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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL THG-17 AT THEISTAREYKIR GEOTHERMAL FIELD, NE–ICELAND

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ABSTRACT

Well ThG-17 is in the Theistareykir geothermal field under the slopes of Mt. Baejarfjall. The geothermal system is caused by an active central volcano. The well was directionally drilled to a depth of 2500 m. This report will focus on data from geological logging down to 2300 m depth. Binocular microscopic, thin-section petrography and X-ray diffraction analyses of samples were the major analytical methods used to analyse rock cuttings collected from a depth of 18 m down to 2300 m to determine the lithology, mineral alteration and the incidence of intrusive rocks in well ThG-17. Well ThG-17 is characterised by different hyaloclastite formations. Glassy basalt is dominant, but also tuff, reworked tuff and basaltic breccia, fine- to medium-grained and medium- to coarse-grained basalts were identified. The hydrothermal alteration minerals in well ThG-17, which were found with increasing depth, provide information on the paleotemperature of the geothermal reservoir as indicated by the presence of alteration minerals that represent low temperature ranging from 50°C to 200°C (e.g. smectite, scolecite, mesolite), intermediate temperature ranging from 200°C to 250°C (e.g. quartz, chlorite) and high temperature ranging from 250°C and higher (e.g. prehnite, epidote, wollastonite, actinolite and garnet). Six alteration mineral zones defined by the first appearance of alteration minerals were established: unaltered (0-24 m), zeolite-smectite (24-172 m), mixed layer clay (172-300 m), chlorite (300-600 m), chlorite-epidote (600-1200 m) and epidote-actinolite (1200-2300 m). All feed zones in well ThG-17 are of small to moderate size and the most permeable feed zones are located at 2030 m and 2300 m. An analysis of the temperature logs illustrates that the geothermal system follows the boiling point curve in the upper 300 m. However, a temperature reversal occurs around 400 m. This decline in measured temperature reflects a cooling of the geothermal system possibly due to an influx of cold water through highly permeable zones. Notwithstanding, the temperature recovers and continues to follow the boiling point curve until another temperature reversal occurs below 2000 m. This decline in measured temperature exhibits a cooling of the geothermal system in the lower section which again could possibly be due to an influx of cold water through highly permeable zones and/or fractures intersecting the lower section of the well.

1. INTRODUCTION

The Theistareykir area is a high-temperature geothermal field in NE Iceland and is estimated to cover an area of 11 km² (Gíslason et al., 1984). Exploration was carried out in this area during 1972 to 1974 and major geothermal assessment was made from 1981 to 1984. Theistareykir has been known for its sulphur deposit that provided the Danish king with raw material for gun power centuries ago (Ármannsson et al., 1986). In 2002 the first deep exploration well was drilled followed by five more exploration wells in 2008 which included three directionally drilled wells (Gautason et al., 2010). From 2016 to 2017 the geothermal field was further developed by Landsvirkjun (National Power Company), and eight production well were drilled. Currently, a 90 MWe geothermal power plant that was completed in 2018 is operating in Theistareykir.

Well ThG-17 was drilled directionally with a target azimuth of 210° and 35° inclination. The well was drilled from drill pad A, located under the slopes of Mt. Baejarfjall. The drilling of the well ThG-17 began on 15th May 2017 and by July 29th, 2017 drilling was completed to a depth of 2500 m. This study focuses on borehole geology to establish the stratigraphy, the location of hydrothermal alteration minerals, intrusions and lithological boundaries, locate feed zones with the aim to assess the permeability and geothermal system history of well ThG-17.

The data presented in this work is obtained from drill cuttings analysis, interpretation of well logs and review of previous surface exploration studies. The analytical methods employed include binocular microscope, thin section petrography and X-ray diffraction (XRD) techniques.

1.1 Geology of Iceland

Iceland is geographically located in the northern part of the Mid-Atlantic Ridge, the rift zone along the constructive boundary between the American and the Eurasian tectonic plates which move apart at an average rate of 2 cm per year. With an area of 103,106 km^2, Iceland is one of the largest islands in the Atlantic Ocean residing on a mantle plume and a hot spot in the rift zone and was formed by frequent volcanic eruptions from Miocene time to present. Presently the active rifting and volcanism zone crosses Iceland from southwest to northeast with volcanic eruptions occurring every few years. Most of the eruptions are gushes of basaltic lava from fissures or shield volcanoes. Each fissure represents a small amount of crustal extension of about one metre on average. Iceland is considered a young country on the geological time scale. About 10% of the country is covered with glaciers, some of which are underlain by active volcanoes (Figure 1). Due to crustal spreading the older rocks are being found in the east and west of the island while the youngest rocks are found in the centre (Thórdarson and Höskuldsson, 2008).

Currently, the plume stem reaches the lithosphere under Vatnajökull glacier about 200 km southeast of the plate boundary defined by the Reykjanes and Kolbeinsey ridges. Rifting along this Mid-Atlantic ridge causes magma to accumulate from the spreading centre, eventually accumulating enough to expose subaerial volcanic rocks. The Iceland mantel plume, or hotspot, formed after this spreading centre, shaped the landscape in this subsection of the Mid Atlantic Ridge. These complex interactions between the divergent boundary and hotspot create an interesting mixture of mafic and intermediate rocks. Therefore, because of its unique location, Iceland is one of the most active and productive subaerial regions on earth, with an eruption frequency of more than 20 events per century and a magma output rate of about eight km^3 per century in historic times, i.e., over the last 1100 years (Thórdarson and Höskuldsson, 2008). The surface geology is entirely composed of igneous rocks of which about 80 to 85% are basaltic in composition while acidic and intermediate rocks compose about 10%. The amount of sediments of volcanic origin is 5 to 10% in a typical Tertiary lava pile but may be locally higher in Quaternary rocks (Saemundsson, 1979).

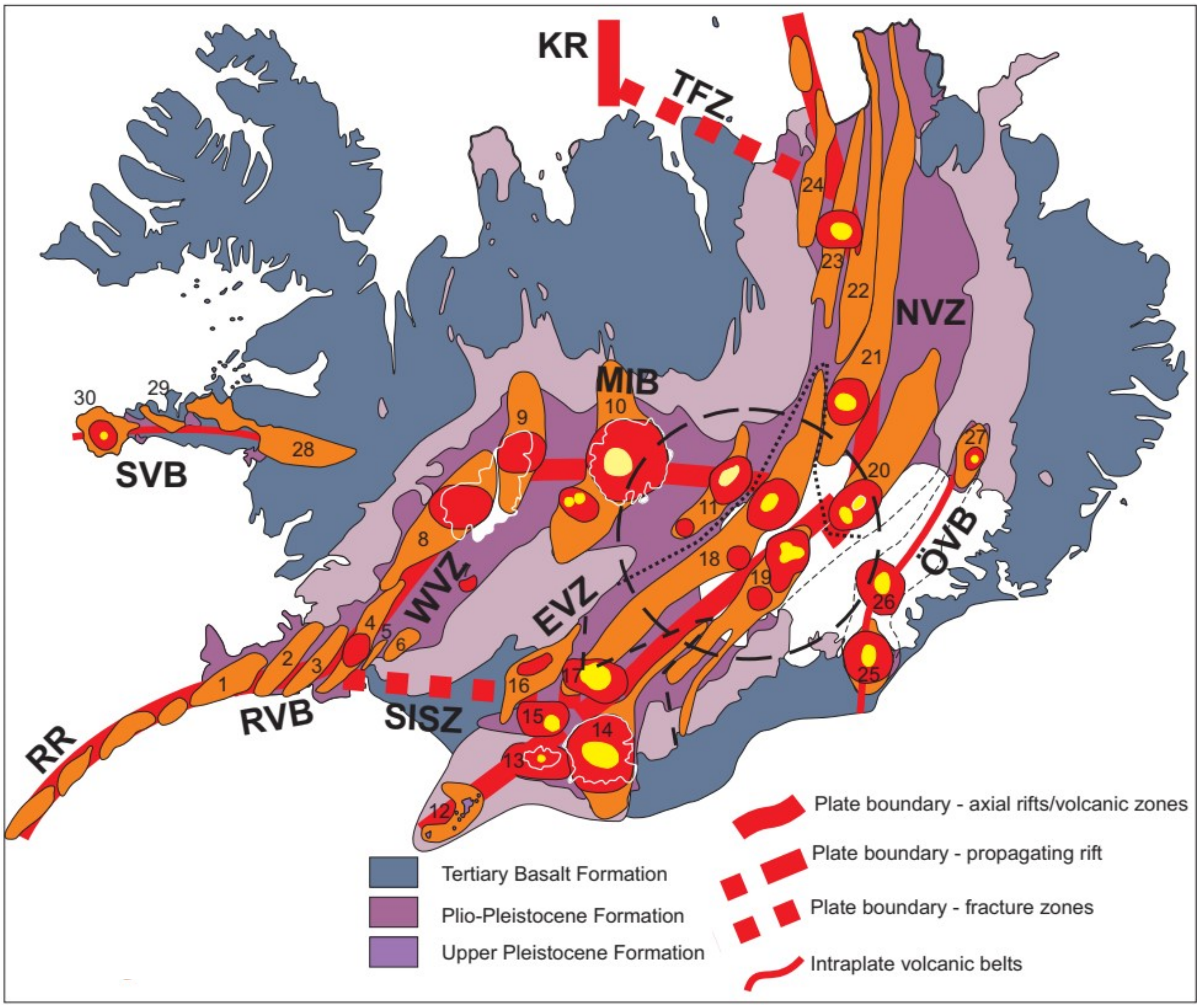


FIGURE 1: The main outline of the geology in Iceland; numbers refer to different volcanic systems (Thórdarson and Höskuldsson, 2008)

1.2 Geothermal fields

Iceland is rich in geothermal resources as it is situated in an active zone of rifting and volcanism. Many volcanoes are located within the active volcanic zone stretching through the country from the southwest to the northeast and at least 30 of them have erupted. In the volcanic zone there are at least 20 high-temperature areas containing steam fields with underground temperatures reaching 200°C within 1,000 m depth. High-temperature areas are confined to the active volcanic zones (Figure 2). They are mostly located on high ground and are geologically very young with permeable rocks. As a result of the topography and high bedrock permeability, the groundwater table in the high-temperature areas are generally deep and most surface manifestations are steam vents. The system's heat source is typically a shallow magma intrusion (Björnsson et al., 2010).

About 250 separate low-temperature areas with temperatures not exceeding 150°C in the uppermost 1,000 m, are found mostly in the areas flanking the active zone. The largest of these systems are in southwest Iceland in the flanks of the western volcanic zone but smaller systems can be found throughout the country. Normally on the surface, low-temperature activity is manifested in hot or boiling springs. Over 600 hot springs (temperature over 20°C) have been located (Figure 2) (Björnsson et al., 2010).

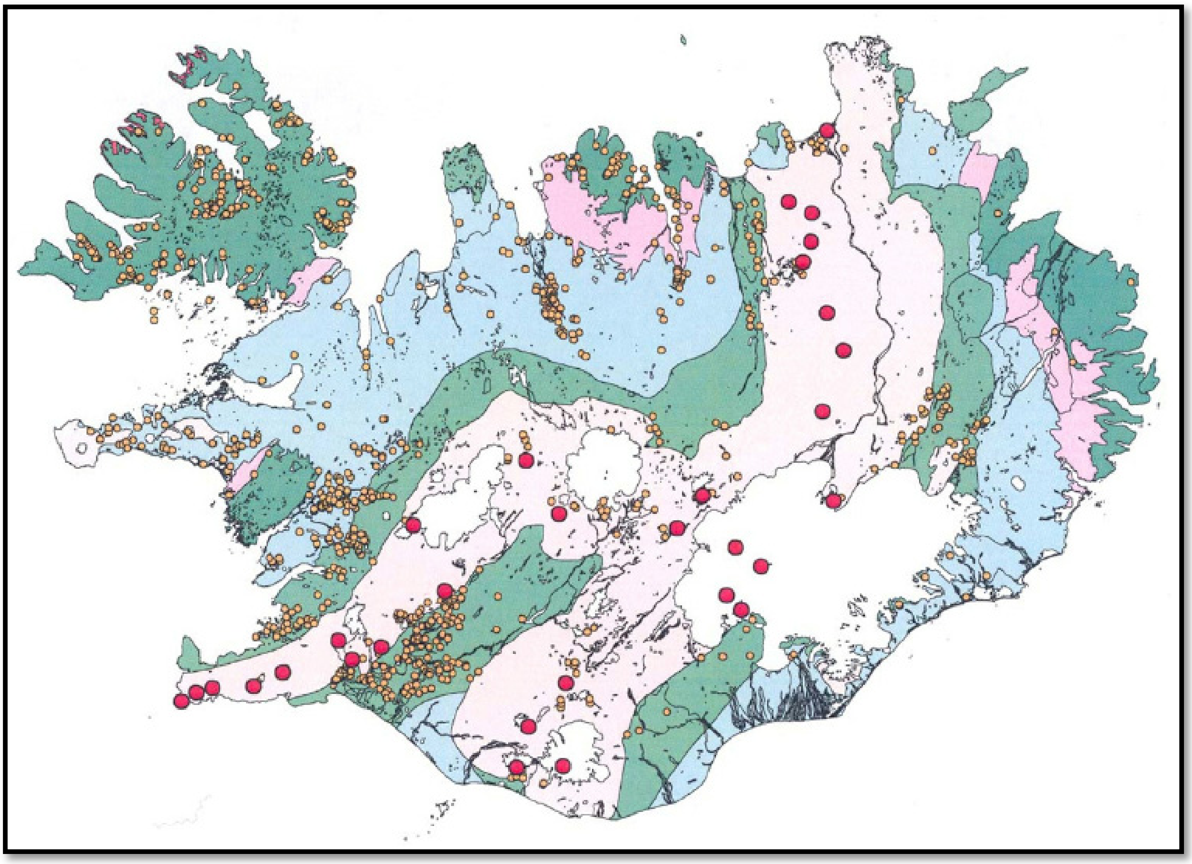


FIGURE 2: Geothermal map of Iceland. High-temperature fields inside the active volcanic zone are shown as large red circles and hot and warm springs as small circles (Steingrímsson et al., 2005)

1.3 Geological and tectonic setting of the Theistareykir area

Exploration drilling for electrical power production in the Theistareykir geothermal area was first carried out in 2002. The area is thought to be one of three largest geothermal areas in northeastern Iceland. The surface manifestations cover an area of 11 km^2 and TEM resistivity measurements in the bedrock conducted in 2006 indicate a size of 45 km^2 (Karlsdóttir et al., 2012).

The geothermal system is the result of an active central volcano. The fissure swarm (NNE- SSW) reaches from lake Mývatn in the south to the sea in Kelduhverfi in the north as shown in Figure 3a. The fissure swarm is up to 5 km wide and 50 to 60 km long. The most recent volcanic activity is the formation of the Theistareykjahraun lava (Saemundsson et al., 2002).

The Theistareykir geothermal field lies in the centre of one of the five volcanic systems that form Iceland's North Volcanic Zone (NVZ). It consists of an east to west trending heat source astride a north to south tectonic structure. The associated fissure swarm is about 7-8 km wide and extends 70-80 km from Lake Mývatn in the south to Öxarfjördur in the north. The area exhibits most of the features of a central volcano except the topographical ones. Volcanic productivity has been greatest near the centre of the system where siliceous rocks are found but a true caldera structure has not developed. The surface is mostly covered in lava flows, of which all but one date from shortly before and after the end of the latest glaciation period. All are shield lavas but of various size and composition. Older formations are generally hyaloclastites and pillow lavas. The most recent volcanic activity in the area occurred about 2,200 years ago and the high-temperature geothermal activity is connected to recent magma intrusions (Figure 3b) (Saemundsson, 2007).

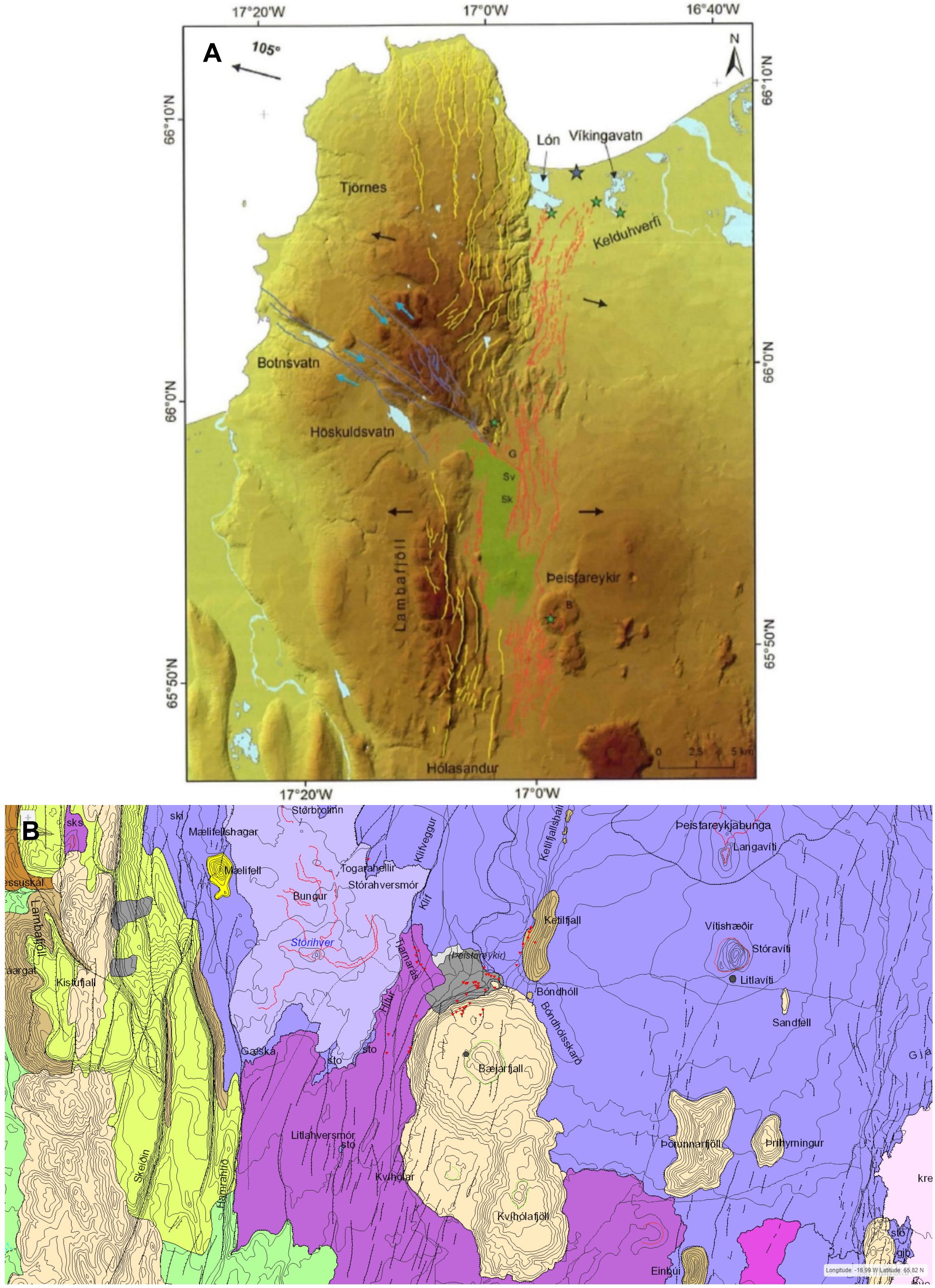


FIGURE 3: a) Structural map of Theistareykir volcanic system showing normal faults near Tjörnes and Lambafjöll, a fissure swarm from Hólasandur to Lón and strike–slip faults within the Húsavík-Flatey fault system. Black arrow denotes the localized spreading direction and two pairs of arrows near Botnsvatn indicate fault movement in the Húsavík-Flatey fault system (Magnúsdóttir and Brandsdóttir, 2011); b) Geological map of Theistareykir. Hyaloclastics are in the centre, Borgarhraun is located to the south west, Theistareykjahraun to the north west, Stóravítishraun light blue and Skildingahraun to the northeast (Saemundsson, 2007)

2. BOREHOLE GEOLOGY

2.1 Drilling of well ThG 17

Well ThG-17 was drilled directionally with a target azimuth of 210° and 35° inclination, with the aim of intersecting the permeability and heat anomaly related to the fracture system extending under Mt. Baejarfjall (Khodayar et al., 2015; Mortensen, 2012). The Icelandic Drilling Company undertook the drilling of the well for Landsvirkjun using the drill rig Ódinn. Geothermal consultancy services, analysis of drill cuttings and geophysical logging were conducted by ISOR – Iceland GeoSurvey.

The well was drilled from drill pad A located under the slopes of Mt. Baejarfjall. The geographical coordinates of well ThG-17 are 592893 east and 598954 north and the drill pad is located at an elevation of 349 m above sea level. The coordinates are in the ISNET93 system. Figure 4 shows the planned path for ThG-17 and the location of production wells and pads in the Theistareykir area.

The production wells ThG-1, ThG-4, ThG-5b (and ThG-5) and ThG-13 are located on the same drill pad. Well ThG-10 is also located on pad A and was abandoned at 193 m depth because of an unmanageable overpressure. Well ThG-17 was drilled in five consecutive phases as shown in Table 1.

TABLE 1: Drilling information of Well ThG-17

	Date	Drill bit (")	Depth (m)	Casing pipe (")
Phase 0 (a) - Pre-drilling	May 17th, 2017	26	60	22 ½
Phase 0 (b) - Surface casing	May 23rd, 2017	21	160	18 ⅝
Phase 1 - Anchor casing	June 2nd, 2017	17 ½	300	13 ⅜
Phase 2 - Production casing	June 7th, 2017	12	950	9 ⅝
Phase 3 - Perforated liner	June 17th, 2017	8 ½	2000-2500	7

2.2 Analytical methods

For the purpose of this report, binocular microscope analyses of drill cuttings, thin section petrography and X-ray diffraction analysis (XRD) of samples were undertaken at the ISOR main office in Reykjavik. Rock cutting from 0 m to 2300 m depth were analysed by using binocular microscope to determine the lithology, mineral alterations and identification of intrusive rocks of well ThG-17. Petrographic analysis was limited to 20 thin sections. The purpose of the thin section study was to confirm rock type(s), texture, and alteration minerals not observed by binocular microscope, but also the identification of depositional sequence of secondary minerals. XRD analysis for clay minerals identification in rock samples were carried out on 14 samples collected from different depths. Geophysical logs interpretation helped to identify the alteration of primary minerals.

2.3 Stratigraphy of well ThG-17

This study shows that the lithology in well ThG-17 consists of three phases. The first phase was composed of different hyaloclastite formations where glassy basalt was dominant, but tuff, reworked tuff and basaltic breccia were also identified. Phase 2 of the well mostly composed of large breccia units and medium- to coarse-grained basalts. This formation is completely altered. The brecciated formations seem layered and the amount of tuff is very variable. Phase 3 of ThG-17 is mostly composed of a large breccia unit down to 1400 m, fine- to medium-grained basalts down to 2000 m and large silicic intrusions from 2000 to about 2300 m. The brecciated formations appear to be layered and the amount of tuff is highly variable. This could indicate pillow breccias. Coarse-grained clays, quartz, wollastonite, epidote and prehnite are common alteration minerals and garnet and amphiboles were seen at intervals. Pyrite

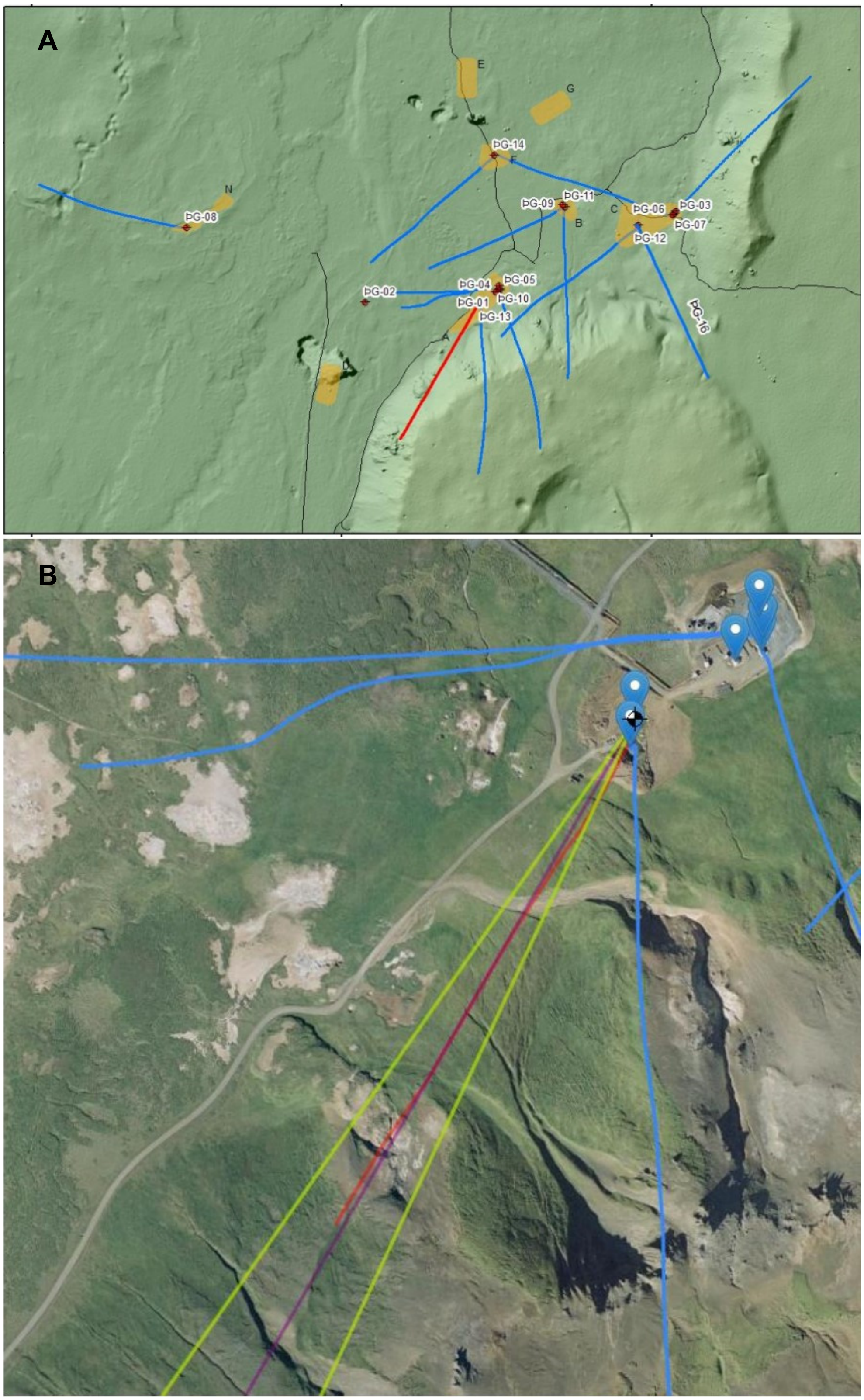


FIGURE 4: a) The planned path of ThG-17 indicated by the arrow on well pad A; well paths for nearby wells are also shown (Gudmundsson et al., 2017a, b, c); b) The well path of ThG-17 (the middle line, red) based on gyro surveys. The middle line shows the designed path and the other lines (yellow) on both sides (Gudmundsson et al., 2017 a, b, c) show the allowed deviations

was rare and vein fillings decreased down the well. Calcite was rare or absent with a few exceptions. The results are summarized in Figure 5.

0–18 m: No cuttings.

18–66 m: Basaltic breccia. Very mixed cuttings composed of fragments of tuff and crystalline basalt. Some fragments moderately altered. Pyrite is abundant.

66–116 m: Glassy basalt. This unit has glass grains both fresh and clay altered. Large number of zeolites, in pores or fractures and as individual crystals. At 58, 76 and 86 m the rock is yellowish in colour. The rock is partly cryptocrystalline, sometimes with small plagioclase needles in groundmass.

166–220 m: Basaltic tuff. This unit consist of tuff that with depth becomes more homogenous and lighter in colour, almost white. In addition, it becomes somewhat coarser. Probably a primary tuff rather than reworked tuff. Precipitations are abundant, mostly calcite, quartz and zeolites. At about 200 m, zeolites seem to disappear and the amount of calcite decreases.

220-300 m: Basaltic breccia. Mixed cuttings comprised of fragments from light coloured tuff and some minor amount of lithics. Precipitations are abundant. The breccia is considerably fractured at intervals. Quartz becomes common and pyrite is abundant. At 260 m epidote appears.

310-312 m: Cement

312-368 m: Basaltic breccia. Mixed breccia, very rich in tuff. Abundance in crystalline grains, with plagioclase needles and phenocrysts. Very altered and rich in precipitations. Some red oxidized grains. Abundance in pyrite. Epidote colour is common and needles are seen. At around 330 m, the formation becomes denser with less precipitations.

368-418 m: Basaltic tuff. White/greenish tuff. Almost completely altered. Abundance in pyrite and precipitations. At 390–394 m probably the same tuff formation is found but somewhat changed. The formation is "coarser" and grainy. Some crystalline grains are admixed as well as reworked tuff.

418-468 m: Basaltic breccia. Probably a mixed breccia. Abundance of freshly looking basaltic fine-grained fragments, brownish in colour, plagioclase porphyritic and densely fractured. Altered green tuff grains admixed. Very few precipitations.

468-518 m: Fine- to medium-grained basalt. Mostly crystalline basalt. At first it seems rather fine grained, but the grain size becomes coarser. Somewhat mixed, but not much tuff is seen. Very altered. Porous, most pores empty. Grainy texture. Increase in epidote. Wollastonite is seen as well as plagioclase porphyritic.

518-568 m: Medium- to coarse-grained basalt. This unit at the top is closer to being fine grained but as we go down, the grain size increases and most of it is medium grain. This could indicate a surface lava formation. The grains are green or pink in colour. The texture is grainy, and the formation is very altered. Precipitations are scarce, except for an abundance of epidote. Plagioclase is noted. At the bottom, the formation becomes very rich in precipitation and mixed with tuff.

568-618 m: Coarse-grained basalt. Coarse grained. Fresher than the formations above. Large plagioclase and phenocrysts (can be seen without the microscope). Less precipitation than above. Epidote and quartz are seen but finding clay and prehnite is hard. Some oxidation is seen.

618-668 m: Coarse-grained basalt. Coarse grained. Fresher than the formations above. Large plagioclase and phenocrysts (can be seen without the microscope). Less precipitation than above. Epidote and quartz are seen but finding clay and prehnite is hard. Some oxidation seen. Large plagioclase and phenocrysts porous.

668-718 m: Basaltic breccia. In addition to a breccia, a possible intrusion is seen. There are still brecciated cuttings. The basaltic grains are very dark and cryptocrystalline. Less precipitation, the formation is very dense. At 708 m, the formation becomes very dense, also the breccia. Few precipitations are seen, but the formation is fractured.

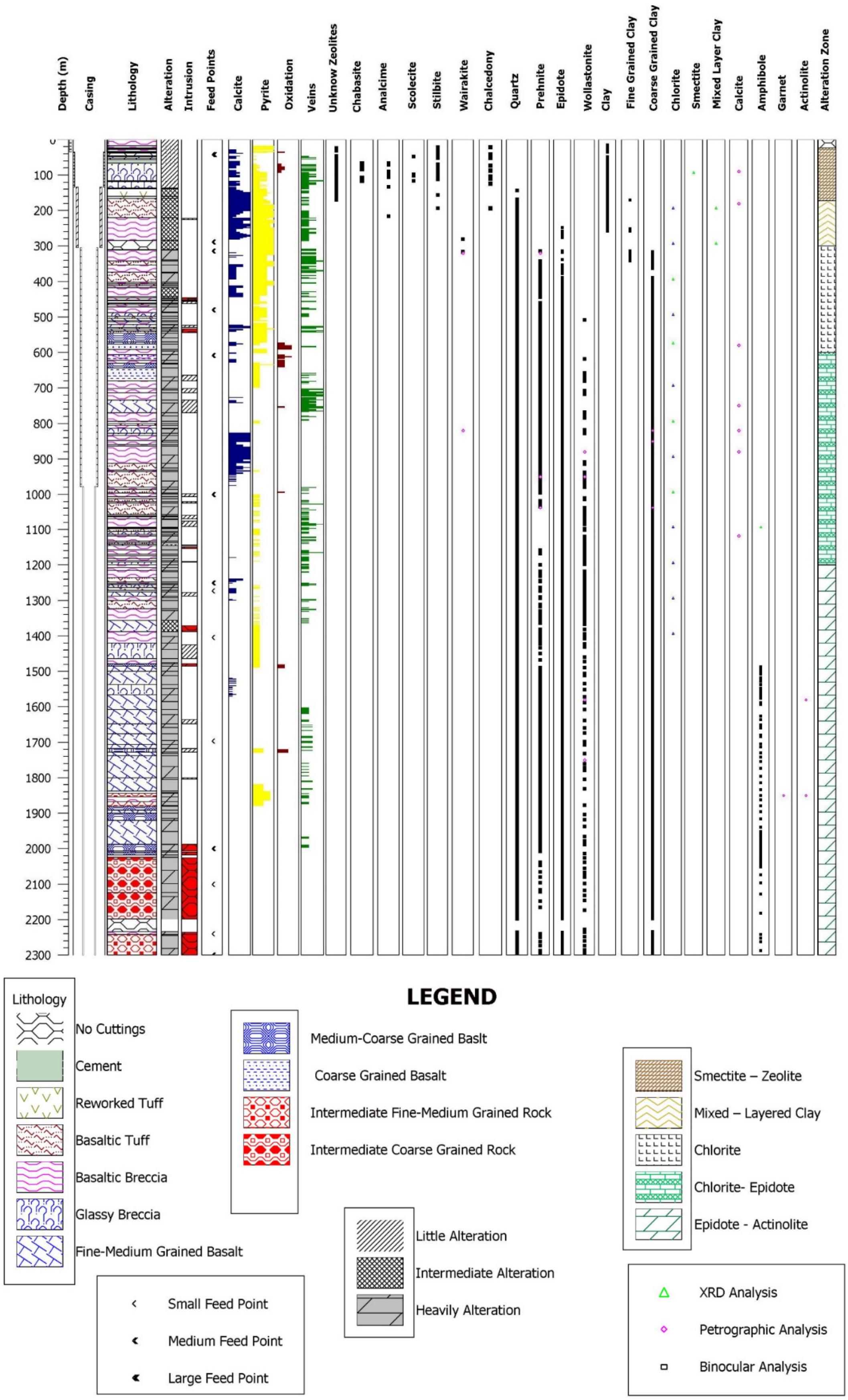


FIGURE 5: Lithology, alteration mineral distribution, intrusions, aquifers and alteration zones of well ThG-17 from 0 to 2300 m based on XRD analysis, petrographic and binocular analysis

718-768 m: Basaltic breccia. This unit contains very few of the fresh grains, most of it is altered breccia rich in tuff. Many grains look more like pumice than tuff. The breccia is composed of all grain sizes. Precipitations are scarce. At 725 m, almost all of the grains look like pumice and could be tuff. Almost no secondary minerals are seen except for some veining and some clays in the small pores.

768-818 m: Basaltic breccia. Altered breccia. Altered tuff grains mixed with plagioclase porphyritic basalt. Crystalline grains are seen, glassy and cryptocrystalline. Rich in tuff and precipitations.

818–868 m: Glassy basalt. This unit has many crystalline or crystalline grains mixed with glassy grains and tuff seems dense and not fractured. Abundance of precipitations. Calcite appears in high concentrations.

868-918 m: Basaltic breccia. Very similar to the large formation from 848 to 860 m. Very altered breccia rich in tuff. Precipitations are scarce but the amount of epidote increases at around 900 m. In most samples, it is possible to see quartz, epidote, chlorite and prehnite. In few samples, wollastonite is seen. Calcite is very common but starts decreasing a bit at 900 m. Some samples almost only consist of tuff, but most have some crystalline grains.

918-968 m: Basaltic tuff. Mostly tuff (90 to 95%) but could be a breccia since some crystalline grains are present in most samples (both very altered and less altered). Very rich in epidote. Wollastonite reappears. Cuttings are very small. Calcite had started to disappear and at 966 m and below, very little calcite is seen.

968–1018 m: Basaltic tuff. This formation has a large concentration of mostly tuff (90 to 95%). However, this could be a breccia since some crystalline grains are present in most samples (both very altered and less altered). Very rich in epidote. Wollastonite reappears. Cuttings are very small. Calcite had started to disappear and at 966 m and below, very little calcite is seen.

1018–1068 m: Fine- to medium-grained basalt. Mostly crystalline basalt mixed with some tuff.

1068-1118 m: Basaltic breccia. Intrusion grains decrease. Mostly glassy and half-crystalline grains. Very epidote rich and abundance of wollastonite. Some intrusion like grains, dense and dark grey.

1118-1168 m: Fine- to medium-grained basalt. Intrusion of dark and fine-grained basalt. Slightly plagioclase porphyritic. Little amounts of alteration minerals and decrease in alteration.

1168-1218 m: Basaltic breccia. Very tuff-rich formation. Tuff, partly crystalline grains and crystalline grains mixed.

1218-1268 m: Glassy basalt. Seems to consist of a lot of partly crystalline and crystalline grains, mixed with tuff.

1268-1318 m: Basaltic tuff. Some of the grains seem crystalline, with some red coating (oxidation?). Plagioclase needles often noticed in groundmass. Could be a tuff-rich breccia.

1318-1368 m: *Basaltic breccia.* This formation has coarser cuttings, crystalline basalt and glassy basalt mixed with tuff. Phenocrysts are completely altered. The crystalline basalt is both dark grey and green.

1368-1374 m: Glassy basalt. This formation has medium-grained basalt with plagioclase phenocrysts. Slight decrease in alteration minerals. At some intervals, the formation seems to be pillow breccia like, with more tuff grains.

1374-1420 m: Basaltic breccia. Mixed with fine- to medium-grained basalt, clinopyroxene-porphyritic and tuff grains.

1420-1464 m: Glassy basalt. Medium-grained basalt with clinopyroxene and plagioclase phenocrysts. Slight decrease in alteration minerals. At intervals the formation seems to be pillow breccia with tuff admixed.

1464-1478 m: Basaltic breccia. Mixed cuttings, composed of fragments from crystalline basalt, green glass and tuff. The basalt is mostly cryptocrystalline.

1478-1486 m: Medium- to coarse-grained basalt. Medium-grained basalt, rich in plagioclase, with granular texture. Very dense rock. Most probably an intrusion.

1486-1500 m: Fine- to medium-grained basalt. Brownish and grey-green fine- to medium-grained granular basalt. Non-porphyritic, with abundant small vesicles. Glass fragments are few. Most probably a lava flow. Wollastonite and actinolite are common.

1500-1538 m: Fine- to medium-grained basalt. Dense grey-green vesicular basalt. Mostly cryptocrystalline. With coarse-grained clays in vesicles. Lava flows. Sporadic calcite is seen at 1526-1540 m.

1538-1566 m: Glassy basalt. More diverse cuttings than above, grey to green in colour. Fine and cryptocrystalline. With abundant small vesicles filled with green coarse clay. With a moderate amount of green glass fragments admixed.

1566-1608 m: Fine- to medium-grained basalt. Dark grey and red-brown fine-grained basalt. With granular texture and sparse plagioclase porphyritic. With abundant small vesicles filled with clays. Most probably tholeiite basalt.

1608-1648 m: Fine- to medium-grained basalt. Grey brownish dense fine-grained basalt. With granular texture and non-porphyritic. The amount of epidote increases. Precipitations are few. Possibly an intrusion. Garnet is found within this unit.

1648-1676 m: Fine- to medium-grained basalt. The formation becomes more homogeneous than above but otherwise the same type of basalt. Precipitations are few.

1676-1706 m: Fine- to medium-grained basalt. Dark grey dense non-vesicular basalt. With granular texture, moderately vesicular. Tholeiite basalt. Garnet is seen occasionally.

1706-1718 m: Fine- to medium-grained basalt. Light green fine-grained basalt, dense. Light grey-brown cryptocrystalline basalt is found admixed. Sparsely plagioclase, porphyritic.

1718-1728 m: Medium- to coarse-grained basalt. Dark grey dense medium-grained intrusive rock. Minor amount of pyrite is seen.

1728-1738 m: Fine- to medium-grained basalt. Dense grey, red brown and green fragments of dense fine-grained basalt. Minor oxidation is seen.

1738-1800 m: Fine- to medium-grained. Dense fine-grained basalt, non-porphyritic. Epidote is abundant. Other alteration minerals are wollastonite, actinolite and garnet. Rather homogenous formation down to 1800 m. Lava boundaries may be present at 1770 and 1782 m (based of changes in colour). At intervals veins filled with epidote and clays are seen. Garnet is seen occasionally; no calcite is present.

1800-1838 m: Fine- to medium-grained. Grey and grey brown fine-grained basalt, non-vesicular. Rather diverse cuttings. Small vesicles filled with clays are common. Possible intrusion.

1838-1844 m: *Basaltic breccia.* Mixed cuttings composed of various types of crystalline basalt. Moderate amount of pyrite is present.

1844-1854 m: Intermediate- to fine- to medium-grained rock. Grey-white to white cuttings. Fine-grained and cryptocrystalline rock, with a glassy groundmass. Most probably a rock of silicic composition.

1854-1867 m: *Basaltic breccia.* Cuttings of various types of basalt and light-coloured rock above.

1867-1881 m: *Intermediate- to fine- to medium-grained rock.* Fragments of grey-white and whitish rock similar to what was found at 1844 m. The rock has a glassy groundmass.

1881-1892 m: Medium- to coarse-grained basalt. Dark grey and blackish medium-grained basalt. Actinolite is common.

1892-1900 m: Fine- to medium-grained basalt. Grey green and dark coloured fine-grained dense basalt, with just a few vesicles. Rather mixed cuttings.

1900-1920 m: Medium- to coarse-grained basalt. Mostly dark coloured dark grey medium-grained basalt, non-vesicular. With abundant epidote and actinolite.

1920-1987 m: Fine- to medium-grained basalt. From 1920 to 1987 m the formation is composed of fine-grained grey-brown and grey-green basalt. In general, the rock is dense with few vesicles. The grade of alteration is high. Epidote, actinolite and wollastonite are common alteration minerals. Possible lava boundaries may be present at 1936, 1946 and 1960 m. Rather homogenous formation.

1987-2007 m: Medium- to coarse-grained basalt/intermediate rock. Light coloured medium-grained rock with a white groundmass. With abundant small blackish speckles (iron-oxides and mafic minerals). Most probably an intrusion of a silicic composition.

2007-2010 m: Basaltic breccia. A layer of mixed cuttings from dark coloured basalt and light-coloured rock from above.

2010-2018 m: Medium- to coarse-grained basalt/intermediate rock. Light coloured medium-grained rock, most probably of silicic composition as at 1987 m.

2018-2024 m: Basaltic breccia. Mixed cuttings composed of various types of basalt and light-coloured rock.

2024-2030 m: Intermediate medium-grained rock. Light coloured medium-grained rock. Most probably an intrusion of silicic composition.

2024-2124 m: Intermediate medium- to coarse-grained rock. Light coloured medium-grained rock. Most probably an intrusion of silicic composition (diorite?). Epidote and green coarse-grained clay are abundant. Pyroxene and feldspar porphyritic.

2124-2198 m: Intermediate medium-grained rock. Light coloured medium-grained intrusive rock of silicic composition (diorite?). Mafic minerals are more pronounced than above, indicated by abundant small dark coloured speckles. The amount of pyroxene phenocrysts decreases.

2198-2234 m: No cuttings. Total loss of circulation, no cuttings retrieved.

2234-2242 m: Basaltic breccia. Mixed cuttings from medium-grained crystalline basalt and whitish silicic rock from above.

2242-2300 m: Intermediate medium- to coarse-grained rock/intrusion. Medium-grained silicic rock. Mostly composed of feldspar and pyroxene but with abundant small dark coloured speckles (mafic minerals). Epidote and dark green coarse-grained clays are abundant. Intrusion.

2.4 Intrusive rocks

An intrusion is an emplacement of magma into pre-existing rock. As such, intrusions usually show relatively coarser textures compared to the host rock since the subterranean magma cools slowly giving time for crystal growth (Lugaizi, 2011). Intrusive rocks are characterized by their massive compact nature and they appear fresh in comparison to the surrounding lithology and are sometimes marked by oxidation near their margins. Some intrusions were identified in well ThG-17 at different depths. Most of them appeared as darker and less altered formations, often crystalline and fresh at depth 446-770 m. However, at 998-1388 m many of them are thin and are composed of fine- and medium-grained basalt, moderately altered.

At 1400-1900 m dark-grey and blackish medium- to coarse-grained basalt are noted while at 1987-2300 m intermediate- to coarse-grained rocks were found.

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration refers to the change in mineralogy, texture, porosity and permeability of rocks due to its interaction with hydrothermal fluids. Secondary minerals replace the primary minerals because of the changes which the rock is subjected to. These changes are primarily variations in temperature, pressure, or chemical conditions or any combination of these. The fluids carry metals in solution, either from a nearby igneous source or from leaching out of nearby rocks. Hydrothermal fluids cause hydrothermal alteration of rocks by passing hot fluids through the rocks and changing their composition by adding or removing or redistributing components. Temperatures can range from weakly elevated to boiling. Fluid composition is extremely variable. They may contain various types of gases, salts (brines), water, and metals. The metals are carried as different complexes, thought to involve mainly sulphur and chlorine (Lagat, 2009).

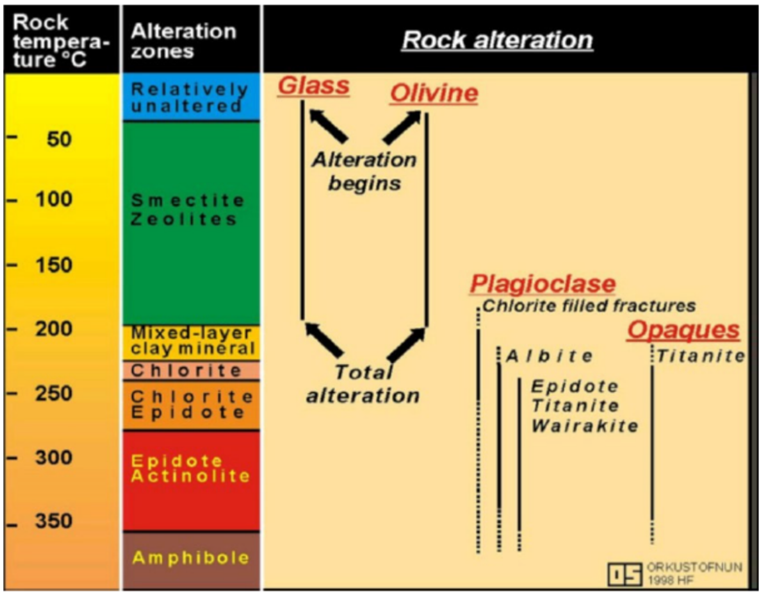


FIGURE 6: Mineral alteration vs. temperature diagram (Franzson, 1998)

In a geothermal system, hydrothermal alteration can reveal the history, and possibly the future, of the system involved. In addition, hydrothermal minerals are useful geothermometers and are used, for example, to assist in determining the depth of the production casing during drilling. Hydrothermal minerals are also used to determine the alteration temperatures of wells and, when compared to formation temperatures, can predict whether the rock formations in a specific area are cooling or heating (Reyes, 2000). Epidote, for example, starts to appear at about 240°C (Table 2). Figure 6 shows the mineral alteration zones in Iceland and the alteration of primary minerals vs. temperature.

TABLE 2: Selected temperature dependent index minerals in high-temperature areas in Iceland (Kristmannsdóttir, 1979; Franzson, 1998)

Minerals	Min. temperature (°C)	Max. temperature (°C)
Zeolites	40	120
*Laumonite	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 zeolite group ** Mixed layered clay		

3.1 Primary rock minerals and alteration products in well ThG-17

Primary minerals, crystallized from magma, governed by the physio-chemical conditions under which the magma solidifies, become unstable in a geothermal environment where there is high permeability, elevated temperature and intense fluid activity (Gebrehiwot, 2010). The primary constituents found in well ThG-17 are glass, olivine, plagioclase, pyroxene and opaque minerals shown in Table 3. The interaction between the host rocks and the hydrothermal fluids is the main factor that leads to the replacement of primary minerals with hydrothermal minerals while the process of fluid circulation affects mineral deposition in veins and cavities (Browne, 1978).

In Iceland's basaltic rocks Glass and primary minerals such as olivine, plagioclase, pyroxene and opaque minerals are seen. Glass is the most unstable constituent of basaltic rocks (Gebrehiwot, 2010).

TABLE 3: Glass and Primary minerals alteration in well ThG-17
(the arrow shows decreasing susceptibility to alteration)

Fresh / unaltered	Alteration products
glass	clay, zeolites, calcite, quartz
olivine	clay, calcite, quartz
plagioclase	clay, calcite, wairakite
pyroxene	clays, chlorite, wollastonite and actinolite
opaque	ferric oxides, pyrite

Volcanic glass: Amorphous quenched magma showing a highly vitreous lustre and good conchoidal fractures. It is the first constituent to be altered and replaced by alteration minerals. The replacement products of volcanic glass are clays, zeolites (e.g. mordenite, laumontite), quartz and calcite (Browne, 1978). At 90 m glass is been altered in well ThG-17 (Figure 7).

Olivine: Is very susceptible to alteration. It is distinguished in thin sections by its high birefringence, distinctive irregular fracture pattern and lack of cleavage. Olivine is green (colourless in thin sections) but transparent or translucent with a vitreous lustre (Figure 6).

Plagioclase: Is the most abundant primary rock mineral found in well ThG-17 and occurs as phenocrysts and in fine matrix. It is easily identified by its low relief and conspicuous polysynthetic twinning under a petrographic microscope (Figure 8). Plagioclase is relatively resistant to alteration but starts to alter to

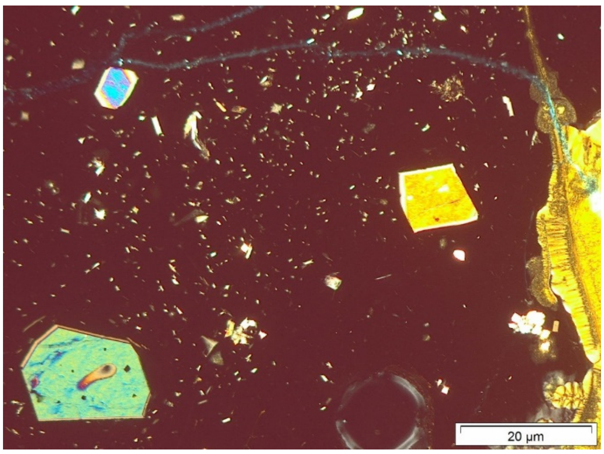


FIGURE 7: Thin section photograph under polarized light showing volcanic glass (black) with olivine (blue) and pyroxene (yellow) found at 90 m depth in well ThG-17

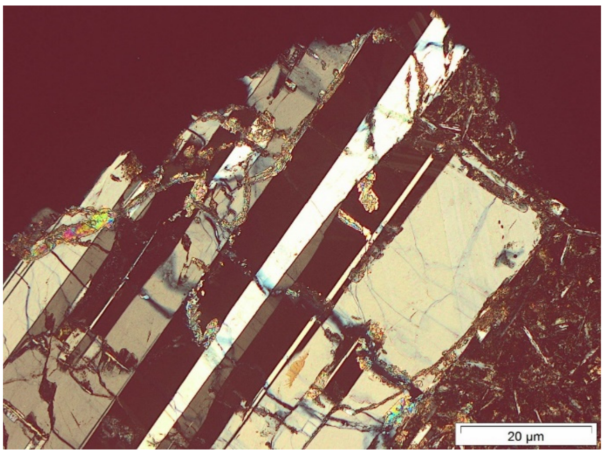


FIGURE 8: Plagioclase seen under polarized light at 390 m depth in well ThG-17

clay minerals and, with increasing temperature, changes to zeolite, albite, calcite, wairakite, chlorite and epidote.

Clinopyroxene: This is the main pyroxene mineral identified in well ThG-17. In the petrographic microscope it resembles olivine but differs by the presence of cleavage and inclined extinction. It is also resistant to hydrothermal alteration but may alter to clay, wollastonite and actinolite at higher temperatures. Some fresh pyroxene/clinopyroxene was identified in a thin section at 90 m (Figure 6).

Opaque: Those minerals are less altered compared to others. Magnetite/ilmenite occurs in small amounts in basaltic rocks and appears opaque in transmitted light. It is mildly altered in the well, in most cases only showing some signs of oxidation.

3.2 Distribution of hydrothermal alteration minerals in well ThG-17

Zeolites: They are classified into three main groups based on their shapes; fibrous/acicular, tabular/prismatic and granular (Kristmannsdóttir, 1979). In the uppermost part of the well zeolites are common in pores and fractures. In nature, zeolites are temperature dependent which can help to determine the temperature at a given depth in geothermal systems. In well ThG-17, zeolites appear at 26 m and can be found down to 172 m. The different types of zeolites in well ThG-17 are described below:

Unknown zeolites: In well ThG-17, there are several zeolites which are not identified. These zeolites were found between at following depths 26, 34, 48, 50, 56-136, 140 and 144-172 m.

Chabazite: Appears white or clear, rarely yellowish brown or slightly reddish. They are near-cubic crystals that show twinning, penetrating each other with corners projecting from their crystal faces. In this well, they appeared along with chalcedony at 70, 72, 74, 86, 110 and 118 m.

Analcime: Mainly forms colourless or white, many-sided crystals with a vitreous lustre. It occurs either as individual crystals or as clusters which glitter, as in the case of the colourless crystals. This crystal was found in the well at 68, 72, 74, 92, 100, 104, 108, 136 and 218 m depth.

Scolecite: It was found with the binocular microscope at 56, 100, 104, 118 and 230 m depth. It is a typical fibrous zeolite, four-sided and often densely packed. Crystals are flattened and form groups. It is colourless or white with vitreous or slightly silky lustre. It also appeared in the presence of other minerals like analcime and chabazite.

Stilbite: This mineral appears in many forms but most commonly as thick, tabular crystals with pointed terminations. It is generally milky-white but clear and translucent variations exist and coloured types, usually reddish-brown but sometimes greenish. Stilbite was seen at 24, 34, 38, 48, 54, 72, 78, 80, 82, 84, 88-92, 100-104, 114, 158 and 196 m depth.

FIGURE 9: Quartz found at 146 m with the binocular microscope

Quartz: In the binocular microscope, quartz is distinguished by its hexagonal shape and forms at temperature above 180°C (Franzson, 1998). Quartz first appears at about 146 m depth (Figure 9), but is seen continuously below 170 m.

Chalcedony: It is a form of silica with a cryptocrystalline texture (Kristmannsdóttir, 1979). It occurs in thin sections as a thin lining inside vesicles. It is colourless, grey to greyish blue and semi-transparent to translucent with a waxy lustre and occurs at 26, 90, 160 and180 m depth. Below that depth it was replaced by quartz. In thin sections, it is a vesicle filling, followed by fine-grained clay at 90 m depth (Figure 10).

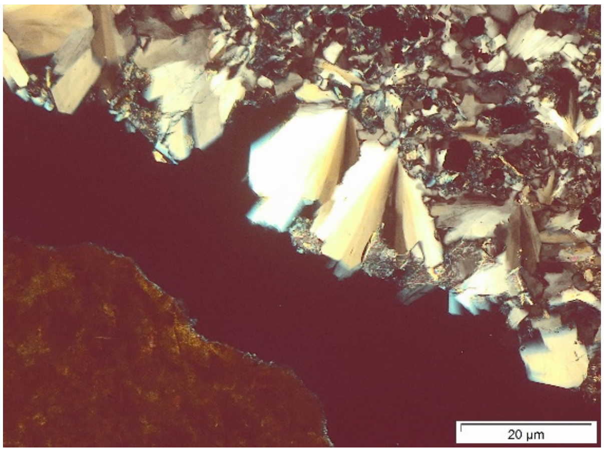
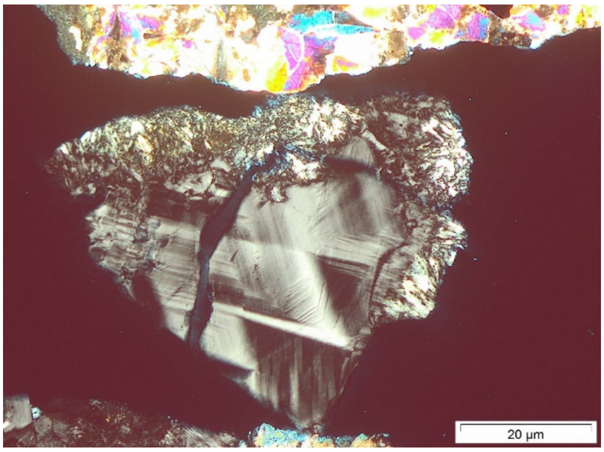


FIGURE 10: Cross polarized light photo of chalcedony in thin section sample found at 90 m depth in well ThG-17

Wairakite: This is considered a zeolite mineral that forms at temperature greater than 200°C (Kristmannsdóttir, 1979). This was seen at 282, 318, 320 and 820 m depth (Figure 11).

Epidote: This mineral forms at temperatures above 230°C and occurs in vesicles and fractures (Saemundsson and Gunnlaugsson, 2002). In well ThG-17, the first indication of epidote was at around 250 m, the cuttings had a yellowish colour,



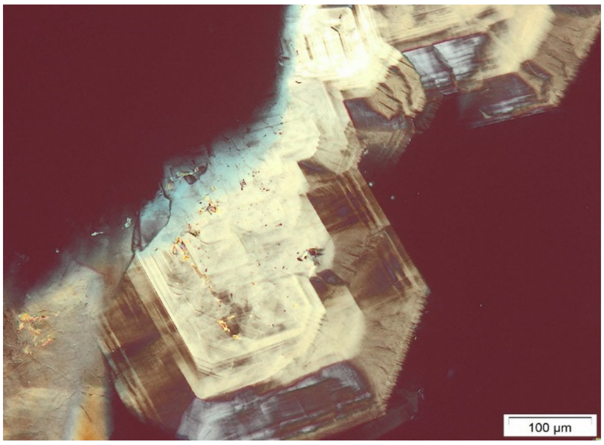


FIGURE 11: Cross polarized light photo of Wairakite found at 320 m depth (above), and under cross polarized light found at 820 m depth in well ThG-17

but the appearance of a well-crystallized epidote was seen at 398 m and in the thin section sample at 820 m (Figure 12).

Xonolite: This mineral crystallizes as a monoclinic prismatic crystal with typically an acicular crystal form or habit. It can be colourless, grey, light grey, lemon white, or pink. It is transparent with a vitreous to silky lustre (Figure 13).

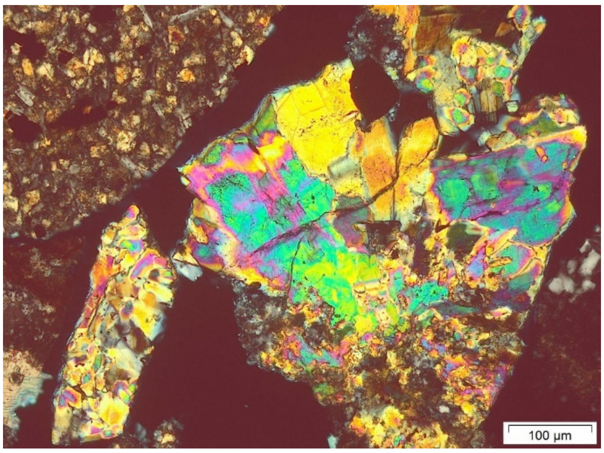


FIGURE 12: Cross polarized light photo of epidote seen in thin section sample at 820 m depth in well ThG-17

Pyrite: Like every other metallic mineral, pyrite is opaque and black in thin sections. However, unlike most other metallic minerals, it can often be identified by its cubic shape. In well ThG-17, pyrite is very common in the cuttings especially below 26 m. In thin section microscope, it appears opaque and yellowish (Figure 14).

Calcite: Its very easily identified using hydrochloric acid. In well ThG-17 the amount of calcite is very variable. It is most abundant below 180 m but at other deeper depth levels it is just a minor component (Figure 15).

Prehnite: It forms at a temperature above 240°C (Kristmannsdóttir, 1977). It forms small spherical crystal clusters with vitreous lustre, usually pale green in colour. In well ThG-17, prehnite was observed at 320 m depth (Figure 16).

Wollastonite: It has a needle/hair-like habit when observed under a binocular microscope. Formation temperature for wollastonite is about 270°C (Franzson, 1998). In well ThG-17, wollastonite was first identified in cuttings at 510 m and becomes common below 620 m (Figure 17).

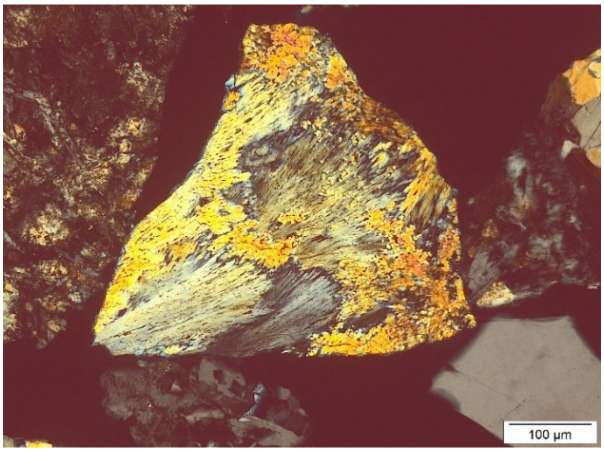


FIGURE 13: Cross polarized light photo of xonolite found at 1450 m depth, well ThG-17

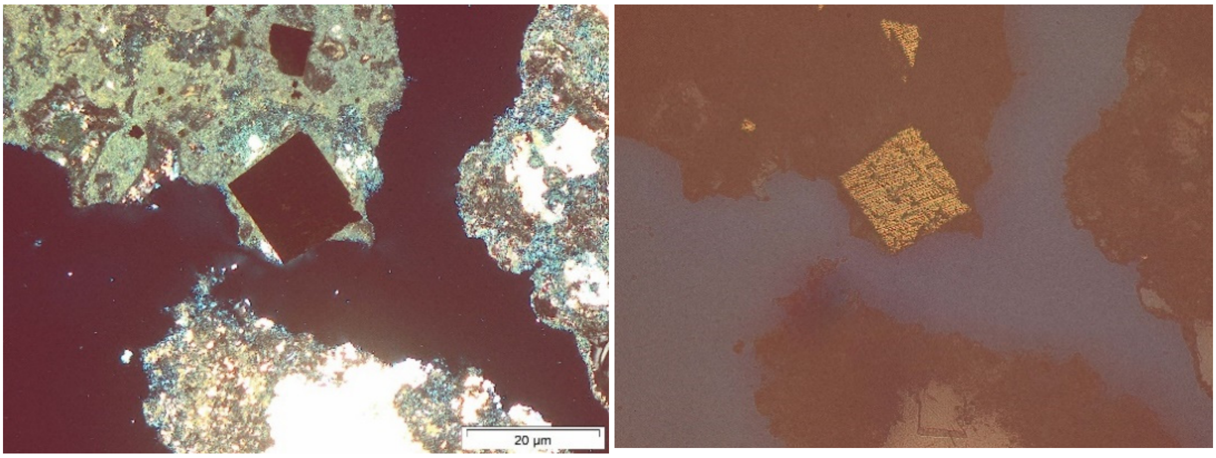


FIGURE 14: Pyrite found at 180 m depth in well ThG-17. Left: As black cube; Right: Plane polarized light and cross polarized light

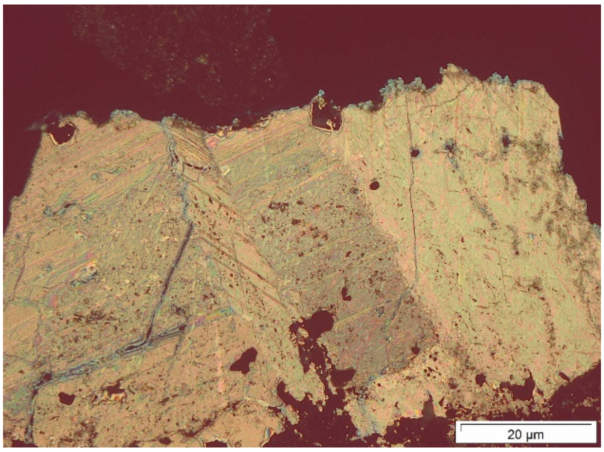


FIGURE 15: Plane polarized light photo of calcite found at 180 m depth in well ThG-17

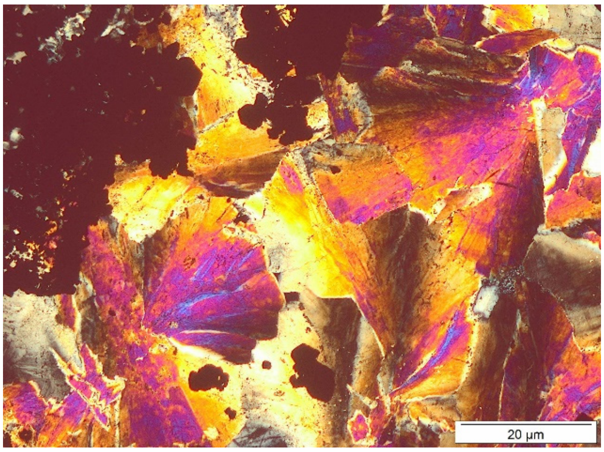


FIGURE 16: Plane polarized light photo of prehnite found at 320 m depth in well ThG-17

Actinolite: It belongs to the amphibole group and formation temperatures are above 280°C (Kristmannsdóttir, 1979). Actinolite is pale green coloured and exhibits a prismatic and fibrous habit under a binocular microscope. It was observed in cuttings at 1490 m depth and in thin sections at 1580 m (Figure 18) while XRD analysis identifies actinolite at 1094 m.

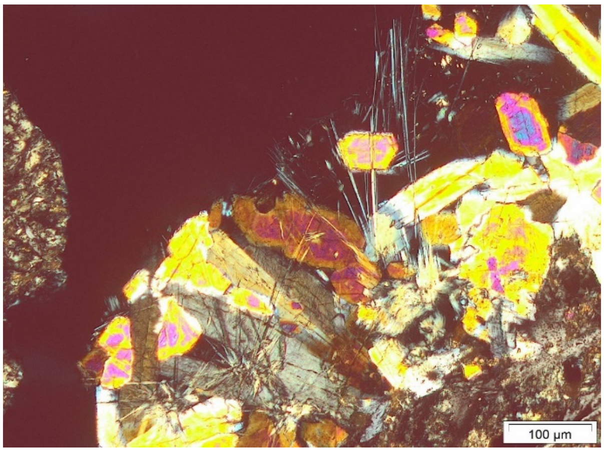


FIGURE 17: Plane polarized light photo of wollastonite seen at 1580 m in a thin section sample in well ThG-17

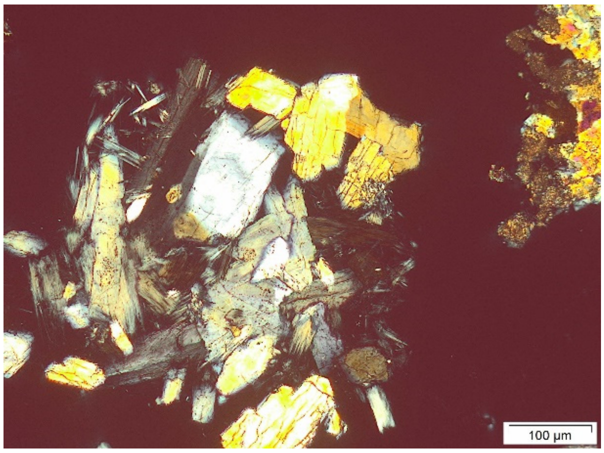


FIGURE 18: Plane polarized light photo of actinolite seen at 1580 m in a thin section sample in well ThG-17

Clay minerals: These phyllosilicates form by the alteration of primary silicate minerals such as plagioclase, pyroxene and olivine. Clay minerals were analysed using a petrographic microscope and XRD analysis. Table 3 lists clay minerals identified by the XRD method.

Smectite: It forms at temperatures below 200°C (Kristmannsdóttir, 1977). XRD analysis of the cuttings indicates that smectite occurs together with zeolite at 94 m.

Mixed-layer clay (MLC): This is formed by multiple clays filling fractures and voids. XRD and petrographic analyses of the cuttings from well ThG-17 identified mixed-layer clays at 172 m.

Chlorite: Chlorite is a clay mineral that forms at temperatures above 230°C (Kristmannsdóttir, 1979). In well ThG-17, chlorite occurs in a wide depth range. It was first identified by XRD analysis at 194 m and occurs throughout down to 994 m depth.

Garnet: In thin sections, garnet was found at 1850 m depth. This mineral was not very common in well ThG-17. It is found as a small and isotropic crystal. Garnet is usually seen as contact alteration mineral and indicates high-temperature conditions (Figure 19).

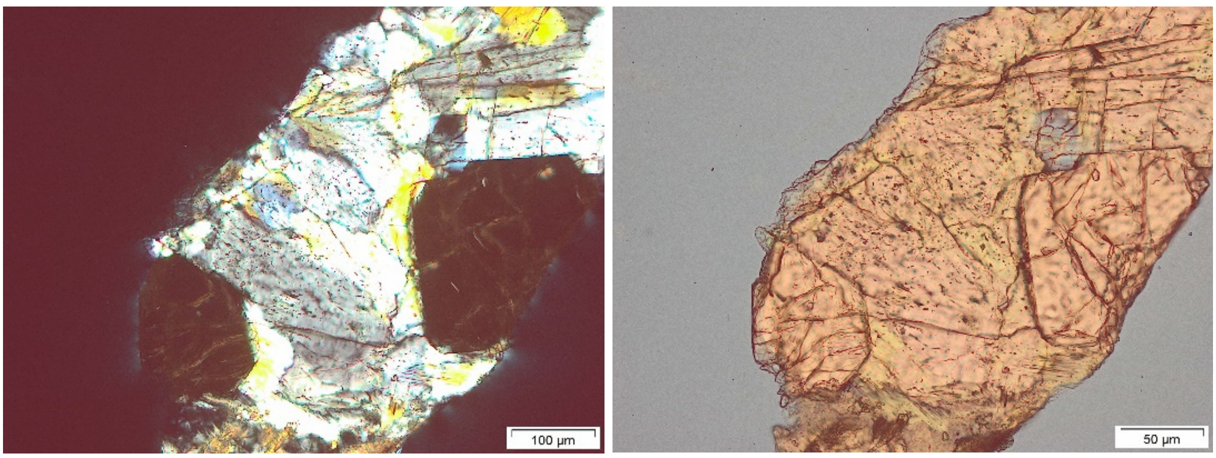


FIGURE 19: Plane polarized light photo of garnet seen at 1850 m in a thin section sample in well ThG-17

3.3 Alteration mineral zonation of well ThG-17

The first and last appearance of the hydrothermal minerals studied under both the binocular and petrographic microscopes were combined with the clay analyses from the XRD to create a time relationship of the minerals relating to the formation temperatures in well ThG-17. According to Kristmannsdóttir (1979), Saemundsson and Gunnlaugsson (2002) and Franzson (1998), in the Icelandic geothermal setting, low-temperature zeolites and amorphous silica form below 100°C, chalcedony below 180°C, quartz above 180°C, wairakite above 200°C, epidote above 230-250°C and garnet and amphibole above 280°C. From the group of alteration minerals identified in this study and with respect to their temperature of formation and their identification in XRD clay analysis, the alteration zones in well ThG-17 will be presented in these two forms:

1. Distribution of alteration minerals depending on zonation
Several alteration minerals zones were noted in well ThG17. These zones reach from low temperature to high temperature, beginning with an unaltered zone from the surface to a shallow depth, followed by the zeolite zone, quartz and wairakite zone, epidote zone and wollastonite zone.

2. Zonation based on clay analysis
Different zones of alteration were identified from the XRD analysis of clays which was carried out at several depths. These results were combined with the petrographic analysis and the zones identified are as follows. From the surface to a shallow depth there is an unaltered zone followed by the smectite zone, chlorite zone, mixed layer clay zone and finally the chlorite-amphibole zone. Based on temperature and abundance of clay alteration within a certain depth interval, the clay zones are described in Table 4.

Unaltered zone (0-24 m): This zone is composed of fresh rocks with no signature of alteration or development of any secondary minerals.

Zeolite-smectite zone (24-172 m): This zone is marked by the appearance of zeolite and smectite. Smectite were identified by XRD analysis at 94 m. Secondary calcite, pyrite, chalcedony and quartz are present in this zone.

Mixed-layer clay zone (172-300 m): This zone is characterized by mixed-layer clays forming in voids and fractures. XRD analysis identified mixed layered clay at 194 and 294 m. Illite was observed in this zone at 194 m.

TABLE 4: Results of clay minerals analysis by XRD

Sample no.	Depth (m)	d(001) untreated (Å)	d(001) glycolated (Å)	d(001) heated (Å)	d(002) (Å)	Type of clay
1	94	12.9	14.3	9.9	0	Smectite
2	194	31.2/14.6	31.2/14.6	0	7.2	MLC- unstable chlorite
3	294	31.6/14.6	14.6/7.2	0	10.2	MLC-unstable chlorite-illite
4	394	14.6	7.2	7.2	0	Chlorite
5	494	14.6	7.2	0	0	Unstable chlorite
6	594	14.6	7.2	7.2	0	Chlorite
7	694	14.6	7.2	0	0	Unstable chlorite
8	794	14.6	7.2	7.2	0	Chlorite
9	894	14.6	7.2	0	0	Unstable chlorite
10	994	14.6	7.2	7.2	0	Chlorite
11	1094	14.5/8.6/7.2	14.5/8.6/7.2	14.5/8.6	8.6	Unstable chlorite - amphibole
12	1194	14.6	7.2	0	0	Unstable chlorite
13	1294	14.7	7.2	0	0	Unstable chlorite
14	1394	14.7	7.2	0	0	Unstable chlorite

Chlorite zone (300-600 m): This zone is defined by the appearance of chlorite at 394 and 594 m. Wairakite and prehnite were observed at 320 and 580 m.

Chlorite-epidote zone (600-1200 m): It is defined by the appearance of epidote and chlorite. Wollastonite appears in this zone at 510 m.

Epidote-actinolite zone (1200- 2300 m): This zone is defined by the appearance of epidote and actinolite. Chlorite is also common in this zone. In cuttings, actinolite appears at 1490 m while in the XRD analysis it was observed at 1094 m depth.

3.4 Mineral deposition sequence

Minerals are formed at characteristic physio-chemical conditions during the history of geothermal systems. Many of these minerals formed by either replacement or deposition and are temperature dependent, hence, by studying their depositional sequence in veins or vesicles, one can scrutinize the parent thermal history and relative time scale of alteration minerals within a system (Gebrehiwot, 2010). The depositional minerals were mostly found in vesicles. The alteration mineral assemblages change from low-temperature minerals to moderate- to high-temperature minerals with increasing depth, indicating heating up of the system. Clay and calcite are the most common minerals in the mineral sequence in this well. The fine-grained clay is mostly found as thin linings in the walls of vesicles. Coarse-grained clay is found, especially as fillings in veins or vesicles (Table 5).

TABLE 5: Sequence of mineral deposition in well ThG-17

Depth	**Lithology**	**Alteration mineral sequence (older 4, 3, 2, 1, 0 younger)**
90	Glassy basalt	4. Fine-grained clay 3. Opaque minerals 2. Quartz
180	Basaltic tuff	4. Calcite 3. Chlorite 2. Pyrite
320	Basaltic breccia	4. Plagioclase 3. Chlorite 2. Coarse-grained clay 1. Calcite 0. Pyrite
390	Basaltic tuff	4. Coarse-grained clay 3. Wairakite
474	Basaltic breccia	4. Fine-grained clay 3. Quartz
580	Coarse-grained basalt	4. Chlorite 3. Calcite
660	Coarse-grained basalt	4. Fine-grained clay 3. Epidote
750	Fine- to med.-grained glassy b.	4. Fine-grained clay 3. Quartz 2. Epidote 1. Clay
820	Basalt	4. Coarse-grained clay 3. Quartz 2. Epidote 1. Opaque min.
880	Basalt breccia	4. Fine-grained clay 3. Calcite
950	Basaltic tuff	4. Epidote 3. Fine-grained clay
1038	Basaltic tuff	4. Fine-grained clay 3. Epidote
1118	Glassy basalt	4. Epidote 3. Clay
1312	Basaltic tuff	4. Chlorite 3. Wollastonite 2. Clay
1450	Glassy basalt	4. Fine-grained clay 3. Xonotlite
1580	Fine- to medium-grained basalt	4. Quartz 3. Actinolite
1750	Fine- to medium-grained basalt	4. Chlorite 3. Pyrite
1850	Inter. fine- to medium-grained basalt	4. Chlorite 3. Epidote 2. Opaque minerals
2050	Inter. fine- to medium-grained basalt	4. Coarse-grained clay 3. Epidote
2330	Inter. medium- to coarse-grained basalt	4. Plagioclase 3. Epidote 2. Actinolite

3.5 Thin section petrography

Sixteen thin sections samples from well ThG-17 were analysed using a Leica petrographic microscope at ÍSOR head office in Reykjavik. The sample intervals ranged from 90 to 2330 m (Table 4). Moreover, the objective of the analysis of the samples was to identify rock types, texture, primary minerals, alteration minerals, and the deposition sequence of alteration minerals in pores or fractures.

Primary minerals observed in thin sections are glass, plagioclase, pyroxene, olivine and opaque minerals. Plagioclase is the most abundant primary mineral in well ThG-17 (Table 6). Plagioclase occurred in the groundmass as well as phenocrysts in fine to medium-grained crystalline basaltic rocks. Secondary minerals identified in thin sections are chalcedony, quartz, chlorite, oxides, wairakite, pyrite, calcite, epidote, wollastonite, prehnite and xonotlite. Figures 8 to 16 show photographs of secondary alteration minerals observed at various depths.

TABLE 6: Results from the thin section petrography

Depth (m)	Rock type	Primary minerals	Secondary minerals	Comments
90	Glassy basalt	Pl, Gl, Op	Zeo, Py, Chal	Glass, freshly altered
180	Basaltic tuff	Pl, Op	Zeo, Qz, Cal, Py	Tuff, more homogenous
320	Basaltic breccia	Pl, Px, Op	Zeo, Qz, Cal, Wrk	Breccia, very altered
390	Basaltic tuff	Pl, Op, Px	Zeo, Qz,	Completely altered
474	Basaltic breccia	Pl,	Zeo, Qz, Py	Very altered & porous
580	Coarse-grained basalt	Pl, Px,	Qz, Cal, Ph, oxide	Coarse-grained basalt
660	Coarse-grained basalt	Pl, Px, Op	Qz, oxide	Coarser-grained basalt
750	Fine- to med.-grained gla. b.	Pl, Px, Op	Qz, Cal, Ep, oxide	Intrusive, dark grains
820	Basalt	Pl, Px, Op, Ol	Chl, Qz, Cal, Ep	Mostly glassy basalt
880	Basaltic breccia	Pl, Op, Px	Chl, Ep, Qz, Cal, py	Very altered breccia
950	Basaltic tuff	Op, Px,	Chl, Ep, Qz, Wo, Ph	Rich in epidote
1038	Basaltic tuff	Px	Qz, Ph, Chl	Fractured grains
1118	Glassy basalt	Pl, Op, Px	Qz, Ep, Chl, Cal	Glassy basalt & porous
1312	Basaltic tuff	Pl, Op, Ol, Px	Qz, Ep, Oxide	Red coating (oxidation)
1450	Glassy basalt	Pl, Op, Ol, Px	Ph, Ep, Wo, Xo	Possible pillow breccia
1580	Fine- to medium-grained basalt	Px, Pl, Op	Qz, Cal, Ph, Ep, Wo, Act	Vesicles filled with clay
1750	Fine- to medium-grained basalt	Pl, Op, Px	Qz, Cal, Ph, Py, Ep, Wo	Abundant in epidote
1850	Inter. fine- to medium-grained basalt	Pl, Px, Op	Qz, Py, Ep, Act, Gnt, Oxide	Glassy groundmass
2050	Inter. fine- to medium-grained basalt	Pl, Op, Px	Qz, Ph, Py, Ep	Coarse-grained clays
2330	Inter. medium- to coarse-grained basalt	Pl, Op, Px	Qz, Py, Cal, Ep, Act	Coarse-grained clays
Pl: plagioclase; Qz: quartz; Zeo: Zeolites; Ol: olivine; Gl: glass; Chl: chlorite; Op: opaque minerals; Act; actinolite; Cal: calcite; Ep: epidote; Py: Pyrite; Wrk: wairakite; Wo: Wollastonite; Px: pyroxene; Ph: Prehnite; Chal: Chalcedony; Xo: Xonotlite, Act: Actinolite, Gnt: Garnet				

4. AQUIFERS (FEED ZONES)

Feed zones or aquifers are horizons or limits that are sufficiently permeable to produce significant quantities of water for wells and springs. An aquifer simply involves the ability of rock layers to store and transmit water. Generally, aquifers are extensive and may be overlain or underlain by confining layers of relatively impermeable rocks. The type of rock formation, permeability and its porosity govern the movement of ground water. The pores, cavities and apertures serve as water conduits. Secondary structures such as faults, joints, fractures, solution openings and lithological contacts are fundamental indicators of feed zones in wells (Reyes, 2000). The main objective of geothermal production drilling is to penetrate a permeable high-temperature zone. In Iceland, geothermal fields with the highest permeable zones intercepted during drilling are associated with dykes and faults (Arnórsson, 1995).

The feed zones in ThG-17 are attested by drilling data, loss of circulation, temperature logs and wireline logs carried out after drilling. The feed zones are ranked into three classes, from 1–3, based on their relative sizes. All the feed zones are considered small to moderate in size. The most permeable feed zones are located at 2030 m and 2300 m (Figure 5 and 20).

Small feed points: Nine small feed points were observed throughout the well at various depths.

Medium feed points: Seven medium feed points were identified at 288, 314, 480, 608, 1250, 2000 and 2300 m. Only two of these feed points are in the production zone of the geothermal reservoir, the three that are higher up have been cased off.

Large feed points: Only two large feed points, located at 42 and 56 m, have been identified. These, however, are not within the production zone of the geothermal reservoir.

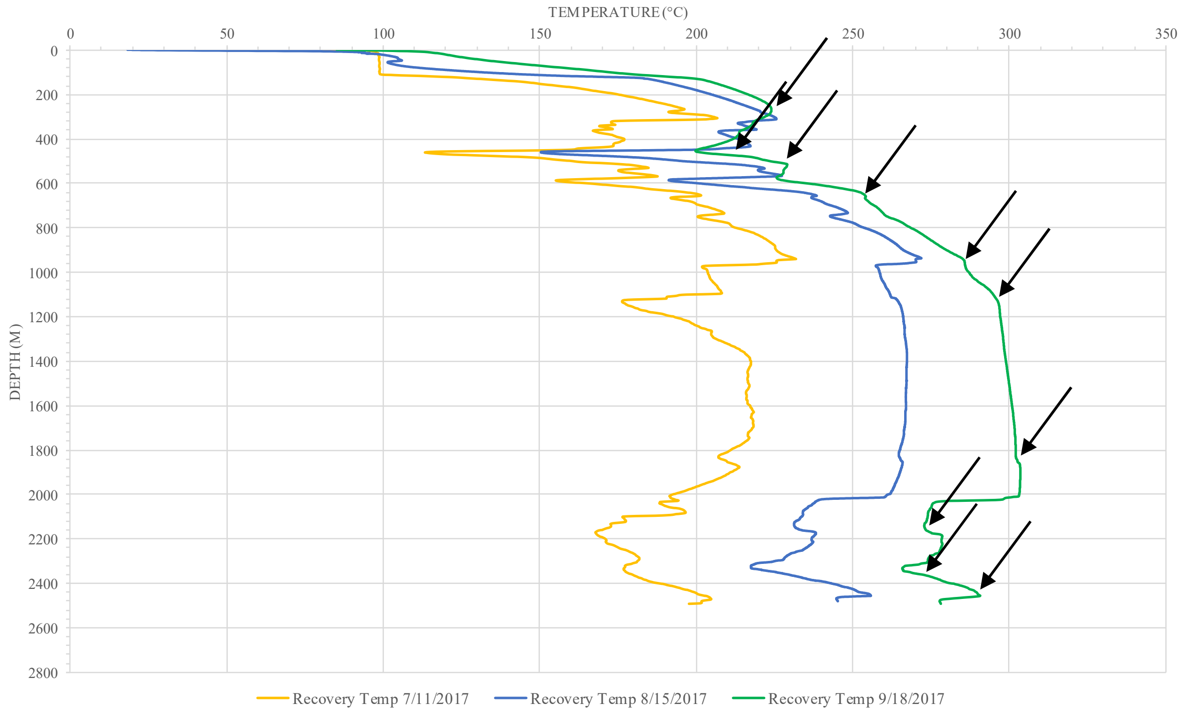


FIGURE 20: Temperature logs from the time of drilling showing aquifers (black arrows) based on temperature change in well ThG-17

5. DISCUSSION

Generally, the stratigraphy of well ThG-17 consist of hyaloclastites (breccia, tuff and glassy basalt, fine- to medium-grained rocks, intermediate-fine- to medium-grained rocks and intermediate-medium- to coarse-grained rocks). These phases were composed of different hyaloclastite formation with glassy basalt being dominant but also tuff, reworked tuff and basaltic breccia were identified.

The distribution of alteration minerals in well ThG-17 is divided into three zones, shallow zones, the middle zone and the lower zone. The temperature ranges from low temperature to high temperature. In the shallow zone there are some unknown zeolites, stilbite and chalcedony are found. Zeolite minerals such as scolecite, analcime and chabazite appear at 56, 68 and 70 m, respectively. These are followed by moderate-temperature alteration minerals such as zeolites which are replaced by quartz, mixed layer clay, and wairakite from 146, 160 and 282 m, respectively, in the lower middle zone of the well. High-temperature alteration minerals like prehnite, epidote and wollastonite, garnet and actinolite are common within the upper middle and lower zone of the well.

Minerals that were hydrothermally altered in well ThG-17 were studied and significant insight was obtained regarding their temperature, permeability and thermal evolution within the geothermal system. The manifestation of temperature dependent alteration minerals like zeolites, quartz, wairakite, epidote, chlorite, prehnite, wollastonite, garnet and actinolite allow the establishment of a temperature curve (Figure 21) for comparison with the measured temperature logs of the well.

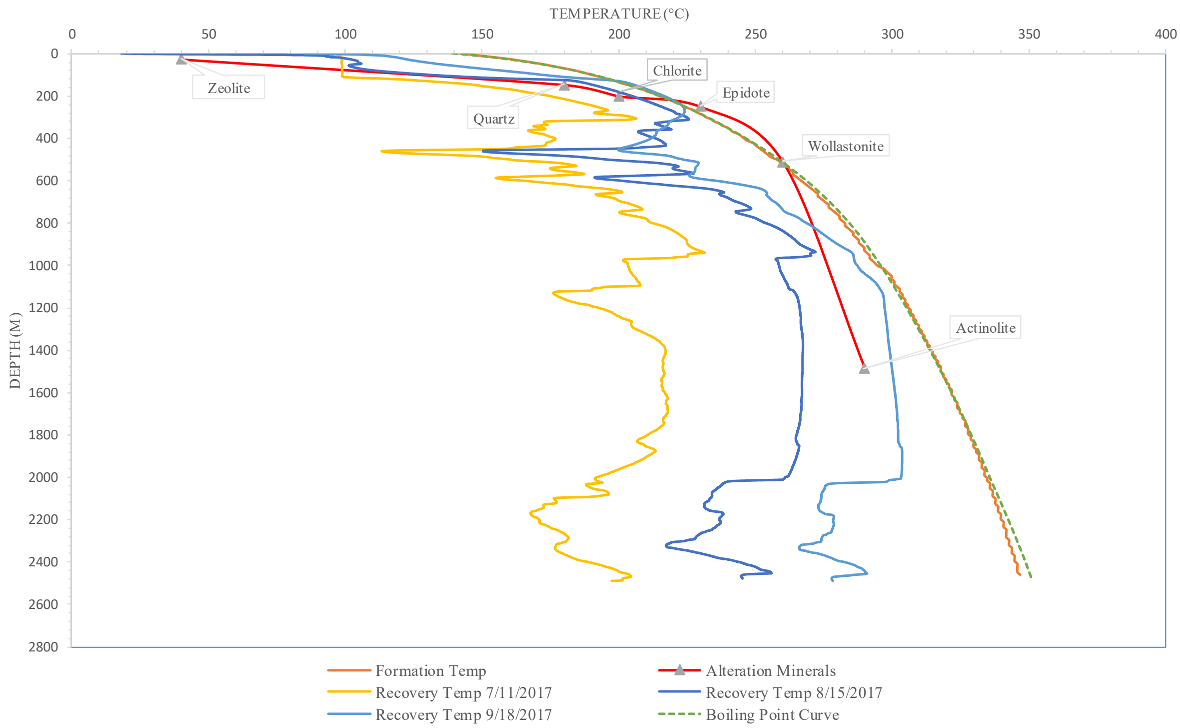


FIGURE 21: Formation profile, recovery profile, boiling point curve, and alteration temperature of well ThG-17

An analysis of the temperature logs (Figure 21) illustrates that the geothermal system follows the boiling point curve in the upper 300 m. However, a temperature reversal occurs around 400 m. This decline in measured temperature reflects cooling of the geothermal system possibly due to an influx of cold water through highly permeable zones. Notwithstanding, the temperature recovers and continues to follow the boiling point curve and alteration. However, another temperature reversal occurs below 2000 m. This decline in measured temperature exhibits a cooling of the geothermal system in the lower section which again could possibly be due to an influx of cold water through highly permeable zones and/or fractures intersected in the lower section of the well.

6. CONCLUSIONS

Based on the results of the study of well ThG-17 using various methods, the following can be concluded:

- The stratigraphy of well ThG-17 is composed of a hyaloclastite formation (glassy basalt being dominant, tuff, reworked tuff and basaltic breccia) with fine- to medium-grained and medium- to coarse-grained crystalline basalt. In the deepest part, where no cuttings were recuperated, the formation seems to be composed of intrusive rocks most likely of intermediate and silicic composition.

- Two types of alteration zones were identified. The first was based on the clay minerals and the other on the alteration mineral assemblages. Based on the clay mineral congregation, six alteration zones were recognized. These zones are an unaltered zone (0-24 m), a zeolite-smectite zone (24-172 m), a mixed layer clay zone (172-300), a chlorite zone (300-600 m), a chlorite-epidote zone (600-1200 m) and a epidote-actinolite zone (1200-2300 m).

- The second type, based on the alteration minerals, includes a quartz zone (146-282 m), a wairakite zone (282-320 m), a prehnite zone (320-398 m), an epidote zone (398-510 m), a wollastonite zone (510-1094 m), an actinolite zone (1094-1850 m), and a garnet zone (1850-2300 m).

- Within well ThG-17 all feed zones are considered small to moderate in size but generally the well has moderate permeability. The major permeable feed zones are located between 1252 and 2117 m, and between 2148 and 2300 m. However, the most permeable feed zone is considered to be at 2030 m and 2300 m, are associated with circulation losses, and measured temperature logs after drilling.

- The correlation of alteration temperature and homogenization temperature with formation temperature shows that the system is experiencing variable conditions. In the upper 400 m of the well it seems to be in equilibrium, but below for the next 200 m, a feed zone or a shallow well is indicated by the temperature decline. In the middle part from 600 to 2000 m, the system seems to be heating and in the lower part from 2000 m, the system seems to be cooling.

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