various depths. Seven drill-cutting samples were prepared for chemical analysis. All the samples were cleaned of external material such as mica as it is used during drilling as an additive to the drilling mud to prevent circulation loss and can give anomalous results for the different elements especially Potassium. Rock sample were weighed in with lithium metaborate and fluxed in graphite crucible for 30 min at 100°C. After melting the resulting glass beds were dissolved in acid solution. Then ICP analyses were made with a cross-flow nebulizer at sample consumption of about 2 ml/min with the argon plasma running at 1200V. All the data is then corrected and normalized to 100%. The details of preparation of the samples for ICP analysis and steps for correcting the data are shown in Appendix B.

3. RESULTS

3.1 Lithology

The main rock types that comprise the subsurface geology of the studied wells are basaltic tuff or volcanic glass, glassy basalt or pillow basalt containing dominantly crystallized rock with minor amounts of volcanic glass, basaltic breccia a mixture of partially crystallized basalt and volcanic glass, and finally intermediate rock, fine, medium and coarse grained crystallized basalt, which forms either lavas or intrusions. Minor sedimentary layers are also part of the lithology occuring locally in between some of the different rock formations. The hyaloclastite formations have been differentiated based on their texture (aphyric vs porphyritic) and composition being olivine tholeiite or tholeiitic the latter being equigranular. In addition to these, crystallinity is also used to differentiate between the formations. The volcanic products in most cases experience different degree of alteration as they are porous while the intrusives are dense and tight exhibiting slight to moderate alteration if any. The stratigraphy of the wells generally consists of subglacial hyaloclastites, subaerial lavas and intrusives.

3.1.1 Well HE-24

Well HE-24 is a vertical well of a wider type drilled in the top of Mount. Skardsmýrarfjall aiming at exploring the temperature and permeability of the geothermal system beneath (Figure 5). It is drilled down to 2587 m with predrilling and three phases the last phase being drilled aerated with mixture of air and water as circulation fluid (Mortensen et al., 2006a, b). Figures 6-10 shows the lithological column along with feedpoints, circulation losses and geophysical lithological logs. The different phases and the casing procedure and depth are described in Appendix C.

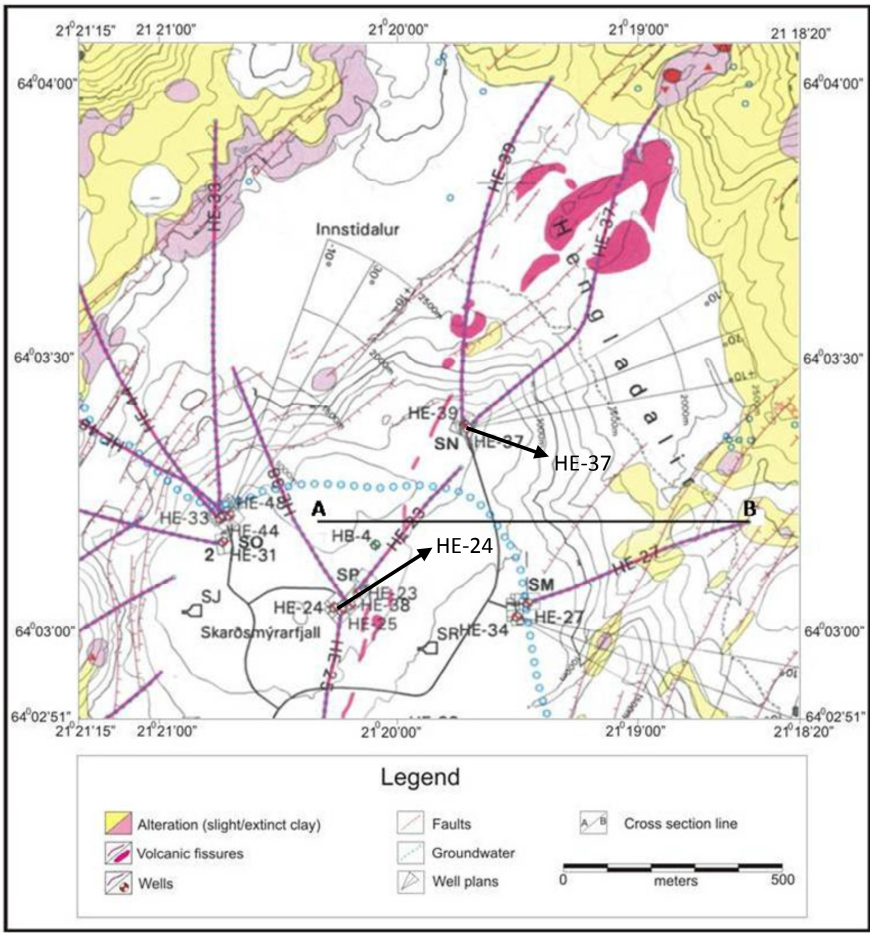


FIGURE 5: Location map of HE-24, HE-37, surrounding wells and cross-section line A-B

Hyaloclastite formations
Skardsmýrarfjall formation (12-351 m)
This formation covers the top part of the well and consists dominantly of pillow lavas with some hyaloclastite tuff intruded by medium to coarse grained basalt.

Hyaloclastite tuff: At the top of the formation is a hyaloclastite tuff unit which is coarse grained, porous, foamy and plagioclase and olivine porphyritic. This unit is fresh and is assumed to be formed from the same volcanic vent as the pillow lava below. Total circulation loss occurs at about 20 m

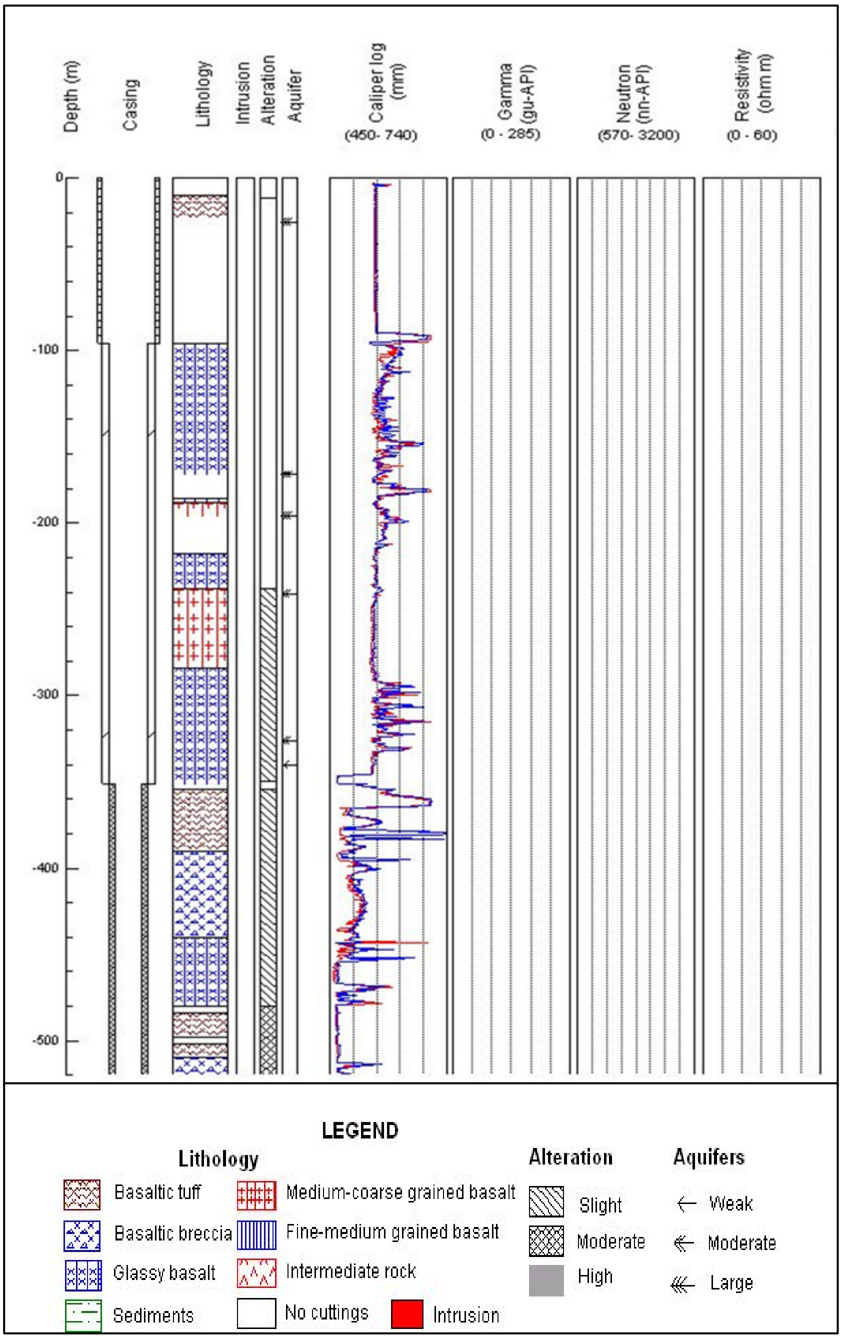


FIGURE 6: Stratigraphic section and geophysical logs of well HE-24 from 0-520 m

depth, but a comparison with well HE-25, a few meters away, indicates that the tuff extends down to 54 m.

Pillow lava: It is plagioclase and olivine porphyritic and consists of fresh, porous crystalline glassed basalt of olivine tholeiite composition. Almost no alteration, except siderite, limonite and some clay. The porosity is variable within the rock and pores are empty with some exceptions filled with radial carbonates (siderite). At about 238 m the rock changes to medium to coarse grained basalt, which has been interpretated as being a lava lobe and a part of the Skardsmýrarfjall formation and not an intrusion.

Hyaloclastite formation I (351-478 m)
This formation dominantly consists of hyaloclastite tuff, breccia and glassy basalt and occurs below the Skardsmýrarfjall formation.

Basaltic tuff: It occurs at the top of the formation, dark to partly green in colour, vesicular, fresh and dominated by glass some showing development of plagioclase and pyroxene towards the bottom part of the unit.

Basalt breccia: A mixture of glassy basalt and tuff covering the central part of the formation; relatively fresh with variable amounts of the two rock types througout the depth. The proportion of glassy basalt and tuff is generally equal in most of the unit but the amount of glassy basalt increases towards the bottom part. It is oxidized in the top part below which pyrite comes intermittently increasing in amount towards the bottom. Siderite occuring in most parts and traces of calcite as well as limonite contributes to some extent in filling the pores.

Glassy basalt: Dark grey in colour, porous, and partially crystalline. The rock is fresh, fine grained having aphanitic groundmass with no developmenet of phenocrysts. Some pyrite, siderite and limonite within the unit.

Hyaloclastites II (478 – 502 m)
A mixture of palagonitized dark brown and altered green basalt tuff. It is porous with large plagioclase phenol-crysts. Calcite and pyrite are the dominant alteration minerals and fill voids within this formation. The colour of the tuff changes from brown to green indicating an increase in alteration with depth. Below this formation is a sedimentary layer (498-502 m) which is silty and soft.

Hyaloclastite III
(502- 576 m)
This hyaloclastite formation is generally aphyric in texture and constitutes dominantly basaltic tuff and breccia units. A sedimentary layer occurs between this and the above formation.

Basalt tuff: Green in colour, porous, showing no plagioclase phenocrsts. Alteration is moderate in this unit and secondary minerals become dominant. Clay, calcite, zeolites, chalcedony and carbonates are the different alteration minerals occuring either as vein or vesicle fillings. Generally the rock is fine grained and slightly to moderately altered. The glass which is more succeptible to alteration is being altered to clay. Calcification is observed in the unit.

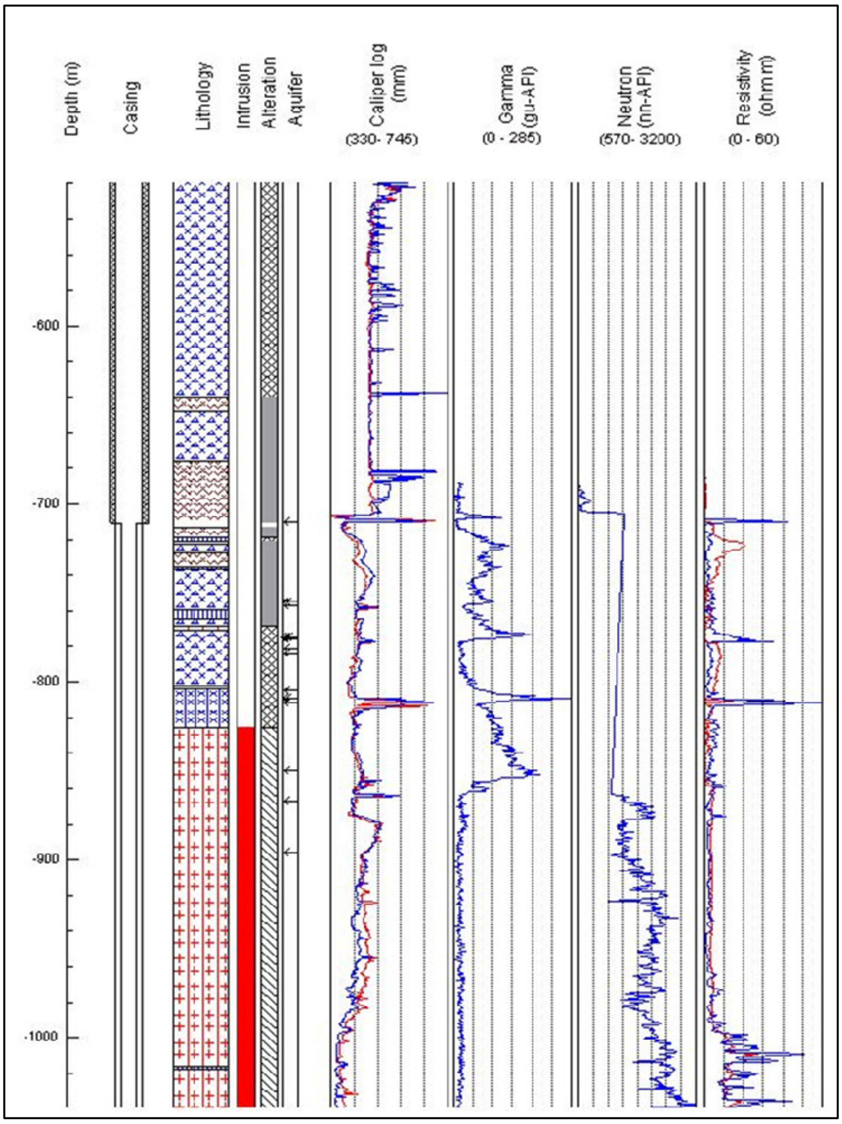


FIGURE 7: Stratigraphic section and geophysical logs of well HE-24 from 520-1040 m (Legend as in Figure 6)

Basalt breccia: This unit is a mixture of tuff, glassy basalt and in some cases fine grained tholeiite with variable proportions. The tuff is fine grained, green, partially altered and porous which is filled with clay. It is aphyric and shows locally some oxidation in its groundmass. Calcite as well as pyrite becomes more common. Fresh glass has almost disappeared and altered to clay giving the tuff green colour. Lenses of grey silty sediments are observed at 532 and 554m depth showing some oxidation.

Hyaloclastite IV (576- 718 m)
Basaltic tuff and breccia units are the main rock types in this hyaloclastite formation. It is densely plagioclase porphyritic and moderately to strongly altered, where alteration increases with depth. The basaltic tuff unit is light green partly white, tight, less mineralized with a little oxidized groundmass. The basaltic breccia is a mixture of green porous tuff with oxidized groundmass, glassy basalt and porous fine grained basalt with variable proportions. Calcite, pyrite and quartz are the common alteration minerals while wairakite first appears in this formation at 686 m.

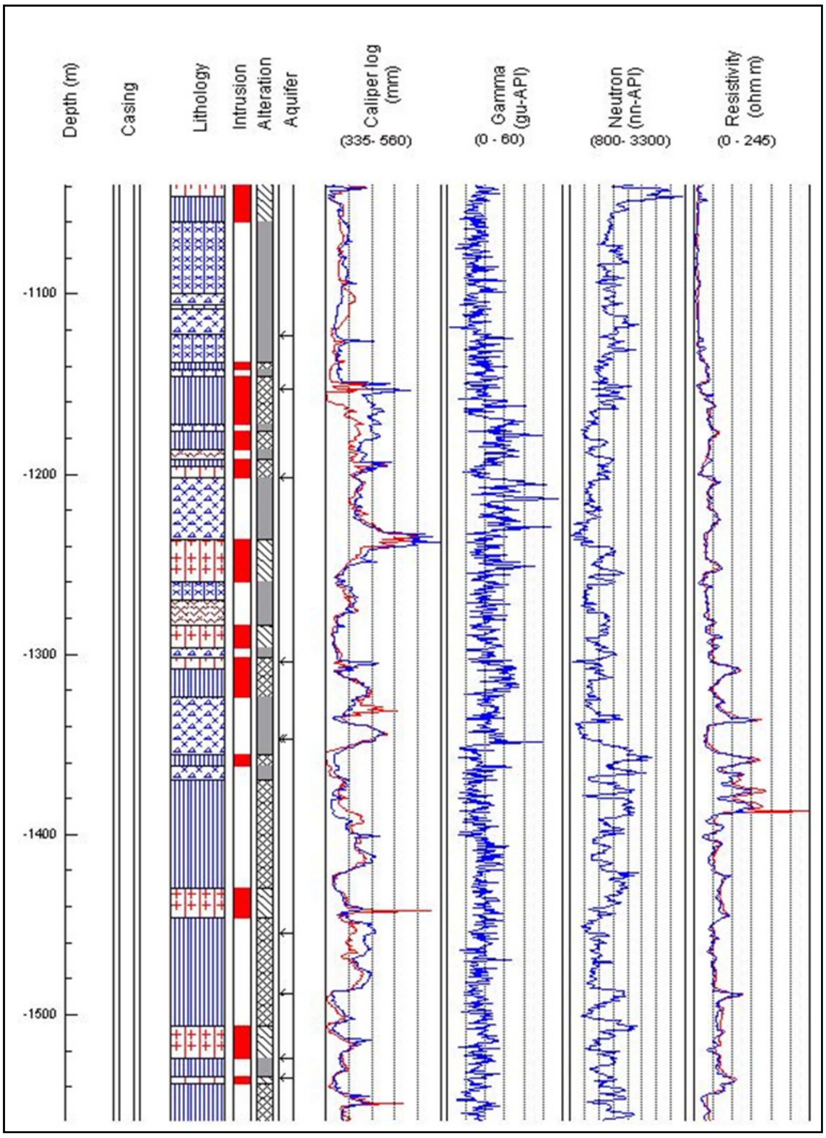


FIGURE 8: Stratigraphic section and geophysical logs of well HE-24 from 1040-1560 m (Legend as in Figure 6)

Hyaloclastite V
(718- 768 m)

The main rock units in this formation are tuff, breccia and fine to medium grained basalt. It is generally aphyric to sparesely plagioclase porphyritic. It is oxidized, porous and looks scoracious. The tuff is light green in colour and porous. Alteration is high in this unit and secondary minerals become dominant including quartz, wairakite and prehnite. The breccia dominantly constitutes tuff with a mixture of altered and porpous fine to medium grained basalt. The fine to medium grained basalt is aphyric and tholeiite in composition partly equigranular.

Hyaloclastite VI
(768- 826 m)

This hyaloclastite formation is dominantly made up of basaltic breccia and glassy basalt units of olivine tholeiite composi-tion. The breccia is quite similar to the above a mixture of tuff and crystallized basalt. The crystallized basalt is coarse grained with large plagioclase, pyroxene and olivine crystals. The unit in genaral could be part of a pillow basalt and shows oxidation which could be due to the intrusive occuring below this formation. The glassy basalt is light green, partly dark where less altered, plagioclase porphyritic, poorly crystalline and glass rich showing little alteration with the development of few secondary minerals. The intrusion below screens off the view to the volcanic units between 826 and 1058 m depth. A comparison with wells HE-23 and HE-25 has to be done to map the character of the formation further.

Hyaloclastite VII (1058- 1370m)

Glassy basalt and breccia intruded by fine to medium and coarse grained basalt make up this formation. The unit is equigranular and tholeiitic in composition. The glassy basalt is light to brownish green, partly dark where less altered, aphyric, partially crystalline and glass bearing. It is strongly altered and porous leading the way to the precipitation of more secondary minerals. A variation in alteration at the contact between the fine to medium grained basalt and the glassy basalt is observed at 1172 m, where it becomes finer in size suggesting a sudden increase in rock temperature resulting in the formation of high temperature minerals as wollastonite and actinolite below this depth.

Lava series (1370- 2587 m)
The rock types comprising the lava succession in this well are fine to medium grained and coarse grained crystalline basalt. The fine to medium grained basalt is grey to partly greenish in colour, with or without plagioclase phenocrysts and occurs as both tight, homogeneous, relatively fresh or weakly altered intrusion with few secondary minerals filling vesicles or veins if any; and porous more altered with dominant mineralization in which veins and vesicle fillings becomes more common. The former is tight and relatively less altered and in some cases shows oxidation along its contact with the adjacent rocks hence, could be a possible intrusion while the latter is more porous with development of secondary minerals and does not show an intrusive nature. The fine grained basalt alternates with coarse grained crystalline basalt which shows an intrusive nature. The resolution of the analysis diminishes dowwnwards both because of smaller grainsize of the cuttings as well as circulation loses become large below 1600 m causing more mixing of the cuttings.

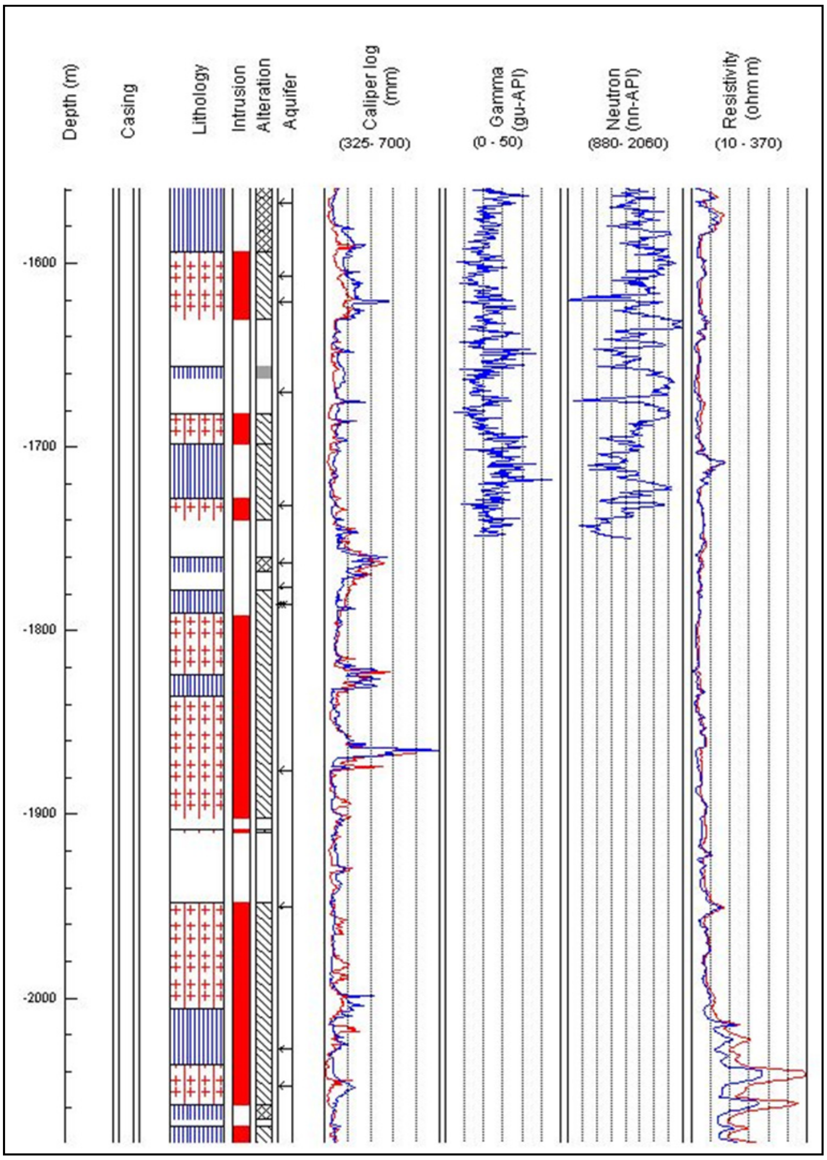


FIGURE 9: Stratigraphic section and geophysical logs of well HE-24 from 1560-2080 m (Legend as in Figure 6)

3.1.2 Well HE-37

HE-37 is located in the northern part of Skardsmýrafjall. It is drilled directionally to intersect the 2000 and 5000 years old volcanic fractures and understand the geothermal conditions under the little known Innstidalur valley. It has intersected these fissures as can be seen from the trace of the well in Figure 5. The well is a wider type and has been drilled in three phases using mud as circulation fluid down to production casing and aerated water in the production part of the well (Gunnarsdóttir and Haraldsdóttir, 2008, Gunnarsdóttir, 2009). The total depth of the well is 3111.5 m. Figures 11-16 shows the lithological column along with feedpoints, circulation losses and geophysical lithological logs. The different phases and the casing procedure and depth are described in Appendix D.

Hyaloclastite formations
Skardsmýrarfjall formation (14-297 m)
This formation covers the top part of the well and consists of hyaloclastite tuff, glassy basalt (pillow lava) and basaltic breccia of olivine tholeiite composition.

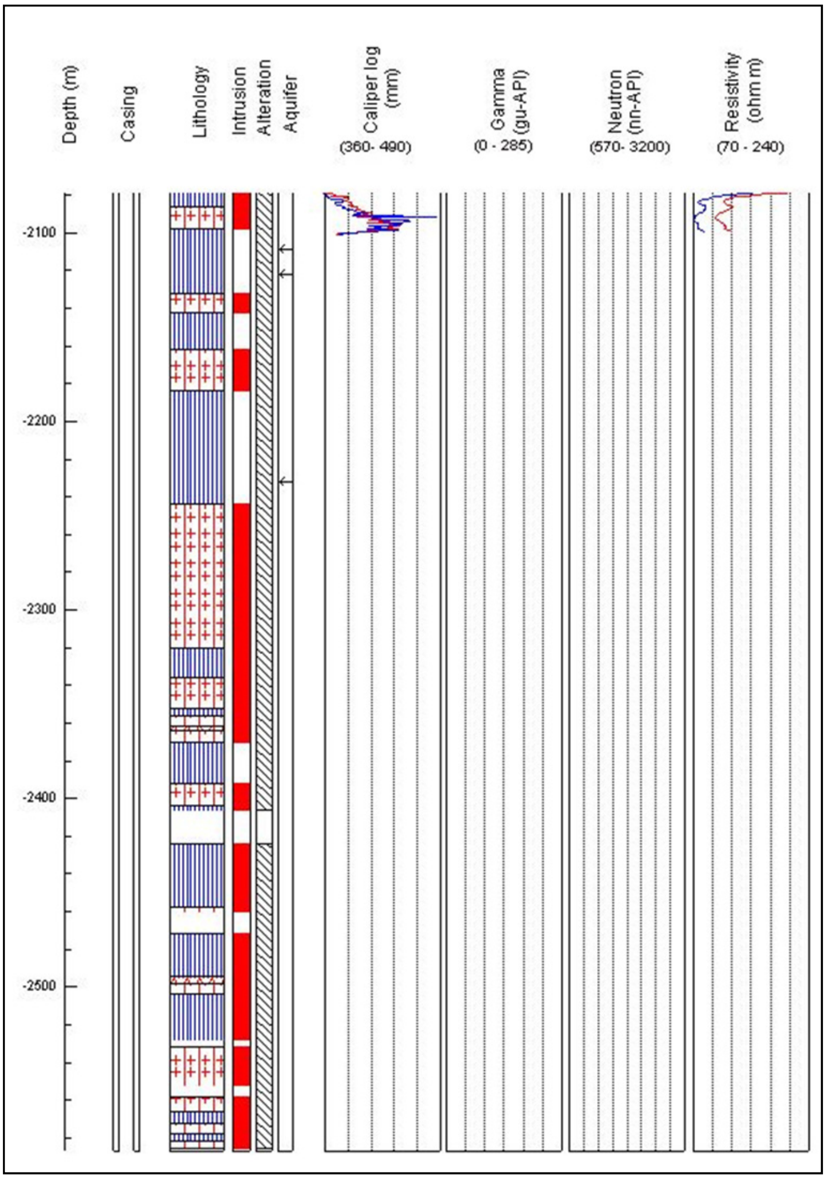


FIGURE 10: Stratigraphic section and geophysical logs of well HE-24 from 2080-2587 m (Legend as in Figure 6)

Basalt breccia: At the top of the formation is a dark grey mixture of fresh, foamy glassy basalt and tuff with variable amount of the two rock types througout the depth. It is oxidized and the common alteration minerals being siderite and limonite filling the pores.

Pillow lava: It is dark grey to yellowish brown in colour, plagioclase and olivine porphyritic and consists of fresh, porous crystalline glassed basalt of olivine tholeiite composition. Almost no alteration, except siderite, limonite and some clay. The porosity is variable within the rock and pores are empty with some exceptions filled with radial carbonates (siderite). The amount of glass fragments decreases with depth and shows variable oxidation.

Hyaloclastite tuff: This hyaloclastite tuff unit is yellowish brown in colour, fine grained with glass fragments. It is porous, foamy and plagioclase and olivine porphyritic. This unit is fresh and is assumed to be formed from the same volcanic vent as the pillow lava.

Hyaloclastite formation I (297-332 m)
This formation occuring below the Skardsmýrarfjall formation dominantly consists of green in colour and aphyric hyaloclastite tuff. The glass within this unit is either dark and fresh or becomes greenish showing alteration colour. The formation is moderately aletered and is dominated by relatively lower temperature alteration minerals as scolesite/mesolite and stilbite. In addition to the above minerals pyrite and calcite also becomes more common.

Hyaloclastite formation II (332-402 m)
This formation is plagioclase porphyritic and dominantly consists of hyaloclastite tuff and breccia. It is differentiated from the first hyaloclastite formation by its texture the latter being aphyric.

Basaltic tuff: It occurs at the top and bottom part of the formation, green in colour and plagioclase porphyritic. The intensity of alteration within this formation is in general moderate the top part being dominated by relatively lower temperature alteration minerals as scolesite/mesolite and stilbite while calcedony, quartz and wairakite starts to appear at the bottom part showing an increase in alteration temperature. In addition to the above minerals pyrite and calcite also continue to become more common.

Basalt breccia: A mixture of either glassy basalt or partly crystalline basalt with green tuff covering the central part of the formation. Alteration is moderate and is dominated by the zeolite group alteration minerals as scolesite/mesolite and stilbite. In addition to the above minerals pyrite and calcite as well become more common in this unit.

Sediment (402-414m)
A thick grey silty sedimentary layer is observed at this depth similar to the sediments observed in well HE-24. This layer occurs below the hyaloclastite formation II in both wells.

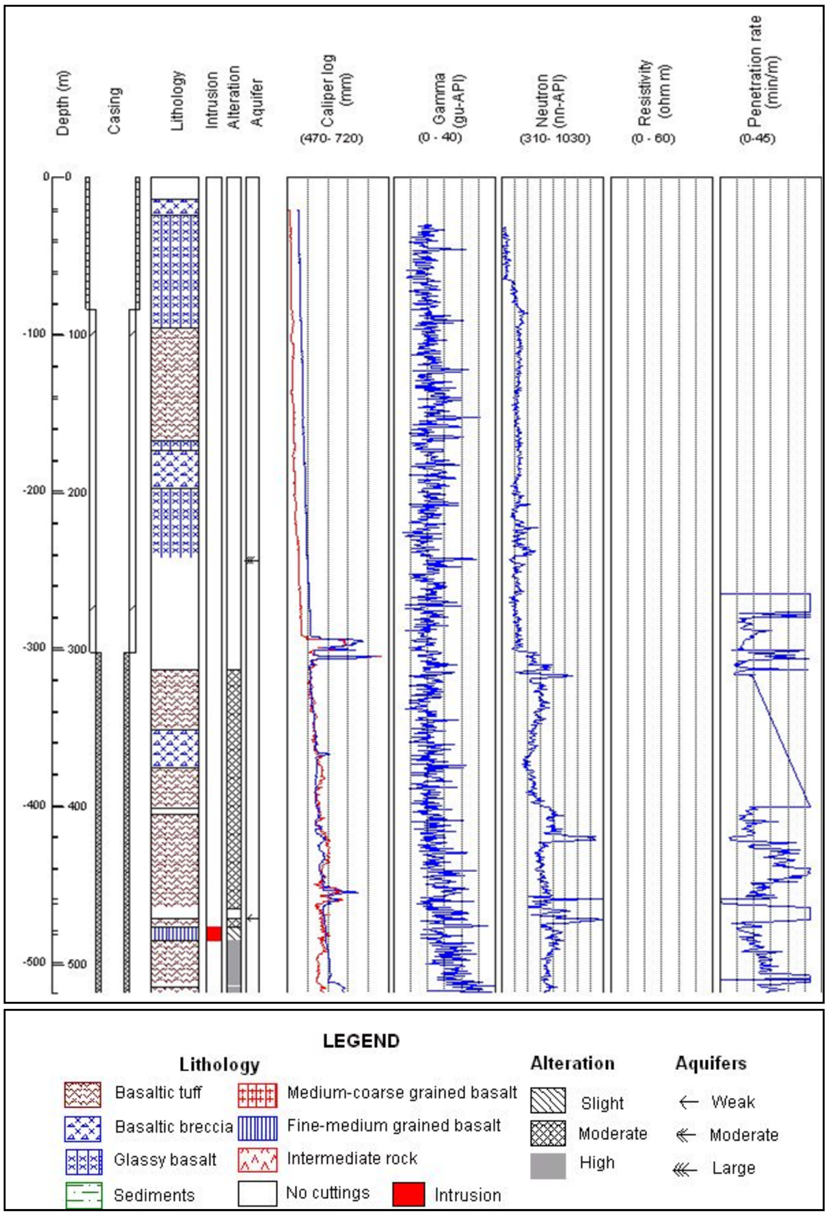


FIGURE 11: Stratigraphic section and geophysical logs of well HE-37 from 0-520 m

Hyaloclastite III (414m – 598 m)
Light green in colour, fine grained and porous basaltic tuff is the rock unit that composes this formation intruded by medium to fine grained basalt. It is aphyric to sparsely plagioclase porphyritic. It shows slight to moderate oxidation in the central part of the unit. The calcite and pyrite continues to be the dominant alteration minerals and quartz also occurs in addition to these minerals. Traces of light grey sediments are noted at 474 m depth.

Hyaloclastite V (598-774 m)
This hyaloclastite formation is dominantly made of basaltic tuff and breccia. It is aphyric to sparsely plagioclase porphyritic, scoracious, partly oxidized and crystallized. This unit is pecuiliar in that it contains dark coloured finely crystallized basaltic fragments in the lighter colour tuffaceous material.

Basalt tuff: Light green in colour, porous showing no plagioclase phenocrsts. It dominantly shows strong alteration with wide range of development of secondary minerals.

Basalt breccia: Basaltic breccia is the dominant unit in the bottom part of this formation. It is a mixture of tuff with crystalline basalt of different texture with variable ratios between the two components. It is weakly to moderately oxidized in the top part. The first appearance of epidote is observed in this unit at 700 m depth.

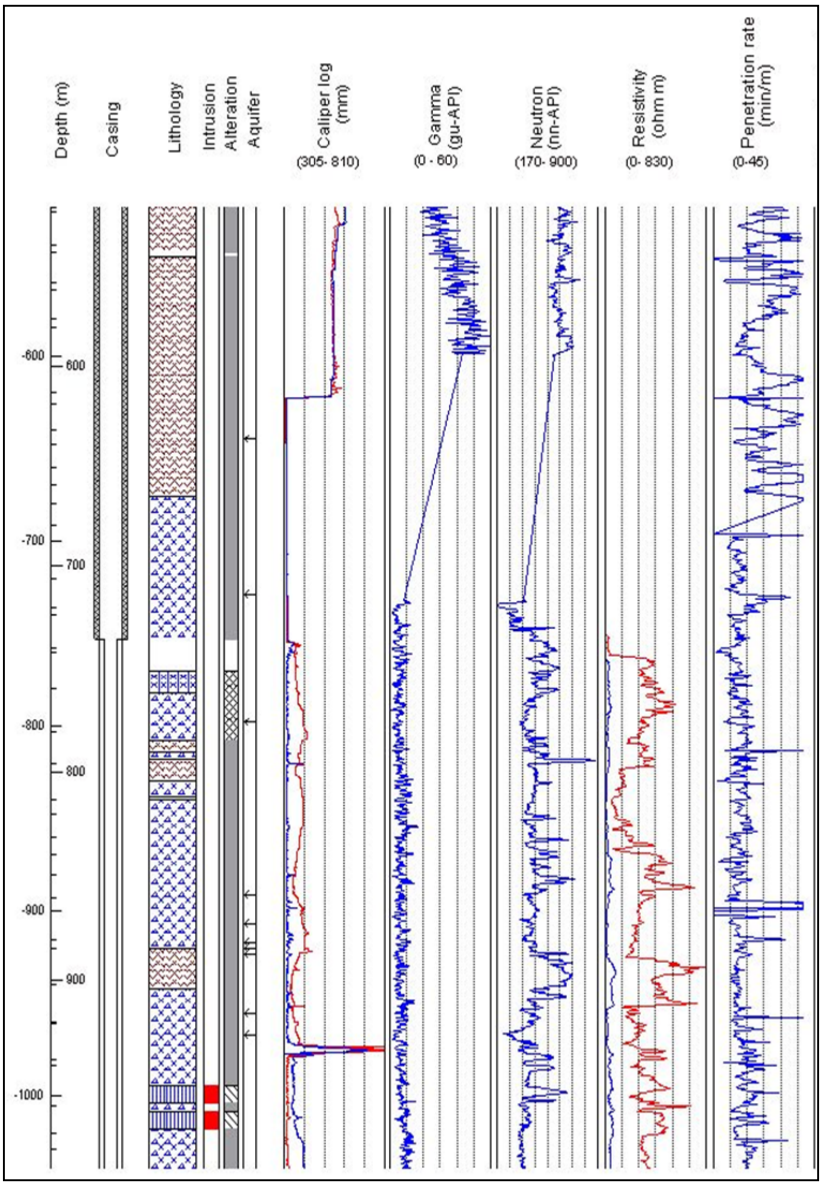


FIGURE 12: Stratigraphic section and geophysical logs of well HE-37 from 520-1040 m (Legend as in Figure 11)

Hyaloclastite VI
(774- 814 m)
Basaltic tuff, breccia and glassy basalt are the dominant constituents of this hyaloclastite formation. It is in general aphyric and olivine tholeiite in compostion. The tuff is light in colour showing glass structure and altered. The breccia is a mixture of tuff and crystallized basalt with variable proportions. The glassy basalt is green in colour, moderately to strongly altered, mixture of fine equigranular crystalline basalt and tuff which could be pillow basalt. The ratio or proportion of glass to crystalline material is variable throughout the unit. Secondary minerals in voids are also very common in this unit, including chalcedony, quartz, wairakite, prehnite and epidote.

Hyaloclastite VII
(814-1358 m)
It is constituted of basaltic breccia, tuff and glassy basalt and intruded by fine to medium grained basalt. The unit is aphyric, equigranular and tholeiitic in composition. It is weakly oxidized in the top part and locally bears some metal oxides. The tuff is light green and partly brownish in colour, porous showing rare plagioclase phenocrsts. Basaltic breccia in this formation occurs alternating with the tuff unit especially in the top part. Below 1132m the fine to medium grained crystalline rock, tuff and glassy basalt becomes more dominant. It is a mixture of tuff and crystalline basalt with variable ratios between the two components. The glassy basalt is dark and partly crystalline. The metal oxides present in the crystalline part of the unit have altered to sphene.

Lava series (1358- 3111.5 m)
The production part of the well was drilled with aerated fluids, which resulted in that cuttings were relatively fine. A total circulation loss occurred at 1446 m, with only scanty mixed very fine cutting samples reaching surface down to 1736 m depth. Another total circulation loss occurred at 1966 m, again resulting in rare mixed samples taken down to 2776 m, where sampling started again down to bottom of well. The resolution of the analysis, particulary below the circulation loss zones, is therefore limited.

Fine, medium to coarse grained crystalline basalt dominate in this formation in the well. Rocks of intermediate and basaltic compositions are also parts of the intrusion swarm in this formation. In addition to these basalts are also noted in the top part of the lava bed series with a slight tuff mixture. The fine to medium grained basalt in this well occurs as more porous and with fillings of secondary minerals. This more porous and altered basalt exhibits dominant mineralization in which veins and vesicle fillings become more common. Metal oxides of different sizes and abundance are noticable in this formation most altered into sphene with some traces of magnetite. According to Franzson et al. (2005), the top of this formation may represent the base of the fourth last glacial and the onset of central volcanic activity in the Hengill area. The total loss of cuttings from 1446-1555 and 1966-2208 m and intermittent appearnace of cuttings from 1555-1736 as well as from 2208 m to the bottom of the well was a setback to the complete description of this formation. At depths where there is intermittent availability of cuttings thinsections has confirmed the crystalline nature of the rock where available and geophysical logs showing the presence of intrusives at different depths. Rocks have been noted with high gamma, neutron and resistivity values especially at depths 1576-1590, 1604-1610, 1624-1628, 1662-1664 and 1714-1720 m which could possibly be intrusives.

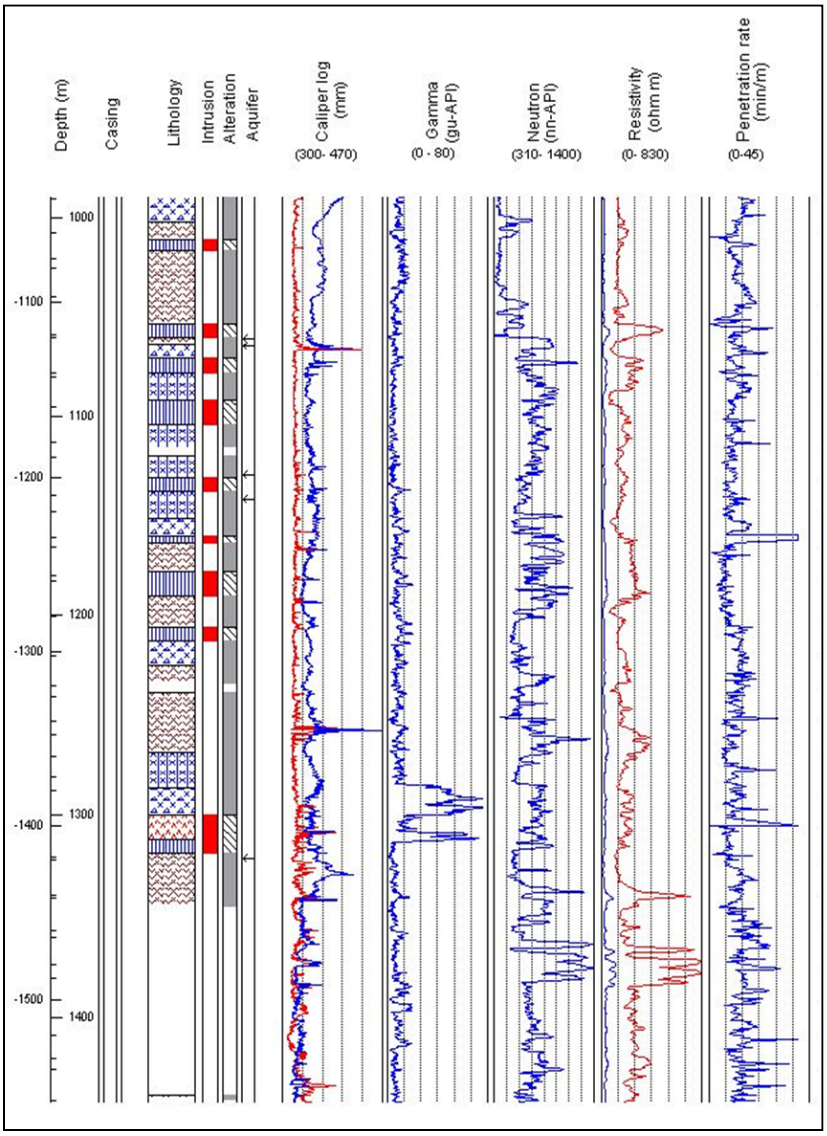


FIGURE 13: Stratigraphic section and geophysical logs of well HE-37 from 1040-1560 m (Legend as in Figure 11)

3.1.3 Intrusions

Intrusions are common within the different hyaloclastite and pillow lava formations in the wells and are identified by their massive, tight and compact nature hence less altered, as well as having relatively coarser texture as compared to the host rock. It also shows oxidation where heating effect has been prominent along its boundary with the surrounding wall rocks. The dominant intrusions in the wells occuring at different depth intervals are the fine, medium to coarse grained rocks as well as intermediate rocks most showing elevated peaks in the geophysical logs especially in the neutron, gamma and resistivity (Figures 6-16). Intrusions become dominant in the bottom part of both wells.

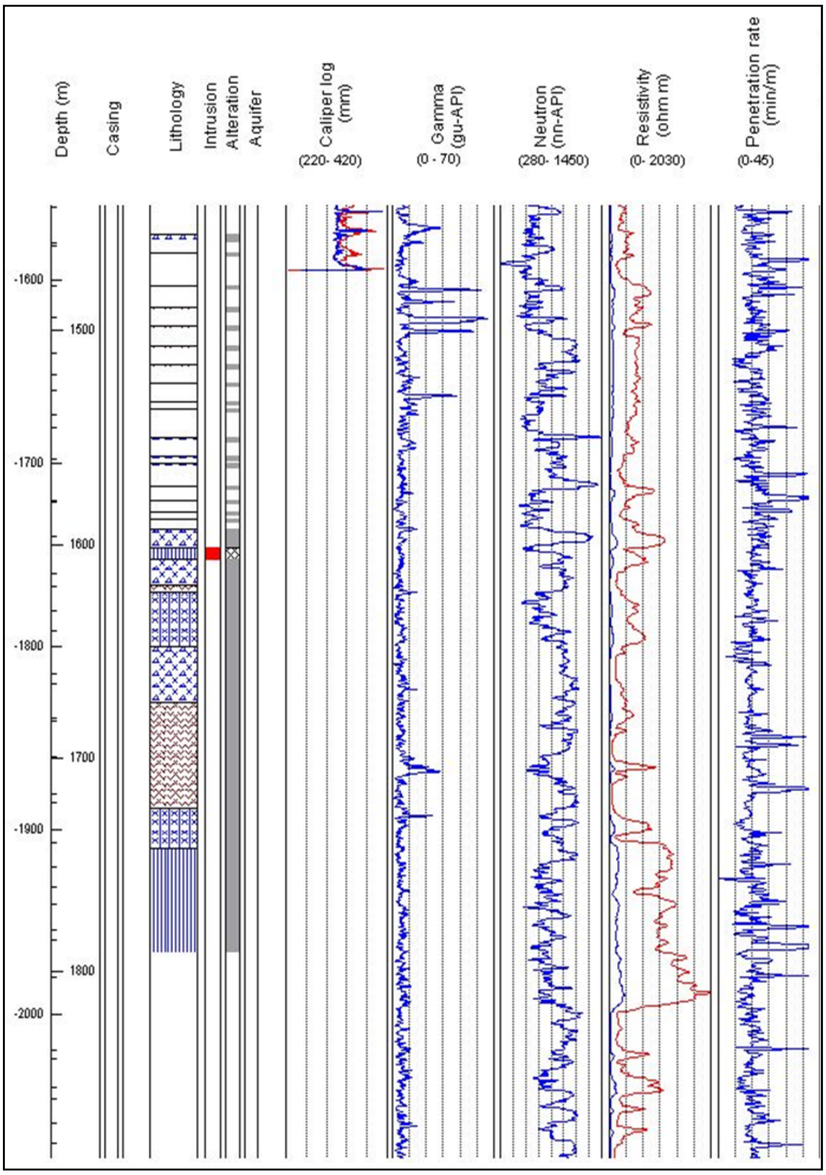


FIGURE 14: Stratigraphic section and geophysical logs of well HE-37 from 1560-2080 m (Legend as in Figure 11)

Well HE-24

Medium to coarse grained basalt

Medium to coarse grained basalt intrusions occur at different depths in this well. The uppermost intrusion occurs at 826-1058 m which is dark grey to partly light green in colour, aphyric to sparsely plagioclase porphyritic, tight and relatively fresh to weakly altered. The intrusive is tighter at the bottom part which is also supported by high peaks in the geophysical logs (neutron and resistivity). Associated is fine to medium grained intrusive occuring at 1014-1018 and 1048-1058 m which possibly indicates that the same intrusive event produced multiple dykes. Oxidation which could be associated with this intrusion occurs below 720 m all the way to its top could indicate that the well is drilled along and close to the dyke in this depth interval. It occurs in most of the wells in Skardsmýrarfjall such as HE-25, HE-38, HE-28 and HE-49 which may indicate a low dipping structure.

Medium to coarse grained basalt intrusions also occurs dominantly in the bottom part of the well below 1370 m alternating with the fine to medium grained basalt. The rocks are dark grey to light green in colour, with variable plagioclase phenocrysts both in amount and in size. It is well crystalline, tight, dominantly fresh to weakly altered with development of very few secondary minerals if any. Locally it contains dark glass fragments and it also shows spotted oxidation some being pyrite.

Fine to medium grained basalt

Grey in colour, with or without plagioclase phenocrysts, tight, homogeneous, relatively fresh or weakly altered intrusions with few secondary minerals filling vesicles or veins if any. In some cases it shows oxidation along its contact with the adjacent rocks. It occurs at depths 2070-2086 m, 2320-2336 m, 2424-2458 m, 2472-2494 m and 2504-2528 m. Their fine grained nature implies that these are relatively thin intrusions, dykes or sills.

Intermediate rocks
Intermediate intrusions are not common in the well. These intrusions were observed at depths 2462-2464 and 2494-2498 m. The rock is characterized by very light green to white colour, fine to medium grained and containing opaque minerals of different sizes and shapes. These intrusives usually give high peaks in neutron, gamma and resistivity measurments but because of high temperature it was not possible to measure the gamma and neutron below 1750 m hence was not possible to confirm the intermediate nature of these intrusives from the geophysical logs. Hence samples were analyzed by ICP to confirm their intermediate nature. The results have shown that two of the samples out of seven analysed has elevated silica content in the basaltic andesite range. (See chapter 6).

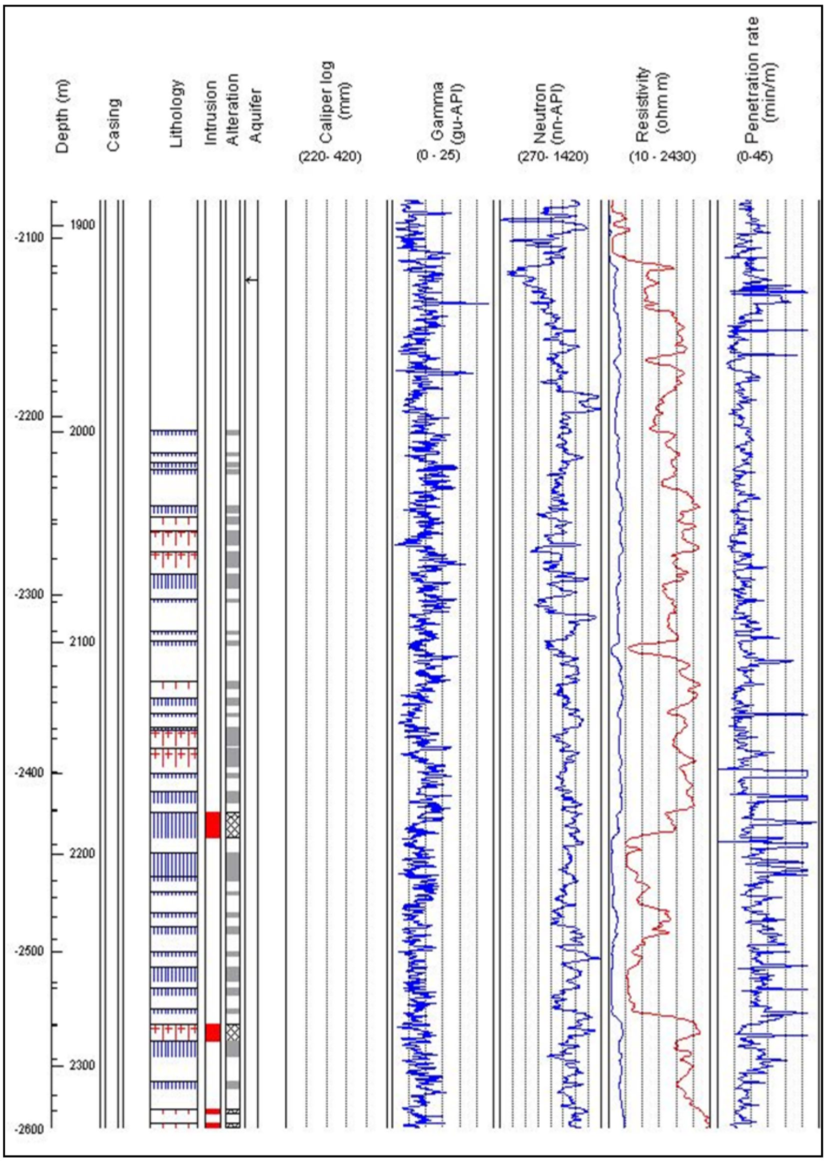


FIGURE 15: Stratigraphic section and geophysical logs of well HE-37 from 2080-2600 m (Legend as in Figure 11)

Well HE-37

Fine to medium grained basalt
These rocks are dark to brownish partly light greenish in colour, tight with variable plagioclase phenocrysts. Fine to medium grained basalt intrusion occur at 478 m with an apparent thickness of 8 m. Cutting analysis also show indications of about 10 fine to medium grained basalt intrusions below 1000 m depth. The majority of these are found between 1000 m and 1400 m with an apparent thickness ranging from 5-20 m. Circulation losses below 1446 m has made identification of intrusions difficult. A future study of geophysical logs is proposed to evaluate possible intrusions below this depth.

Medium to coarse grained basalt
This unit is light green in colour, plagioclase porphyritic, moderately altered, well crystalline and occurs in the bottom part of the well. The results of cutting analysis shows the presence of 3 medium to coarse grained intrusions below 2240 m depth with an apparent thicknesse ranging from 10 to 30 m.

Intermediate rocks
This intrusive was observed at 1394-1408 m depth showing well pronounced two high gamma peaks indicating that there may be two separate intrusions (Figure 13). It is characterized by dominant opaque minerals having very light green colour and is fine to medium grained. Petrographic analysis has also confirmed the intermediate nature of these rocks.

3.2 Stratigraphic correlation

The subsurface geology of Skardsmýrarfjall Mountain situated in the northern part of the Hellisheidi high tempertaure geothermal field is composed of different rock types of basaltic compositions and grouped into various formations. The classification into different formations is mainly based on the crystallinity of the rocks, texture (aphyric vs porphyritic) and composition being olivine tholeiite or tholeiitic the latter being equigranular, more silicic and resistant to alteration. The different volcanic formations that occur in the two wells are the following and also seen in Figure 17. The Skardsmýrarfjall forma-tion which consists dominantly of pillow lavas with some hyaloclastite tuff and basaltic breccia intruded by medium to coarse grained basalt; below the Skardsmýrarfjall formation seven hyaloclastite formations have been identified consisting of hyaloclastite tuff, breccia and glassy basalt with local sedimentary layers intruded by fine medium to coarse grained basalt and intermediate intrusions.

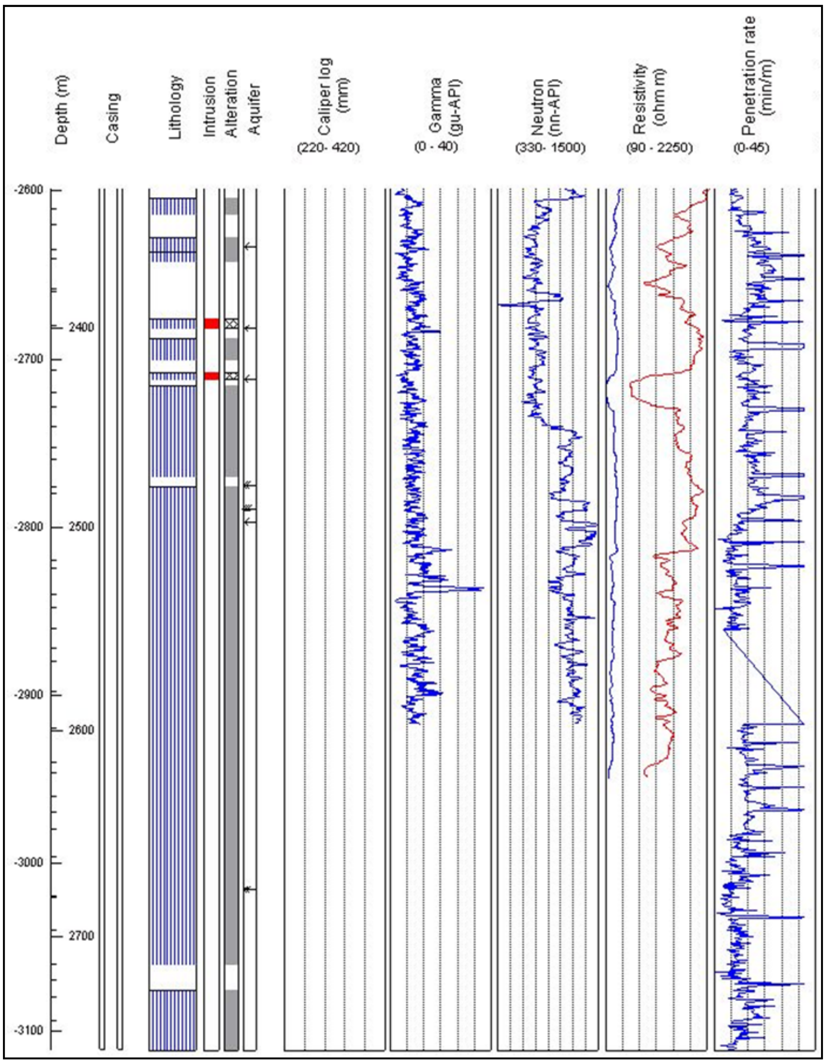


FIGURE 16: Stratigraphic section and geophysical logs of well HE-37 from 2600-3111.5 m (Legend as in Figure 11)

In addition to the studied two wells an attempt has been made to differentiate the different hyaloclastite formations on two other wells HE-39 drilled from the same drill pad as HE-37 and HE-27 drilled to the east of HE-24. Both HE-39 and HE-27 are directional wells drilled to study the geothermal system below the little known Innstidalur valley to the north and Middalur to the east respectively (Figure 5). This tenatative classification of formations in these wells is solely based on cutting analysis and by no means complete and must be confirmed by later petrographic analysis. In addition to these, the boundaries of some of the formations could not be identified in well HE-27 because of loss of cuttings between 700-752 m and 880-1259 m and intermittent cutting samples below these depths to the bottom of the well.

Geological cross-section across these wells (A-B) shows the correlation of the main formations (Figures 5 and 17). All the formations occur in variable thicknesses in all the wells. The top Skardsmýrarfjall formation is 351 m thick in HE-24 while the bottom boundary of this formation is unknown in HE-37 because of circulation loss below 242 m. Caliper log has been used to infer where the soft formation of the underlying hyaloclastite unit starts. The log showed an increase in width of the well at 297 m which is interpreted to be the base of this formation. It has tuff layer at the top and medium to coarse grained basalt in HE-24 which is not observed in the other wells. Apart from that the lithology is similar. The other formations below the Skardsmýrarfjall formation hyaloclastite formations I through VII (Figure 17) also correlate very well except the thick dominantly plagioclase porphyritic hyaloclastite IV formation (132 m) in well HE-24 and occuring in variable thicknesses in the other wells was not observed in HE-37. Sedimentary layer which grades downwards from siltstone to sandstone occuring below Skardsmýrarfjall formation in well HE-27 was not observed in any of the other wells.

According to Franzson et al. (2005) subglacially erupted hyaloclastite formations (pillow basalt, breccia and tuff dominate the upper part of the wells while subaerially erupted lava dominate the lower part. This lithological change may represent the base of the fourth last glacial and the onset of central volcanic activity in the Hengill area and puts thus a maximum age on the Hengill hydrothermal system.

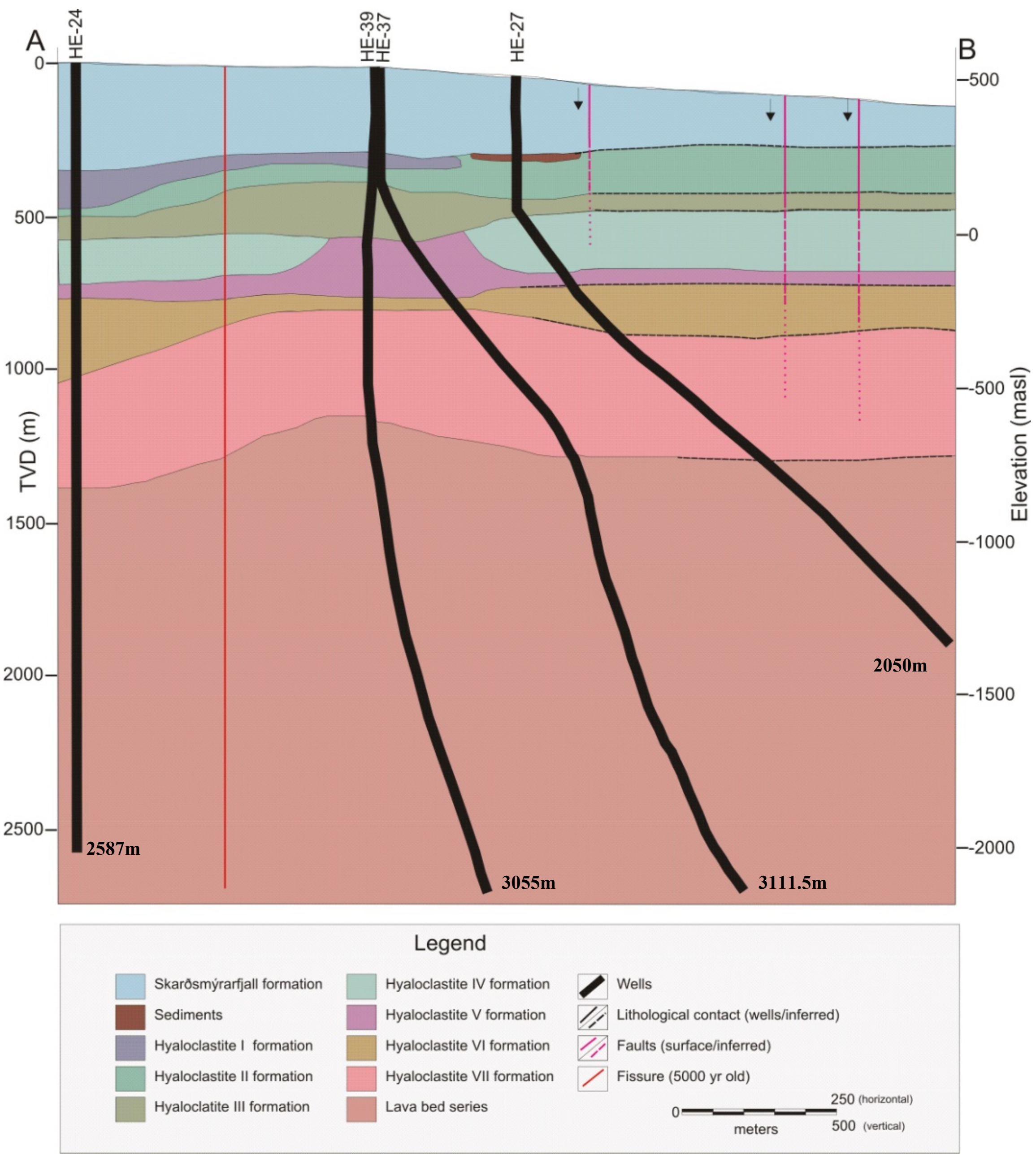


FIGURE 17: Geological cross-section along A-B shown in Figure 5 (arrows indicate throw of faults and numbers at the bottom of wells represent measured depth)

4. AQUIFERS

The data used to locate aquifers (feed points) in wells are deduced mainly from temperature and pressure logs, circulation losses, alteration and geophysical/geological logs (Franzson, 1998). A total of 67 feedpoints have been identified in the two wells (42 in HE-24 and 25 in HE-37) mainly from temperature logs and circulation losses as well as taking into consideration the other stated factors as alteration intensity, pressure drop during drilling and variation in penetration rate. It is also interesting to note that some of the aquifers correlate very well with cavities shown in caliper log (Figures 18 and 19).

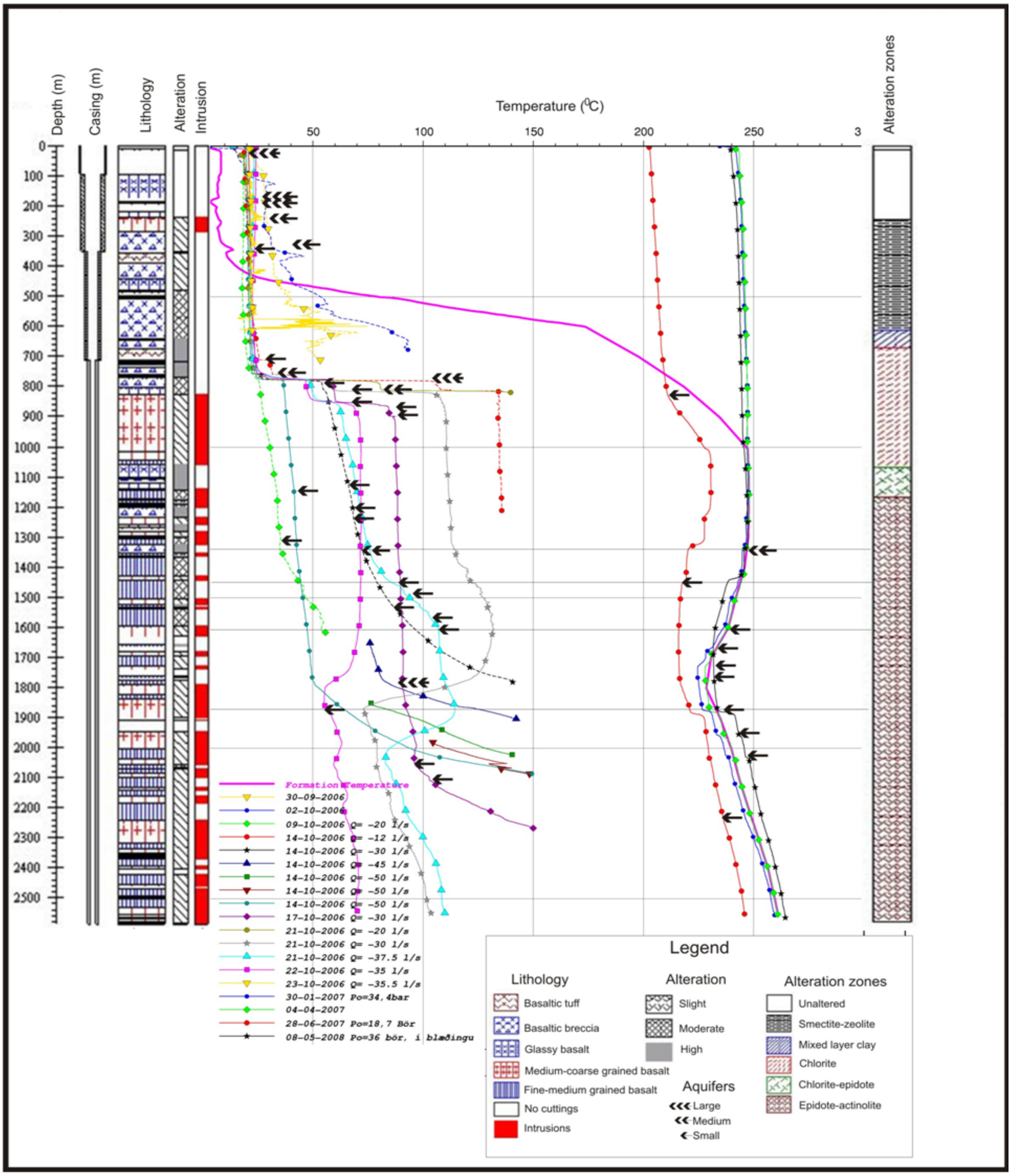


FIGURE 18: Lithology, alteration and temperature logs with interpreted aquifers for well HE-24

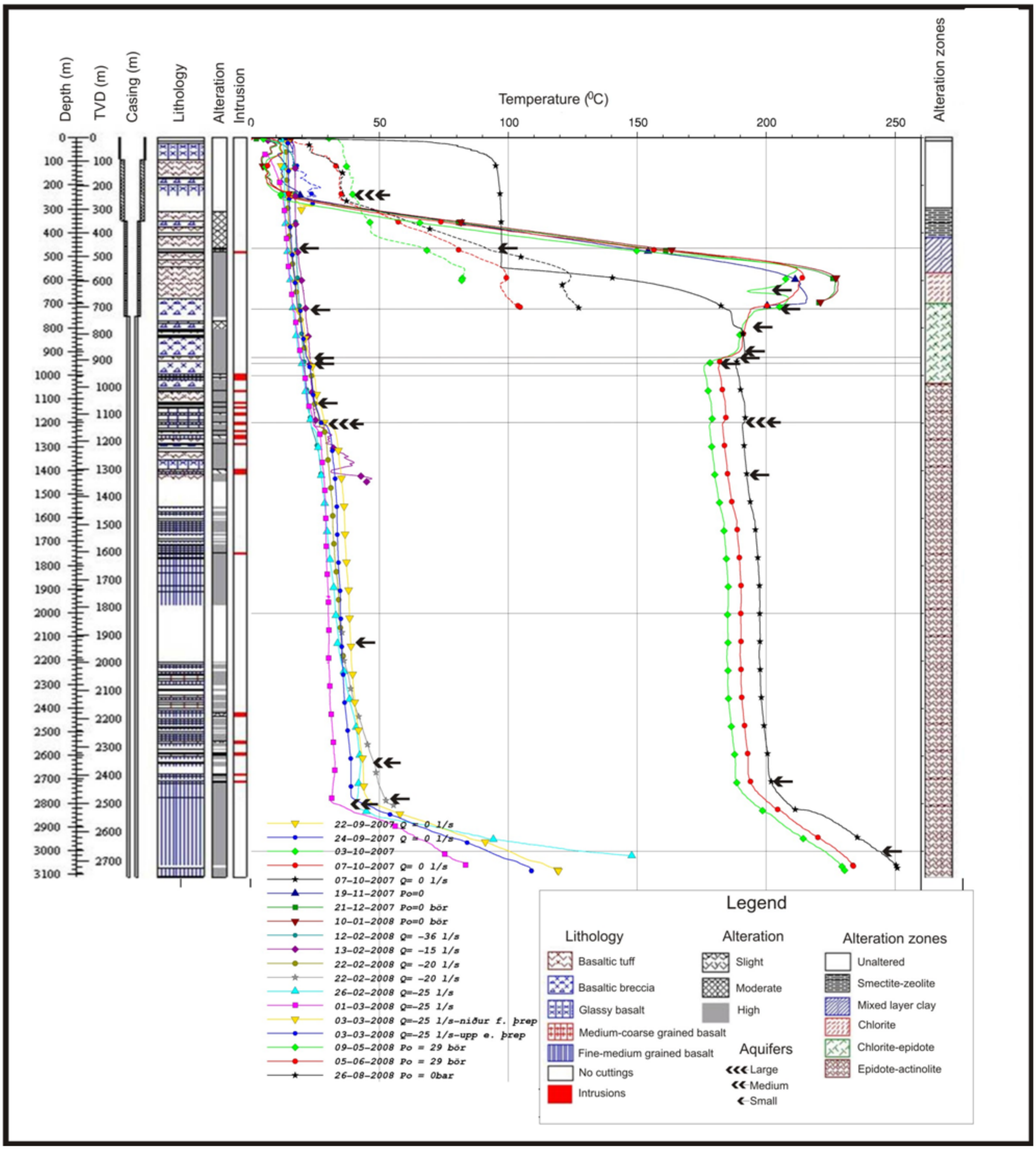


FIGURE 19: Lithology, alteration and temperature logs with interpreted aquifers for well HE-37

The main sources of permeability in the studied wells and in general in Hellisheidi field include lithological contacts, intrusive boundaries major faults and fractures. These aquifers have been subdivided into small, medium or large based on how well they show up in the various logs. Comparing the locations of the aqufers with the detailed geology has shown that the feed points generally occur either along stratigraphic boundaries or associated with the intrusive boundaries (Figures 18-19). Neither clear relationship between the alteration minerals and the aquifers nor the development of a specific mineral related to the aquifers is noticed in the wells but the alteration minerals are observed to be bigger (coarser) along some of the fractures indicating that they crystallized within larger open spaces. Intensity of alteration becomes also high in association with some of the aquifers.

Circulation losses are recorded both shallow and deep in both wells. In well HE-24 it occurs at depths 26, 96, 172 and 180, 196 and 241 m with a total loss of 40-50l/s while at other depths the range varies 1-10 l/s (Mortensen et al. 2006a). The total circulation loss in this well occurs at shallower depth within the Skardmýrarfjall formation which could be due to the more porous tuff at the top, permeable pillow basalts and medium to coarse grained basalt intrusives. At 852 m a sudden drop in pressure from 45 to 25 bar for 1-2 minutes with an increase in drillspeed is recorded (Mortensen et al., 2006b). This drop in pressure shows the presence of an aquifer related to an intrusion at that depth and is confirmed by temperature log.

In well HE-37 the only complete circulation loss occurred at 244 m where the drill string fell for about 2 m indicating a large aquifer. No circulation loss was recorded in the second phase of drilling (up to 753 m) which usually means that the well is tight. However, mud was used as drilling fluid which reduces the chance of ciculation loss (Gunnarsdóttir et al., 2008). The interpretation of temperature log also shows few and small aquifers during this phase of drilling. At 1990-2020 and 3016 m a drop in pressure was recorded which could reflect permeability (Gunnarsdóttir, 2009). A kink in temperature log shows the presence of an aquifer at 3016 m depth but the pressure drop at 1990-2020 m is not well pronounced in the temperature log which could indicate a circulation loss.

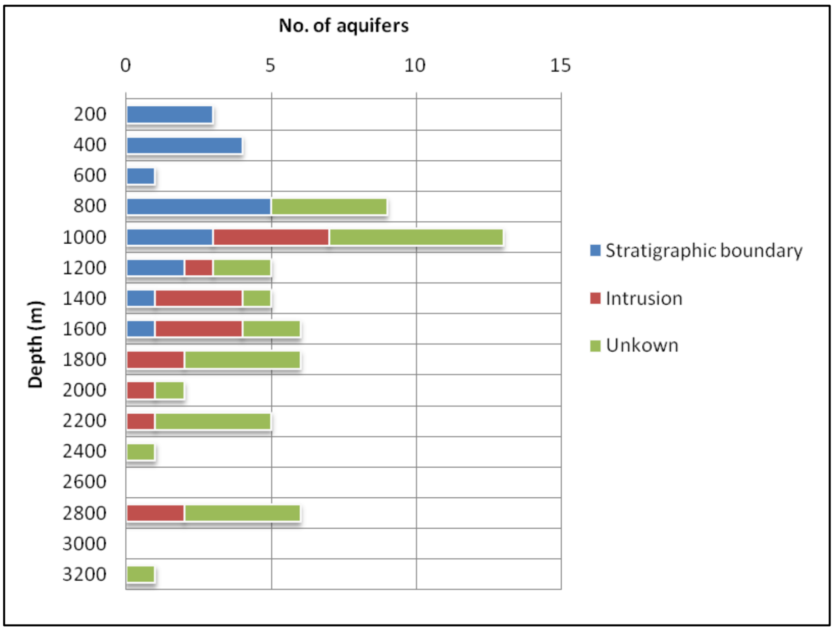


FIGURE 20: Plot of number of aquifers vs. depth based on their relation to geological formation

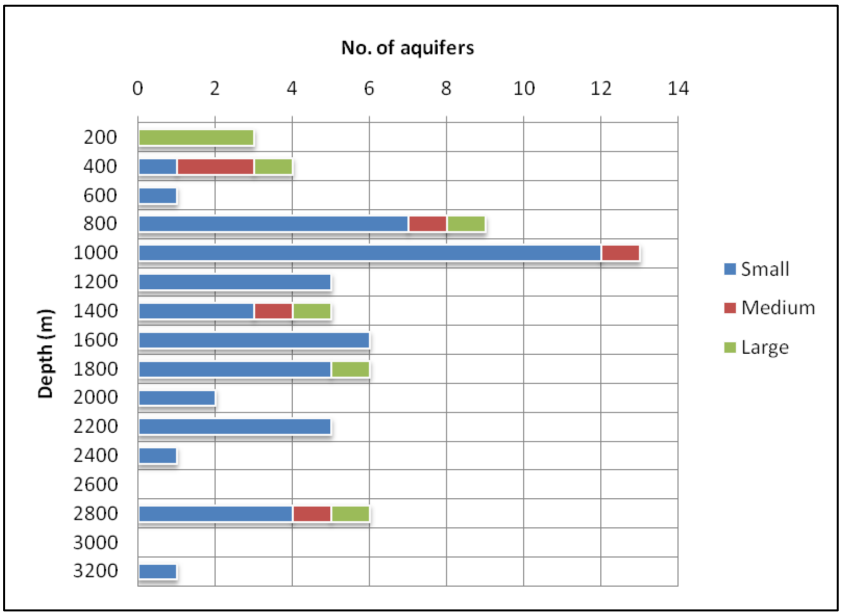


FIGURE 21: Plot of number of aquifers vs. depth based on their relative sizes

The feed points are shown in Figures 6-16 and marked also on the temperature logs in Figures 18-19. Figures 20-21 show the number, relative sizes of the aquifers and their relation to the geological formations for the two wells for each 200 m depth interval. The Figures show that aquifers related to the stratigraphic boundary are dominant in the shallower parts of the wells and diminish and become insignificant below 1200 m while the permeability due to aquifers related to intrusive rocks becomes dominant at depth. Geological relation is diffuse for a significant number of feed points in the produciton part of the wells, due to some extent to the limited resolution of the cutting analysis. The reason for the downward diminishing of this permeability is possibly to be due to the precipitation of alteration minerals and rock load compaction. High permeability with relatively fewer aquifers is noticed in the shallower part of the wells (up to 400 m). The reason could be that the wells are drilled with mud which clogs the permeability. Below 600 m depth, size of the aquifers becomes smaller and the number of aquifers increases considerably.

5. HYDROTHERMAL ALTERATION

Hydrothermal alteration is a phenomenon by which circulating fluids and reservoir rocks in geothermal systems react together resulting in the compositional change of both the solid and the fluid phase as interaction between rock and fluid usually involves addition and/or removal of major rock-forming components. The factors usually controlling alteration in geothermal systems are temperature, rock type, permeability, fluid composition and the duration of fluid-rock interactions (Browne, 1978; Elders et al., 1981). In addition to these pressure also has an important aspect even though its variation within geothermal reservoir rarely exceeds 200 bars which is a small change in terms of mineral phase equilibria; it controls the depths at which boiling occurs and consequently separation of vapor and gases. Boiling zones are often characterized by vein minerals such as quartz, K-feldspar and bladed calcite (Browne and Ellis, 1970; Bargar and Muffler, 1982; Simmons and Christenson, 1994).

Hydrothermal alteration brings about changes in the properties of rocks by changing their texture, porosity and permeability through chemical reactions or changes leading to either replacement of the primary minerals, depletion of some constituents (leaching) or deposition. Access of fluids is an important factor to attain equilibrium between fluids and surrounding rocks during hydrothermal alteration. It is mainly controlled by permeability, facilitating the alteration of the rocks and precipitating secondary minerals either in vesicles or veins. It also determines what alteration minerals form, as it controls the amount of contact between circulating fluids and reservoir rocks. If rocks have low permeability the primary minerals remain unaltered even at high temperatures. Fluid compositions also control the end products of hydrothermal alteration. Fluids of variable chemistry result in diverse alteration mineralogy. Many of the dissolved components in geothermal fluid are closely related in alteration mineralogy. According to Sveinbjörnsdóttir (1992), the composition of the fluid appears to affect how the minerals respond to differences in the original rock composition and further explained that the analysis of alteration minerals from Reykjanes where sea water appears to be controlling the composition of the secondary minerals while at Krafla where the fluid is very dilute the composition of the alteration minerals appears to reflect more closely the parental rock composition. Temperature is one of the most important factors as the stability of many hydrothermal alteration minerals is highly dependant upon temperature. The parent rock influences hydrothermal alteration mainly through the control of permeability by texture and porosity (Brown, 1978). The rock type does not apparently influence the equilibrium assemblage at temperatures <200°C. Duration of thermal area is difficult to assess but in many cases is assumed to correlate with age of magmatic activity.

In Iceland, reaction between hydrothermal fluids with the dominant basaltic host rocks in high temperature geothermal systems has resulted in the progressive hydrothermal alteration sequence with increasing depth recognized by key temperature dependent index minerals (Tómasson and Kristmannsdóttir, 1972; Franzson et al., 2002). Hydrothermal alteration is essentially made up of either replacement of primary components in the rocks by alteration minerals or precipitation of alteration minerals into voids in the rock. Hydrothermal alteration in these active geothermal systems is systematically zoned with respect to temperature. The top zone, which contains relatively fresh rocks, includes a sequence that does not show any indication of geothermal interaction and may at the most show minor oxidation due to groundwater circulation (Franzson et al., 2008). Below the top zone in order of increasing alteration grades the zones are as follows: smectite-zeolite, mixed-layer smectite–chlorite, chlorite, epidote-chlorite, epidote-actinolite and finally amphibole zones. These minerals are temperature dependent and the top of the alteration zones is defined either at the first appearance of the respective minerals or where the mineral becomes abundant. Zeolites which are the first alteration minerals to precipitate during progressive hydrothermal alteration in high temperature geothermal areas starts to form at temperatures as low as 40°C while the minimum temperature of formation for actinolite is 280°C (Table 1) (Kristmannsdóttir, 1979; Franzson, 1998). Olivine and glass are completely altered near the upper boundary of the mixed layer clay zone. Plagioclase and opaques are more resistant to alteration starting to alter at relatively deeper depth and may be only partially altered to albite, epidote, wairakite and titanite (sphene) respectively (Figure 24). Pyroxene also shows similar resistance to alteration as plagioclase and mainly seen altering into clays and then actinolite at deeper levels (Figure 33). In general the hydrothermal alteration in the wells spans all the typical hydrothermal alteration zones from totally fresh rocks to amphibole zone. The hydrothermal system is exemplified by the first occurrence of zeolites, mixed layer clay, chlorite, epidote, actinolite and rarely hornblende.

TABLE 1: Some temperature dependent minerals in high temperature areas in Iceland (Kristmansdóttir, 1979, Franzson, 1998)

Minerals	Min. temp. °C	Max. temp. °C
zeolites	40	120
*laumontite	120	180
*wairakite	200	
smectite		<200
**MLC	200	230
chlorite	230	>300
calcite	50-100	280-300
quartz	180	>300
prehnite	240	>300
epidote	230-250	>300
wollastonite	270	>300
actinolite	280	>300

*Belong to the zeolite group.
**Mixed layer clay.

5.1 Alteration of primary mineral assemblages

Primary minerals, crystallized from magma, governed by the physico-chemical conditions under which the magma solidifies, become unstable in a geothermal environment where there is high permeability, elevated temperature and intense fluid activity. These minerals undergo chemical reactions with the hydrothermal fluids and readily alter to secondary minerals to become stable under the newly created natural conditions. Secondary minerals are then formed by replacement of the primary minerals. The main primary minerals in Iceland in basaltic rocks are glass, olivine, plagioclase, pyroxene and opaques inorder of their succeptibility to alteration, glass being the most unstable of all the other primary minerals. The alteration of volcanic glass and primary mineral assemblage of the two wells has been studied and is decribed below.

Volcanic glass: It shows a highly vitreous lustre and has good conchoidal fracture. It is the first constituent to be altered and replaced. The replacement products of volcanic glass are zeolites (mordenite, laumontite), cristobalite, quartz, calcite and clays (montmorillonite) (Browne, 1984).

Olivine: It is one of the primary minerals that form basaltic rocks (olivine tholeiites) and is very succeptible to alteration. It is distinguished in thinsection by its high birefringence, distinctive irregular fracture pattern, lack of cleavage, and alteration products usually clay along fractures. It occurs in the medium to coarse grained intrusive which experienced very weak alteration at 826 m depth in well HE-24. At 500 m depth in well HE-37 olivine is completely replaced by calcite and clay identified by its irregular fracture pattern. The clay occurs along fracture (Figures 22 and 23).

Plagioclase: It is the most abundant mineral occuring in most igneous rocks and a major mineral in basalts. In crystalline rocks it is readily identified by its low relief and conspicous polysynthetic twinning. The untwinned plagioclase (albite) which resembles quartz shows the incipient alteration or

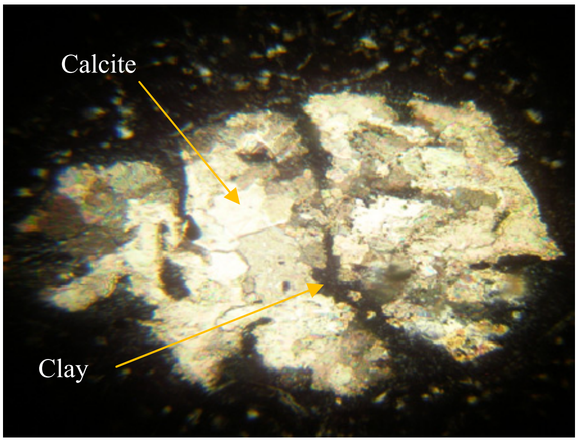


FIGURE 22: Olivine being replaced by calcite and clay HE-37, 500 m (XPL)

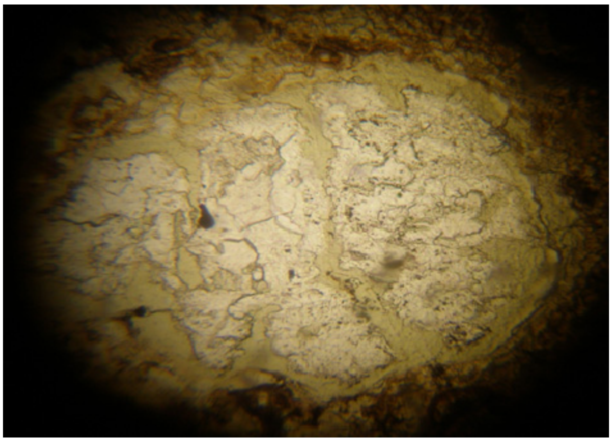


FIGURE 23: Olivine being replaced by calcite and clay HE-37, 500 m (PPL)

clouding which is not common in quartz. It also occurs as fine groundmass in rocks exhibiting porphyritic textures. In both wells it is observed to be progressively altered as temperature increases and finally replaced by albite and occasionally by calcite, wairakite, chlorite and epidote.

Pyroxene: The dominant pyroxenes that occur in Icelandic basalts are the clinopyroxenes occuring mostly as phenocrysts and in the groundmass. The pyroxenes resemble olivine but differ by the presence of better cleavage and inclined extinction. Pyroxene is observed to alter to clay as well as to actinolite at higher temperature, the latter being at depths of 1172 and 1034 m in wells HE-24 and HE-37 respectively.

Opaque minerals: These minerals (magnetite/ilmenite) occur in minor amounts in basaltic rocks and appear as opaque in transmitted light. It occurs as idiomorphic, disseminated or irregular shaped aggregates within the groundmass. Its amount becomes considerable in the intermediate intrusives at 2364 and 2498 m depths in well HE-24 and at 1398 m in well HE-37. They are generally more resistant to alteration but when altered sphene (titanite) is the main alteration product of these minerals and are common in both wells (Figure 24).

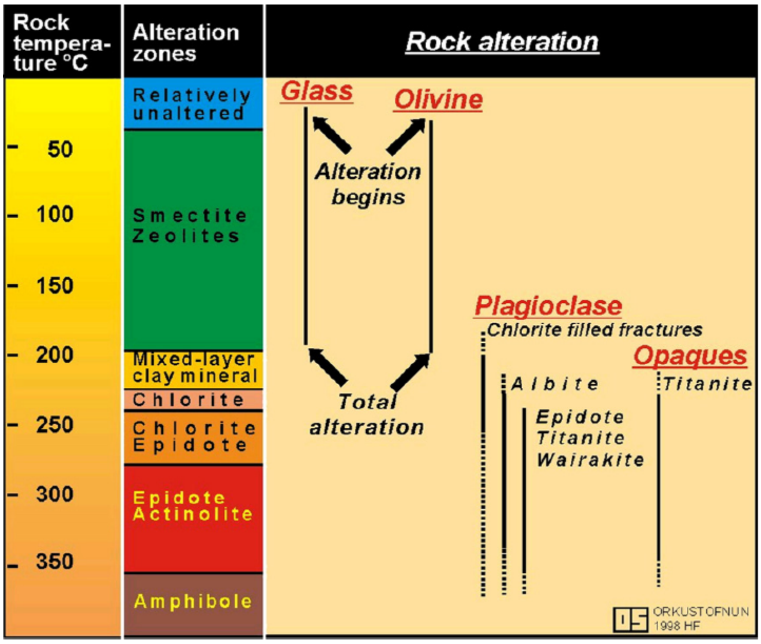


FIGURE 24: Alteration zones recognized in high-temperature systems in Iceland, their dependence on temperature and the main alteration features of the primary basaltic rock components (Franzson, 2008)

5.2 Distribution and description of hydrothermal alteration minerals

Hydrothermally altered zones in the Hellisheidi high temperature geothermal field has been investigated by X-ray diffraction, binacular microscope, petrographic analysis and microprobe analysis. Examination of drill cuttings from the two wells has shown that the hydrothermal minerals occuring in the wells include: limonite, siderite, zelolite groups occuring at different temperature ranges, calcite, pyrite, different types of clays, chalcedony, quartz, albite, sphene, prehnite, epidote, wollastonite garnet and actinolite (Figures 34-37). The distribution of these hydrothermal alteration minerals shows change in chemical composition of the hydrothermal fluid creating these diverse secondary mineral assemblages at their respective physico-chemical conditions. The different alteration minerals encountered in the two wells of the Hellishedi high temperature geothermal field are described below.

Limonite forms at surface or near surface conditions where there is abundant oxygen. It often forms spherical precipitation in vesicles. It is mostly associated with cold ground water systems. It is reddish brown in colour, showing concentric pattern in thinsection and occurs to about 350 m depth in well HE-24 and 320 m in HE-37.

Siderite is a carbonate that forms small spherically shaped deposition within open spaces at shallow levels above the cap rock of the geothermal system and is therfore considered to belong to the slightly warm groundwater system. It occurs at similar depths with limonite in both wells.

Zeolite group minerals are hydrated aluminium silicates occuring at low temperature geothermal conditions formed by the chemical reaction of the different types of volcanic rocks with alkaline ground water. There are different types of zeolites with variable physical and chemical properties the primary differences being in their crystal structure and chemical composition. The different types of zeolites occuring within the studied wells are described below.

Thomsonite occurs as acicular radiating crystals, spherical aggregates or clusters of prismatic crystals filling vesicles or veins associated with the other zeolite minerals as scolesite. This mineral was seen in well HE-24 below 244 m depth.

Chabasite often is found filling vesicles and is detected below 250 m in well HE-24. It is transparent or white and rhombohedral in shape.

Scolesite/Mesolite are closely related minerals often occuring together as fibrous, acicular and radiating crystals from a common center (Figure 25). These minerals are colourless, vitreous, transparent and occur also as thread or hair like radiating from the center and precipitate usually in vesicles. These minerals occur associated with other zeolite group minerals as stilbite, thomsonite and chabasite. Scolesite/mesolite first appears at 244 m and 314 m in wells HE-24 and HE-37 respectively.

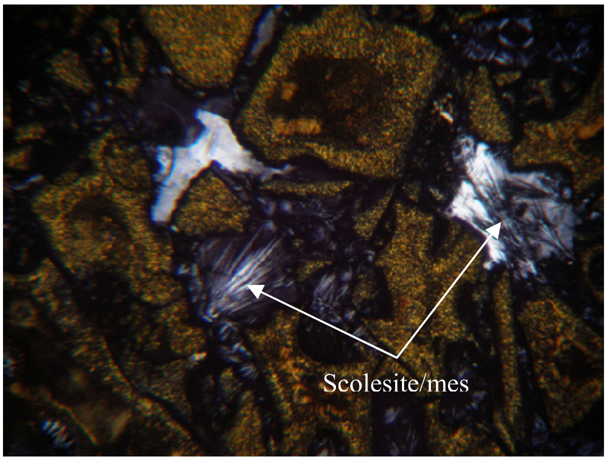


FIGURE 25: Scolesite/mesolite filling vesicle in tuff. HE-37, 348 m

Stilbite is a white, transparent to translucent with vitreous luster occuring as radiating crystals from a common center and is detected at 510 m in thinsection and at 586 m in binocular microscope analysis in well HE-24 and at a relatively shallower depth in well HE-37 at 320 m and 348 m in the former and latter analyses.

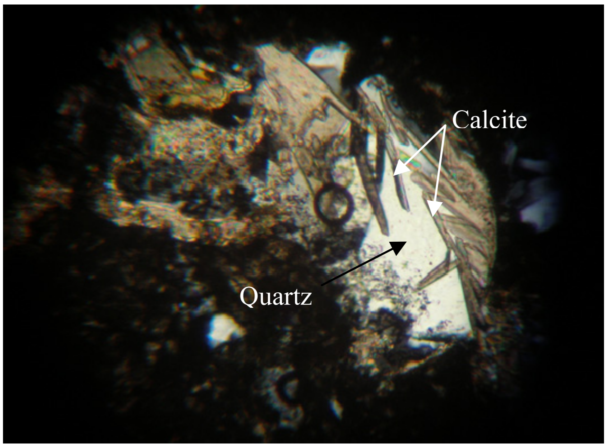


FIGURE 26: Platy calcite succeded by quartz HE-37, 732 m

Calcite is a very common and widespread mineral occuring filling veins and vesicles in the studied wells. It occurs in variable shapes the dominant one being the euhedral with very rare platy ones (Figure 26). It is white to colourless, transparent to translucent with perfect cleavage having resinous to dull luster the latter in massive forms. Calcite is recognized by its cleavage, extreme birefringence, change of relief with rotation, and reaction with weak acid. It is assessed quantitatively and is dominant between depths 500 m and 1200 m below which its intensity decreases although it occurs until the bottom of the well. In well HE-37 calcite occurs below 322 m depth which continues to be dominant until it decreases in amount from 1555 m depth and finally disappears below 1890 m.Locally agressive calcification is observed in both wells indicative of boiling in the system.

Pyrite is a brass yellow, cubic euhedral mineal readily identified by its colour and shape and occurs in both wells. It is also assessed quantitatively and occurs below about 500 m in well HE-24 continuously until about 1800 m and sporadically until it disappears below 2400 m. In well HE-37 it first appears at 322 m depth below which occurs almost continuously until 2900 m. Its occurrence appears to be consistent with calcite except in the bottom part of well HE-37 where it occurs far below the disappearance depth of calcite which is 1890 m. It is observed to be altered into iron oxides which often form pseudomorphs after this mineral.

Clay minerals: The formation of clay minerals involves the chemical actions and physical movement of hydrothermal fluids and in many cases there is a zonal arrangement of the clay minerals around the source of alteration depending on the parent rock and the nature of the hydrothermal solutions. Hence these minerals occur almost throughout the wells in wide stability fields ranging from low temperature smectites occuring at surface and shallower depths to chlorite occuring at deeper and relatively higher temperature. X-ray diffraction analysis has been done on the different samples in addition to the petrography and binocular microscope analysis to better identify the types of clay minerals as these different types of clay minerals can be used as temperature indicators (Kristmannsdóttir, 1979, Franzson, 1998). The different types of clay minerals encountered in the studied wells are described below.

Smectite is a low-temperature clay formed from alteration of glass and ferromagnesian primary minerals as olivine. Olivine and glass are observed to be altered to clay possibly smectite the former along fracture boundaries (replacement). Smectite also precipitates in pores and occurs as lining in vesicles at shallower depths. It occurs either a discrete phase or interlayered with chlorite. The XRD signature for this mineral on the samples analyzed has shown peaks 13.78-17.08 Å for untreated, 13.10-15.19 Å for glycolated and 10.03-10.17 Å for the heated samples.

Mixed layer clays are intermediate products of reactions involving clay minerals end member in which the different kinds of clay layers alternate with each other. The reactions that produce mixed layer clays are progressive high-temperature reactions altering smectite into chlorite via mixed-layer smectite/chlorite. The XRD analysis done in the wells shows peaks for these clays at 14.20-14.30 Å for the untreated and the glycolated and collapsing to 12.45 Å in the heated and an unchanged chlorite peak at 7.2 Å for all runs. These clays are also well identified in thinsections by their conspicous high order birefringence and strong pleochroism.The first appearance of these clays occuring at temperatures of 200-230°C is at 616 m in well HE-24 and at 420 m in well HE-37.

Chlorites are generally green forming radiating, flaky or fibrous microscopic crystals or anhedral aggregates with stacked structure. In thinsection it is colourless, devoid of pleochroism, has perfect cleavage and low birefringence maximum interference colours rarely above first order grey. Chlorite is common secondary mineral forming after mafic primary minerals or smectites and fills dominantly vesicles and occurs associated with quartz, epidote, prehnite and wollastonite (Figure 27 and 28). It marks a minimum temperature of 230°C (Table 1) and occurs below 672 m in well HE-24 and 500 m in HE-37. It has an XRD unchanged peaks of 7.28 Å for the untreated and glycolated and completely collapses after being heated to 550°C.

Chalcedony is a variety of silica containing cryptocrystalline aggregates. It dominantly is colourless, grey to greyish blue and semitransparent to translucent with waxy luster. It dominantly occurs as thin lining, filling vesicles and is progressively altered to quartz as temperature increases. It was identified at 348 m in thinsection in well HE-37 while it first appeared at 510 m depth in well HE-24.

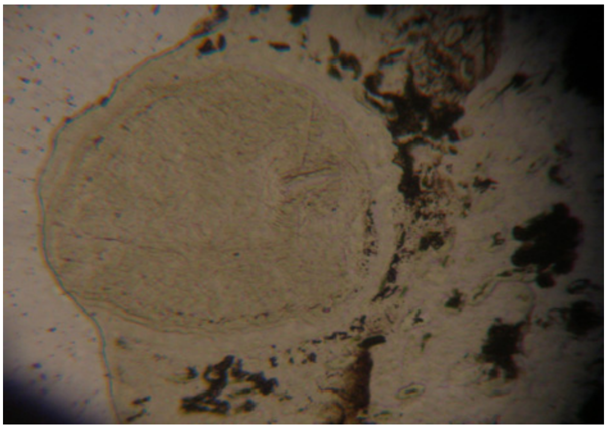


FIGURE 27: Previous chalcedony-clay sequence altered to quartz-chlorite HE-37, 500 m (PPL)

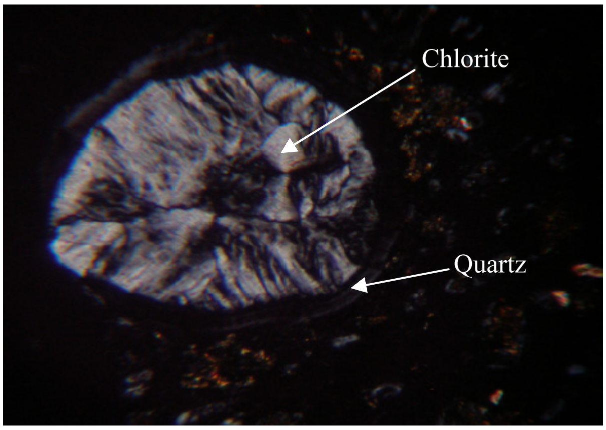


FIGURE 28: Previous chalcedony-clay sequence altered to quartz-chlorite HE-37, 500 m (XPL)

Quartz is a common colourless to white or cloudy (milky), glassy to vitreous, transparent to translucent mineral occuring either as an alteration product of chalcedony or precipitate to fill a vesicle or as vein filling together with epidote, prehnite, wairakite, pyrite and calcite (Figures 28 and 29). It is colourless in thinsection and devoid of twinning and forms undulatory extinction. It is recognized by its low relief, low birefringence and lack of cleavage or twinning. It occurs below 510 m in well HE-24 and 348 m in well HE-37. The first appearance of quartz represents a temperature of 180°C (Table 1).

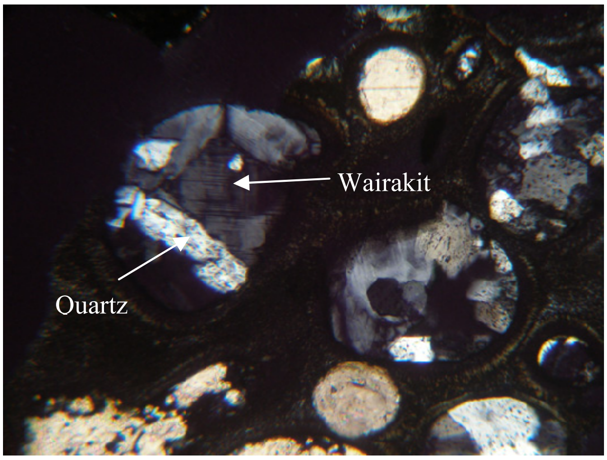


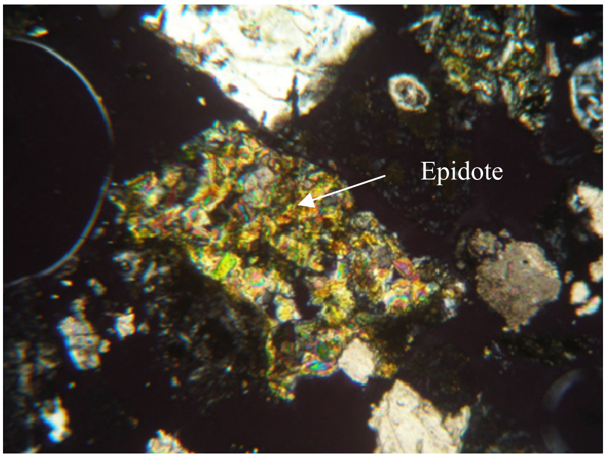
FIGURE 29: Wairakite in pores succeding quartz HE-37, 698 m

Wairakite occurs in pores and cavities deposited from hydrothermal fluids. It is well identified in thinsection by its conspicous cross hatched twinning (Figure 29). It is a high temperature alteration product of other zeolite minerals in the presence of water and is stable above 200°C. It occurs in both wells first appearing at 348 m in HE-37 and deeper in HE-24 616 m.

Albite is dominantly the alteration product of primary feldspars specifically plagioclase but also occur as a precipitation. It is white to grey, translucent usually cloudy and with equant anhedral to subhedral crystal shapes. At higher temperatures the polysynthethic twinning of plagioclase disappears and become cloudy as it progresses towards albite. This partial or complete replacement of plagioclase by albite is often termed albitization. Albite resembles quartz but differentiated by its lower refractive index and its cloudy nature which is not seen in quartz. It occurs in both wells and first appears at 668 m in well HE-24 and is seen at 600 m in well HE-37.

Prehnite is a colourless to white partly grey in colour occuring both as vesicle and vein fillings and was not observed as a replacement mineral in both wells. It is transclusent partly vitreous with an irregular or uneven fracture and one good and distinct cleavage. It occurs as rounded to nearly spherical in binocular microscope and is differtiated in thinsection by its strong birefringence (high order interference colours) and "bow-tie" structure. It is found associated with epidote, wollastonite, chlorite, quartz wairakite and actinolite. This mineral was first seen in thin section at 747 m depth in well HE-24 and at 654 m in well HE-37.

Epidote is a fairly common and widely distributed mineral in both wells having greenish to yellowish colour, transparent to transclusent with vitreous luster occuring as veins and vesicle fillings as well as replacement product of plagioclases. It occurs as idiomorphic crystals in deeper parts where the shapes are well developed and as diffused yellow green coloured anhedral mineral in the early stages of its formation at relatively shallower depth. It forms mineral associations usually with quartz and chlorite as well as prehnite, wairakite, calcite wollastonite and actinolite. In thin section epidote is identified by its high relief, light yellow to green colours having variable pleochroism from weak to moderate depending on the iron content of the mineral (Figures 30 and 31). Well developed crystals of epidote were first observed at 700 m in well HE-37 although diffuse yellow greenish minerals looking like epidote were observed at shallower depth. In well HE-24 epidote comes at 1074 m depth and occurs to the bottom of both wells. Microprobe analysis of epidotes from both wells has shown variable range of compositions and does not show any systematic compositional changes with depth or compositional zoning. The compositions has been analyzed based on the molar ratio of pistachite (X_{ps} defined as Fe/Fe+Al), the Fe being in the trivalent state. The major compositional variation in epidotes results from the substitution of Fe^{3+} and Al^{3+} in the octahedral sites (Marks et al., 2009). This ratio at 1336 m depth in well HE-24 range from 0.29-0.37 with an average of 0.33 while at 1724 m the range becomes lower 0.19-0.22 with an average of 0.2 (Figure 32). In well HE-37 the molar ratio of pistachite at 1208 m range from 0.21-0.29 with an average of 0.25 and at 1770 m the range is 0.22-0.3 with an average of 0.26 having similar compositional average with the epidote at 1724 m in



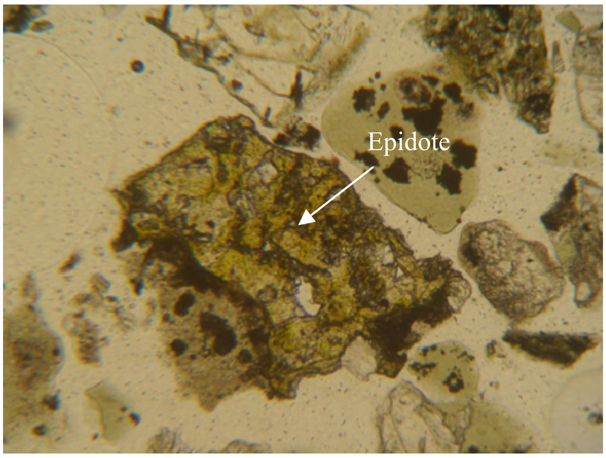


FIGURE 30: Epidote HE-37,880 m (XPL)

FIGURE 31: Epidote HE-37,880 m (PPL)

well HE-24. This range is in general aggrement with observations in other active and extinct geothermal systems. (Bird et al., 1984; Rose and Bird, 1987; Hreggvidsdóttir, 1987). A slight decrease with depth in the composition of pistachite which also shows a decrease in temperature was noticed in the epidote analysis from Rekjanes (Marks et al., 2009) and in Nesjavellir system (Hreggvidsdóttir, 1987). Hence, these lower X_{ps} ranges in the wells might indicate lower temperatures.

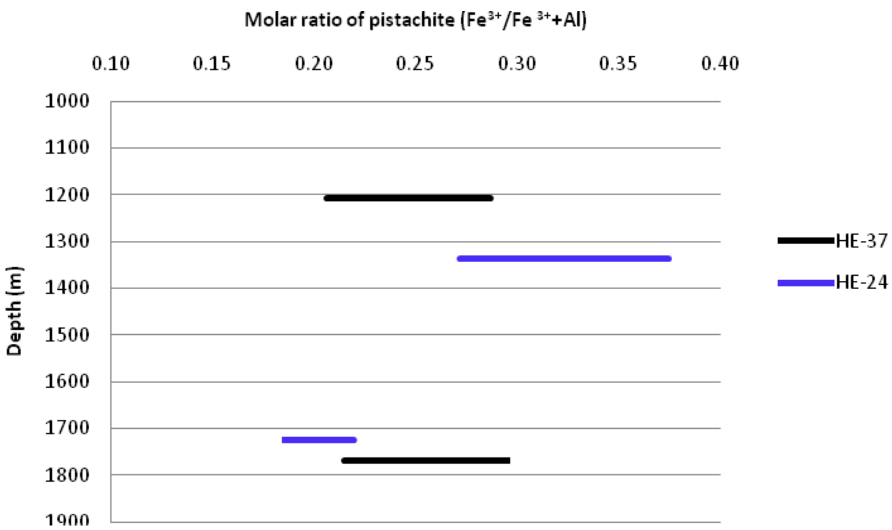


FIGURE 32: Compositions of epidote based on the molar ratio of pistachite at two depth intervals for the two wells

Wollastonite is a typically white to grey mineral occuring as radiating, compact and fine fibrous aggregates filling vesicles. It rarely occurs as a single crystal and has also columunar to acicular habit. It commonly is associated with quartz, epidote and calcite. It is colourless in thinsection with low interference colour of first order grey. It was first observed at 1172 m in well HE-24 and at 722 m in well HE-37. The first appearance of wollastonite marks a temperature of 270°C and can be stable to temperatures above 300°C (Table 1).

Actinolite is an intermediate member between ferro-actinolite and tremolite series solid solution minerals of the amphibole group. It is green to grey-green in colour variable depending on the amount of iron, silky to vitreous, occuring as radiating or fibrous and very compact or as thin, elongated lath like crystal aggregates. In thin section it is colourless, pale green to dark green showing variable pleochroism with moderate relief, the iron rich varieties being more pleochroic. Actinolite is commonly observed to replace clinopyroxenes at various depths in both wells (Figure 33). In well HE-37 it was first seen at 1034 m and at 1172 m in well HE-24.

Garnet is a solid solution mineral with variable compositions between the common end members as almandine, pyrope, andradite and grossular. It is commonly orange red to brown colours and occurs as subhedral crystal aggregates in highly altered rocks associated with actinolite, wollastonite, epidote, prehnite and quartz. It was observed in well HE-24 below 1184 m and in well HE-37 below 1808 m depth. In thinsection it is isotropic, has high relief and subhedral to euhedral shape.

Sphene (Titanite) is dark brown or yellow brown in colour and is a common replacement product of opaque minerals. In thinsection it has very high relief and occurs as irregular anhedral grains. This mineral was observed in both wells. In well HE-24 it was identified in thin section at 510 m depth and in well HE-37 at 600 m.

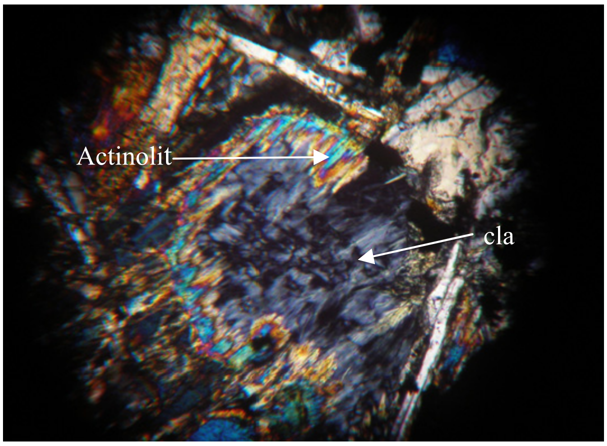


FIGURE 33: Pyroxene replaced by clay and actinolite HE-24, 2470 m

5.3 Vein and vesicle fillings

Porosity and permeability are two of the primary factors that control the movement and storage of fluids in rocks which lead to the deposition of minerals either in veins or vesicles. The basaltic rocks in the studied wells are either highly porous with dominant open voids or tightly packed with lower porosity. During progressive alteration these open voids become gradually filled with secondary minerals at their respective precipitation temperatures and fluid composition. The first minerals precipitating and starting to fill the voids in basalts in both wells are zeolites which start to form at temperatures as low as 40°C. These are found in the top part of the wells associated with low temperature clays or smectites and chalcedony. These clays are dominantly occuring as linings in vesicles. Calcite is also the other vesicle filling mineral occuring in a wide range of temperature which could be stable upto 290°C (Table 1). As temperature increases and hydrothermal alteration progresses these minerals are altered to relatively high temperature stable varieties as quartz, wairakite, chlorite, prehnite, epidote and actinolite. Vein fillings are also dominant in both wells and are determined quantitatively (Figures 34-37). Quartz and calcite are the dominant veinfilling minerals in both wells. In addition to these wairakite, prehnite and albite are also observed as vein fillings (Figures 38 and 39). Calcite is observed to be the latest mineral to be deposited either in veins or vesicles.

5.4 Alteration mineral zonations

Mineralogical examination of basaltic rock cuttings from the studied wells in Hellisheidi high temperature geothermal field reveals five zones of hydrothermal alteration beneath a zone of unaltered rocks. Each alteration zone is characterized by the dominance of particular mineral(s): zone 1, zeolite-smectite; zone 2, mixed layer clay; zone 3, chlorite; zone 4, chlorite-epidote; zone 5, epidote actinolite. The top of an alteration zone is defined at the depth of the first appearance of the mineral. In addition to the studied wells clay mineral analysis result of well HE-27 and binocular analysis of HE-39 and HE-27 is also used to correlate the alteration zonation (Figure 40). As no clay analysis results are available for well HE-39 the clay mineral zonation boundary is inferred from HE-37 drilled on the same pad. The results of XRD and binocular analysis of well HE-27 show that the respective top progressive boundaries of the different zones for this well occur at 264 m (chabasite starts to appear intermittently from 125 m), 512 m, 764 m, 1259 m and 1366 m. Togeteher with the hydrothermal alteration zonations isograds of the different hydrothermal alteration minerals has also been constructed inorder to understand the general distribution of alteration temperature. The different minerals used for the construction of isograds are quartz, prehnite, epidote, wollastonite and actinolite. The isograds indicate high alteration temperature at shallow depth towards wells HE-37 and HE-39 indicating shallow hydrothermal alteration in these wells while the high temperature minerals appearing at a relatively deeper depth in wells HE-24 and HE-27 (Figure 40).The following description of the different alteration zones on the studied wells is based on petrography and XRD clay analysis results.

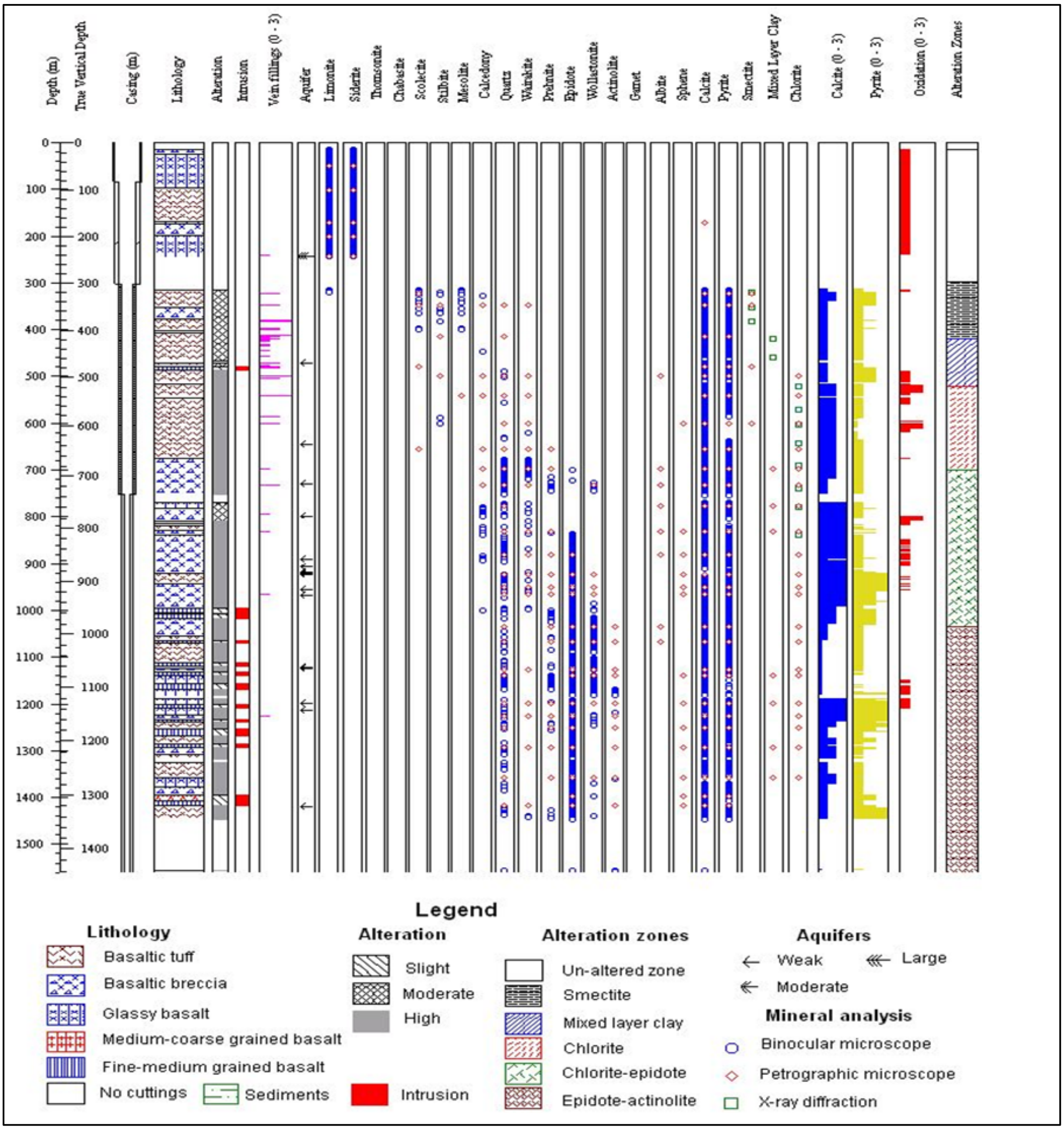


FIGURE 34: Lithological logs feedpoints, intrusions and mineral distribution of well HE-37 from 0-1560 m, 0-3 in the Figure represents intensity from none (0) to dominant (3)

5.4.1 Unaltered zone

The unaltered zone is composed of fresh rocks with no signature of alteration or development of any secondary minerals. The only minerals present in this zone are limonite and radial carbonates (siderite) which are related to ground water activities. It occurs from surface to 297 m and 244 m in wells HE-37 and HE-24 respectively which is represented by the Skardsmýrarfjall formation.

5.4.2 Zeolite-smectite zone

The early and low temperature alteration zone occurs below the unaltered zone and is characterized by the presence of zeolites and low temperature clays. The top boundary of this zone is represented by the first appearance of zeolites at 244 m in HE-24 and 322 m in well HE-37. This zone is characterized by the presence of abundant zeolites as stilbite, scolesite/mesolite, chabasite and thomsonite as well as secondary calcite and quartz. XRD has shown that smectite is the dominant clay

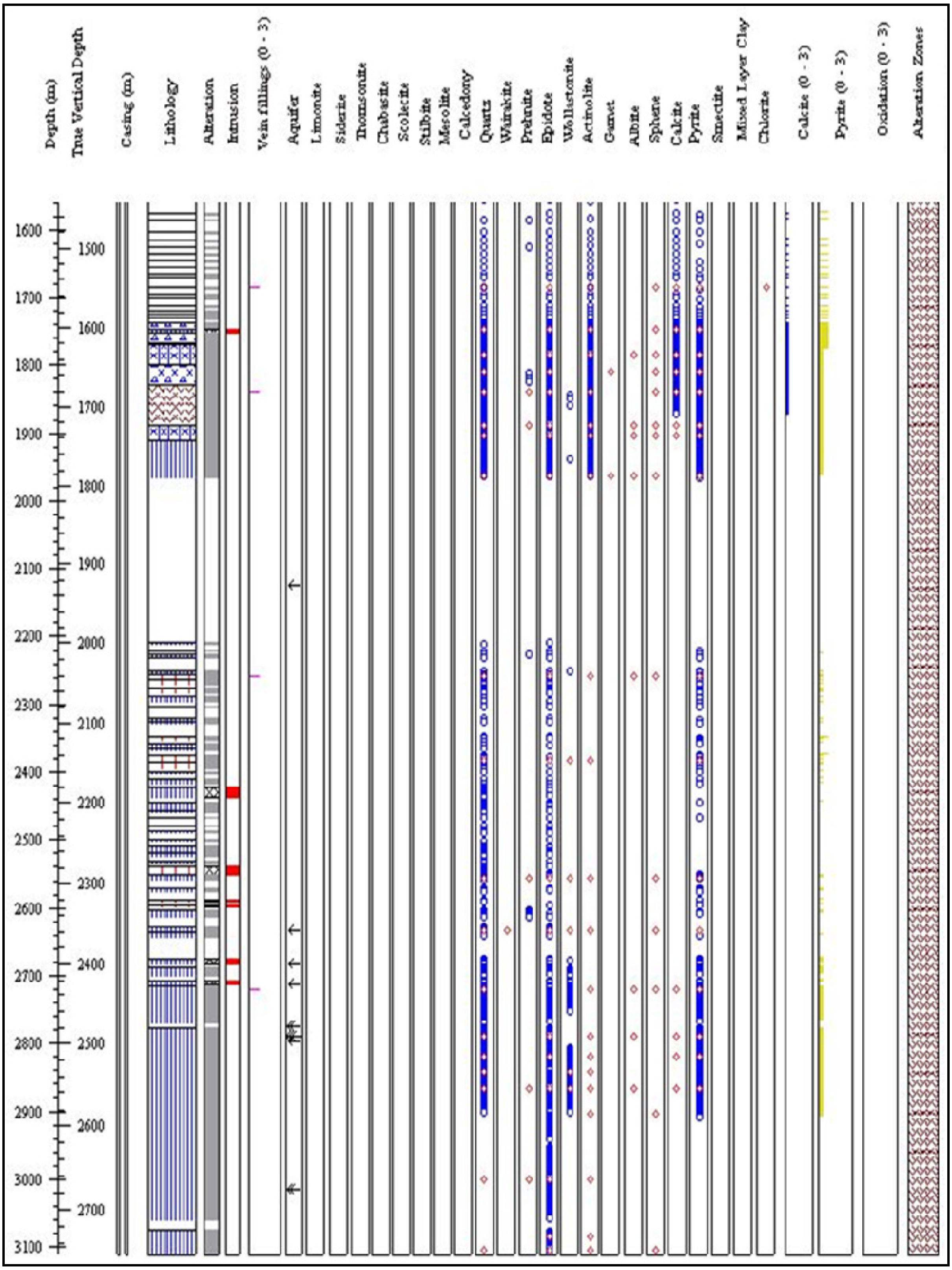


FIGURE 35: Lithological logs feedpoints, intrusions and mineral distribution of well HE-37 from 1560-3111.5 m (legend as in Figure 34)

mineral to 616 m in well HE-24 and 420 m in well HE-37 below which the mixed layer clays start to appear and become the dominant clay component. Pyrite and calcite becomes more common below 480 m, 314 m and 448 m, 314 m in wells HE-24 and HE-37 respectively. Shallower hydrothermal alteration is noticed in well HE-37 where the zeolites start to alter to their high temperature variety wairakite as well as the first appearance of quartz representing a temperature of 180°C is witnessed at 348 m in this well. Mineral sequences of the different zeolites, clays, chalcedony and quartz become dominant in this zone. These fillings show initial smectite or fine grained clay formation with subsequent deposition of zeolites, quartz and calcite. Dominant calcification is also observed in this zone in both wells. Towards the bottom part of this zone zeolites and smectites start to decline in abundance and chalcedony, quartz, wairakite and mixed layer clays become more common.

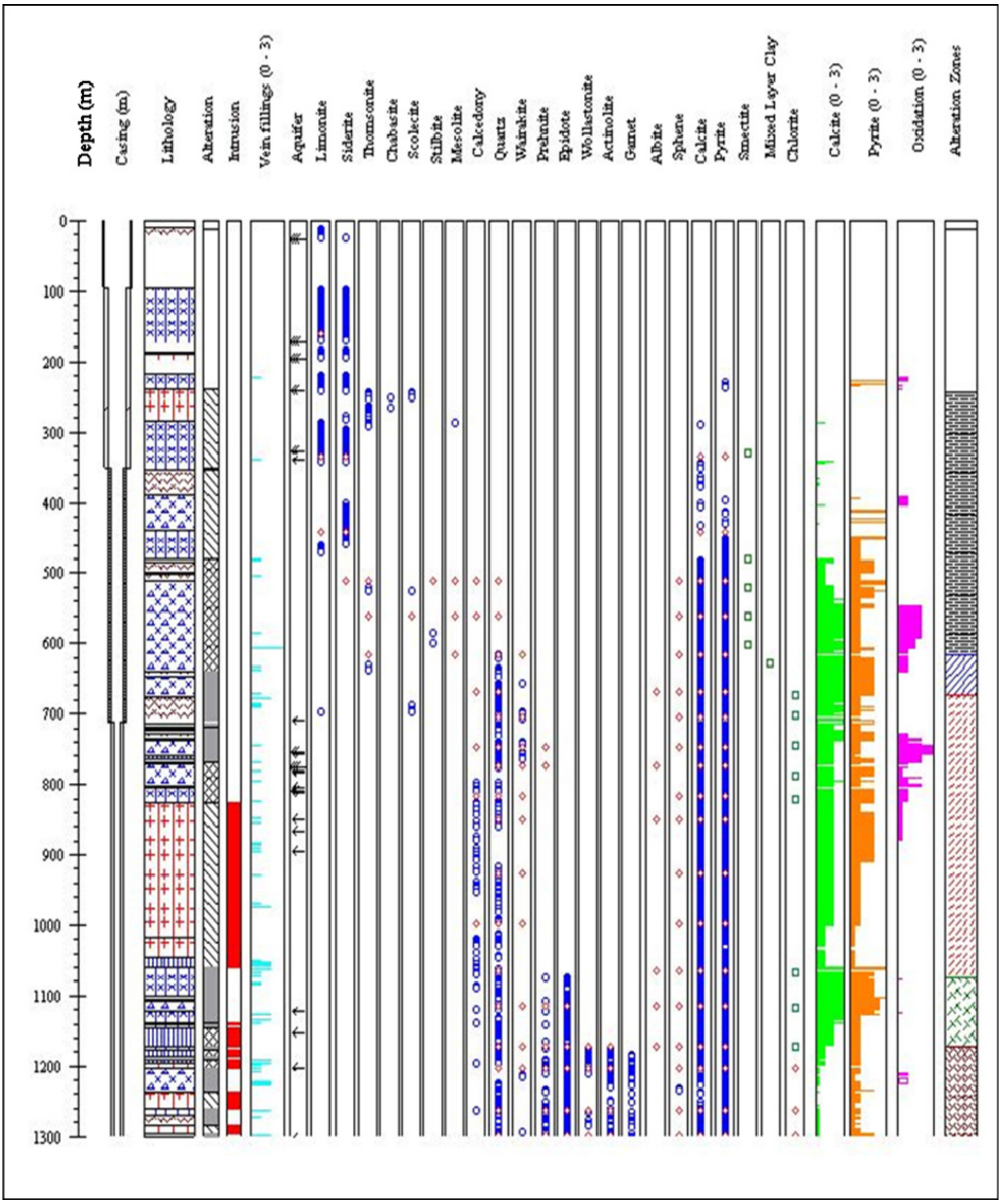


FIGURE 36: Lithological logs feedpoints, intrusions and mineral distribution of well HE-24 from 0-1300 m (legend as in Figure 34)

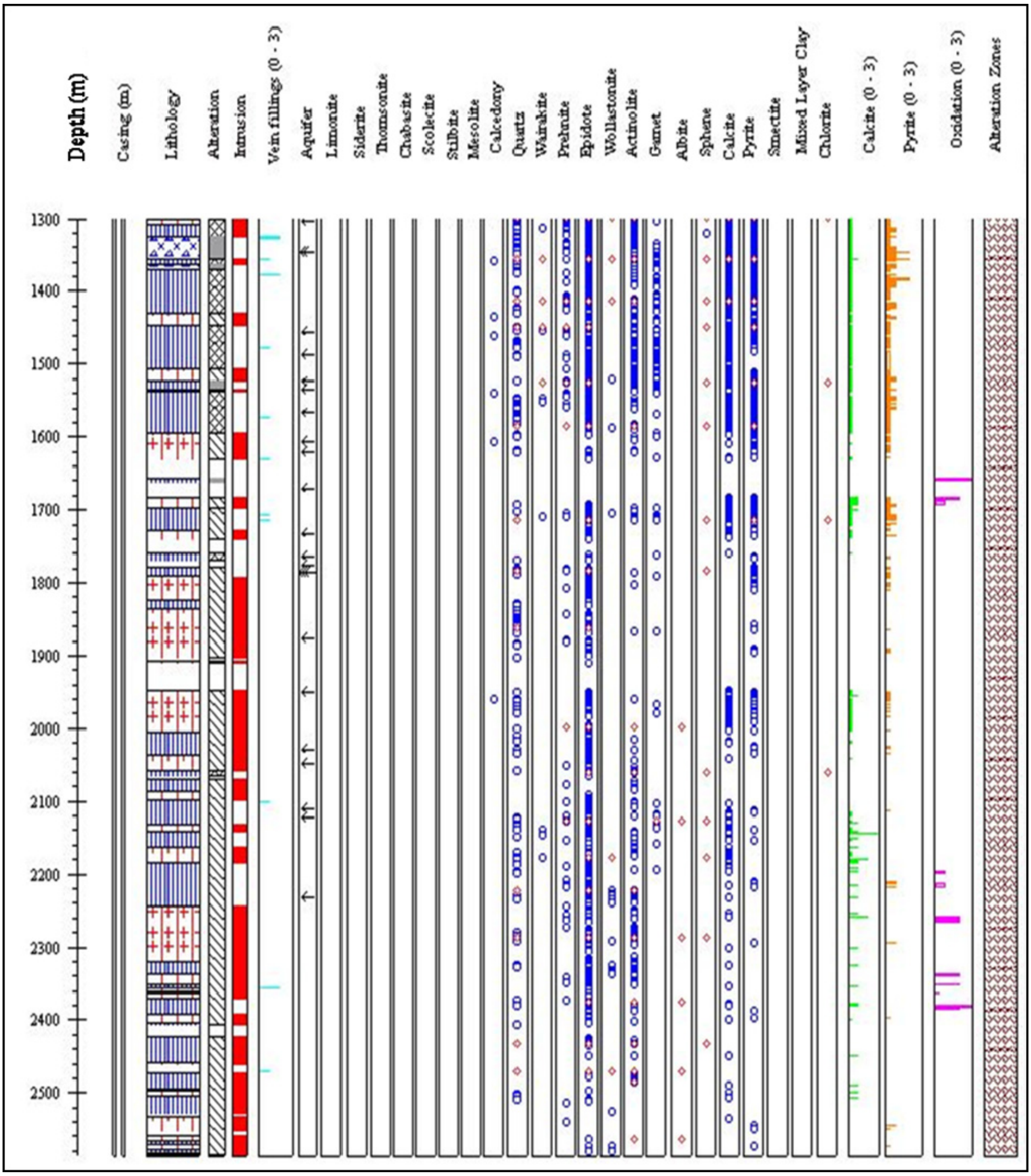


FIGURE 37: Lithological logs feedpoints, intrusions and mineral distribution of well HE-24 from 1300-2587 m (legend as in Figure 34)

5.4.3 Mixed layer clay zone

Mixed layer clays occur at 616 m in well HE-24 and 420 m in well HE-37 and mark the top boundary of the mixed layer clay zone. These clays are the intermediate products of reactions involving clay minerals (smectite and chlorite) in which the different kinds of clay layers alternate with each other formed through progressive high-temperature reactions. Chlorite smectite mixed layer clay is the dominant clay in this zone. The shallower portion of this zone is characterized by the presence of chalcedony, quartz, wairakite, mixed layer clays and few zelolites. In addition to these calcite and pyrite continues to become more common in this zone. Amygdales are completely or partly filled with chalcedony, clay, wairakite, calcite, quartz and chlorite. Chalcedony and low temperaure clays are observed petrographically to be altered to quartz and chlorite respectively in a vesicle in well HE-37 at 500 m depth. Calcite, clay, quartz, wairakite and albite occur in veins.

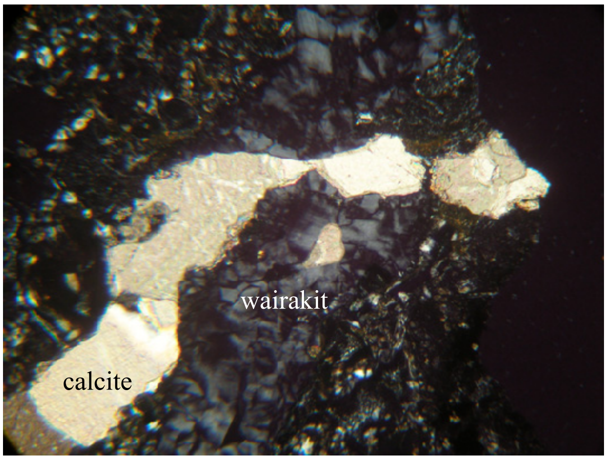


FIGURE 38: Wairakite cut by calcite vein HE-37, 480 m

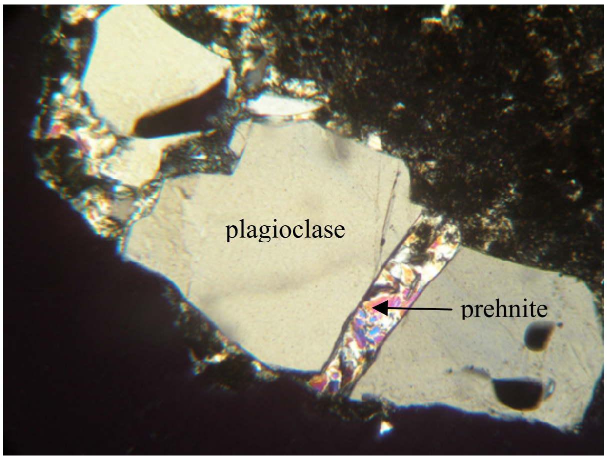


FIGURE 39: Plagioclase being cut by prehnite vein HE-37, 654 m

5.4.4 Chlorite zone

The high temperature variety of clay is chlorite, the first appearance of which defines the top boundary of the chlorite zone. It first appears at 672 m and 520 m in wells HE-24 and HE-37 respectively and is dominant throughout the zone filling vesicles. It is identified by XRD clay analysis having unchanged

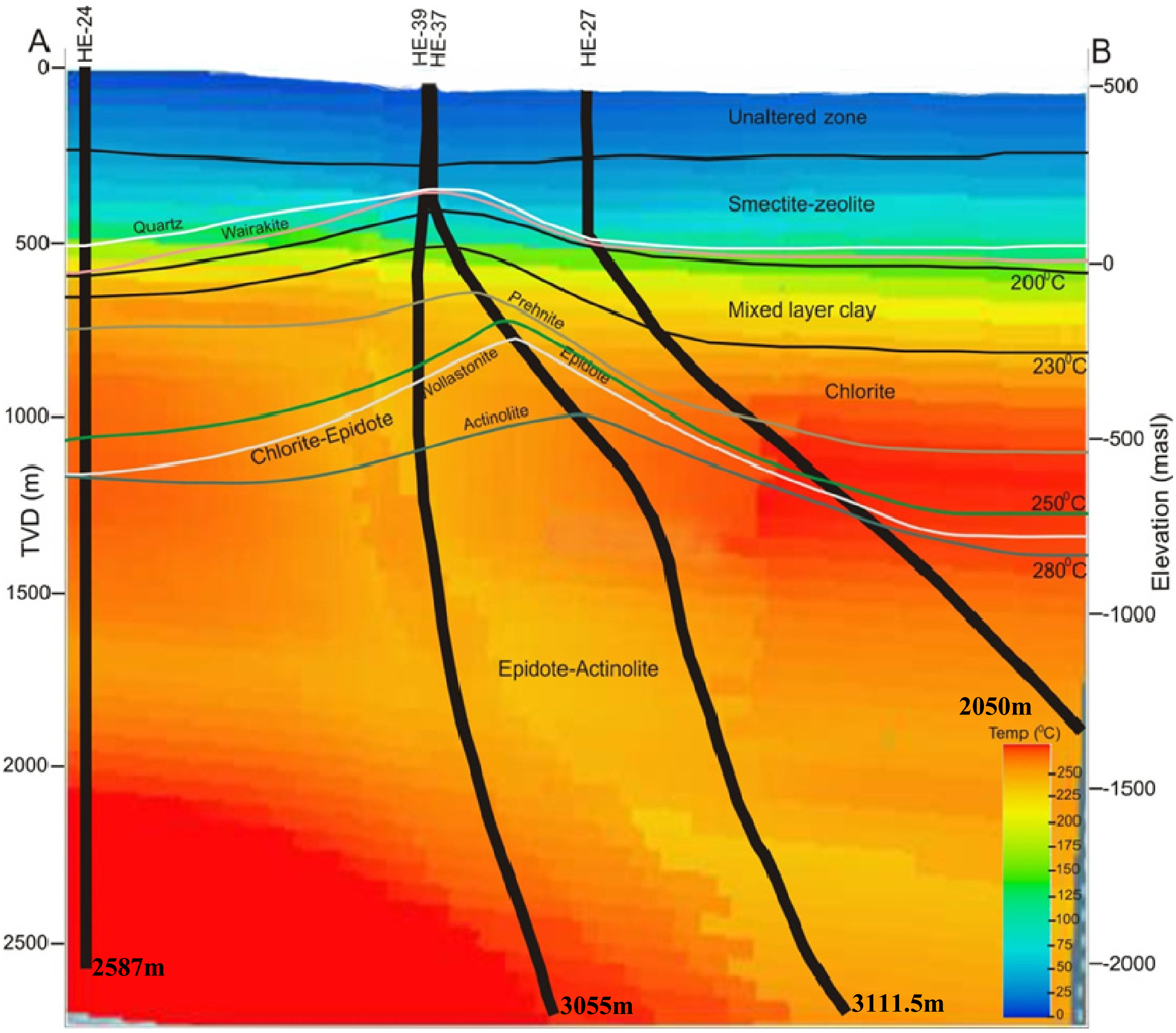


FIGURE 40: Distribution of formation, alteration temperature, alteration zonations and mineral isograds in the four wells, numbers at the bottom of wells represent measured depth

peaks of 7.28 Å for the untreated and glycolated and completely collapses after being heated to 550°C as well as petrographic microscope with no pleochroism and low birefringence rarely above first order grey. Pyrite and calcite still continues to be common with an assemblage chalcedony-quartz-wairakite- chlorite-prehnite. Sphene and albite also forms in this zone through progressive alteration of primary minerals opaque and plagioclase respectively. Mineral sequences involving fine grained clay, with susequent depositions of chalcedony, wairakite, coarse grained clay, quartz, and calcite is noticable in this zone. Calcite, quartz, wairakite, clay and rarely prehnite are the vein fillings.

5.4.5 Chlorite-epidote zone

The top of the chlorite-epidote zone is defined by the first appearance of epidote occuring at depths of 1074 m and 700 m in wells HE-24 and HE-37 respectively. Epidote occurs either as a replacement product after plagioclase or a vesicle filling or as an alteration product of primary minerals. Chlorite continues to be the main clay mineral phase in this zone. The mineral assemblages chalcedony-quartz-wairakite- chlorite-prehnite still continue and include the high temperature alteration minerals wollastonite and epiodte. In addition to the above assemblage pyrite and calcite still continue to be the common secondary minerals. Other secondary minerals occuring are albite and sphene. Dominant vesicle fillings showing deposition of mineral sequences are observed in this zone involving chalcedony with subequent deposition of wairakite, coarse grained clay, wollastonite, albite, quartz, prehnite, epidote and calcite. Calcite and quartz are the main veinfillings.

5.4.6 Epidote-actinolite zone

Petrographic analysis on the wells have revealed the first appearance of actinolite at 1172 m and 1034m in wells HE-24 and HE-37 respectively which marks the top boundary of this zone. Pervasive alteration of pyroxenes with depth has resulted in its replacement by actinolite. Quartz, wairakite, prehnite, epidote and wollastonite continue to be the main secondary minerals. In addition to these pyrite and calcite are also common minerals. In well HE-37 calcite disappears below 1864 m depth while the occurrence of pyrite becomes intermittent below 2200 m until 2680 m below which again becomes continuous until it disappears at 2910 m. Albite occurs at 1034 and 1068 m while sphene occurs below 1140 m within this zone. In well HE-24 both calcite and pyrite occur to the bottom of the well but their appearance becomes intermittent below 1960 m.

The mineralogical analysis in this part of well HE-37 is diffuse firstly because of dominant circulation losses occuring at depths 1446 m and 1966 m which resulted in intermittent appearance of cutting samples for wider range of depths and secondly the limited cutting samples are very fine due to that the well was drilled with aerated fluids.

5.5 Sequence of mineral deposition

Minerals are formed at their characterstic physico-chemical conditions during the history of geothermal systems. Many of these minerals formed either by replacement or deposition, are temperature dependent hence studying their depositional sequence in veins or vesicles, one can explore the parent thermal history and relative time scale of alteration minerals within a system. The sequence of mineral deposition has been studied petrographically for the two wells HE-24 and HE-37 to deduce the relative time scale of their deposition. In both wells progressive sequences have been observed starting from low temperature minerals as fine grained clay usually occuring as linings around vesicle walls and partly chalcedony which later are filled with zeolites dominantly scolesite/mesolite and stilbite. Within the zeolite assemblage the stilbite comes first and scolesite precipitates later which are overlain or replaced by their high temperature variety wairakite (Figure 42). In addition to wairakite medium to coarse grained clay also starts to form. Quartz is also observed to replace the zeolites especially scolesite/mesolite in the early stage of hydrothermal alteration occuring at shallow depth in HE-37 (Figure 41). In the deeper parts of the wells higher temperature minerals become dominant progressing from coarse grained clay, wollastonite, albite, quartz, prehnite, epidote and actinolite (Tables 2-3). Quartz is observed at later stage than wollastonite

TABLE 2: Sequence of mineral deposition in well HE-37 (explanations see Table 3)

Depth (m)	Earliest													Latest
322	fgc	chal												cc
	fgc			scol/mes										cc
348	fgc		stil	scol/mes										
	fgc			scol/mes	qtz									cc
		chal		scol/mes										cc
	fgc	chal			qtz									
414	fgc						cgc							cc
480	fgc			scol/mes			cgc							
				scol/mes										cc
500	fgc	chal												
	fgc						cgc							
		chal					cgc							
		chal					cgc							cc
	fgc			scol/mes										cc
600		chal					cgc							
							cgc							cc
654	fgc				qtz									
	fgc													cc
	fgc					wai								
					qtz	wai								
698	fgc													cc
	fgc				qtz	wai								
732							cgc			qtz				
	fgc									qtz				cc
	fgc	chal				wai								
						wai								cc
						wai	cgc							
							cgc			qtz				
								wo		qtz				
							cgc		alb	qtz				cc
							cgc	wo						cc
								wo	alb	qtz				
		chal					cgc							cc
832							cgc			qtz				cc
	fgc									qtz				
924										qtz	preh			
											preh			cc
								wo		qtz	preh			
950								wo			preh			
966								wo						cc
											preh	epid		
1034								wo		qtz				
							cgc						act	
1068								wo		qtz				
1126	fgc						cgc			qtz				
								wo		qtz				
1140										qtz			act	
1226							cgc			qtz				cc
1358							cgc			qtz				cc
1686										qtz				cc
							cgc			qtz				
1840							cgc			qtz				
2556								wo		qtz				
2720							cgc							cc
2818										qtz		epid		
2866								wo		qtz		epid		

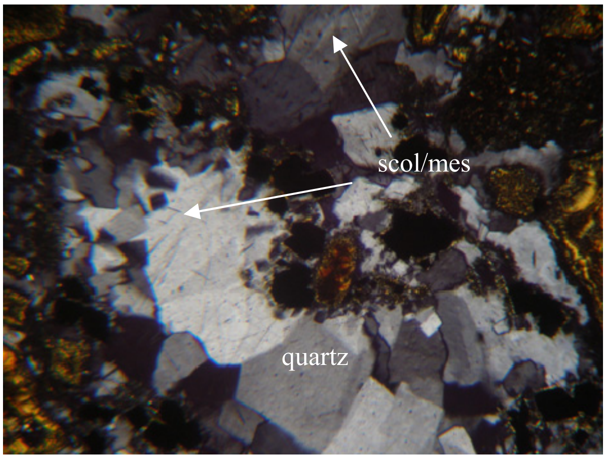


FIGURE 41: Quartz after scolesite/mesolite
HE-37, 348 m

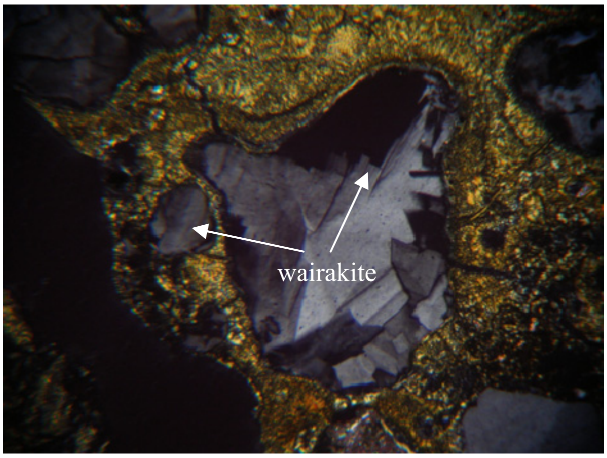


FIGURE 42: Zeolite starts to alter to wairakite
HE-37, 348 m

in both wells which might be due to another phase late precipitation of quartz within the geothermal system. The presence of quartz succeding the high temperature minerals as wollastonite were observed at 732 m in well HE-37 and 1204 m in well HE-24 (Tables 2-3). Calcite comes at a later stage in both wells indicating cooling probably representing closest time to the present system.

TABLE 3: Sequence of mineral deposition in well HE-24

Depth (m)	**Earliest**												**Latest**
510	fgc												cc
	fgc		stil										
560	fgc						cgc						cc
	fgc												cc
616				Scol/mes									cc
	fgc												cc
668	fgc	chal			qtz								
	fgc	chal											cc
704	fgc	chal		Scol/mes	qtz								cc
747					qtz	wai							cc
773					qtz	wai							
816		chal			qtz								cc
850	fgc				qtz								cc
926	fgc				qtz								cc
998	fgc				qtz								
1064	fgc						cgc						cc
1114					qtz								cc
1172										preh		act	
1204								wo	qtz		epid		
									qtz		epid		
1262									qtz	preh			
1298								wo	qtz	preh	epid	act	
							cgc		qtz				
								wo	qtz		epid		
	fgc	chal							qtz				cc
1356									qtz				cc
1412								wo	qtz		epid		
								wo	qtz				
1584									qtz	preh			
2178								wo			epid		
2470								wo	qtz				

fgc= fine grained clay, chal= chalcedony, stil= stilbite, scol/mes= scolesite/mesolite, qtz= quartz, wai= wairakite, cgc= coarse grained clay, wo= wollastonite, alb= albite, preh= prehnite, epid= epidote, act= actinolite, cc= calcite

The sequence generally shows the hydrothermal system to have been evolved from low to high temperature conditions. This has been empahasized by the similarity in the sequences of minerals deposited on the two wells i.e. fine grained clay being the first to be deposited on both wells as lining in the walls of the vesicles succeded by chalcedony and zeolites. Quartz and wairakite comes later in the sequence succeded by coarse grained clay. The formation of quartz and wairakite could also be by replacement of zeolites, quartz seems to be replacing the zeolites before wairakite. In the high temperature mineral assemblage wollastonite, albite, quartz, prehnite, epidote and actinolite are the main minerals in the sequence with an order of mineral deposition from early to late found within the asemblage being wollastonite > albite > quartz > prehnite > epidote > actinolite (Tables 2-3). Albite occurs only in well HE-37 and was not observed within a sequence in well HE-24. The last mineral to be deposited in both wells is calcite. The last stage precipiattion of calcite in the system may indicate cooling. An attempt has been made to come up with a general sequence for the two wells based on the deposition of mineral sequences which show similarities in their deposition history. The proposed general sequenence of the wells is as follows (abbreviations for the names are as in Table 3):

fgc > chal > stil > scol/mes > qtz > wai > cgc > wo > alb > qtz > preh > epid > act > cc

6. ICP-OES ANALYSIS

Whole-rock chemical analyses were made by ICP-OES spectrometry for the altered rocks of well HE-24, at various depths. Before the analysis the samples were selectively handpicked and cleared of the presence of any mica to make the samples representative of the rock in question. Mica is used during drilling as an additive to the drilling mud to prevent circulation loss and can contaminate the sample. Seven samples were analysed at the University of Iceland laboratory for major, minor and several trace elements. These samples has been selected for analysis to prove the acidic nature of the rocks as these rocks are lighter and seems to contain to some extent opaque minerals under binocular microscope. It could not be confirmed by natural gamma logs as these measurments could not go below 1750 m because of temperature constraints. All the analyses have been normalized to 100% to allow direct comparison with fresh rocks. The results and their respective depths of the samples are tabulated below (Table 4). The results show that two of the samples have elevated silica concentration as compared to the basaltic range. The composition of these rocks was compared with other sources to evaluate whether the analysis showed evidence of chemical transport due to hydrothermal alteration. These are samples of relatively fresh basaltic intrusives and diorites from Nesjavellir wells (Franzson, unpublished results) and analysis of unaltered rocks of basaltic glass from south west Iceland from Trönnes (1990).

Oxides show variable stability during hydrothermal alteration. It has been shown that Zr and TiO2 show the highest resistance to alteration (Franzson et al., 2008). Chemical components have thus been plotted against zircon and primary compositional fields have been delineated based on the unaltered and relatively fresh rocks from Trönnes and Franzson respectively. The plots show that all the samples fall within the primary evolutionary trend of the Hengill volcano (Figure 43). The two samples with elevated silica concentrations fall in the basaltic andesite range of intermediate composition and seem very comparable to the diorites from the Nesjavellir field in the north. The other five samples are of basaltic compositions and not intermediate as previously interpreted from binocular analysis. Further studies are expected to be done to analyze the intermediate intrusions within the southern part of Hengill, and these results will be included there.

TABLE 4: Selected ICP analysis results of samples from well HE-24

Depth (m)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	Zr	Y
2114	48.72	2.12	14.09	12.37	6.65	12.62	2.39	0.29	0.37	0.0132	0.0040
2118	49.35	1.80	14.24	11.82	6.82	12.71	2.19	0.42	0.30	0.0119	0.0035
2128	49.11	2.43	15.80	12.38	4.58	11.16	3.14	0.48	0.56	0.0193	0.0049
2290	49.51	1.67	14.48	11.77	6.58	12.91	2.35	0.14	0.25	0.0097	0.0033
2364	54.94	2.01	13.79	11.19	4.31	8.66	3.35	0.45	0.97	0.0339	0.0081
2382	49.46	1.87	15.42	11.17	6.13	12.55	2.38	0.30	0.37	0.0159	0.0039
2498	55.31	1.86	13.58	10.62	4.73	9.21	2.99	0.98	0.37	0.0277	0.0062

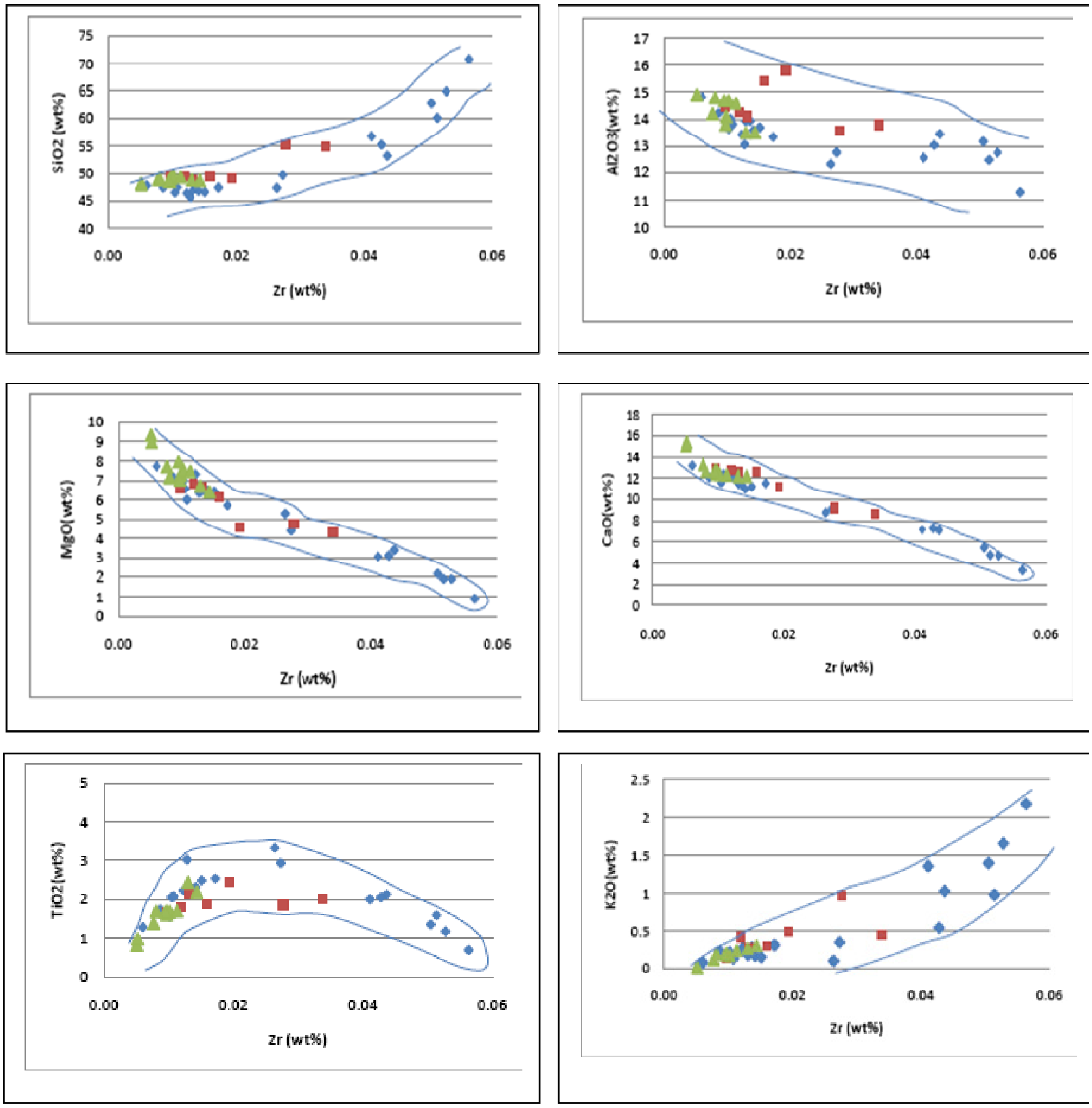


FIGURE 43: Plot of the different oxide components against Zircon. Triangles are data from Trönnes, diamonds are data from Franzson and squares are samples from well HE-24. The line delineates the primary compositional fields

7. FLUID INCLUSION GEOTHERMOMETRY

Fluid inclusion measurements were carried out in quartz samples obtained from wells HE-37 and HE-24 drilled into the Hellisheidi geothermal field to characterize the temperature of mineral formation (homogenization temperatures) within the reservoir rocks. These fluids deposited quartz on the vein walls and in the wall rocks.

7.1 Well HE-37

A total of 60 primary and secondary inclusions in well HE-37 at 734 and 1162 m depth show a wide range of homogenization temperature (Th) between 175 and 320°C (Figure 44). Downhole temperatures for this well at the respective depths were measured at 213 and 181°C. The fluid inclusions are concentrated in three temperature ranges at both depths; 175, 205-225 and 255-290°C at 734 m and 175-185, 205-215 and 270-320°C at 1162 m. The first homogenization temperature for the 734m depth in HE-37 is 175°C which is much lower than the formation temperature, the second range which lie between 205-225°C the average of which is consistent with the measured formation temperature of 213°C at this depth and the quartz crystals are fractured reflecting secondary inclusion temperature. The other range from the same depth 255-290°C the minimum of which is 40°C higher than the present formation temperature. At 1162 m depth the homogenization temperatures range between 175-185°C the average of which is consistent with the current formation temperature at that depth 181°C; the other range 205-215°C the average of which is 30°C higher than the present formation temperature while at the same depth primary inclusions also show anomalously high temperatures ranging from 270-320°C which is much higher than the present formation temperature.

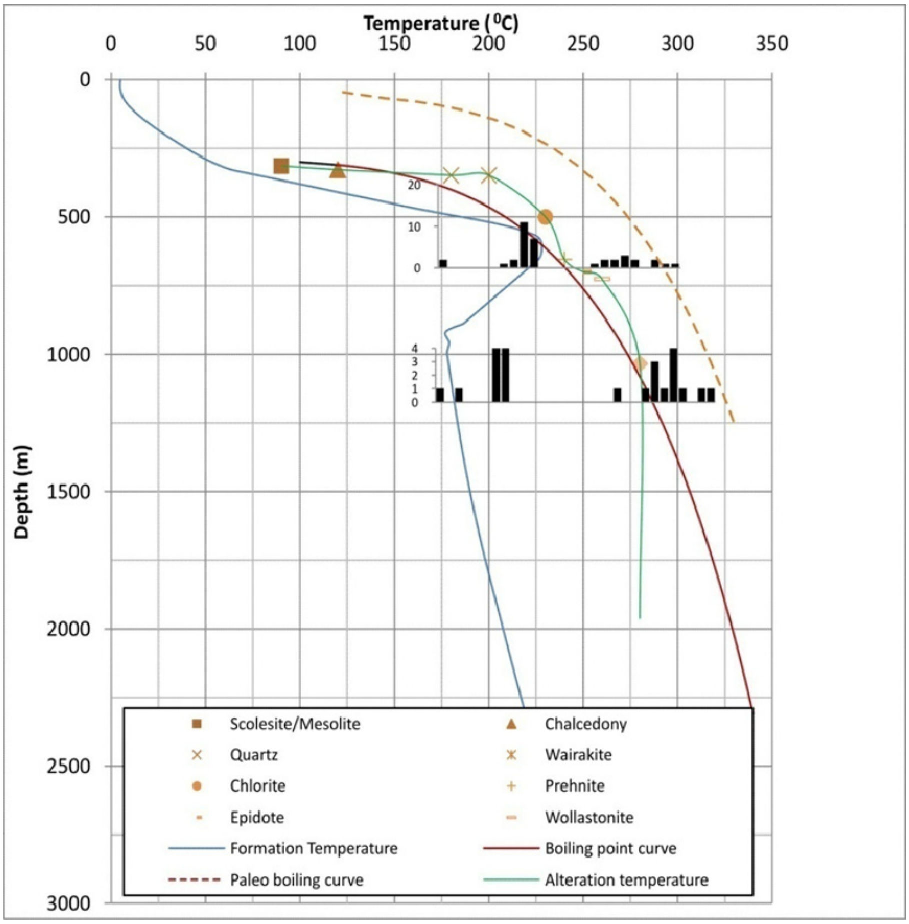


FIGURE 44: Plot of formation, alteration and fluid inclusion temperatures of well HE-37

These measurments indicate two or even may be three phases of geothermal activity at both depth locations; an earlier one with high rather anomalous temperature up to 320°C and a lower temperature range of 215-230°C which conforms to present formation temperature at 734 m but is higher than the formation temperature at 1162 m. A third stage may be present, showing temperatures as low as 175°C at 734 m, which is lower than formation temepratures at that depth but conforms to the temperature at 1162m.

7.2 Well HE-24

Fluid inclusion measurments were done in well HE-24 at 1658 m depth where a temperature reversal occurs in the well. All 28 primary and secondary inclusions occur in quartz and have two ranges of homogenization temperatures between 175 and 255°C. The first range between 175-185°C is much lower than the current formation temperature at that depth 234°C. The other range lying between 230 and 255°C which is consistent with the present formation temperature (Figure 45).

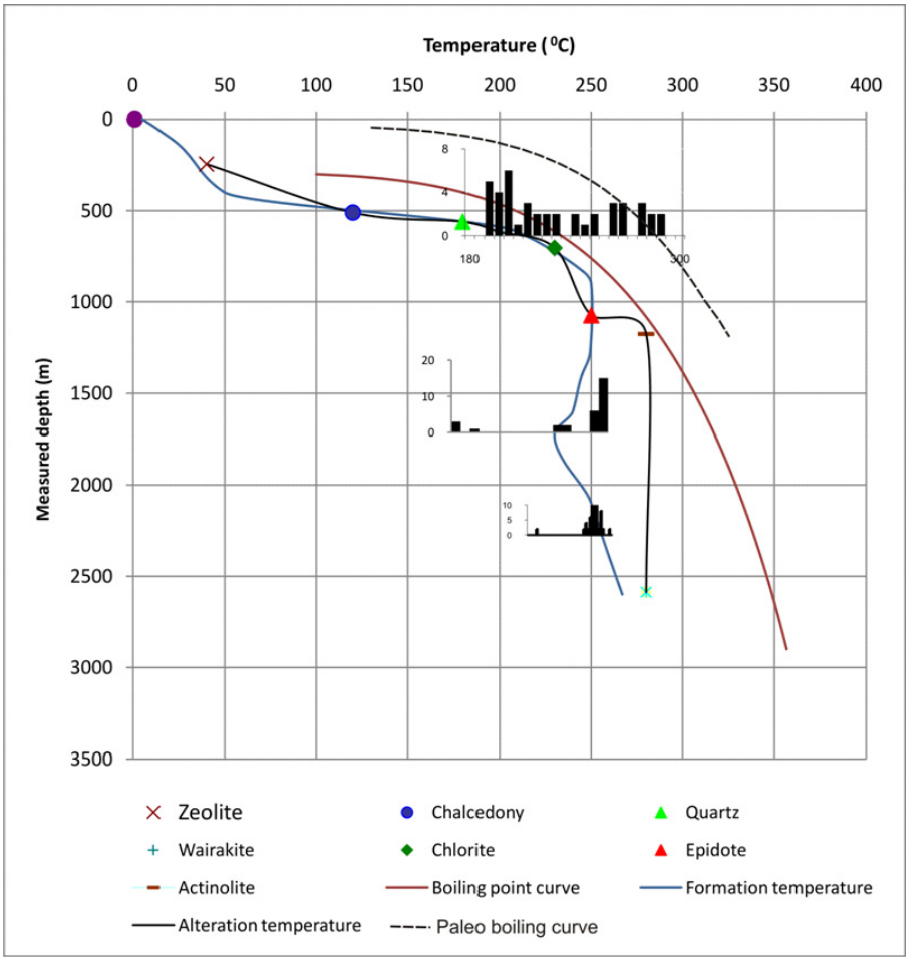


FIGURE 45: Plot of formation, alteration and fluid inclusion temperatures of well HE-24. Inclusions in the top part of the well are from Koestono (2007) and the bottom part is from Mortensen and Franzson (2006)

Previous work in this well at 2190 m with a total of 48 inclusions from calcite has also shown a range of homogenization temperature between 220 and 254°C (Mortensen and Franzson, 2006). All the inclusions show temperature ranges between 220 and 254°C, dominantly between 240-254°C. The downhole temperature measurment at this depth is 253°C. Koestono (2007) has also done fluid inclusion work collected from calcite in the top part of the well from 664-710 m depth range. The homogenization temperatures were assessed from 44 primary inclusions. The inclusions show a wide range of temperature from 195 to 285°C. The formation temperature in this depth range is 224°C.

7.3 Comparison of alteration, fluid inclusion and formation temperatures

Hydrothermal alteration of basaltic host rocks in Hellisheidi high temperature geothermal field has resulted in a diverse mineral assemblage. These mineral assemblages (Table 1) which best indicate the changes in the subsurface thermal regime of a system are widely used while comparing the alteration, fluid inclusion and formation temperatures in order to evaluate temperature history of the reservoir.

In well HE-37 the alteration temperatures are considerably higher than the measured formation temperatures at all depths implying the hydrothermal minerals are occuring way below their stability range especially for the high temperature minerals indicating cooling with time (Figure 44). The fluid inclusions show even higher Th values than the alteration temperatures. The third phase which shows higher formation temperature 213°C as compared to the fluid inclusion temperature of 175°C at 734 m depth indicates probable heating in the system. This heating phase is not conspicous at 1162 m having comparable temperatures in both formation and fluid inclusion measurments. The fluid inclusions that show the occurrence of heating are few and have to be confirmed by further work. The formation temperature in the well shows an abrubt increase below 300 m to about 225°C which resulted in the formation of quartz and wairakite at shallower depth. From this abrupt increase in formation and even much higher alteration temperature together with the fluid inclusion data one would be tempted to speculate that the system reflects thermal condition expected during a geothermal episode in glacial times.

In well HE-24 the hydrothermal alteration minerals with the exception of wollastonite and actinolite seems to be in equilibrium with the present thermal regime occuring within their stability ranges alteration temperatures being comparable with the current formation temperature (Figure 45). Wollastonite and actinolite however, occur below their stability ranges indicating probable cooling with time. The fluid inclusion temperatures of 175°C at 1658 m depth comparable with the third phase in HE-37 showing much lower temperatures as compared to the current formation temperature of 234°C indicates probable heating in the system. The other population at this depth have fluid inclusion temperature consistent with the present formation temperature. The downhole temperature measurment at 2190m depth is 253°C which is consistent with the maximum fluid inclusion temperature of 254°C suggesting equilibrium.

The fluid inclusions in the top part of this well show also a wide range of temperatures similar to well HE-37 generally shows cooling with time although not as conspicious as the three population groups in the later. It might also be that the peaks could have grown together. If so the alteration pattern looks similar in both wells except that it is diminishing in well HE-24 observed from the shallower alteration in well HE-37. This shallow alteration in well HE-37 as compared to HE-24 again could imply that the upflow zone responsible for the variation in alteration for these wells might be from north possibly related to the Hengill system as this system shows extensive fossil hydrothermal alteration on surface. The inclusions in the middle and bottom part of the well reflect heating in the system as well as equilibrium conditions reflected by the lower fluid inclusion temperatures and consistent temperatures with the current formation temperature respectively.

8. DISCUSSION

Skardsmýrarfjall is part of the Hengill-Hellisheidi high temperature geothermal system. The general subsurface basaltic strata as depicted from the studied wells shows hyaloclastite volcanic formations down to some 1400 m depth underlain by a more dominant lava accumulation. The hyaloclastites has further been subdivided into seven distinct formations based or either their texture (aphyric vs porphyritic) or composition (olivine tholeiite and tholeitic) the latter being silicic and more resistant to alteration as compared to the former (Figure 17). A tenatative classification of formations on two additional wells (HE-39 and HE-27) has also been made solely based on cutting analysis which must be confirmed by later petrographic work. The top of the lava series, good marker horizon, occuring below these hyaloclastite formations was identified in all the wells which is believed to be the base of the Hengill central volcano. According to Franzson et al., (2005), an age of about 0.4 m.y. is proposed for this central volcano, which also puts an upper age limit on the geothermal system. The resolution of the analysis however, diminishes downwards both because of smaller grainsize of the cuttings as well as large circulation loses causing more mixing of cuttings mostly within the lava sequence in all the wells or even at shallower depth below 880 m in well HE-27. Intrusions which are identified by their massive, tight and compact nature as well as from geophysical logs are scarce at the top part of the wells and become more common below 1000 m depth. Most of the intrusions are basaltic in composition with few being evolved.

The main sources of permeability in the wells are believed to be related to intrusive and lithological boundaries, and fractures. Aquifers occur at different depths in the wells having different sizes and occuring associated with different geological formations. Aquifers related to the stratigraphic boundary are dominant in the shallower parts of the wells while the permeability due to aquifers related to intrusive rocks becomes dominant at depth. The main dykes of 2000 and 5000 fissure eruptions are in general believed to be providing the main geothermal flow channel in the system. These eruptive fissures play a similar role in the Nesjavellir system on the north side of Hengill central volcano (Franzson et al., 2005).

The distribution of hydrothermal alteration minerals occuring in veins, vesicles and as replacement of the primary minerals shows a progressive variation with temperature. The minerals undergo chemical reactions with respect to changes in the physico chemical conditions which resulted in the formation of diverse secondary mineral assemblages, these changes in mineral assemblages being from clay and zeolites at shallower depths to wollastonite and actinolite in the deeper parts. Based on the formation of these progressive temperature dependent key index minerals five zones of hydrothermal alteration have been identidied beneath a zone of unaltered rocks in the studied wells each characterized by the first appearance or the dominance of the respective mineral(s). These zones are zeolite-smectite, mixed layer clay, chlorite, chlorite-epidote and epidote actinolite. These alterations appear to connect to the fissure eruptions which feed the main flow of the geothermal fluids. The sequence of mineral deposition within the wells generally shows the hydrothermal system to have been evolved from low to high temperature conditions ranging from fine grained clay at low temperatures to actinolite to high temperatures in a later cooling stage of the system which has resulted in the precipitation of calcite. Within this general sequence quartz seems to be occuring in both high and low temperature assemblages the reason might be that in low temperature assemblages it replaces the earlier deposited zeolite sequences without being precipitating in the vesicles indicative of the quartz formation temperatures while at high temperatures precipitation of quartz might have occured as quartz has a wide range of stability within the geothermal system. Quartz has also been noted as part of a high temperature mineral assemblage sequence in Nesjavellir along with chlorite, wollastonite, garnet, amphibole and sulphides (Franzson, 2000).

Comparison of the fluid inclusion, formation temperature and alteration temperature in both wells has shown that generally cooling has occured in both the wells as the alteration temperature is higher even much higher in well HE-37 as compared to the current formation temperature. However, in well HE-37 the third and low temperature phase having current formation temperature of 213°C at 734 m depth seems to be much higher as compared to the fluid inclusion temperature of 175°C which might indicate that heating has occured on that part of the well which is not shown at 1162 m depth having conformable temperatures of both measurments. In well HE-24 fluid inclusions show cooling, conformable temperatures and heating as compared to the alteration and formation temperatures. Cooling was observed at 700 m depth as the fluid inclusion temperatures are much higher than the current formation temperature. At 1658 m depth both probable heating and consistent temperatures were noticed while the fluid inclusion measurment conducted at the 2190 m shows equilibrium.

The wide range of temperatures in the fluid inclusion measurments in well HE-37 seems to be comparable with a similar fluid inclusion study made in well ÖJ-1 at Ölkelduháls east of Hengill where the Th values along with the alteration showed a much higher temperatures than both the present temperatures and even the boiling point curve (Steingrímsson et al 1997). This led to the conclusion that the maximum thermal condition reflected conditions expected during a geothermal episode in glacial times, with hydrostatic pressures connected to water table within the overlying icesheet, which in turn made boiling point curve rise to shallower levels. The anomalously high Th values in HE-37 may similarily imply that the water table and the boiling point curve were about 300 m higher than at present which would put the top of it near the surface of Skardsmýrarfjall (Figure 44). HE-24 also seems to show similar features with wide range and high Th values at 700 m depicting probable boiling in the system (Figure 45). This could imply a geothermal system under the influence of an overlying glacial icesheet, and if so place a time frame of 13000-11500 years to that episode. The comparison also shows that the much higher differences in these temperatures could possibly show glacial influence in well HE-37, which diminishes towards south in well HE-24 (evidenced by shallower alteration in well HE-37) implies that the centre of the hydrothermal system that made the alteration pattern is towards north, i.e. Innstidalur and probably the Hengill Mountain north of Innstidalur. Hengill Mountain has a very extensive fossil surface alteration while these features are scanty in Skardsmyrarfjall indicating that the Hengill system may be the upflow channel of the geothermal system. This also further indicates that the studied wells are located in the outflow zone of the geothermal system.

The heating depicted in both the wells are based on very few measurments and has to be confirmed by further fluid inclusion work. It has shown that there is a recent heating episode occuring in the system which could be related to the opening up of the 2000 and 5000 years old fissure eruptions. A new heating episode is postulated to be associated with these fissure eruptions which dissect the Hengill central volcano, probably deriving fluids from the roots of the Hengill geothermal reservoir (Franzson et al., 2010). It is also suggested that these same fissures are causing an inflow of colder water towards the center of the reservoir to the north of the Skardsmýrarfjall mountain (Franzson et al., 2005) (Figure 46). The temperature reversal noticed below 1500 m depth in well HE-24 could be due to this infiltration of colder water caused by these fissures. The cooling episode in the system is represented by the deposition of calcite closest to the present time related to cooling in the reservoir caused by an inflow of colder groundwater becoming progressively oversaturated by calcite as it gains heat from the surrounding rock (Franzson, 2000). The heating which has succeded the cooling as evidenced by the fluid inclusions and interpreted to be due to the opening up of the 2000 and 5000 years old fissure eruptions might have also contributed to the deposition of calcite by heating up the colder groundwater.

The evidence from this study has shown that there are three successive stages within the history of the geothermal system. Firstly, the progressive heating as evidenced by the development of hydrothermal minerals from lower to higher temperature ranges and the anomalously high fluid inclusion temperatures reaching as high as 320°C interpreted to be related to the initial heating up of the Hengill system; secondly a cooling episode represented by the deposition of calcite evidenced from the petrographic study of the sequence of mineral deposition, related to the inflow of cold ground water; and thirdly, a probable another heating phase evidenced from fluid inclusion measurments showing lower homogenization temperatures as compared to the current formation temperatures which might be related to the opening up of the two post glacial fissure eruptions (Figure 46).

Conceptual model for the Hellisheidi high temperature geothermal system has been proposed by Franzson et al., (2005). It shows the main structures that contribute to the permeability of the reservoir as well as suggests two upflow zones in the southern and eastern part of Hellisheidi field. Based on the interpretation of the data collected from the studied wells a conceptual model is proposed which indicates the upflow, outflow and inflow zones in relation to the Hengill system in Skardsmýrarfjall, northern part of Hellisheidi. The data as discussed earlier shows that the main upflow zone that contributes to the alteration pattern in this area is the main Hengill central volcano which flows towards Skardsmýrarfjall in which a later cooling has invaded the area through inflow of cold ground water. A recent opening of the two postglacial volcanic fissures is beleved to contribute to the present high temperature permeability of the system.

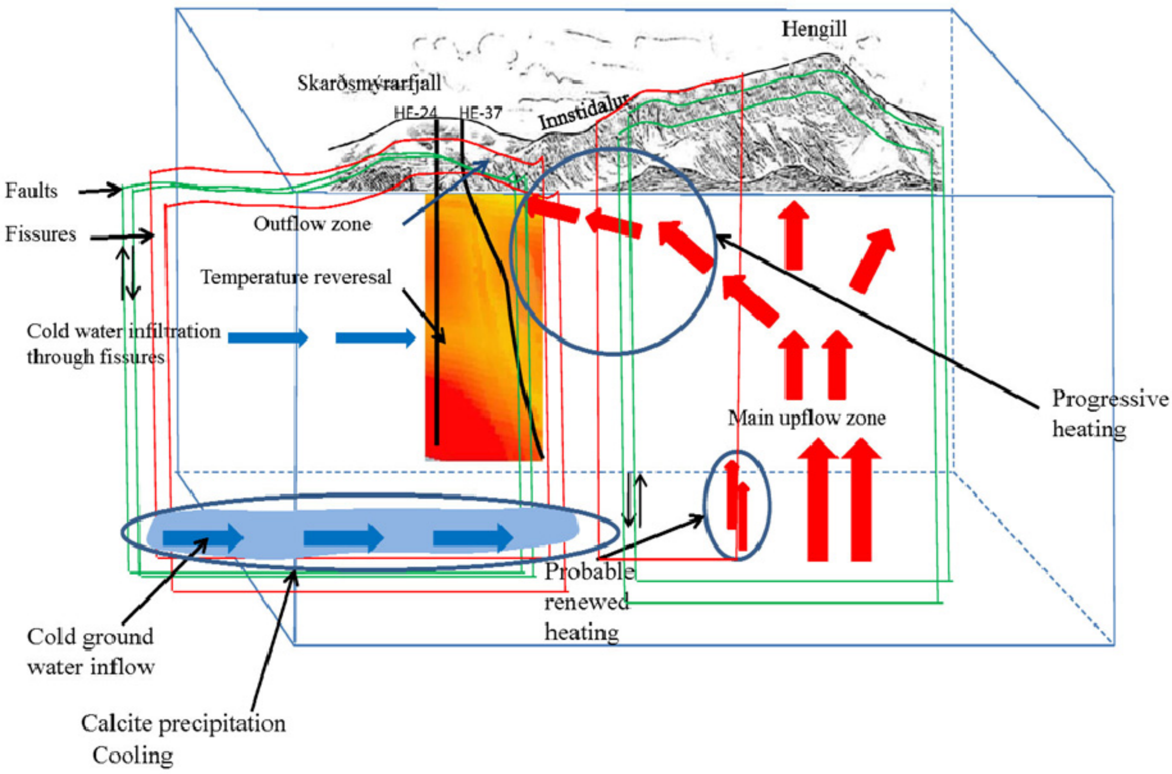


FIGURE 46: Conceptual model of Northern Skardsmýrarfjall

9. CONCLUSIONS

The following conclusions can be deduced:

1. The main rock types that comprise the subsurface geology of the studied wells are basaltic tuff or volcanic glass, glassy basalt or pillow basalt, basaltic breccia, sediments and finally intermediate rock, fine, medium and coarse grained crystallized basalt, which forms either lavas or intrusions.

2. The main sources of permeability in the studied wells and in general in Hellishedi field include lithological contacts, intrusive boundaries, major faults and fractures.

3. The hydrothermal alteration mineral assemblages are controlled by temperature, rock type, permeability.

4. Mineralogical examination of the studied wells in Hellisheidi high temperature geothermal field has revealed five zones of hydrothermal alteration beneath a zone of unaltered rocks. These zones are zeolite-smectite, mixed layer clay, chlorite, chlorite-epidote and epidote actinolite.

5. Hydrothermal alteration mineralogy has indicated cooling has occured in the system.

6. The sequence of mineral deposition within the wells generally shows the hydrothermal system to have been evolved from low to high temperature conditions ranging from fine grained clay at low temperatures to actinolite to high temperatures in a later cooling stage of the system which has resulted in the precipitation of calcite.

7. Fluid inclusion has shown anomalously high temperatures which indicate probable boiling in the system.

8. In general the evidence from this study has shown that there are three successive stages within the history of the geothermal system. The progressive heating, cooling episode and thirdly, a renewed heating phase.

9. The studied wells are located in the outflow zone, the main upflow zone of the system being beneath Hengill central volcano.

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APPENDIX A: Procedure and preparation of samples for clay mineral analysis

1. Into a clean test tube place a small amount of clay. Fill the tube to approximately two-thirds full with distilled water. Place the tube in a mechanical shaker for 2 - 3 hours.
2. Pipette a few millilitres from each tube and place approximately 5 drops on a labelled glass plate, not making the film thick and let them dry at room temperature overnight.
3. Run the samples in the range 2 - 14° for a time of about 13 minutes on the XRD machine.
4. After running the samples air dried place them at a desiccator containing glycol ($C_2H_6O_2$) solution. Store it at room temperature for at least 24 hours.
5. Run the glycolated samples in the same way in the XRD machine.
6. After the glycolated samples are analysed the samples are put into an oven and heated at 500 - 550°C for one hour. When the samples have cooled, the samples are analysed through the same process on the XRD machine.

APPENDIX B: Procedure for ICP-OES analysis

Sample preparation

Rock sample were weighed in with lithium metaborate and fluxed in graphite crucible for 30 min at 100°C. A constant rock/flux mass ratio of 2 was maintained. Reference samples for instrument calibration were the "in house standards" A-THO, B-ALK and B-HTO (BIR-1).

Reference samples were made of 250 mg rock powder and 500 mg flux and the unknown samples were made of 100 mg rock powder and 200 mg flux.

After melting the resulting glass beds were dissolved with continuous agitation in 100 x its weight of acid mixture (75 g for reference samples, 30 g for the unknowns). The acid mixture is made of deionized water with vol 5% nitric acid, 1.33 vol % hydrochloric acid and 1.33 vol% semi-saturated oxalic acid.

Instrument setup and analyses

ICP- analyses were made with a cross-flow nebulizer at sample consumption about 2 ml/min. The argon plasma was run at 1200V. Measurements were made in four 25 sec reading sessions after 40 sec flushing of the nebulizer with the sample itself.

Analytical session starts with running of the three calibration standards. The SpectraVision software is then used to calculate a two or three point calibration line for each element of the analytical routine. Instrumental reference sample (REF) for monitoring eventual fluctuations during analysis was made of equal parts of the three reference samples. This sample was analyzed at the beginning of the session and with ten samples interval through the session. One of the reference samples (B-THO) was analyzed within each batch of 10 samples in order to demonstrate instrument reproducibility in multiple analyses.

Data processing and correction

Raw data were processed in the following manner.

The data is copied and pasted into a correction spreadsheet All analyses of the batch are normalized to 100% sum.

The spreadsheet then calculates time dependant variation down each column (element) of the analysis by finding the difference between the first and last readings of the reference sample. The total variation is then divided into ten equal parts. Each line is then corrected by adding the variation-increment which is also added to all subsequent lines of the batch. Then all sums are normalized to 100%.

After the time dependant variation-correction has been applied to the batch the absolute values of the reference samples at the beginning and at the end are equal. Next, the observed absolute value of the reference sample is recalculated to the nominal values of that sample by a linear correction factor which then is applied to all the unknown samples of the batch.

Finally, all the unknown samples are normalized to 100% sum.

APPENDIX C: The different phases and casing depth for Well HE-24

HE-24 is a vertical well and is drilled to a depth of 2587m to explore temperature and permeability of the geothermal system under Skardsmýrarfjall. Its location is 385418.13E and 396557.04N and elevation of 572.5 m. It is of the wider type. It's divided into predrilling and three phases. Sleipnir drilled with 26“ crown to 96 m for a 22 ½“ surface casing. First phase for 18 3/8“ safety casing was drilled with a 21“ crown down to 351 m. Sleipnir´s drill rig is 6 m above the basement edge and depth numbers are in relation with the drill rig.

At the end of first phase Ódinn came and drilled the second and third phase. Ódin´s drillrig is at 8 m. And depths are in relation with to the drill rig. The second phase was drilled with 17 1/2“ crown down to 711 m for a 13 3/8“ production casing.

Predrill was conducted with a 26“ crown on August 26th, 2006 and encountered a total loss of circulation (>45 l/s) occurred at 26 m, 49.5 m and 96 m depth. The well was cased at 96m with a 22 ½“ surface casing.

First phase

First phase started on September 4th, 2006. They drilled with a 21“ crown and encountered there was a total loss of circulation at 172 m. Drilling continued down to 180 m then cemented the well. A total loss came again at 196 m and 241 m. Drilling stopped September 13th at 351 m. The well was then flushed and then temperature and width measured. It was cased down to 351 m the casing diameter being 18 3/8“.

Second phase

Ódinn began drilling with a 17 ½“ crown on september 19th at 351 m and continued upto 711 m. No circulation loss was in the well. Heat and width was measured. Production casing with a casing diameter of 13 3/8“ was set at 708,2 m.

At the end of first phase Ódinn came and drilled the second and third phase. Ódin´s drillrig is at 8 m. And depths are in relation with to the drill rig. The second phase was drilled with 17 1/2“ crown down to 711 m for a 13 3/8“ production casing.

Third Phase

The third phase was drilled aerated with a 12 ¼“ crown and circulation fluid a mixture of air and waterdown to 2587 m and that is the production part of the well. The third phase was cased with a 9 3/8“ liner. Casing depth of the different phases is tabulated below.

Drilll	Phase	Crown	depth	Casing depth	Casing diameter	Height of drill rig
Sleipnir	predrill	26”	96 m	90,0 m	22½”	6 m
Sleipnir	1. phase	21”	351 m	350,0 m	18⅝”	6 m
Ódinn	2. phase	17½”	711 m	708,2 m	13⅜”	8 m
Ódinn	3. phase	12¼”	2587 m	650,9-2550,8 m	9⅝”	8 m

APPENDIX D: The different phases and casing depth for Well HE-37

HE-37 is located on the northern part of Skardsmýrafjall, having coordinates 385870.37 E and 397166.39N and an elevation of 561 m. It is directionally drilled to research the geothermal field to the north, under the little known Innstidalur and two volcanic fractures, 2000 and 5000 years old. It is of the wider type. Sleipnir was used to drilll the predrill, first and second phase. Jardboranir did the drilling. VGK-hönnun did the supervision ÍSOR did the research and counselling.

The predrill began September 9th, 2008 with a 26" crown down to 85 m and it was cased it with 22 ½" casing down to 84 m.

The first phase was drilled with a 21" crown to 303,8 m and cased at 302m with a complete circulation loss occuring at 242 m. In the second phase drilling continued with a 17 ½" crown to 753,5. They put a 13 ⅜" production casing down to 753 m. Sleipnir ended work on the second phase on October 7th the 39th workday. Týr did the 3rd phase.

Drill	Phase	Crown	Depth	Diameter and casing	Casing depth	Height of drillrig
Sleipnir	predrill	26"	85 m	22 ½"	84 m	5.8 m a.s.
Sleipnir	1 phase	21"	303.8 m	18 ⅝"	302 m	5.8 m a.s.
Sleipnir	2. phase	17 ½"	753.5 m	13 $^3/_8$"	753 m	5.8 m a.s.

The third phase began on 7th of February, 2009. In this phase aireated drilling was used which it makes it difficult to see ciculation loss. The drilling ended at 3111,5 m depth. Gyromeasurements showed that the direction is N35° and the slope is 35°. A a 9 ⅝" liner was put all the way to the bottom.

Drill History

Drill	Phase	Crown	Depth	Diameter and casing	Casing depth	Height of drillrig
Sleipnir	predrilling	26"	85 m	22 ½" surface cas.	84 m	5.8 m a.s.
Sleipnir	1. phase	21"	303.8 m	18 ⅝" safetycasing	302 m	5.8 m a.s.
Sleipnir	2. phase	17 ½"	753.5 m	13 ⅜ safetycasing	753 m	5.8 m a.s.
Týr	3. phase	12 ¼"	3111.5 m	9 ⅝" liner	3111.5 m	7.1 m a.s.

Results of downhole survey

Measured depth (m)	Slope (°)	Direction (°)	Horizontal lateralization (m)	True vertical depth (m)	East (m)	North (m)
0	0	0	0	0	0	0
30	0.34	96.51	0.1	30.0	0.1	0
60	0.44	90.73	0.3	60.0	0.3	0
90	0.47	91.62	0.5	90.0	0.5	0
120	0.45	94.16	0.8	120.0	0.8	0
150	0.54	102.19	1.0	150.0	1.0	-0.1
180	0.55	107.01	1.3	180.0	1.3	-0.1
210	0.63	107.53	1.6	210.0	1.6	-0.2
240	1.02	72.12	2.0	240.0	2.0	-0.2
270	1.77	63.18	2.7	270.0	2.7	0.1
300	1.89	64.14	3.6	300.0	3.5	0.5
330	2.62	52.69	4.7	329.9	4.5	1.1
360	3.77	41.70	6.2	359.9	5.7	2.3
390	5.17	37.68	8.3	389.8	7.2	4.1
420	7.91	35.19	11.5	419.6	9.2	6.8

Measured depth (m)	Slope (°)	Direction (°)	Horizontal lateralization (m)	True vertical depth (m)	East (m)	North (m)
450	9.59	34.39	15.9	449.2	11.8	10.6
480	10.89	36.09	21.1	478.8	14.9	14.9
510	12.53	39.74	27.2	508.1	18.6	19.7
540	14.07	41.71	34.1	537.3	23.2	25.0
570	15.37	43.69	41.7	566.3	28.3	30.6
600	16.44	48.24	49.9	595.2	34.2	36.3
630	18.23	50.21	58.8	623.8	41.0	42.1
660	20.72	50.46	68.7	652.1	48.7	48.5
690	23.67	51.26	80.0	679.9	57.5	55.6
720	25.88	51.22	92.5	707.1	67.3	63.5
750	27.10	50.72	105.9	734.0	77.7	71.9
780	27.33	50.89	119.6	760.6	88.3	80.6
810	27.20	50.50	133.3	787.3	99.0	89.3
840	27.20	50.28	147.0	814.0	109.5	98.0
870	27.52	50.17	160.8	840.6	120.1	106.9
900	27.43	50.20	174.6	867.2	130.8	115.7
930	27.72	50.23	188.5	893.8	141.4	124.6
960	27.83	50.39	202.5	920.4	152.2	133.5
990	28.08	50.57	216.5	946.9	163.0	142.5
1020	28.08	50.83	230.7	973.4	174.0	151.4
1050	28.46	51.04	244.8	999.8	185.0	160.4
1080	28.51	50.84	259.1	1026.1	196.1	169.4
1110	28.68	50.99	273.5	1052.5	207.3	178.5
1140	28.83	51.01	287.9	1078.8	218.5	187.5
1170	29.11	51.26	302.4	1105.0	229.8	196.7
1200	29.00	51.36	317.0	1131.2	241.2	205.8
1230	29.12	51.21	331.6	1157.5	252.5	214.9
1260	29.34	50.93	346.2	1183.7	263.9	224.1
1290	29.42	50.44	360.9	1209.8	275.3	233.4
1320	29.54	50.21	375.7	1235.9	286.7	242.8
1350	29.73	50.29	390.5	1262.0	298.1	252.3
1380	29.67	50.32	405.4	1288.0	309.5	261.8
1410	30.02	50.60	420.3	1314.1	321.0	271.3
1440	30.33	50.59	435.4	1340.0	332.7	280.9
1470	30.47	46.05	450.6	1365.9	344.0	291.0
1500	30.82	42.62	465.8	1391.7	354.7	301.9
1530	31.16	38.9	481.1	1417.4	364.8	313.6
1560	31.46	36.33	496.3	1443.0	374.3	326.0
1590	31.06	32.26	511.4	1468.7	383.1	338.8
1620	30.60	27.79	526.0	1494.4	390.7	352.1
1650	31.18	23.80	540.3	1520.2	397.4	366.0
1680	31.39	18.88	554.3	1545.8	403.1	380.5
1710	31.10	13.38	567.7	1571.5	407.4	395.4
1740	31.32	10.85	580.7	1597.1	410.7	410.6
1770	31.71	10.63	593.8	1622.7	413.6	426.0
1800	31.08	10.68	606.9	1648.3	416.5	441.4
1830	31.18	10.62	620.0	1674.0	419.4	456.6
1860	29.88	10.71	632.9	1699.8	422.2	471.6
1890	30.19	10.78	645.9	1725.8	425.0	486.3
1920	30.38	10.78	659.0	1751.7	427.8	501.2
1950	30.59	11.54	672.3	1777.5	430.7	516.1
1980	31.09	11.21	685.8	1803.3	433.8	531.2
2010	31.66	11.21	699.6	1828.9	436.8	546.5
2040	30.15	12.45	713.4	1854.7	440.0	561.6

Measured depth (m)	Slope (°)	Direction (°)	Horizontal lateralization (m)	True vertical depth (m)	East (m)	North (m)
2070	30.58	12.79	727.1	1880.5	443.3	576.4
2100	30.70	13.35	741.1	1906.4	446.7	591.3
2130	29.95	13.73	755.0	1932.3	450.3	606.0
2160	30.88	13.59	769.0	1958.1	453.9	620.8
2190	31.17	13.57	783.3	1983.8	457.5	635.8
2220	31.29	13.70	797.7	2009.5	461.2	650.9
2250	31.75	13.68	812.3	2035.1	464.9	666.2
2280	31.77	14.07	827.1	2060.6	468.7	681.5
2310	31.73	14.45	841.9	2086.1	472.6	696.8
2340	32.20	14.60	856.9	2111.5	476.5	712.2
2370	32.39	14.41	872.0	2136.9	480.6	727.7
2400	32.48	14.48	887.3	2162.2	484.6	743.3
2430	32.34	14.73	902.5	2187.5	488.6	758.8
2460	32.77	14.92	917.9	2212.8	492.8	774.4
2490	32.60	17.99	933.5	2238.1	497.3	790.0
2520	32.24	21.05	949.2	2263.4	502.7	805.1
2550	32.16	23.39	964.9	2288.8	508.8	819.9
2580	32.42	23.43	980.8	2314.1	515.1	834.6
2610	31.95	23.52	996.6	2339.5	521.5	849.3
2640	31.56	23.37	1012.2	2365.0	527.8	863.8
2670	31.84	22.55	1027.8	2390.6	533.9	878.3
2700	31.99	22.12	1043.5	2416.0	539.9	893.0
2730	32.08	22.22	1059.2	2441.5	546.0	907.7
2760	32.50	23.67	1075.1	2466.8	552.2	922.4
2790	33.35	22.19	1091.2	2492.0	558.5	937.5
2820	33.48	23.15	1107.6	2517.1	564.9	952.7
2850	34.36	23.52	1124.2	2541.9	571.5	968.1
2880	34.91	24.43	1141.1	2566.6	578.5	983.7
2910	34.99	26.68	1158.3	2591.2	585.9	999.2
2940	35.62	28.25	1175.6	2615.7	593.9	1014.5
2970	35.64	31.41	1193.0	2640.1	602.6	1029.7
3000	35.80	33.52	1210.5	2664.4	612.0	1044.5
3030	36.15	34.46	1228.1	2688.7	621.8	1059.1
3052	35.69	35.36	1241.1	2706.6	629.2	1069.7

APPENDIX E: Clay mineral analysis results of Well HE-37

Sample No.	Depth (m)	d(001) Untreated	d(001) Glycolated	d(001) Heated	d(002)	Mineral
1	320	13.774	13.065	10.162	0	Smectite
2	352	15.182	17.116	10.011	0	Smectite
3	382	14.019/13.341/12.875	16.724/14.644	9.842	0	Smectite
4	420	14.393/13.075	14.194	10.011	7.251	Mixed layer clay
5	460	14.552/12.749	14.447/13.977	9.977	7.186	Mixed layer clay
6	520	14.996	14.968	15.091	7.27	Chlorite
7	570	14.639/12.927	14.442/13.868	10.054	7.248	Mixed layer clay
8	602	14.081	14.232	14.442	7.15	Chlorite
9	642	14.199	14.429	0	7.18	Chlorite
10	690	13.412	13.66	9.931	7.135	Mixed layer clay
11	740	14.457	14.471/13.489	14.677	7.16	Chlorite
12	780	14.612/12.862	14.612/13.661	14.92/10.274	7.201	Mixed layer clay
13	840	14.512	14.544	14.48	7.16	Chlorite
14	980	14.582	17.796	14.731	7.203	Chlorite
15	1100	14.846	14.867	15.218	7.256	Chlorite
16	1160	14.769	14.791	15.038	7.237	Chlorite
17	1300	14.622	14.661	14.889	7.192	Chlorite
18	1603	14.798	14.843	14.964	7.245	Chlorite
19	1700	14.681	14.66	15.015	7.2	Chlorite
20	1750	14.498	14.563	14.595	7.173	Chlorite
21	1790	14.343	14.356	14.598	7.121	Chlorite
22	1830	15.384/14.868	18.04	15.397	7.25	Chlorite
23	1870	14.928	18.097	15.095	7.25	Chlorite
24	1920	14.675/13.103	14.707/13.720	14.995/10.224	7.216	Mixed layer clay
25	1960	14.876	17.421/14.562	14.683	7.17	Chlorite
26	2208	15.295/14.824	17.686/14.816	14.707	7.233	Chlorite

APPENDIX F: World Geothermal Congress paper

Proceedings World Geothermal Congress 2010,
Bali, Indonesia, 25-29 April 2010.

Borehole Geology and Hydrothermal Alteration of Well HE-24, Hellisheidi Geothermal Field, SW-Iceland

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Keywords: Hellisheidi, sub-surface geology, hydrothermal alteration

ABSTRACT

Well HE-24 is located in the Hellisheidi high temperature field, a part of the Hengill central volcano in SW-Iceland. It is a vertical well reaching a total depth of 2587 m. The well was drilled with targeting a 5000 years old NE-SW trending volcanic fissure. The lithology of well HE-24 comprises basaltic hyaloclastite formations and dyke intrusions. Different alteration zones were identified in the well; zone of no alteration, smectite-zeolite, mixed layer clay, chlorite, chlorite-epidote and epidote-actinolite zone. These zones depict a trend from a cold groundwater system down to 244 m through a cap rock and into a high temperature system. Based on mineral sequence deposition and comparison between hydrothermal alteration mineral and formation temperature the geothermal system appears to have cooled, particularly in the upper 700-800 m of the well. Feed points were found in the well and categorized into weak, moderate and large aquifers. Some of these are located in the production part and are mostly associated with intrusions while others are located above the production part, and they are mostly associated with stratification boundaries.

1. INTRODUCTION

The Mid-Atlantic ridge, a constructive plate margin appears above sea-level in Iceland, one of few countries in the world attaining an increase in its surface area due to the creation of new lithosphere by sea floor spreading. The newly created lithosphere occurring at the plate boundaries is characterized by high heat flow due to volcanic activity and extensional tectonics. This active zone of volcanism and tectonism across Iceland strikes roughly NE-SW. The rock sequence within this active rift zone consists of interglacial lavas and sub-glacial hyaloclastites with an age of less than 0.7 million years (Björnsson et.al., 1986). The active geothermal areas in Iceland are distinguished as low-temperature areas and high temperature areas. The low-temperature areas are located outside the volcanic rift zone and have reservoir temperatures lower than 150°C at 1 km depth. High temperature fields, on the other hand, are confined to the active rift zone and characterized by reservoir temperatures of more than 200°C at a depth of 1 km (Bödvarsson and Pálmason, 1961). One of the largest high temperature geothermal areas in Iceland is found within the Hengill central volcano about 30 km east of Reykjavik, the capital city of Iceland. Hellisheidi field where well HE 24 is located is a part of the Hengill geothermal area.
The data on the geology and alteration of the well were collected from cutting analysis using binocular microscope, thin section petrography, X-ray diffraction analysis, fluid inclusion geothermometry, and geophysical logs.

2. GEOLOGICAL OUTLINE

2.1. Regional Geology

Iceland is located where the astenospheric flow under the NE Atlantic plate boundary interacts and mixes with a deep seated mantle plume. The buoyancy of the Iceland plume leads to a dynamic uplift of the Iceland plateau, and high volcanic productivity over the plume produces a relatively thick crust. Because the lithosphere tends to break up above the mantle plume and the plume has been moving east relative to the plate boundary the main volcanic belts in Iceland are displaced eastward relative to the crest zone of the Mid Atlantic Ridge.

Vertical sections of the volcanic sequence in Iceland expose up to 1500 m thick pile of volcanic rocks below which lies at least another 2 – 5 km thick sequence of extrusives. The exposed volcanic pile is built predominantly of basalts (80-85%), while acidic rocks, including intermediate rocks constitute about 10%. The amount of sediments of volcanic origin is in the order of 5-10% in a typical Tertiary lava pile but much higher in Quaternary rocks (Saemundsson, 1979).

2.2. Hengill Volcanic System

The Hellisheidi high temperature field is part of the Hengill volcanic system. This volcanic system includes about 60-100 km long NNE-trending fissure swarm with normal faults, fissures, frequent magma intrusions and a central volcano (Figure 1). Exploration started in the Hengill system in 1985 with a well drilled at Kolvidarholl and followed by a well at Olkelduhals in 1995 (Franzson et al., 2005).

The rock sequence of the Hengill central volcano predominantly consists of hyaloclastites and lava series. Hyaloclastites formed in subglacial eruptions are formations of relatively limited horizontal extent which makes them of limited use as marker horizons. Lava series are seen to bank up against the volcano in the western part, as lavas are a feature of lowland accumulation. Unusually large faults delineate the western margin of the fissure swarm and indicate the termination of volcanic activity west of Hengill area.

This may furthermore have the implication that the high temperature reservoir deepens sharply west of the faults (Franzson et al., 2005).

Fault and major fractures strike mostly NNE-SSW and are conspicuous in the east and west marking the boundaries of the fault and fissure zone of the volcano. Post glacial volcanism includes three fissure eruptions of 9000, 5000 and 2000 years. The fissures can be traced further to the north, through Nesjavellir field and into Lake Thingvallavatn (Saemundsson, 1995).

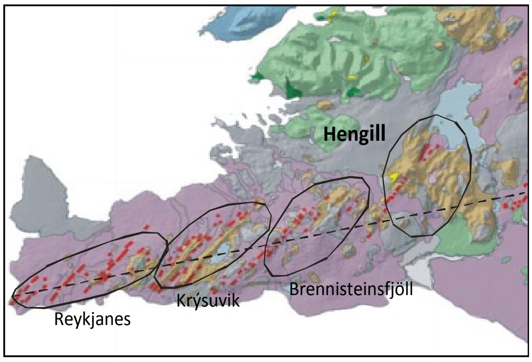

Figure 1. Simplified geological map of SW-Iceland showing volcanic zone, fissure systems and location of Hengill volcanic system.

2.2. Geophysics

Aeromagnetic, gravity and DC-resistivity surveys were carried out between 1975 and 1986. These delineated a 110 km^2 low resistivity area at 200 m b.s.l. and furthermore showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds (Björnsson et al., 1986). The resistivity map was revised between 1986 and 2000, by applying the central loop transient electromagnetic sounding method (TEM). These data imply that despite being widespread, the resistivity anomaly is complex and affected by processes such as faulting, shearing and spreading (Árnason and Magnússon, 2001).

3. BOREHOLE GEOLOGY

Skardsmýrarfjall mountain is part of the Hellisheidi geothermal field. Geologically Skardsmýrarfjall consists of hyaloclastites and post glacial lava. The mountain is succeeded by 5000 years volcanic fissures trending NNE and SSW. The well HE-24 is sited beside the volcanic fissure and meant to cut through the feeder of that eruption (Figure 2). The well is vertical and is aimed at exploring the deeper part of the reservoir. The well reached 2500m depth. The cutting samples on which the geological data are based on are taken at 2m interval during drilling and studied with binocular, petrographic and fluid inclusion microscopes. The cutting analysis was aided by geophysical lithological logs.

3.1. Stratigraphy

The stratigraphy of well HE-24 is shown in Appendix 1. It is divided into a number of rock types mainly depending on the crystallinity of the rock. Basaltic tuff composed of volcanic glass, basaltic breccia which is a mixture of partially crystallized basalt and volcanic glass, glassy basalt, which often is interpreted as pillow basalt, is mostly made up of partially crystallized rock with minor amounts of volcanic glass, and finally crystallized (fine to coarse grained) basalt, which forms either sub-aerial lavas or intrusions. The volcanic products are in most cases very porous, while intrusions are dense. Porphyritic or aphyric character of the rock is very useful in separating one volcanic formation from another.

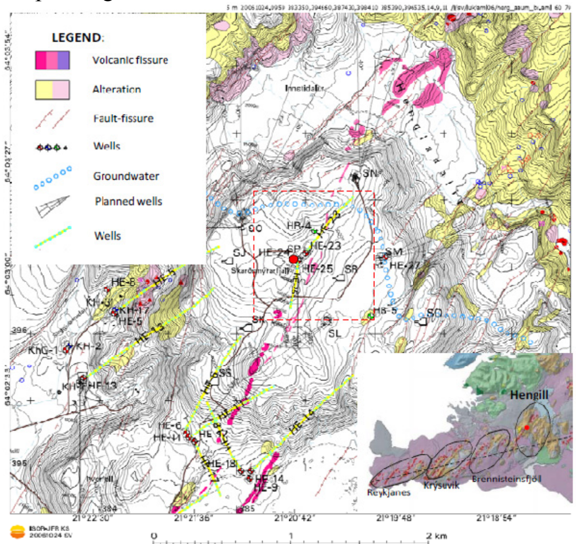

Figure 2: Volcanic activity, alteration, fissure system and location of well HE-24 and surrounding wells at Skardsmýrarfjall

The description of the rock formation of well HE-24 is mostly based on the binocular microscope and aided by petrographic thin section analysis. The stratigraphy of the well consists predominantly of alternating sequence of sub-glacial hyaloclastites and basaltic intrusive rocks. Intrusive rocks are mostly characterized by relatively low alteration compared to the surrounding rock, compact nature, and sometimes marked by oxidation at their margin. Intrusions usually show relatively high peaks value in neutron-neutron and resistivity logs (Franzson et al., 2005).

4. HYDROTHERMAL ALTERATION

4.1. Primary Rock Minerals

The primary minerals in the rocks penetrated by well HE-24 are characterized by the abundance of glass, olivine, plagioclase, pyroxene and opaques (Table 1). The replacement of the mineral can best be studied by petrographic thin section analysis. The primary minerals first start to alter intensively in this well below 478 m depth.

4.2. Distribution of Hydrothermal Minerals

The most common hydrothermal alteration minerals in well HE-24 are quartz, calcite, and pyrite, low temperature minerals such as the zeolite group, smectite and chlorite. Calcite is of special importance as it is deposited closest to the present time in the geothermal system. Temperature of calcite deposition is relatively difficult to determine, experience has shown that this mineral disappears at temperatures above 290°C (Franzson, 2000, Krismannsdóttir, 1979).

Table 1: Primary rock minerals and their product as found in well HE-24

Relative susceptibility	Primary rock minerals	Alteration mineral products
Most susceptible	Glass	clay, calcite, quartz
	Olivine	clay, calcite, sphene
↓	Plagioclase	clay, albite, calcite, quartz, wairakite, epidote
Least susceptible	Pyroxene	clay, actinolite, sphene
	Opaque	sphene, sulfides (pyrite)

4.3. Vein and Vesicles Fillings

The rocks encountered in the well are generally porous with a number of veins. Porosity can be classified into several types such as intergranular, joint and vesicular or vug type. Vesicular is common in Iceland where basaltic rocks predominate (Browne, 1984). These open voids become gradually filled with increasing alteration where limonite, siderite, and low temperature zeolite are found in the upper part and mostly clay, calcite, quartz, wairakite and epidote filling the vesicles in higher alteration. Hydrothermal alteration mineral deposition is mostly found in vesicles and veins. Voids are abundant in the hyaloclastites.

4.4. Alteration Mineral Zonation

In the geothermal areas, the study of altered basaltic rocks shows that the sequence of mineral assemblages relates to increased temperature and depth. The most common alteration minerals are the clay minerals. Other hydrothermal minerals present are silica, feldspar, calc-silicates, zeolites, carbonates, iron oxide, iron sulfides, sulfate, and sulfides (Browne, 1978). Below the hydrothermal alteration has been divided into temperature dependant zones as practiced in Iceland.

Unaltered zone (0-244 m)
The formations down to 244 m depth contain no alteration that is related to hydrothermal. XRD analysis show hardly any indication of smectite and the only mineral precipitations are limonite and siderite, both of which relate more cold groundwater conditions. The Skardsmýrarfjall formation belongs to this zone.

Smectite-zeolite zone (244-616 m)
The upper boundary of this zone coincides with the first occurrence of zeolites (including thomsonite, chabazite, scolesite) at about 244 m depth. XRD signature of smectite is still weak and remains so until below 446 m where it becomes stronger. Experience and data have confirmed that smectite starts to form below 200°C (Kristmannsdóttir, 1979).

Mixed layer clay zone (616-672 m)
The upper boundary is set by the first analysis of mixed layered clay at 620 m depth and the lower boundary is determined by the first appearance of chlorite at 672 m. The temperature assessment of this zone is 200-230°C (Browne, 1978, Kristmannsdóttir, 1979). Petrographic evidence shows the mixed layered clays as high coloured and very pleochroic clays.

Chlorite zone (672-1074 m)
The upper boundary of this zone is marked by the first appearance of chlorite in the XRD analysis at 672 m and the lower boundary is marked by the first appearance of epidote at 1074 m depth. Chlorite is identified petrographically as low-colour and non-pleochroic radial clays. With XRD-analysis chlorite is identified with peaks appearing at 14 and 7 Å, although the chlorite is considered unstable as the 7 Å peak collapses on heating. Chlorite has been estimated as forming at a minimum temperature of 230°C (Browne, 1978; Franzson, 1987).

Chlorite-epidote zone (1074-1172 m)
The upper boundary of this zone is characterized by the appearance of epidote. Other minerals in the zone include quartz, wollastonite and sometimes prehnite. The upper boundary of the zone is believed to conform to 240-250°C (Kristmannsdóttir, 1979).

Epidote-actinolite zone (>1172m)
The upper boundary of this zone is marked by the first appearance of actinolite. Actinolite was first identified from petrographic thin section at 1172 m depth and binocular microscope at 1176 m. This mineral is mainly found as an alteration of pyroxene. Actinolite appears to form at a minimum of about 280°C (Kristmanndóttir, 1979).

4.5. Mineral Deposition Sequence

The mineral sequences deposited from the geothermal system in to vesicles and veins were studied petrographically. The depositional minerals were found mostly in vesicles and veins. The alteration mineral assemblages change from low temperature minerals such as zeolites to moderate-high temperature minerals with increasing depth, such as quartz, wairakite, prehnite, wollastonite and actinolite.
Clay and calcite are the most common minerals participating in the mineral sequence in this well. The fine grained clay is mostly found as thin lining in the wall of the vesicles and veins, associated or deposited after chalcedony, which is also found near the boundary of veins and vesicles. Coarse grained clay is found especially filling in the veins or vesicles.

4.6. Fluid Inclusions

In well HE-24 quartz and calcite crystals were collected, but only calcite crystals were found to contain measurable fluid inclusions. A fluid inclusion study was conducted to assess temperature variation in the geothermal system. The fluid inclusion study in well HE-24 was done with samples collected at a depth around 660 and 2400 m. The homogenization temperature (Th) was identified from 101 primary and secondary inclusions. The range of homogenization temperatures vary from 195°C to 285°C at 660m depth (Figure 3) indicating changes in geothermal conditions from its formation. The wide range of temperatures probably reflect that at this depth is a very high thermal gradient of the cap rock. A few Th measurements were done in fluid inclusions in calcite at 2100 and 2400m depth about 250°C, which is considerably lower than estimated from the presence of actinolite (>280°C) at this depth range. The temperature however conforms with the present formation temperature in the well. Calcite in many cases has been seen to be a mineral depositing at a later stage in the geothermal system at Hellisheidi. Further study is underway to study these temperature variations in more detail.

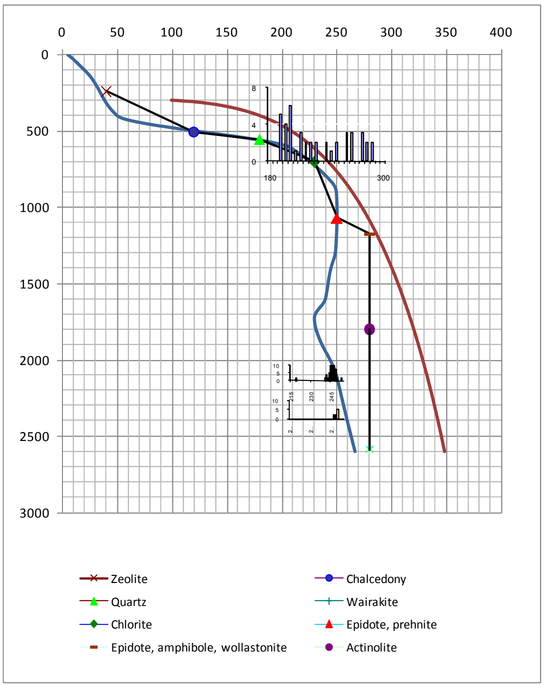

Figure 3: Formation temperature, Alteration temperature and fluid inclusion in calcite and quartz in well HE-24.

5. AQUIFERS

In this well, aquifers (feed points) were identified using various methods such as circulation loss data, temperature logs, intensity of alteration and other geological data. These feed points are divided into three relative sizes of aquifers as large, moderate and small aquifers which are located above and in the production part. In this well, the aquifers are mainly located at stratigraphic boundaries above the production part, while they appear mainly to be related to intrusions in the production part.

6. DISCUSSION

Generally, stratigraphy of well HE-24 consists of hyaloclastites and basaltic intrusions. The volcanic sequence is divided into different units based on the textural differences. The distinction of the volcanic sequences in the well is predominantly based on whether they are porphyritic or aphyric. Hyaloclastite units (sub-glacial eruptions) and subaerial basalts and intrusions were identified in the well.

The geological and hydrothermal alteration study shows that the degree and the intensity of rock alteration and the distribution of mineral alteration increase with depth. Below about 478 m depth, the degree of alteration increases rapidly both on grounds of temperature dependent minerals and alteration intensity.

Temperature has been defined in two ways in the well. Hydrothermal alteration mineral temperature, which was assessed according to the first appearance of the hydrothermal alteration minerals. The second one is the formation temperature which was determined by calculations based on the temperature measurements during the heating-up period. The alteration temperature curve of the well shows a progressive temperature increase with depth. The alteration mineral assemblage shows a trend, where low temperature minerals like zeolites forms in the upper part of the well and are gradually replaced by the moderate temperature minerals like chalcedony, quartz and wairakite which in turn give way to a higher-temperature mineral assemblages like chlorite, prehnite, epidote, wollastonite, actinolite and garnet in the lower part of the of well. The correlation of hydrothermal alteration, formation, and boiling point temperature curves is shown in Figure 4.

The mineral deposition sequence shows that low temperature zeolites form at an early stage of depositional sequence and in the later stage moderate temperature minerals such as quartz and wairakite are deposited in veins and vesicles. In the lower part of the well high temperature minerals such as wollastonite and actinolite precipitate. The clay minerals on the other hand are sensitive to changes in temperature and are found to become more crystalline with depth. In petrographic thin sections the clay minerals deposited in vesicles are observed to be either fine grained clay which usually is found as a thin layer lining the voids and vesicles and coarse grained clay usually as a chlorite and mixed layer clay, similarly deposited in the veins and vesicles. In this well, calcite is predominantly deposited in the last stage of the mineral sequences in the well. Data from the Hellisheidi geothermal field indicate that the last deposition of calcite might be associated with cooling in the later stages of the geothermal system (Franzson, 2000).

The aquifers in the production part down to 1200 m mostly relate to a basaltic intrusion. Feed points below 758 m are believed to be associated with a vertical dyke, possibly the feeder to the 5000 years old eruption. The rock, where the feed points appear, is heavily oxidized and is interpreted as a contact aureole adjacent to the dyke. Below this, the aquifer is located within the relatively fresh intrusive bodies.

7. CONCLUSIONS

The following conclusions can be deduced:

Stratigraphy of the first 1200 m of well HE-24 consists of sub-glacial hyaloclastite formations and basaltic intrusion.

According to the distribution of alteration minerals, one un-altered zone and five alteration zones were identified. Un-altered zone, smectite-zeolite zone (<200°C), mixed layer zone clay (200-230°C), chlorite zone (230-250°C), chlorite-epidote zone (>250°C) and epidote-actinolite zone (>280°C).

According to circulation loss data, temperature logs, and intensity of alteration three relative sizes of aquifers are distinguished located above and in the production part.

By studying the hydrothermal alteration minerals, it was found that the temperature rises rapidly at about 472-672 m depth with the appearance of zeolites, quarts, wairakite and mixed layered clays, while the temperature gradient is lower in the fairly thick chlorite zone at 672-1072 m depth. Below 1072 m depth the alteration increases again with the deposition of epidote, wollastonite, actinolite and garnet.

Comparison of alteration mineral temperature and measured temperature shows that the geothermal system has cooled in the upper 700 to 800 m of the well, while cooling appears to be minor 750- 1200 m depth. In the lowermost parts of the wells, especially below 1600 m the reservoir appears to be cooling again.

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